High–altitude wind energy generation using controlled tethered airfoils

Lorenzo Fagiano, Mario Milanese, and Dario Piga

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 technology are described and the design of large scale plants is investigated here, in order to show that Kitenergy may bring noticeable advantages in wind energy generation and 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.**

I. INTRODUCTION

The problem of sustainable energy generation is one of the most urgent challenges that mankind is facing today. On the one hand, the world energy consumption is projected to grow by 50% from 2005 to 2030 (see [1]). On the other hand, the problems related to the actual distribution of energy production among the different sources are evident and documented by many studies. Fossil fuels (i.e. oil, gas and coal) actually cover about 80% of the global primary energy demand (as reported in [1], updated to 2006) and they are supplied by few producer countries, which own limited reservoirs. The cost of energy obtained from fossil sources is continuously increasing due to increasing demand, related to the rapidly growing economies of the highly populated countries. Moreover, the negative effects of energy generation from fossil sources on global warming and climate change, due to excessive carbon dioxide emissions, and the negative impact of fossil energy on the environment are recognized worldwide and lead to additional indirect costs. One of the key points to solve these issues is the use of a suitable combination of alternative renewable energy sources. However, the actual costs related to such sources are not competitive with respect to fossil energy. Focusing the attention on wind energy, it can be noted that wind power actually supplies about 0.3% of the global energy demand, with an average global growth of the installed capacity of about 27% in 2007 [2]. Recent studies [3] showed that by exploiting 20% of the global land sites of class 3 or more (i.e. with average wind speed greater than 6.9 m/s at 80 m above the ground), the entire world's energy demand could be supplied. However, such potential can not be harvested with competitive costs by the actual wind technology, based on wind towers, which require heavy foundations and huge blades, with massive investments. 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. Wind turbines can operate at a maximum height of about 150 m, a value hardly improvably, due to structural constraints which have reached their technological limits. The power density of a wind farm, realized with 1.5–MW wind towers, is around 9 MW/km^2, about 200–300 times lower than that of large coal–fired thermal plants [5]. Moreover, due to the wind intermittency, a wind farm is able to produce an average power which is a fraction only of its rated power (i.e. the level for which the electrical system has been designed, see [4]), denoted as "capacity factor" (CF). This fraction is typically in the range 0.3–0.45 for "good" sites. All these issues lead to wind energy production costs that are higher than those of fossil sources. Therefore, a quantum leap would be needed in this field to reach competitive costs with respect to those of the actual fossil sources, thus no more requiring incentives for green energy production.

Such a breakthrough in wind energy generation can be realized by capturing high–altitude wind power. The basic idea is to use tethered airfoils (e.g. power kites like the ones used for surfing or sailing), linked to the ground with cables which are employed to control their flight and to convert the aerodynamical forces into mechanical and electrical power, using suitable rotating mechanisms and electric generators kept at ground level. The airfoils are able to exploit wind flows at higher altitudes than those of wind towers (up to 1000 m), where stronger and more constant wind can be found basically everywhere in the world: thus, this technology can be used in a much larger number of locations. The potential of such a technology, denoted here as Kitenergy, has been theoretically investigated almost 30 years ago [6], showing that if the airfoils are driven to fly in "crosswind" conditions, the resulting aerodynamical forces can generate surprisingly high power values. However, only in the past few years more intensive studies have been carried out by some research groups ([7], [8], [9]), to deeply investigate this idea from the theoretical, technological and experimental point of views. In particular, exploiting the recent advances in the modeling and control of complex systems, automated control strategies have been developed to drive the airfoil flight in crosswind conditions. Moreover, small–scale prototypes have been realized to experimentally verify the obtained theoretical and numerical results.

This paper describes the advances of the research activities

This research was supported in part by Regione Piemonte, Italy, under the Project "Power Kites for Naval Propulsion".

