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Electric power generation in wind farms with pumping kites: An economical analysis

M. De Lellis [a], [*], A.K. Mendonça [b], R. Saraiva [a], A. Trofino [a], Á. Lezana [b]

[a] Department of Automation and Systems, Federal University of Santa Catarina, 88040-900, Florianópolis, Brazil
[b] Department of Production and Systems Engineering, Federal University of Santa Catarina, 88040-900, Florianópolis, Brazil

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ABSTRACT

The main contribution of this paper is to indicate the economical viability of a Pumping Kite (PK) system as an airborne wind energy approach for large-scale electricity generation. In our study case a 2 MW PK unit is compared to a horizontal-axis 3-bladed Wind Turbine (WT) of same rated power. The PK airfoil area corresponds to the area of the 3 blades, and the same aerodynamic characteristics were assumed. The PK capacity factor obtained is 45 %, compared to 31 % of the WT. Given conservative PK cost estimates we found the investment in a PK-based wind farm can be 74 % of that in a conventional wind farm. By adding 13 PKs to an existing wind farm with 21 WTs the Internal Rate of Return (IRR) practically doubles, whereas if each WT is replaced by a PK, the IRR is approximately multiplied by 3. We also show that PK wind farms can be economically attractive in locations where WTs are not.

1. Introduction

In face of the constant expansion of the world economies and population growth, the global energy demand has been increasing at a fast pace. Given the undesired environmental impacts of fossil fuels usage for energy generation, besides the fact that they are becoming more scarce and thus more expensive to obtain, renewable sources are progressively occupying a larger share in the energy mix. Among them is the wind energy, whose estimated global potential exceeded the worldwide electricity production in 2012 [1].

The kinetic power in the wind flow is given by $P_w = 0.5\rho A_w W_n(z)^3$, where ρ is the air density, A_w is the cross-sectional area, z is the altitude, and $W_n(z)$ is the wind speed. It is well known that the wind speed generally grows with altitude inside the troposphere. On the other hand, the air density decreases more or less linearly, and also depends on the humidity. Considering how these quantities vary with altitude on a world map grid, an optimal height can be determined at which a wind speed maximum occurs and hence the power density P_w/A_w is also maximum [2,3]. These optimal heights are usually well above the highest operating altitude of Wind Turbines (WTs), whose blade tips currently reach about 200 m high. Because of the "square-cube law" [4], economical aspects impose a limit to building larger turbines atop higher towers: as the rotor size increases, the energy output grows with the swept area, i.e. as a function of the diameter squared, whereas the material volume and cost grow with the cube of the diameter. Consequently, at some point the increase in energy output does not pay off for the increase in material cost.

In the last decade, Airborne Wind Energy (AWE) technology has been investigated as a feasible alternative to exploiting the larger wind potential at higher altitudes and at a cheaper cost than conventional WT technology. Most references found in the literature focus on electric energy generation, but AWE technology can also be applied for auxiliary ship propulsion (towing), as studied e.g. by Refs. [5,6]. Some AWE approaches make use of lighter-than-air devices, like turbines kept aloft by balloons tethered to the ground, but most of the academic investigations have focused on *tethered airfoils* (see e.g. Refs. [7–11]). One of the reasons for this is the possibility of operation in the *crosswind*, when the wing flies approximately in a perpendicular plane to the nominal wind flow.[1] Thus, depending on its aerodynamic efficiency, the kite may reach a

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* Corresponding author.
E-mail addresses: marcelo.lellis@posgrad.ufsc.br (M. De Lellis), anny.mendonca@posgrad.ufsc.br (A.K. Mendonça), ramiro.saraiva@posgrad.ufsc.br (R. Saraiva), alexandre.trofino@ufsc.br (A. Trofino), alvaro.lezana@ufsc.br (Á. Lezana).

[1] We refer to the "nominal wind" (speed/flow) as the wind speed with respect to the ground, averaged in some time interval.

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speed up to 10 times higher than the nominal wind, according to the refined crosswind motion law [12]. In contrast, because of the decrease in the nominal wind driving the blades due to their rotation, the optimal *tip speed ratio*, i.e. the ratio between the speed of the blade tips and the nominal wind, is usually around 5, as shown e.g. by Ref. [13]. As a result AWE technology can reach higher power densities for a same airfoil area when compared to conventional WT technology, as hypothesized by Ref. [14] and demonstrated in this paper.

The use of tethered airfoils is also advantageous in other ways. For instance, the amount of airborne material, basically the tethers and the wing, is reduced by two orders of magnitude – from dozens of tons to hundreds of kilos – when compared to the tower, nacelle and rotor of a WT. Consequently, material costs should decrease substantially. Alongside comes a reduction of the logistics costs, since there is less material to transport, as well as a reduction on the installation costs, because the concrete foundations are subject to less stress (no tower thrust). Also, it is known that conventional wind turbines cause environmental impacts on human life, for instance noise and visual pollution [15,16]. The use of AWE technology may alleviate such issues. For instance, a noise-canceling housing can be more easily deployed for AWE systems with a ground-based generator, whereas the airfoil flying 2 to 3 times higher than the conventional rotor and the replacement of the tower by tethers could yield a lower visual impact.

