Kitenergy: a radical innovation in wind energy generation

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ABSTRACT

This paper presents an innovative technology for high-altitude wind power generation, indicated as Kitenergy, which exploits the automatic flight of tethered airfoils (e.g. power kites) to extract energy from wind blowing between 200 and 800 meters above the ground. The key points of such a technology are described, in order to show that Kitenergy technology has the potential to provide large quantities of renewable energy with competitive cost with respect to fossil sources. Such claims are supported by the results obtained so far in the research activities undergoing at Politecnico di Torino, Italy, including numerical simulations, prototype experiments and wind data analyses.

Keywords: Innovative wind energy concepts, High-altitude wind energy

1 INTRODUCTION

Sustainable energy generation is one of the most urgent challenges that mankind is facing today. Fossil sources (oil, gas, coal) cover at present about 80% of the global primary energy demand [1], posing large problems, ranging from increasing fossil source costs to increasing energy demand in front of limited resources, to impact on climate change and on environment pollution, to geopolitical consequences of the fact that fossil sources are supplied by few producer countries. A key strategy for facing these issues is a much more extensive use of renewable energy sources. In this paper we focus on wind energy, which has at present a value of about 30 billion $/year and, apart from hydropower plants, is the largest renewable source, with an yearly global growth of the installed capacity of about 30% in the last years. Indeed, by exploiting 20% only of the world land sites that are economical for the actual wind technology, based on wind towers, the entire world's energy demand could be supplied [2]. However, the current wind technology has limitations in terms of energy production costs, which are still higher then from fossil sources, and in terms of land occupation, since wind farms based on modern wind tower of 2-3 MW rated power have a power density of 10-12 MW/km^2 [3], about 100 times lower than that of large thermal plants. A comprehensive overview of the present wind technology is given in [4], where it is also pointed out that no dramatic improvement is expected in this field. The main reason is that wind turbines operate at a maximum height of about 150 m over the ground, a value hardly improvably, due to structural constraints which have reached their technological limits. On the other hand, wind generally increase with height above the ground: at the height of 500–1000 meters the mean wind power density is about 4 times the one at 50–150 meters, and at 10,000 meters it is 40 times, [5]. This suggests that a breakthrough in wind energy generation can be realized by capturing wind power at altitudes over the ground that cannot be reached by wind towers. The idea of harnessing high altitude wind power using tethered aircraft has been proposed at least as far back as the 1970's, [6]–[8]. However, only in the past few years more intensive theoretical, technological and experimental studies have been carried out by academic research groups and/or high-tech companies, and many different High Altitude Wind (HAW) technologies have been proposed and investigated see e.g. [9], [10],[11],[12],[13],[14],[15],[16]. These HAW technologies present a large spectrum of technical solutions, presenting different features in terms of: *Operating altitude over the ground* (200-1000 m or 8000-10000 m); *Lift type of the aircraft* (aerodynamical lift, as exerted by airplane wings or kites; rotor-craft lift, as realized helicopters or autogyros; aerostatic lift as realized by lighter-than-air aircrafts); *Electric energy generation* (on board of the aircraft or at the ground level). Starting from 2005, Politecnico di Torino in collaboration with academic start ups, has extensively investigated, through modeling, control design, computer simulation and experimental verification on a prototype [12], [17], a technology aimed to operate at altitudes of 200-1000 meters over the ground, exploiting "cross-wind" aerodynamical lift and having electric energy generation at the ground level. The basic concepts of this technology, indicated as Kitenergy, are presented in the next section.

2 KITENERGY TECHNOLOGY

2.1 Basic concepts

The key idea of Kitenergy is to harvest high-altitude wind energy with the minimal effort in terms of generator structure, cost and land occupation. In the actual wind towers, the outermost 30% of the blade surface contributes for 80% of the generated power. The main reason is that the blade tangential speed (and, consequently, the effective wind speed) is higher in the outer part, and wind power grows with the cube of the effective wind speed. Thus, the tower and the inner part of the blades do not directly contribute to energy generation. To understand the concept of Kitenergy, one can imagine to remove all the bulky structure of a wind tower and just keep the outer part of the blades, which becomes a much lighter kite flying fast in crosswind conditions (see Figure 1), connected to the ground by two cables, realized in composite materials, with a traction resistance 8-10 times higher than that of steel cables of the same weight. The cables are rolled around two