The authors are with the Dipartimento di Automatica e Informatica, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy; e-mail: lorenzo.fagiano@polito.it, mario.milanese@polito.it, dario.piga@polito.it

undergoing at Politecnico di Torino, Italy, to develop this technology. Moreover, as a new contribution with respect to previous works (see [7]), which were focused on the control design of a single Kitenergy unit, in this paper several generators operating in the same site are considered and their positions and flight parameters are optimized in order to maximize the generated power per unit area. This way, the potentials of large scale plants, denoted as KE–farms, are investigated and compared with those of the actual wind tower farms. An analysis of wind speed data collected in some locations in Italy and in the Netherlands is also performed, in order to estimate the CF that can be obtained with Kitenergy. Finally, on the basis of these studies, a preliminary analysis of the costs of the electricity generated with a KE–farm is presented.

II. KITENERGY: HIGH–ALTITUDE WIND ENERGY USING CONTROLLED AIRFOILS

A. 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 20% 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. Yet, the structure of a wind tower determines most of its cost and imposes a limit to the elevation that can be reached. 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 Fig. 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 drums, linked to two electric drives which are able to act either as generators or as motors. An electronic control system controls the kite flight, by differentially pulling the cables. The kite is tracked 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 typically about 250 tons [10]. As reported below, a kite generator of the same rated power can be obtained using a 500–m^2 kite and cables 1000–m long, with a total weight of about 2 tons only.

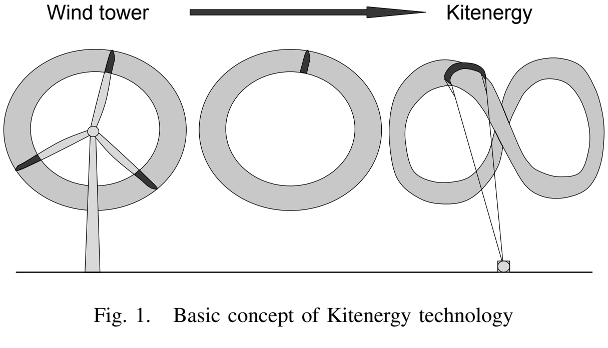

Fig. 1. Basic concept of Kitenergy technology

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 to realize the so–called KE–yoyo generator, that captures the wind power by unrolling the kite lines, as described in the next Section.

B. KE–yoyo energy generation cycle and simulation results

In the KE–yoyo configuration (see [7], [11] for more details), the KSU is fixed with respect to the ground. Energy is obtained by continuously performing a two-phase cycle, depicted in Fig. 2: 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 the traction 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 quite small fraction (less than 10%) of the amount generated in the traction phase. Such an operational cycle has been developed and tested through numerical simulations, considering a quite accurate model, which takes into account the aerodynamic characteristics of the kite and the cables, and employing advanced control techniques (i.e. efficient model predictive control, see e.g. [12]) to maximize the net generated energy. The employed control technique is able to keep the kite path inside a limited space region, while optimizing the generated energy, also in the presence of quite strong wind disturbance. In particular, the flight trajectory is kept inside a space region which is limited by a polyhedron of dimensions $a \times a \times \Delta r$ (see Fig. 2) that depend on the KE–yoyo operational parameters and airfoil characteristics. Table I shows the characteristics of the KE–yoyo model employed in the numerical simulations.

From such simulations, the power curve of the considered KE–yoyo has been also computed (see Fig. 3): such a curve gives the generated power as a function of wind speed and it can be employed to compare the performances of the KE–yoyo with those of a commercial wind turbine with the same nominal power, whose power curve is reported in Fig. 3 too. In particular, it can be noted that a net power value of 2 MW is obtained by the KE–yoyo with 9–m/s wind speed, while a commercial wind tower can produce only 1 MW in the same conditions. The power curves are saturated at the nominal value of 2 MW, corresponding to the maximum that can be obtained with the employed electric generator. Moreover, a

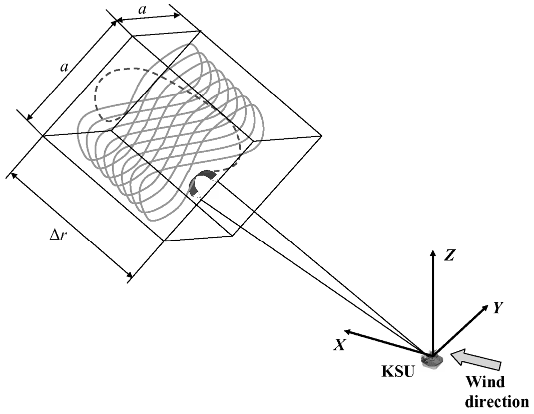

Fig. 2. KE–yoyo configuration cycle: traction (solid) and passive (dashed) phases. The kite is kept inside a polyhedral space region whose dimensions are $(a \times a \times \Delta r)$ meters.