Regardless of the attractive features mentioned above, some aspects are crucial for the commercial deployment of AWE systems. According to survey results with field experts [17], one of these aspects is reliability: the airborne part must fly safely in spite of dangerous conditions such as storms. Governmental regulations must also be dealt with: there must be an agreement with the airspace regulatory authorities to avoid collisions with aircraft. Once these issues are resolved, two deployment scenarios may be envisioned: AWE technology-based wind farms, and hybrid wind farms with both AWE systems and WTs. The latter is thought to be especially interesting in the early stages of commercial usage because the AWE units can be inserted into the existing wind farms with hypothetically no interference in the WT operation, as will be demonstrated. This way one can take advantage of the existing power lines and infrastructure, thus reducing the necessary start-up investment, while increasing the land power density of the wind farm.

The main contribution and goal of this paper is to present an economical analysis of the “Pumping Kite” (PK) AWE concept for electric energy generation. To this end, the rest of the paper is organized as follows: in Section 2 the PK is briefly explained, followed by the wind analysis of a Brazilian location in Section 3. The PK and WT power curves and capacity factors are obtained in Section 4. Based on data of an existing wind farm and PK cost estimates obtained from the literature, an economical analysis of power generation is carried out in Section 5. Section 6 concludes the paper.

2. The pumping kite

Several structures using tethered airfoils have been proposed, some of which summarized by Ref. [18]. They can vary e.g. in the amount of wings (single or multiple), their stiffness (rigid or flexible), amount of tethers, and location of the airfoil steering actuators (on the ground or airborne). Probably due to its simpler concept, which makes it easier to work with, the most studied structure found in the literature is the *Pumping Kite* (PK), also known as *Yo–yo*, presented in Fig. 1. Considering the mass-point model from Refs. [19,20], the airfoil center of mass cartesian coordinates in the inertial frame i are $(x_a, y_a, z_a)_i$, with the **x** direction being defined by the nominal wind $\mathbf{W_n}$. The airfoil position vector $\mathbf{r_a}$ can also be represented by the spherical coordinates $(\theta_a, \phi_a, r_a)_i$, where the perfectly stretched (no sagging) tethers have length r_a.

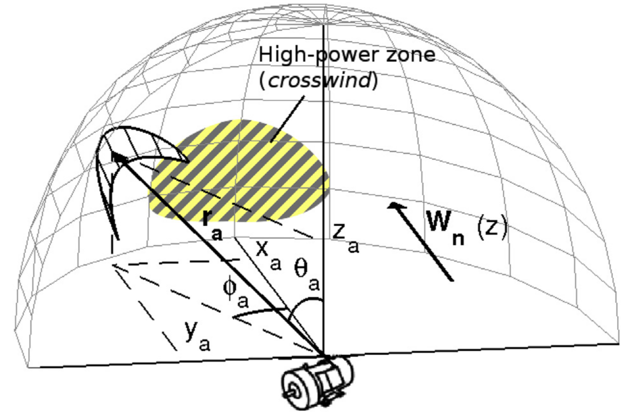

Fig. 1. The Pumping Kite AWE concept.

During the traction phase – when electric energy is generated – in order to maximize the tether traction force T the airfoil flies in the high-power (*crosswind*) zone, where the airfoil speed vector is approximately perpendicular to $\mathbf{W_n}$. Also, to avoid accumulated tether torsion, the airfoil follows a “lying eight”-figure (∞) trajectory reference, e.g. *Bernoulli's lemniscate* used by Ref. [21], centered at $\theta_L \in [0, \pi/2]$ and, usually, $\phi_L = 0$. The mechanical power harnessed from the wind is $P = T\dot{r}_a$, where $\dot{r}_a$ is the speed with which the tether is reeled out from the drum connected to the electric machine on the ground, operating as generator. When the tether reaches its maximum length the passive phase begins, in which the tether is reeled back in, ideally at only a small expense of energy and time. The net produced power in the operating cycle consisting of these two adjacent phases is referred to as the *cycle power*.

For our numerical analysis henceforth we will consider an airfoil with the lift and drag coefficient curves, $C_L(\alpha)$ and $C_D(\alpha)$, respectively, shown in Fig. 2, where α is the angle of attack. The same curves will be assumed for the Wind Turbine (WT). To calculate the PK power curve in Section 4 and the initial investment cost in Section 5 we will consider the PK variant with only one main tether and an airborne control pod.

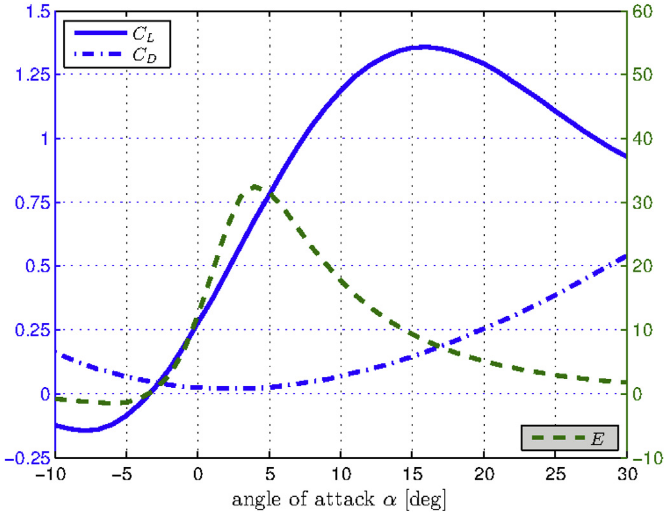

Fig. 2. Aerodynamic coefficients for the PK and WT airfoil.