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Layout optimization of an airborne wind energy farm for maximum power generation

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Abstract

We consider a farm of Kite Power Systems (KPS) in the field of Airborne Wind Energy (AWE), in which each kite is connected to an electric ground generator by a tether. In particular, we address the problem of selecting the best layout of such farm in a given land area such that the total electrical power generated is maximized. The kites, typically, fly at high altitudes, sweep a greater area than that of traditional wind turbines, and move within a conic shaped volume with vertex on the ground station. Therefore, constraints concerning kite collision avoidance and terrain boundaries must be considered. The efficient use of a given land area by a set of KPS depends on the location of each unit, on its tether length and on the elevation angle. In this work, we formulate the KPS farm layout optimization problem. Considering a specific KPS and wind characteristics of the given location, we study the power curve as a function of the tether length and elevation angle. Combining these results with an area with specified length and width, we develop and implement a heuristic optimization procedure to devise the layout of a KPS farm that maximizes wind power generation.

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Keywords: Airborne wind energy systems; Wind power; Wind farm; Layout; Heuristic optimization

1. Introduction

In recent years, Airborne Wind Energy (AWE) systems have received attention from a growing academic and entrepreneurial community. These technologies aim to harvest power from winds at higher altitude than conventional wind turbines [1]. Such winds are generally stronger and more consistent, as assessed by Archer and Caldeira [2]

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and Archer et al. [3]. Lunney et al. [4] present a state-of-the-art review, summarizing several system topologies and working principles of AWES. One of the most explored solutions is the Kite Power Systems (KPS), which is based on the conclusions reached by Loyd [5] of the possible mechanical power withdrawn from a tethered kite in a crosswind motion. It consists of an airfoil connected through a cable to a winch drum coupled to a motor/generator system. The working principle is based on a two-phased cycle comprising a production phase and a consumption phase. During the traction phase, or reel-out phase, the airfoil is controlled to define a fast crosswind motion with low elevation, typically elliptical or 8-shaped, which maximizes the tether tension force. The cable unwinds from the winch drum and the generator produces electrical power. During the retraction phase, the tether is reeled-in and the kite is controlled in order to minimize the tether tension and the power consumption, thus guaranteeing a final positive energy balance.

In this paper, we address the problem of the layout of KPS units in order to optimize the global power production of a kite wind farm. In traditional wind farms, which consist on several wind turbines, the optimal location of the units depends not only on turbine specifications, but also on terrain topography, local wind characteristics, and the wake effects from one turbine to its neighbors. In contrast, in kite wind farms, the kites typically fly at higher altitudes and the ratio between wing area over the swept area is much smaller; thus, terrain topography and wake effects have a minor impact in the wind farm layout. The main constraints are terrain boundaries and collision avoidance among kites [6,7]. Each kite and its tether move within a conic shaped volume rooted on the ground station. The efficient use of a given land area depends not only on the location of each kite, but also on its tether length and on its elevation angle. On the one hand, long tether lengths and small elevation angles contribute to improve the efficiency of a single unit. On the other hand, such combination makes each kite use a larger area; thus, reducing the number of kites to be installed. The optimal compromise for these values, given the KPS specifications, the local wind characteristics, and the farm boundaries, is sought here.

In this work, we start by choosing the values of the main parameters of a single unit using a Biased Random Key Genetic Algorithm (BRKGA) based on that of Roque et al. [8] to maximize the average production cycle.

Once the parameters that optimize a single unit operation are found, they are used to simulate farms of several equal units. The optimization and study of the kite wind farm is performed using a heuristic implementation. We maximize the average cycle power, taking into account the elevation angle and reel-in and reel-out speeds. The optimal values for such speeds are obtained using optimization and optimal control techniques. Thereafter, we calculate the power production for a given angle and wind speed under the given constraints for power and force and we obtain the altitude corresponding to the best potential wind power through the logarithmic wind shear model. Finally, we estimate the Annual Energy Production (AEP), Capacity Factor (CF) and Pumping Efficiency (PE), based on which we obtain the Levelized Cost of Energy (LCOE) of the kite wind farm.

2. Problem formulation

Our ultimate goal is to find out how many kites should be installed, and their respective locations, in a given wind farm area such that the total power production is maximized. Nevertheless, given our approach to the problem, we address first the single KPS unit optimization problem.