TABLE I

NUMERICAL VALUES OF KE–YOYO MODEL EMPLOYED IN THE NUMERICAL SIMULATIONS.

Kite mass (kg)	300
Characteristic area (m^2)	500
Lift coefficient	1.2
Kite aerodynamic efficiency	13
Diameter of a single line (m)	0.03
Line density (kg/m^3)	970
Line drag coefficient	1.2
Minimum cable length (m)	850
Air density (kg/m^3)	1.2

cut–out wind speed of 25 m/s has been also considered for structural safety reason, as it is done for wind turbines.

The numerical simulation analyses have been also employed to investigate show how the generated power of a KE–yoyo depends on several design and wind parameters. In particular, the generated power grows linearly with the kite area, with the cube of wind speed and according to a logistic–type function with the kite aerodynamic efficiency (see [7]). Thus, for example, using a kite with the characteristics reported in Table I and a cable diameter of 4.2 cm, a KE–yoyo can generate a net power of 10 MW with 15 m/s wind speed.

C. Experimental results

At Politecnico di Torino, a small–scale KE–yoyo prototype has been built (see Fig. 4), equipped with two Siemens® permanent-magnet synchronous motors/generators with 20–kW peak power and 10–kW rated power each. The energy produced is stored in a series of batteries that have a total voltage of about 340 V. The batteries also supply the energy to roll back the lines when needed. The prototype is capable of driving the flight of 5–20–m^2 kites with cables up to 1000 m long (see [11] for further details on the prototype). The results of the first experimental tests performed at Politecnico di Torino have been compared with numerical simulation results, in order to test the concept and to assess the matching between real–world data and simulation results regarding the generated energy. The considered test has been performed near Torino, Italy. The employed kite had an effective area of 10 m^2 and line length of 800 m, while the wind flow was quite weak (about 3–4 m/s at 500 m of height). A movie clip of this experimental test is available [13]. Fig. 5 shows the comparison between the energy values obtained during the experimental tests and the numerical simulation results. It can be noted that quite a good matching exists between the experimental and the numerical results. The main source of error between the simulated and measured energy courses is the turbulence of wind speed (whose value at the kite's elevation could not be measured with the available test equipments), which may give rise to noticeably different instantaneous real power values with respect to the simulated ones. However, the average power value is quite similar: a mean measured power value of 555 W has been obtained in the test, while the simulated average values is 510 W, i.e. an error of about 10% is observed. Such a quite good matching between the measured and simulated generated energy gives a good confidence level in the numerical and theoretical tools, which can be therefore employed to perform a realistic study of the energy generation potential of large KE–farms, as described in Section IV.

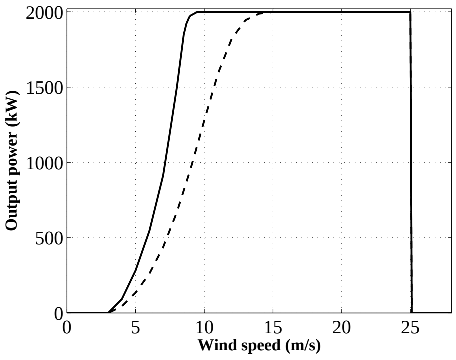

Fig. 3. Comparison between the power curves of a typical wind tower (dashed) and of a KE–yoyo (solid), both with the same rated power of 2 MW.

