

Article

# Key Issues on the Design of an Offshore Wind Farm Layout and Its Equivalent Model

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Received: 11 April 2019; Accepted: 29 April 2019; Published: 9 May 2019



**Featured Application:** This work can be an important reference for offshore wind farm planning and simulation.

**Abstract:** Offshore wind farms will have larger capacities in the future than they do today. Thus, the costs that are associated with the installation of wind turbines and the connection of power grids will be much higher, thus the location of wind turbines and the design of internal cable connections will be even more important. A large wind farm comprises of hundreds of wind turbines. Modeling each using a complex model leads to long simulation times—especially in transient response analyses. Therefore, in the future, simulations of power systems with a high wind power penetration must apply the equivalent wind-farm model to reduce the burden of calculation. This investigation examines significant issues around the optimal design of a modern offshore wind farm layout and its equivalent model. According to a review of the literature, the wake effect and its modeling, layout optimization technologies, cable connection design, and wind farm reliability, are significant issues in offshore wind farm design. This investigation will summarize these important issues and present a list of factors that strongly influence the design of an offshore wind farm.

**Keywords:** offshore wind farms; wake effect; layout optimization; equivalent wind-farm model; wind farm reliability

## 1. Introduction

Wind energy is recognized as an important renewable energy resource, whose development has mostly involved the construction of onshore and offshore wind farms. Worldwide installed wind generation capacity reached 600 GW in early 2019, of which 53.9 GW were added in 2018. A typical offshore wind farm may include hundreds or thousands of wind generators [1], spread over several to tens of kilometers. To maintain a minimum degree of reliability, many schemes are used to locate the wind turbines and design the internal electrical connection system [2–7]. Planners must use the best scheme for their purposes. The integration of large-scale wind generation capacity affects the operation of a power grid. The equivalent modeling of wind farms has become important for analyzing the active and reactive power output characteristics of such power grids [8–11]. The precise modeling of the dynamic properties of a wind farm is the basis for integrating it into a power grid.

This investigation summarizes numerous important issues concerning the optimal design of an offshore wind farm layout and the modeling of an equivalent offshore wind farm. These issues involve wake models, wind farm efficiency, collected system design, techniques for optimizing wind turbine locations and cable connections, wind farm reliability, the cost of development of an offshore wind farm, the equivalent model of a wind power plant, and the parameters of an equivalent wind farm.

## 2. Wake Models

Determined by the layout and the wind conditions of wind farms, the power loss of a downstream wind turbine easily reaches up to 50% under full-wake conditions. Thus, modeling of the wake effect is important. Numerous wind-farm design tools that apply different analytical wake models [12–14] or computational fluid dynamic (CFD) flow solvers [15,16] have been developed to calculate the power losses of wind farms. Generally, analytical wake models, such as Lissaman's model or Jensen's model, are simpler than CFD flow solvers and require less computational time to estimate power generation by wind farms and power losses due to wakes. Such models involve algebraic equations for turbine-induced wake velocities and superpositions of multiple turbine wakes. When these models are used to determine wind farm configuration, the wake intensity for one wind turbine (also called a single wake) is calculated first, and then the superposition of the single wakes of several wind turbines in the wind farm (multiple wake) is calculated.

One of the most widely used wake models (now called the Park model) was proposed by N.O. Jensen, and subsequently modified by Katic. It is a relatively simple wake model, which assumes a linearly expanding wake with a velocity deficit that depends only on the distance of the wake behind the rotor. The Jensen wake model was thus derived by conserving the momentum downstream of the wind turbine. The velocity of the wake is a function of the downstream distance from the turbine hub and the wake is assumed to expand linearly downstream. Accordingly, the Jensen wake model is strictly applicable only in the far wake region. Numerous comparisons of wake models have concluded that all models have highly uncertain performance [16]. However, many researchers recommend the use of the Jensen model to predict the power output of offshore wind farms in the past.

The wake effect is more severe in larger wind farms. A particular turbine may be influenced by the wakes of more than one turbine. Such a situation is called the multiple wake effect [17]. Detailed models that consider the areas in the shadow of upstream wind turbines exist. The corresponding effect is called partial shadowing. Moreover, many investigations provided schematic wake models that involve wind turbines with different hub heights [18]. Some investigations have found that the use of various hub heights increases the power output of a wind farm even if the total number of wind turbines is constant [19].