2.1. Single KPS

The variables considered as main parameters in this problem are the kite area A, the air density ρ, the maximum traction force F_{max}, the maximum tether length L_{max}, and the nominal power of the generator P_N. Other important inputs are the drag coefficient C_D, the maximum and minimum lift coefficients, C_{Lmax} and C_{Lmin}, for the traction and retraction phases, respectively, the efficiency of the conversion of mechanical to electrical power during traction phase, η_{tr}, the efficiency of the reconversion of electrical to mechanical power during retraction phase η_{re}, and the discrete sets of the possible values for wind speed, v_w, and for the elevation angle β between the cable and the ground station. For each combination of β and v_w possible values, the traction and retraction optimal speeds, v_{tr} and v_{re}, respectively, are determined in order to maximize the cycle power production P_c. The output is a matrix with the average of cycle power production for each combination of β and v_w, and estimated power curves of the average cycle power as function of the wind speed v_w. Luchsinger [9] derives explicit formulas to calculate the average power production of a KPS. It is assumed a right-handed coordinate system with the x-axis parallel to the wind direction and the z-axis pointing upwards. The traction force is obtained taking the elevation angle β into account:

$$T_{tr} = \frac{1}{2}\rho A v_w^2 \left(\cos(\beta) - \frac{v_{tr}}{v_w}\right)^2 F_{tr} \tag{1}$$

with the dimensionless force factor $F_{tr} = \frac{C_L^3}{C_D^2}$.

As [10], considering $F_L = \frac{1}{2}\rho v_a^2 A C_L$ and $F_D = \frac{1}{2}\rho v_a^2 A C_D$ the lift and drag forces, which act perpendicular and parallel to the apparent wind velocity v_a, respectively, we obtain the retraction tether force considering that the magnitude of the kite aerodynamic force is

$$F_{aer} = \sqrt{F_L^2 + F_D^2} = \frac{1}{2}\rho A \|v_a\|^2 \sqrt{C_L^2 + C_D^2} \tag{2}$$

where $\|v_a\|$ is the magnitude of the apparent wind speed. From [9], the retraction tether force is

$$T_{re} = \frac{1}{2}\rho A v_w^2 \left(1 + 2\frac{v_{re}}{v_w}\cos(\beta) + \frac{v_{re}^2}{v_w^2}\right)\sqrt{C_L^2 + C_D^2},$$

i.e.,

$$T_{re} = \frac{1}{2}\rho A v_w^2 \left(1 + 2\frac{v_{re}}{v_w}\cos(\beta) + \frac{v_{re}^2}{v_w^2}\right) C_D \sqrt{\left(\frac{C_L}{C_D}\right)^2 + 1} \tag{3}$$

There is a range of possible traction speeds v_{tr} that do not violate the force or speed limit. However, there is a certain speed within the v_{tr} that leads to maximum power production. Above a certain wind speed, the traction force is limited to its nominal value by modulating the reel-out speed. The average power production of a pumping kite generator for the traction phase is:

$$P_{tr} = \frac{1}{2}\rho A v_w^2 \frac{C_L^3}{C_D^2}\left(\cos(\beta) - \frac{v_{tr}}{v_w}\right)^2 v_{tr} \tag{4}$$

and for the reel-in phase:

$$P_{re} = \frac{1}{2}\rho A v_w^2 C_D \sqrt{\left(\frac{F_L}{F_D}\right)^2 + 1}\left(\left(\frac{v_{re}}{v_w}\right)^2 + 2\frac{v_{re}}{v_w}\cos(\beta) + 1\right) v_{re} \tag{5}$$

The average cycle power, the function to be maximized, is given by

$$P_c = \frac{E_{tr} - E_{re}}{T_{out} + T_{in}} = \frac{\frac{\eta_{tr}.P_{tr}}{v_{tr}} - \frac{\eta_{re}.P_{re}}{v_{re}}}{\frac{1}{v_{tr}} + \frac{1}{v_{re}}}. \tag{6}$$

where $E_{tr} = \eta_{tr}.P_{tr}$ and $E_{re} = \eta_{re}.P_{re}$ are the values for produced and consumed energy, respectively, during one cycle with period $T = T_{out} + T_{in}$, where T_{out} and T_{in} are the time spent during the traction and retraction phases, respectively. It should be noticed that the weight of the kite is assumed to be equal to 1 kg and that the weight and drag of the tether are neglected. The height constraint can be formulated as follows:

$$L_{max}\sin(\beta) \leq z_{max} \tag{7}$$

where z_{max} is the allowed maximum height for the kite trajectory.