III. CAPACITY FACTOR ANALYSIS

As recalled in the introduction, due to wind intermittency the average power produced by a wind generator over the year is only a fraction, often indicated as "capacity factor" (CF), of the rated power. 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 II the CFs of a KE–yoyo and of a wind tower with the power curves of Fig. 3 are reported, considering some Italian sites and one location in The Netherlands (results related to other sites are given in [11]). Fig. 6 shows, for two of the considered sites, the histograms of wind speed at 50–150 m over the ground, where the wind tower operates, and at 200–800 m over the ground, where the KE–yoyo can operate. Such estimates have been computed using the daily measurements of sounding stations collected over 11 years (between 1996 and 2006) and

Fig. 4. KE–yoyo small scale prototype operating near Torino, Italy.

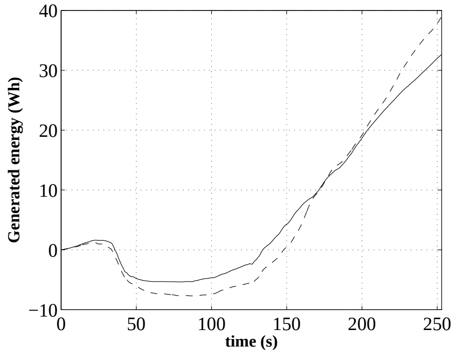

Fig. 5. Comparison between the measured (dashed) and simulated (solid) generated energy obtained with a small–scale KE–yoyo generator. The experimental test has been carried out near Torino, Italy, in January 2008.

TABLE II

CAPACITY FACTORS OF 2–MW RATED POWER WIND TOWER AND KE–YOYO AT DE BILT, IN THE NETHERLANDS, AND AT LINATE, BRINDISI AND CAGLIARI, IN ITALY.

	De Bilt	Linate	Brindisi	Cagliari
wind tower	0.36	0.006	0.31	0.31
KE–yoyo	0.71	0.33	0.60	0.56

available on [14]. In all the considered sites, the wind speed values between 200 m and 800 m are significantly higher than those observed between 50 m and 150 m. Considering as an example the results obtained for De Bilt (Fig. 6(a)), in the Netherlands, it can be noted that in the elevation range 200–800 m the average wind speed is 10 m/s and wind speeds higher than 12 m/s can be found with a probability of 38%, while between 50 and 150 meters above the ground the average wind speed is 7.9 m/s and speed values higher than 12 m/s occur only in the 8% of all the measurements. Similar results have been obtained with the data collected in other sites around the world. The same analysis on the data collected at Linate, Italy, leads to even more interesting results (Fig. 6(b)): in this case, between 50 and 150 meters above the ground the average wind speed is 0.7 m/s and speeds higher than 12 m/s practically never occur. On the other hand, in the operating elevation range of Kitenergy an average speed of 6.9 m/s is obtained, with a probability of 7% to measure wind speed higher than 12 m/s.

Interesting economical considerations can be drawn from the results of Table II. 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, the Kitenergy technology has capacity factors about two times greater than the present wind power technology, thus more than doubling the economic return even assuming the same costs. Indeed, for the structural reasons previously discussed, it is expected that the cost per MW of rated power of a KE–yoyo may be lower than that of a wind tower. In addition, bad sites for the present wind technology can be still economically convenient with Kitenergy technology: this is made extremely evident from the data of Linate, where a negligible CF value could be obtained with a wind tower, while a KE–yoyo could give a CF greater than that of a wind tower in the good sites of