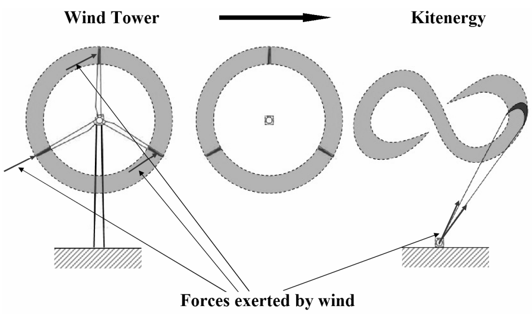

Figure 1: Basic concept of Kitenergy technology

drums, linked to two electric drives which are able to act either as generators or as motors. An electronic control system can drive the kite flight by differentially pulling the cables (see Figure 2). The kite flight is tracked

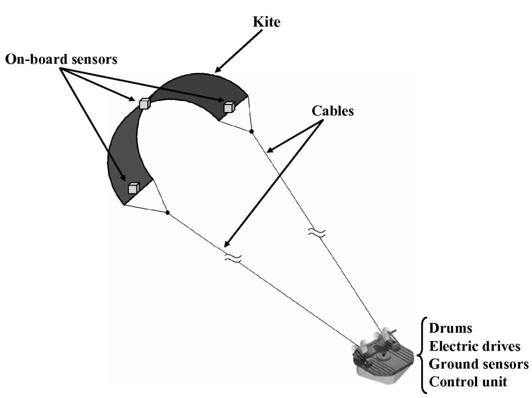

Figure 2: Scheme of a Kite Steering Unit (KSU)

and controlled using on-board wireless instrumentation (GPS, magnetic and inertial sensors) as well as ground sensors, to measure the airfoil speed and position, the power output, the cable force and speed and the wind speed and direction. Thus, the rotor and the tower of the present wind technology are replaced in Kitenergy technology by the kite and its cables, realizing a wind generator which is largely lighter and cheaper. For example, in a 2-MW wind turbine, the weight of the rotor and the tower is about 300 tons [18]. In a kite generator of the same rated power the rotor and the tower are replaced by a 500-m^2 kite and cables 1000-m long, with a total weight of about 3 tons only.

The system composed by the electric drives, the drums, and all the hardware needed to control a single kite is denoted as Kite Steering Unit (KSU) and it is the core of the Kitenergy technology. The KSU can be employed in different ways to generate energy (see [17]): the configuration named KE-yoyo will be considered here.

2.2 KE-yoyo energy generation cycle

In the KE-yoyo configuration, the KSU is fixed with respect to the ground. Energy is obtained by continuously performing a two-phase cycle: in the *traction phase* the kite exploits wind power to unroll the lines and the electric drives act as generators, driven by the rotation of the drums. During this phase, the kite is maneuvered so to fly fast in crosswind direction, to generate the maximum amount of power. When the maximum line length is reached, the *passive phase* begins and the kite is driven in such a way that its aerodynamic lift force collapses: this way, the energy spent to rewind the cables is a fraction (less than 10%) of the amount generated in the traction phase. In the Kitenergy project, numerical and theoretical analyses have been carried out to investigate the potentials of a KE-yoyo unit using the described operating cycle. Moreover, wind farms composed by several KE-yoyo units have been also studied (i.e. KE-farms). The results of such studies are resumed in the next Section.

2.3 Numerical analyses

The operational cycle of a KE-yoyo described in Section 2.2 has been developed and tested through numerical simulations. The detailed analyses can be found in [17], [12]. Moreover, the application in the offshore context and for naval propulsion have been also recently studied [19]-[21]. The simulations have been carried out by using an accurate system model and by employing advanced control techniques to maximize the net generated energy. According to the obtained results, the controller is able to stabilize the system and to keep the flight trajectory inside a limited space region, also in the presence of quite strong wind turbulence. From such simulations, the power curve of a KE-yoyo, with a kite having an area of 500 m^2 and a moderate aerodynamic efficiency of 12, has been computed (see Figure 3): this curve gives the generated power as a function of wind speed and it can be employed to compare the performance of a KE-yoyo with that of a commercial wind turbine with the same rated power (e.g. 2 MW), whose power curve (taken from [18]) is reported in Figure 3 too. Numerical simulations and optimization techniques