Some analytical wake models, such as the Park Model, have been implemented using industry-standard software, including Wind Atlas Analysis and Application Program (WAsP), WindPro and Garrad Hassan (GH) WindFarmer to assess wind resources and for the micro-siting of wind turbines and wind farms [20,21]. A modified version of WAsP allows Jensen's model to be used with turbulence models. Alternatively, CFD solvers are based on the solution to the averaged or filtered Navier Stokes equations. In current years, numerous works [22–24] have presented models for simulating the turbine wakes and associated power losses of actual wind farms.

## 3. Power Losses and Wind Farm Efficiency

Like the wake decay effect, wind direction and wind farm layout importantly influence wind farm performance. Thus, changes in wind direction or wind farm layout cause changes in the interaction of wakes and the power output of a wind turbine. Wind turbine spacing, wind speed, ambient turbulence intensity, and atmospheric stability also affect power losses and wind farm efficiency. One analysis [25] revealed that, averaged over a wind speed from  $5 \text{ m}\cdot\text{s}^{-1}$  to  $15 \text{ m}\cdot\text{s}^{-1}$  and a turbine spacing of 5.8 to 20 rotor diameters, a 1D change in spacing causes a change in efficiency of 1.49% at Nysted and 1.06% at Horns Rev offshore wind farms, respectively. Furthermore, power losses that are caused by wakes depend strongly on wind speed. Efficiency is only 60% of that predicted using the free stream wind speed for directly-down-the-row wakes at low wind speeds but is larger than 97% thereof at wind speeds above  $15 \text{ m}\cdot\text{s}^{-1}$ . Analysis of the variation in efficiency with wind speed from  $5 \text{ m}\cdot\text{s}^{-1}$  to  $15 \text{ m}\cdot\text{s}^{-1}$  demonstrates an increase in efficiency of about 1.73% and 2.39% for every  $1 \text{ m}\cdot\text{s}^{-1}$  increase in wind speed at Nysted and Horns Rev, respectively [25]. Wind farm efficiency increases with ambient

turbulent intensity and atmospheric mixing tends to promote the recovery of wind turbine wakes, increasing wind farm efficiency.

#### 4. Optimization of Wind Turbine Layout

From both engineering and economic perspectives, wind farm layout is a key aspect of wind farm design. Using various wake models, numerous investigations have developed various wind-turbine layout optimization methods. In those studies, the optimal locations of wind turbines were designed by using various objective functions that take the maximum wind generation into account.

Generally, wind farm optimization problem is defined using four basic elements, which are data, problem variables, the objective function, and constraints. Those data comprise wind data, turbine data, wake effect data (such as the decay factor), wind farm data (such as water depth and foundation costs), cable data, and substation data. With regard to wind-speed data, several studies [26] have used the same wind scenarios: (a) Single wind direction with a  $12 \text{ m}\cdot\text{s}^{-1}$  wind speed, (b) single wind speed of  $12 \text{ m}\cdot\text{s}^{-1}$  and variable wind directions ranged between  $0^\circ$  to  $360^\circ$ , and (c) a wind direction that is equally likely to be in ten ranges of  $36^\circ$  and with a variable wind speed of  $8 \text{ m}\cdot\text{s}^{-1}$ ,  $12 \text{ m}\cdot\text{s}^{-1}$  and  $17 \text{ m}\cdot\text{s}^{-1}$ . Other wind scenarios about wind conditions involve (a) a single wind direction with a constant wind speed, (b) measurements made at a real wind farm, (c) single and multiple wind directions with a fixed wind speed, or (d) wind conditions that are generated using a Weibull distribution function.

A set of constraints determines the feasible ranges of problem variables. The numerous important constraints in the wind farm layout problem include minimum distance between turbines and the area limits of the wind farm area. For safety, the minimum distance among wind turbines in a wind farm is generally limited to four rotor diameters. Numerous investigations have utilized the Annual Energy Production (AEP) as the objective function.

As the basic elements of the optimization problem have been defined, its mathematical programming definition can be provided and the solution obtained using various methods. Such a problem is a nonlinear mathematical programming problem with linear and non-linear inequality constraints. Several works have compared different technique about the optimization [27,28]. In the early stage, genetic algorithms have been frequently utilized to solve the optimal wind farm layout problem [29]. However, many other algorithms have recently been proposed for the purpose [30–34]; they include the binary artificial algae algorithm (AAA), the bionic method, the ant colony algorithm, the minimum spanning tree algorithm, particle swarm optimization, Gaussian particle swarm optimization with a local search strategy, the turbine distribution algorithm, the extended pattern search method, the neural network algorithm, the evolutionary strategy algorithm, and quality threshold clustering. For instance, the study in reference [30] applied different binary algorithms with various transfer functions of AAA to solve the problem of wind turbine locations; the result demonstrates that the proposed algorithm obtains an effective placement of wind turbines with a larger number of grids. However, those optimization problems only considered the optimal layout of wind turbines; the internal cable connections and the collector system were not considered.