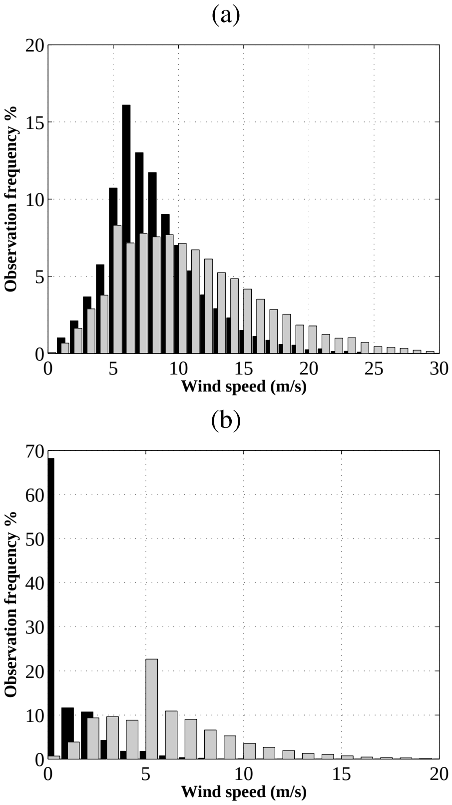

Fig. 6. Histograms of wind speed between 50 and 150 meters above the ground (black) and between 200 and 800 meters above the ground (gray). Data collected at (a) De Bilt (NL) and (b) Linate (IT).

Brindisi and Cagliari.

IV. DESIGN OF LARGE SCALE KITENERGY PLANTS

The problem of suitably allocating several KE–yoyo generators on a given territory is now considered, in order to maximize the generated power per km^2 while avoiding collisions and aerodynamic interferences among the various kites. Indeed, in the present wind farms, in order to limit the aerodynamic interferences between wind towers of a given diameter D, a distance of $7D$ in the prevalent wind direction and of $4D$ in the orthogonal one are typically used [5].

In a KE–farm, collision and aerodynamic interference avoidance are obtained if the space regions in which the different kites fly are kept separated. At the same time, in order to maximize the generated power density per unit area of the KE–farm, it is important to keep the distance between the KSUs as short as possible. A group of 4 KE–yoyo units, placed at the vertices of a square with sides of length L, is now considered (see Fig. 7). The minimum cable length of the upwind kites is indicated with $\underline{r}_1$, while $\underline{r}_2$ is the minimum cable length of the downwind kites and Δr is the cable length variation of all the kites during the KE–yoyo cycle (i.e. the maximum line lengths are $\overline{r}_1 = \underline{r}_1 + \Delta r$ and $\overline{r}_2 = \underline{r}_2 + \Delta r$). Finally, θ_1 and θ_2 are the average inclinations of the upwind and downwind kites respectively, with respect to the vertical axis Z (see Fig. 7). For given characteristic of wind, kite, cables, etc., the values of θ_1, $\underline{r}_1$, θ_2, $\underline{r}_2$, and L can be computed to maximize the average net power per unit area generated by the four KE–yoyo generators, subject to the constraints that the polyhedra limiting the kite flight regions do not intersect and that the maximum flight elevation of the downwind kites is lower than the minimum elevation of the upwind ones, so to avoid aerodynamic interferences. Details on this optimization procedure can be found in [15]. In particular, using the system data given in Table I with a limiting polyhedron of dimensions ($300 \times 300 \times 50$) meters, the values $L = 250\,\text{m}$, $\theta_1 = 46.5°$, $\underline{r}_1 = 1100\,\text{m}$, $\theta_2 = 51.7°$ and $\underline{r}_2 = 530\,\text{m}$ are obtained at De Bilt site. With such a solution, the kite flight elevations are between about 650 m and 850 m for the upwind kites and between about 350 m and 550 m for the downwind kites. Similar values are obtained also for the other sites considered in Table II. Then, several of such groups of 4 KE–yoyo generators can be placed at a distance of $L = 250\,\text{m}$ one from the other, so to avoid collisions among kites of adjacent basic units. With this solution, the kites flying at the same elevation, belonging to adjacent basic units in line with the wind, result to be at a distance of 500 meters, with limited expected aerodynamic interferences. This way, it is possible to realize KE–farms with a density of 16 KE–yoyo units per km^2 and, consequently, a rated power of 32 MW per km^2, with a capacity factor of about 0.6 in a good site like De Bilt in the Netherlands. Indeed, as previously noted, the same 500–m^2 kite can be used to obtain a KE–yoyo with 5 MW rated power, without significant cost increases, except for the electric equipments. Then, a KE–farm using such 5–MW KE–yoyo would have a rated power density of 80 MW per km^2 and a capacity factor of about 0.45 in a site like De Bilt.