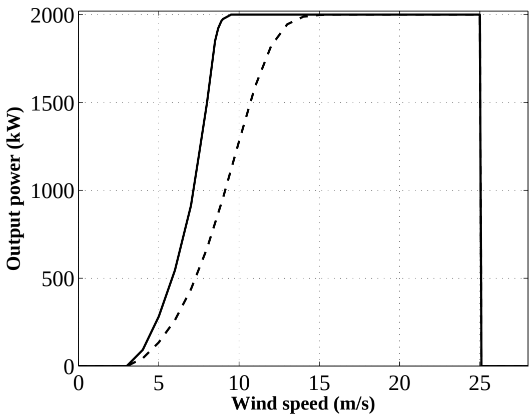

Figure 3: Comparison between the power curves of a typical wind tower (dashed) and of a KE-yoyo (solid), both with the same rated power of 2 MW.

have been also employed to study the characteristics of KE-farms, i.e. several KE-yoyo units operating in the same location. In particular, it has been shown that (see [12]), by exploiting the possibility of making the kites of nearby generators fly at different altitudes, so to avoid aerodynamical interferences, a rated power density of 32 MW/km^2 can be achieved by KE-farms composed by 2-MW KE-yoyo generators. This value is about 4 times higher than the rated power density achieved by the actual commercial 2-MW inland wind towers. Moreover, rated power densities of 80 MW/km^2 and 160 MW/km^2 can be obtained by using 5-MW and 10-ME KE-yoyo units respectively.

2.4 Capacity factor analyses

For a given wind generator on a specific site, the CF can be evaluated knowing the probability density distribution function of wind speed and the generator wind-power curve. For example, in Table 1 the CFs of a KE-yoyo and of a wind tower with the power curves of Figure 3 are reported. Note that the present wind technology is economically convenient for sites with CF > 0.3, according to the level of the incentives for green energy generation. In such good sites Kitenergy technology is able to achieve CFs about two times greater than the present wind power technology, thus more than doubling the economic return even assuming the same costs. In addition, bad sites for the present wind technology can be still economically convenient with Kitenergy technology.

2.5 Energy production costs

On the basis of the results that have been recalled so far, a preliminary estimate of the costs of the electricity produced with Kitenergy has been carried out

Table 1: Capacity factors of 2-MW rated power wind tower and KE-yoyo in several sites around the world, evaluated from daily wind measurements of sounding stations.

Site	2-MW wind tower	2-MW KE-yoyo
Buenos Aires (Argentina)	0.15	0.56
Nice (France)	0.09	0.33
Calcutta (India)	0.02	0.31
Brindisi (Italy)	0.31	0.60
Linate (Italy)	0.006	0.33
Casablanca (Morocco)	0.03	0.45
Bod (Norway)	0.28	0.56
Leba (Poland)	0.38	0.71
Murcia (Spain)	0.03	0.35
De Bilt (The Netherlands)	0.36	0.71
Nottingham (UK)	0.01	0.31

and compared with the costs of the other technologies, under the conservative assumption that a KE-yoyo generator has the same cost as a wind tower of the same rated power. Then, considering the results presented in Sections 2.3-2.4, the estimates presented in Table 2 have been obtained. In particular, Table 2 shows the results (taken from [22]) of the projected cost in 2030 (levelised in 2003 U.S. dollars per MWh) of energy from coal, gas, nuclear, wind and solar sources and the estimate computed for Kitenergy technology.

Table 2: Projected cost in 2030 (levelised in 2003 U.S. dollars per MWh) of energy from different sources, compared with the estimated energy cost of Kitenergy.

Source	Minimal estimated ($/MWh)	Maximal estimated ($/MWh)	Average estimated ($/MWh)
Coal	25	50	34
Gas	37	60	47
Nuclear	21	31	29
Wind	35	95	57
Solar	180	500	325
Kitenergy	10	48	20

2.6 Experimental results

A small-scale KE-yoyo prototype has been built and tested (see Figure 4) and the results of the first experimental tests have been compared with numerical results. Indeed, a quite good matching between simulations and real world data has been evidenced in these first tests regarding the generated energy (see [12]). These results give a good confidence level in the numerical and theoretical tools, which have been employed to derive the results presented in this paper.

Figure 4: KE-yoyo small scale prototype operating near Torino, Italy.

3 CONCLUSIONS

The paper described the features of Kitenergy technology, including numerical simulations, wind data analyses, optimization of KE-farms and prototype experiments. A preliminary electricity cost analysis has been also presented, showing that the Kitenergy technology, by capturing the wind power at significantly higher altitude over the ground than the actual wind towers, has the potential of generating renewable energy, available in large quantities almost everywhere, with production cost lower than that of fossil energy. In view of this potential, Kitenergy company has been founded in 2010 [23], with the aim of leading to an industrial level the presented high-altitude wind energy technology.

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