The placement of wind turbines could also refer to other optimization algorithms that have been applied to other energy-related areas, such as the distribution system expansion planning [35] and the allocation of storage devices and renewable generators [36]. In reference [35], the planning of the electrical power distribution systems was investigated by considering the variation and uncertainty from renewable energy sources, and a two-stage stochastic programming model was used; additionally, different techniques about the optimization were also compared. Reference [36] developed a mixed integer conic programming model to obtain the optimal size and location of distributed generators in a distribution system; the developed model considered the uncertainty from renewable energy sources into its decision-making. The above-mentioned optimization algorithms could be applied to the placement of wind turbines with specific objective functions and constraints. That is, although the same optimization algorithm is used, different industry applications would have different considerations, objective functions, and constraints. For the application of wind turbine placement, the wake loss,

the wind-farm boundary, the distance between two turbines, forbidden zones, and the allowed turbines in a feeder should be considered. However, other applications could have different considerations.

## 5. Collector System in a Wind Farm

The internal electrical system of an offshore wind farm and its connection to the main power system pose special challenges. Electrical power losses affect the economics of wind farm operation. Investments to reduce losses can provide substantial returns in the long run. Electrical collector systems can normally be designed with various layouts, depending on the size of the wind farm and the desired collector reliability [37–40]. Possible configurations of electrical collector systems include radial, single-sided ring, single return, star, double-sided ring, multiple rings, and multi-hub ring configurations [41].

The simplest arrangement of a collector system in wind farms is radial. The main advantages of such a layout are the low cable costs and the simplicity of the control algorithms. The disadvantage is the relatively poor reliability. The ring layout uses a redundant connection between the strings of wind turbines, but the use of longer cables with higher cable ratings increases the expense. Generally, a ring arrangement performs better in large offshore wind system as it provides fewer losses than the radial system in both normal and contingency operations. It also provides larger grid security. The star design enables cable ratings to be reduced and provides a high level of security throughout the wind farm. This design is also likely to support better voltage regulation along the cables between wind turbines. The aforementioned configurations of electrical collector systems all have advantages and disadvantages. However, the basic designs of current offshore wind farms are radial and ring designs [41]. For example, the radial design was used for the 160 MW Horns Rev offshore wind farm in Denmark, and this design has been proposed for many other offshore wind farms that are in the planning stage, including the 640 MW Krieger's Flak wind farm in Sweden and the 420 MW Cape Wind offshore wind farm in the USA.

The IEEE PES Wind Plant Collector System Design Working Group has addressed the issues related to the design of collector systems for offshore wind farms [42], and they have summarized some important design considerations, such as the topology of feeders, the design of collector systems, interconnect, and NESC/NEC requirements. They have also provided design guidelines that are based on reliability, economics, and redundancy.

## 6. Wind Farm Reliability

The wake effect influences the output of a wind farm. The failure of one or more wind turbines may change the wind speed distribution in the farm and consequently its power output. Therefore, the output of an offshore wind farm depends on both wake effect and wind farm reliability [43–45]. Several reliability indices have been proposed to capture the effectiveness of generating systems, including loss of expected energy not supplied (EENS), loss of load probability (LOLP), load expectation (LOLE), and expected energy produced (EEP). These reliability indices can be also applied to wind farm reliability.

Important aspects of a realistic assessment of the reliability of wind generation include wake effects, the offshore environment, wind turbine technology, the types of wind turbines in the installation site, the power collection grid, the output powers of different types of wind turbines, and hub height. For example, the choice of wind turbine technology and its components affect the values of the some of the parameters in the analysis—especially on the failure/repair rate and maintenance for wind turbines. However, few data on the maintenance and failure/repair rates of offshore wind turbines are available owing to their relatively recent development. Power collection system availability also affects the reliability of an offshore wind farm. Numerous investigations have used Monte Carlo simulations to evaluate the reliability of wind farms with various internal cable connections [41,46].