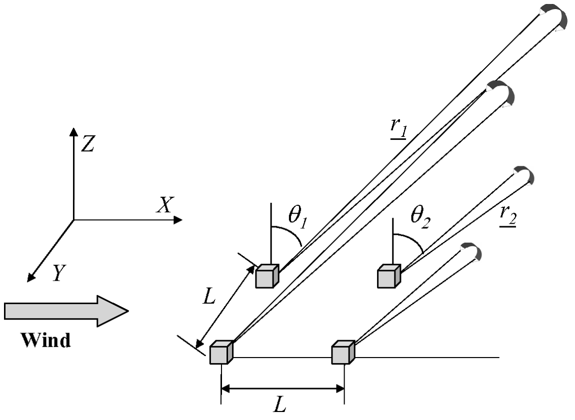

Fig. 7. Group of 4 KE–yoyo placed on the vertices of a square land area.

Note that a wind farm realized with 2–MW, 90–m diameter wind towers has a density of 4.5 towers per km^2 and a rated power of about 9 MW per km^2 [3], [5], with a capacity factor of about 0.3–0.4 in a good site. Thus, the presented analysis shows that a suitably designed KE–farm could provide a rated power per unit area from 3.5 to 9 times higher than that of a present wind tower farm, for the 2–MW and 5–MW KE–yoyo respectively, with a consequent average yearly generated power per km^2 ranging from 7 to 13 times the value obtained by wind towers.

V. ENERGY PRODUCTION COSTS OF KITENERGY

On the basis of the results presented so far, a preliminary estimate of the costs of the electricity produced with Kitenergy can be performed, in order to make a comparison with the costs of the other technologies. The production costs for Kitenergy and wind tower technologies are related essentially to the amortization of the costs of the structures, the foundations, the electrical equipments to connect to the power grid, authorizations, site use, etc., while the maintenance costs are certainly marginal for both technologies, though possibly higher for Kitenergy. Thus, the main differences between the two technologies are related to their structures, foundations and required land, whose costs are significantly lower for Kitenergy. In fact, the heavy tower and the rotor of a wind turbine are replaced by light composite fiber cables and the kite in a KE–yoyo. Given the same rated power, the foundations of a KE–yoyo have to resist to significantly lower strains. A reliable estimate of the energy production costs of a KE–farm certainly requires more experimentations. However, for all of the aspects discussed so far, a very conservative estimate can be obtained, at least in relative terms with respect to the cost of the actual wind technology, by assuming that the cost of a KE–yoyo unit with 2–MW rated power is not greater than that of an actual wind tower with 2–MW rated power.

Table III shows the projected cost in 2030 (levelised in 2003 U.S. dollars per MWh) of energy from coal, gas, nuclear, wind and solar sources. The costs reported in Table III have been taken from [16] where, for each technology, the projections have been computed using data related to power plants installed in more than 10 different countries. Such data, provided by experts from the participating countries, include cost data and technical information. In particular, an average load factor of 85% for coal, gas and nuclear power plants has been considered, as well as a capacity factor from 17% to 38% for wind power and an availability/capacity factor from 9% to 24% for solar plants (for more details on the methodology employed to estimate the energy costs of Table III, the interested reader is referred to [16]). The average estimated costs reported in Table III have been computed by considering, for each source, all of the power plants analyzed in [16]. According to [16], considering sites with CF between 17% and 38%, the projected energy production costs of a wind farm composed of 2–MW towers is between 35 \$/MWh and 95 \$/MWh with a density of about 4.5 towers per km^2 (assuming a diameter $D = 90$ m and applying the "$7D$–$4D$ rule" [3], [5]). On the basis of the analyses presented in this paper, in the same location a KE–farm of the same overall rated power, composed of 2–MW KE–yoyo units using 500–m^2 kites, would produce an average power 2 times higher than that of the wind farm (thanks to the greater capacity factor), with a density of 16 KE–yoyo per km^2, i.e. 3.6 times higher than the wind farm. Then, a conservative energy cost estimate between 18 \$/MWh and 48 \$/MWh is obtained for Kitenergy. Note that the considered cost assumption is a very conservative one and that the higher density of KE–yoyo units leads to lower land occupation (i.e. lower costs) for the same rated power. Thus, scale factors should positively affect the production costs of Kitenergy technology, leading to cost estimates (reported in Table III) of 10–48 \$/MWh with an average value of 20 \$/MWh, showing that high–altitude wind energy may be significantly cheaper than fossil energy.