2.2. Wind farm

We consider an array layout of the farm illustrated in Fig. 1 and that units downwind from each other are operating synchronously. The main parameters and inputs of this problem are based in a single unit and in addition, the width W_{land} and length L_{land} of the terrain where the wind farm is installed. Real data containing wind speed and altitude measurements is also an input. The decision variable is the number of kites (n) to be allocated in the wind farm such that the average cycle power production is maximized. As in the single unit case (n = 1), for each possible number of kites, we compute the matrix with average cycle power nP_c for each combination of

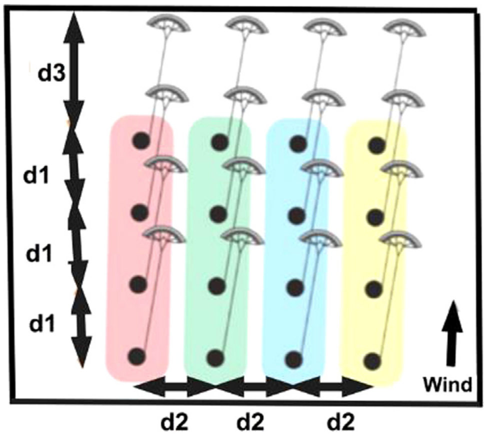

Fig. 1. Layout of wind farm.
Source: Figure adapted from [6].

the elevation angle and wind speed possible values. We estimate the production during the time period concerning the input data. After that, we estimate the AEP and LCOE for each possible number of kites in the layout of the kite wind farm. The distance between the units is the main aspect to consider in the farm layout. If two units are sketched from a top view, the minimum distance between units to avoid interference is:

$$d_2 = 2L_{max}sin(\phi) \tag{8}$$

as illustrated in the left-hand side of Fig. 2. Here ϕ is the maximum azimuth angle. The distance of two units, which are aligned with the wind velocity [6], is:

$$d_1 = \frac{L_{max}}{\sin(\beta - \Delta\beta)\left[\frac{1}{tan(\beta-\Delta\beta)} + \frac{1}{tan(\beta+\Delta\beta)}\right]} \tag{9}$$

The distance between the two last units in each column aligned with wind direction is:

$$d_3 = L_{max}cos(\beta - \Delta\beta) \tag{10}$$

These distance between each two last units in the column aligned with wind direction are illustrated in the right-hand side of Fig. 2.

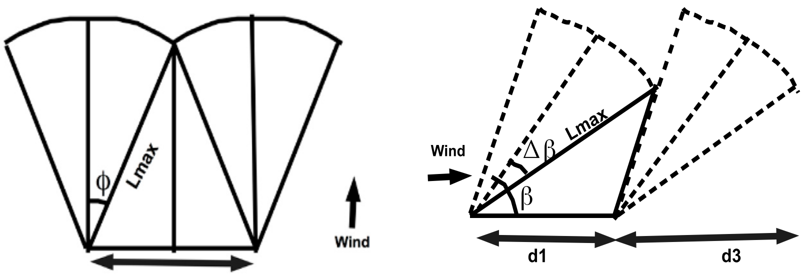

Fig. 2. Minimum distance between two units.
Source: Figure adapted from [6].

Let us consider the rectangular area where the length is aligned with the wind direction and n_w and n_l are the number of kites along the width and length ($n = n_w.n_l$), respectively. The objective function to be maximized is given by $n_w.n_l.P_c$. Therefore, the total power output to be maximized at each cycle is

$$Max \;\; n_w.n_l.P_c,$$

subject to the constraints,

$$(n_l - 1).d_1 + d_3 \leq L_{land} \tag{11}$$

The distance d_2 and the available width define the number of kites to be disposed along each row in the terrain,

$$n_w.d_2 \leq W_{land.} \tag{12}$$

2.3. Variation of wind speed with altitude

The instantaneous increase in wind speed with elevation depends on several meteorological factors, which determine the atmospheric stability. Typically, the vertical profile of wind speed over regions of the earth surface is modeled by the log law. Thus, we follow the approach that is given by $w(z) = w_0 ln(z/z_R)/ln(z_0/z_R)$, where $w(z)$ is the wind speed at altitude z, z_0 and w_0 are a reference height and its correspondent average wind speed, respectively, and z_R is the surface roughness.

3. Methodologies

At first, we use a Genetic Algorithm (GA) to choose the main parameters design in the KPS optimization. In order to maximize the average cycle power output, we want to choose the main parameters (in the feasible region) in an optimal way. To solve this task we apply the BRKGA based on the framework provided by Gonçalves and Resende [11], which has been used effectively and efficiently in other important applications [8,12,13]. The parameters are chosen to obtain the maximum average power defined in Eq. (6). We consider the following variables as the design parameters: the area A of the kite in square meters (m^2), the length L of the tether in meters (m), the nominal generator power P_N and the nominal tether force F_{max}. Then we compute the average power output matrix for each scenario according to n. The combination of the specified wind speed values (assuming values between 2 m/s and 30 m/s) with several elevation angles β (varying between 10° and 60°) allow us to optimize the cycle power curves. It should be noticed that for any possible number of kites, if the maximum distances defined by Eqs. (8)–(10) between the kites are not satisfied for a certain elevation angle and wind speed combination, then the matrix of output generation is set to zero in the corresponding entry.