## 7. Cost of Developing an Offshore Wind Farm

The cost of developing an offshore wind farm has attracted considerable attention in both academia and industry. Numerous models have been developed to estimate the costs of offshore wind farms worldwide [47,48]; for example, a response surface-based wind farm cost model has been proposed for the engineering planning of offshore wind farms using Extended Radial Basis Functions [49]. This model has been used to examine the effects of various designs and economic parameters, including the number of wind turbines, rotor diameter, and labor cost. Some studies have presented a decision support model that incorporates the three key factors that characterize the ac electric power systems of offshore wind farms, which are the cost of the components, system efficiency, and system reliability. The stochasticity of wind speed and the reliability of the main system components have also been considered. The primary decisions concern the layout and the cross-sections of cable connections and the location of the central collection point of the medium-voltage cables. The GAMS language has been used to implement the decision support model.

## 8. Mitigation of Carbon Emissions by Building Offshore Wind Farms

The integration of renewable energies brings challenges on power system planning and operation. The variability of renewable power generation requires additional actions to balance the system. Those variable resources cause thermal power plants to turn on and off more often and thus increase the carbon emissions. Consequently, numerous advance techniques, such as accurate forecasts, fast dispatch, reserves management, demand response, and flexible generation sources, is necessary. A high penetration of renewable energy can mitigate carbon emissions [50]. Additionally, the future trend for developing multiple energy systems (MES) to improve energy efficiency and promote the integration of renewable energy in several areas is obvious. Research works in reference [51] demonstrated the carbon emission flow (CEF) in MES, emphasizing that carbon emission should be allocated along with the energy delivery and conversion. Reference [52] highlighted the importance of coordinating multiple energy systems in both district level and multi-regional level, and applied the CFD model to allocate the carbon emission. Similarly, several works [53–55] allocated the carbon footprint among generation resources, consumers, transmission loss and others to trace carbon emission. The above works reveal that the carbon-emission constraint would also have effects on the planning of offshore wind farms.

## 9. Equivalent Model for a Wind Farm

A large wind farm comprises hundreds or thousands of wind turbines. Therefore, works on the development of a simulation platform and power system analyses are increasing, and much time will be consumed in simulations that involve correspondingly many data. If each wind turbine were modeled in detail, then data preparation and model calculations would involve substantial amounts of time and effort. The most efficient method for simulating a large wind farm uses an equivalent wind farm to reduce complexity and simulation time [56,57]. Equivalent methods for simulating wind farms typically involve a single-machine model or a multi-machine model; however, to reflect actual operating conditions, most equivalent methods use multi-machine models [58–60]. Based on the variation of wind speed among turbines, the single-machine representation method can be further classified as using a “1+1” model (one wind turbine with one generator) or an “n+1” model (n wind turbines with one generator). This method is suited to dynamic equivalent modeling when wind-speed is uniformly distributed throughout the wind farm. However, the distribution of wind speeds in a large wind farm is frequently non-uniform as a result of topography, the wake effect, and the time-lag of wind speeds. Therefore, the single-machine representation method cannot easily capture comprehensively the dynamic characteristics of the entire wind farm. The multi-machine representation method is used to construct an “n+n” model (n wind turbines with n generators), which is based on the principle that wind turbines in the same clustering generate similar amounts of power.

Most of the wind farms are irregularly arranged, thus different wind turbines have different operating conditions. To increase the efficiency of simulation of a wind farm, in multi-machine models, wind turbines have been grouped by wind speed using various clustering methods [60–64].

As an example of the above, reference [64] developed a system cluster algorithm that combines four types of statistics in a standard to the wind farm equivalent. Reference [60] used the growing spanning tree (GST) clustering method for the wind farm equivalent. The advantage of GST is that it captures the operating conditions of different wind turbines. Reference [62] used the Fuzzy C-Mean algorithm and the Xie-Beni exponent to cluster wind turbines in a wind farm. Reference [63] used the annual forecasting of wind speed and wind direction to build the probability distribution of wind. Next, wind speeds and wind directions with high probabilities were selected to evaluate a clustering index and then an equivalent model of a wind farm was established using the support vector clustering (SVC) algorithm. Every equivalent method has advantages and disadvantages. Therefore, equivalent methods must be carefully selected to ensure accuracy of simulation and provide a favorable computation speed.

The single-machine equivalent model has a simple structure but provides low simulation accuracy, while the multi-machine equivalent model provides a higher simulation accuracy. A multi-machine equivalent model of a wind farm must consider the wake effect. However, traditional linear wake models cannot accurately reflect the actual wake effect, reducing the usefulness of wind turbine clustering. Therefore, a more accurate nonlinear wake model should be used to evaluate wake loss in wind farms.