TABLE III

PROJECTED COST IN 2030 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

VI. CONCLUSIONS

The paper described the advances of the research activities undergoing at Politecnico di Torino to develop an innovative concept of high–altitude wind energy generation. Such activities include numerical simulations, prototype experiments, wind data analyses, a newly introduced study on the design of large kite power plants and a preliminary electricity cost analysis. The obtained results show that the Kitenergy technology has the potential to generate renewable energy, available in large quantities almost everywhere, with production cost lower than that of fossil energy.

Thus, high–altitude wind power may contribute to a significant reduction of the global dependance on the fossil sources in a relatively short time. The full industrialization of this technology will involve the fusion of advanced competencies in several engineering fields (like aerodynamics and flight mechanics, materials, modeling and control theory, mechatronics,etc.) and may require from 3 to 5 years. Moreover, substantial new technological innovations, for example in the field of high–efficiency airfoils, may lead to further great performance improvements.

REFERENCES

[1] International Energy Agency (IEA), *World Energy Outlook 2008*. Paris, France: IEA PUBLICATIONS, 2008.

[2] "Global Wind Energy Council, *Global wind 2007 report*," May 2008, (Available online: http://www.gwec.net/fileadmin/documents/test2/gwec-08-update_FINAL.pdf).

[3] C. L. Archer and M. Z. Jacobson, "Evaluation of global wind power," *J. Geophys. Res.*, vol. 110, D12110, 2005.

[4] R. Thresher, M. Robinson, and P. Veers, "To capture the wind," *IEEE Power & Energy Magazine*, vol. 5, no. 6, pp. 34–46, 2007.

[5] G. M. Masters, *Renewable and Efficient Electric Power Systems*. Wiley, 2004.

[6] M. L. Loyd, "Crosswind kite power," *Journal of Energy*, vol. 4, no. 3, pp. 106–111, 1980.

[7] M. Canale, L. Fagiano, and M. Milanese, "High altitude wind energy generation using controlled power kites," *IEEE Transactions on Control Systems Technology*, available online. Doi: 10.1109/TCST.2009.2017933.

[8] A. Ilzhöfer, B. Houska, and M. Diehl, "Nonlinear mpc of kites under varying wind conditions for a new class of large-scale wind power generators," *International Journal of Robust and Nonlinear Control*, vol. 17, p. 1590 1599, 2007.

[9] P. Williams, B. Lansdorp, and W. Ockels, "Optimal crosswind towing and power generation with tethered kites," *Journal of guidance, control, and dynamics*, vol. 31, pp. 81–93, 2008.

[10] Vestas Wind Systems A/S website: http://www.vestas.com.

[11] L. Fagiano, "Control of tethered airfoils for high–altitude wind energy generation," Ph.D. dissertation, Politecnico di Torino, Italy, February 2009, available on–line: http://lorenzofagiano.altervista.org/docs/PhD_thesis_Fagiano_Final.pdf.

[12] M. Canale, L. Fagiano, and M. Milanese, "Set Membership approximation theory for fast implementation of model predictive control laws," *Automatica*, vol. 45, no. 1, pp. 45–54, 2009.

[13] Kitenergy experimental test movie, January 2008. Available on–line: http://lorenzofagiano.altervista.org/movies/Casale_test.wmv.

[14] NOAA/ESRL Radiosonde Database Access: http://raob.fsl.noaa.gov/.

[15] L. Fagiano, M. Milanese, and D. Piga, "High altitude wind power generation," *IEEE Transactions on Energy Conversion*, available online. Doi: 10.1109/TEC.2009.2032582.

[16] International Energy Agency (IEA), *Projected Cost of Generating Energy – 2005 update*. Paris, France: IEA PUBLICATIONS, 2008, available on–line: http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1472.