The required tether length L_{req} is computed considering the $\overline{v_w}$ and $\overline{\beta}$ that maximize power production, taking into account the log law which relates the $\overline{v_w}$ to a certain height $\overline{z}$. If the values satisfy the constraints of the maximum height z_{max} and maximum tether length L_{max} then the height and tether length values are kept for the considered time interval. Otherwise, the second highest value in the power output matrix is considered and the procedure is repeated until height and tether length values satisfying the constraints are achieved. In the case of any value in the matrix is such that the constraints of the maximum height z_{max} and maximum tether length L_{max} are not satisfied, the units should not be operating at this time interval. Next, we estimate the power production for each time interval in the time horizon of the data. Also the average production for a time interval of 1 h is computed.

The average power production for each time interval allows to obtain the $AEP = P_c.PE.CF.8760$ (MWh/year). LCOE is a measure that quantifies the cost per unit of produced energy in €/MWh throughout the project lifetime and is obtained by $LCOE = (ICC * CRF + OMC)/AEP$, where ICC is the Initial Capital Cost including all component costs and the balance of station costs (expressed in €), OMC is the Operating and Maintenance Costs (expressed in €/year), CRF is the Capital Recovery Factor, given by $CRF = i(1+i)^p / \left((1+i)^p - 1\right)$, with discount rate i for the time period p [14–16].

Fig. 3 uses a schematic to describe the proposed methodology.

4. Conclusion

This paper proposes a heuristic method for the maximization of the average cycle power produced from a kite wind farm. In a first stage, the method uses a GA to choose the main parameters in the single KPS optimization. Then, for a given terrain with specified length and width, we determine the optimal number of KPS units that can be installed in the wind farm in such a way that the average cycle power is maximized and the constraints concerning to the maximum distance between kite units are satisfied. The AEP and the LCOE are estimated for each possible

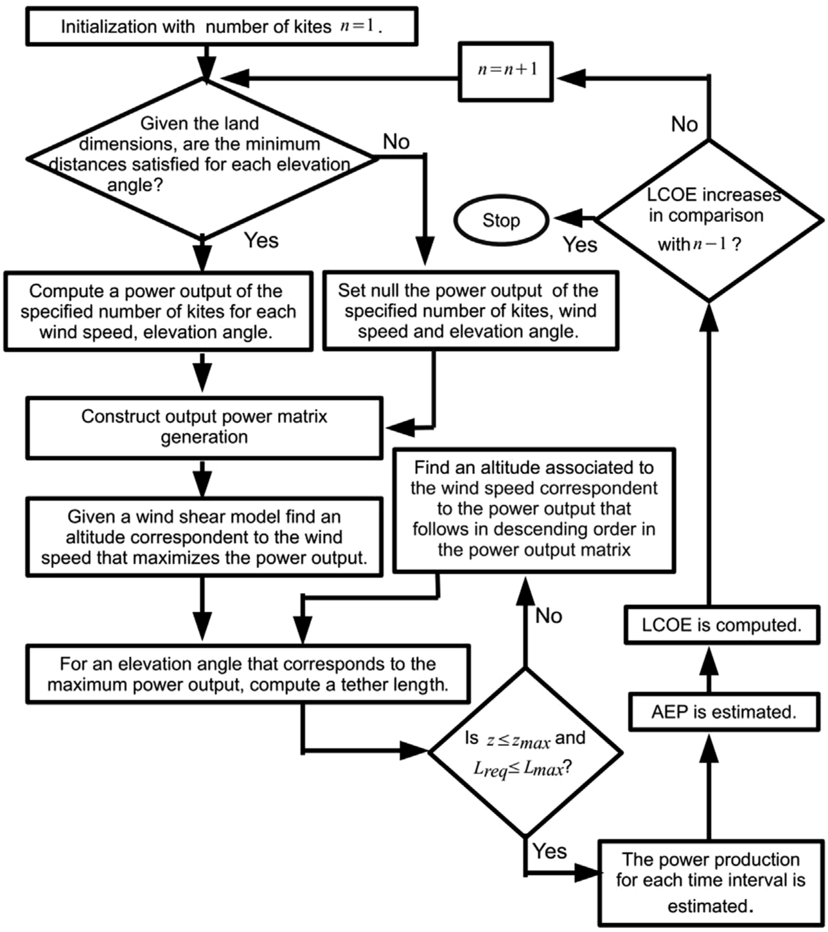

Fig. 3. Algorithm flowchart.

number of the kite units. The developed heuristic may be an important tool to help the decision makers to advance in sense of a kite wind farm installation in a specified terrain and geographic region with some previous wind data information. Further studies will be developed to improve some uncertainties in the wind data forecasting and modelling, as well as simulation and numerical results obtained from the proposed methodology.

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