## 10. Aggregation of Equivalent Parameters of a Wind Farm

A large wind farm typically comprises wind turbines of a single type. If a wind farm has one or a few wind turbines, then some of the parameters of the power system must be adjusted to specify the equivalent network environment, thus that the simulation closely reflects actual operating conditions. Equivalent parameters include wind speeds, wind power generators, power transformers, and power transmission lines. For example, the equivalent parameters of wind generators include the capacity of a wind turbine, rated power, stator reactance, magnetizing reactance, and resistance at the stator and rotor sides. Furthermore, a large offshore wind farm has the capacitance effect in the sea cables. The equivalent impedance of a sea cable is calculated using the constant voltage loss principle: The first step of the calculation is to determine the voltage difference between the high-voltage side and the low-voltage side of the transformer. Then, the average voltage difference through a wind turbine in the group of wind turbines is obtained.

## 11. Main Factors that Strongly Influence the Design of an Offshore Wind Farm

The main target of wind farm designers is to achieve the maximum possible power generation and the minimization of the installation cost. Such an optimization problem is quite challenging. Table 1 summarizes the main factors that strongly influence the design of an offshore wind farm. Additionally, numerous methods in every main factor are also listed in this table. The note in this table addresses the commonly used methods and the future trend for the major factors.

**Table 1.** Main factors that strongly influence the design of an offshore wind farm.

Factor	Method	Note
Optimization algorithms	Neural network, turbine distribution algorithm (TDA), mathematical programming, extended pattern search methodology, bionic method, evolutionary strategy algorithm, ant colony algorithm, gaussian particle swarm optimization with local search strategy, quality threshold clustering, minimum spanning tree algorithm, particle swarm optimization, and numerical experiments, and so on.	Each algorithm has its advantages and weak points. The trend of the optimization algorithms is to use hybrid methods, and the location of wind turbines and internal cable connections are planned simultaneously.
Wake model	Jensen, Katic, virtual particle wake flow model, and others.	The trend of the wake model has been moved from linear to nonlinear models.
Wind speed and direction	Specific wind conditions, single and multiple wind directions with constant wind speed, wind scenarios created by Weibull distribution function, extracted from a real wind farm, and single wind direction with constant wind speed.	The simplified method is to use single wind direction with constant wind speed, or specific wind conditions. The accurate method is to extract the wind conditions from an actual wind farm.
Objective function	Maximum annual energy production (AEP), maximum net present value (NPV), minimum cable costs, minimum power losses, and others.	Most works considered the maximum AEP or NPV as the objective function.
Constraint Limit	Wake loss, wind-farm boundary, the distance between two turbines, forbidden zones, the allowed turbines in a feeder or a clustering, and others, the power curve of a wind turbine, the height of a wind turbine, non-cable crossing, and others.	Each constraint limit is important, and these constraints influence each other.

## 12. Conclusions

Offshore wind farms are much more costly than onshore wind farms of equal capacity. The cost and efficiency of an offshore wind farm are determined by a variety of factors, including the installation sites of the wind turbines, the number of wind turbines, the cable connection topology, long-term wind conditions, and others. Since the number of variables for wind farm planning is large, computational optimization is needed to search an optimal solution for wind farm layouts. This investigation reviewed significant issues around the design of an offshore wind farm. First, numerical modeling of the wind turbine wake represents a fundamental step in overall design optimization for an offshore wind farm. Next, various wind-turbine layout optimization methods were presented. Most algorithms that have been developed for wind turbine layout optimization, such as genetic algorithms, are based on heuristic procedures. However, numerous up-to-date optimization techniques have been developed for wind farm layout. The internal electrical system of an offshore wind farm and its connections are also important for wind farm design. Furthermore, wind farm design should consider system reliability as well as economics, carbon emission, and safety.

Wind farm equivalent is another important topic for wind power simulations because it reduces a large amount of simulation time for wind power integration. Numerous equivalent wind-farm models have been developed, which can capture the real steady-state and dynamic characteristics of a wind farm. Notably, accurate nonlinear wake models and additional functions for frequency regulation or fault ride through should be considered in the equivalent model of an offshore wind farm.

**Author Contributions:** Investigation, Y.-K.W. and J.-J.Z.; writing—original draft preparation, Y.-K.W. and W.-C.W.; writing—review and editing, Y.-K.W.; project administration, Y.-K.W.; funding acquisition, W.-C.W.

**Funding:** This work was financially supported by the Ministry of Education of Taiwan. Project title: Higher Education Sprout Project, Ministry of Education, Taiwan, and the Ministry of Science and Technology (MOST) of Taiwan under Grant 105-3113-E-194-001-CC2. Project title: Development of Integration Technology for Large-Scale Offshore Wind Farms in Taiwan (3/3).

**Conflicts of Interest:** The authors declare no conflict of interest.

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