High-altitude wind power generation for renewable energy cheaper than oil

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The paper presents the innovative technology of high-altitude wind power generation, indicated as KiteGen, 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, in order to show that it has the potential to overcome the limits of the actual wind turbines and 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 KiteGen project, including numerical simulations, prototype experiments and wind data analyses.

Introduction

The problem of sustainable energy generation is one of the most urgent challenges that mankind is facing today. On the one hand, world energy consumption is projected to grow by 50% from 2005 to 2030, mainly due to the development of non-OECD countries (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 86% of the global energy consumption 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. Such a situation gives rise to serious geopolitical and economical problems, affecting almost all of the world's countries. One of the key points to solve these issues is the use of a suitable combination of alternative energy sources. Accurate and deep analysis of the characteristics of the various alternative energy technologies is outside the scope of this paper, and only some concise considerations are now reported, to better motivate the presented research.

Nuclear energy actually represents the second contribution to the world's energy demand, about 6%, and it avoids the problems related to carbon dioxide emissions. However, the issues related to safe nuclear waste management haven't been solved yet, despite the employed strong efforts.

Renewable energy sources like hydropower, biomass, wind, solar and geothermal supply the remaining 8% of the world energy demand, though they could meet the whole global needs, without the issues related to pollution and global warming. However, the cost of the present renewable energies is not competitive with that of fossil ones, mainly due to the high costs of the related technologies, their intermittent and non--uniform availability and the low generated power density per km^2. The use of hydroelectric power is not likely to increase substantially in the future, because most major sites are already being exploited or are unavailable for technological and/or environmental reasons. Biomass and geothermal power have to be managed carefully to avoid local depletion, so they are not able to meet a high percentage of the global consumption. Solar energy has been growing fast during the last years (2), however it has high costs (5-10 times higher than fossil sources) and requires large land occupation, having a power density of about 20 MW/km^2.

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Finally, wind power supplies about 0.3% of the global energy demand, with an average global growth of the installed capacity of about 27% in 2007 (3). It is interesting to note that recent studies (4) 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't be harvested with competitive costs by the actual wind technology, based on wind towers, which require heavy foundations and huge blades, with massive investments. 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 land occupation of the present wind farms is about 6 towers per km^2, considering 1.5 MW, 77-m diameter turbines (5). The corresponding power density of 9 MW/km^2 is about 200-300 times lower than that of thermal plants. Moreover, due to the wind intermittency, a wind farm is able to produce a mean power which is a fraction only of its nominal power (i.e. the maximum power that the generator can produce). 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 wind power technology to overcome these problems and boost its application, providing green energy with competitive costs with respect to those of the actual fossil sources, thus no more requiring incentives for its application.

A new concept of wind energy generation

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 used for surfing or sailing), linked to the ground with one or more 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 potentials of such technology 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 (7-9), to deeply investigate such idea from the theoretical, technological and experimental point of views. In particular, exploiting the recent advances in the modelling 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 theoretical and numerical results.

This paper presents the advances of the projects undergoing at Politecnico di Torino, Italy, to develop this technology, in cooperation with the high-tech Italian companies Sequoia Automation and Modelway. Though the present paper focuses on stationary electric energy generation, the kite technology is at present investigated also for sustainable transportation systems. In particular, in the last quarter of 2008 the EU-FP7 project “KitVes: airfoil based solutions for vessel on-board energy production destined to traction and auxiliary services” started.

The KiteGen project

The key idea of the KiteGen project 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 high-altitude wind energy, one can imagine to remove all the bulky structure of a wind tower and just keep the outer part of the blades (see Figure 1), which becomes a much lighter kite flying fast in crosswind conditions, connected to the ground by two cables, realized in composite materials, with a traction resistance 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 can drive the kite flight by differentially pulling the cables (see Figure 2A).

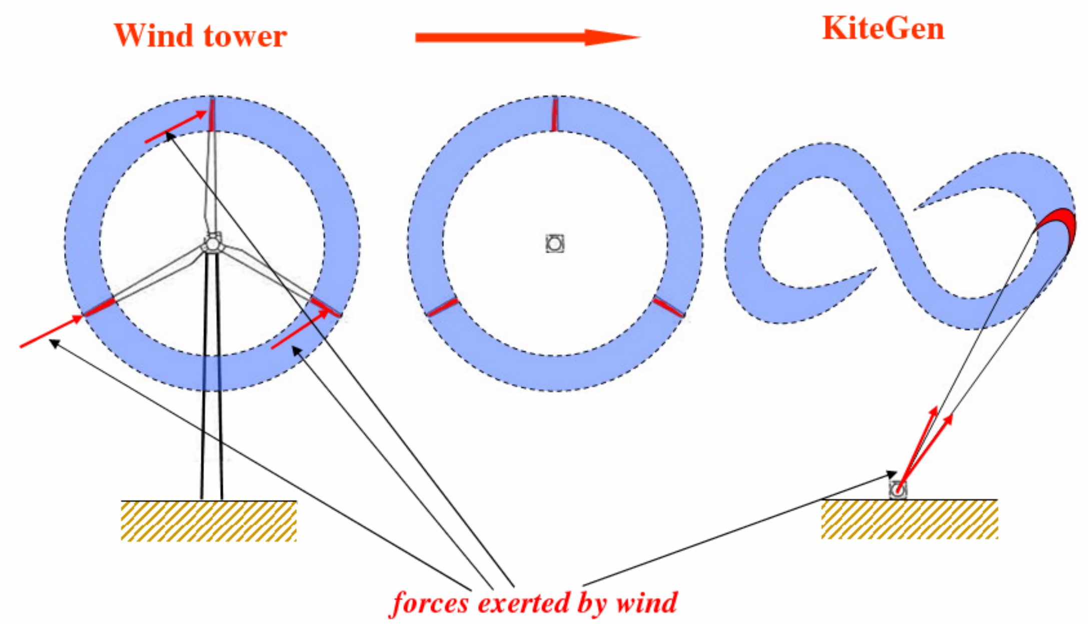


Figure 1: Basic concept of KiteGen technology

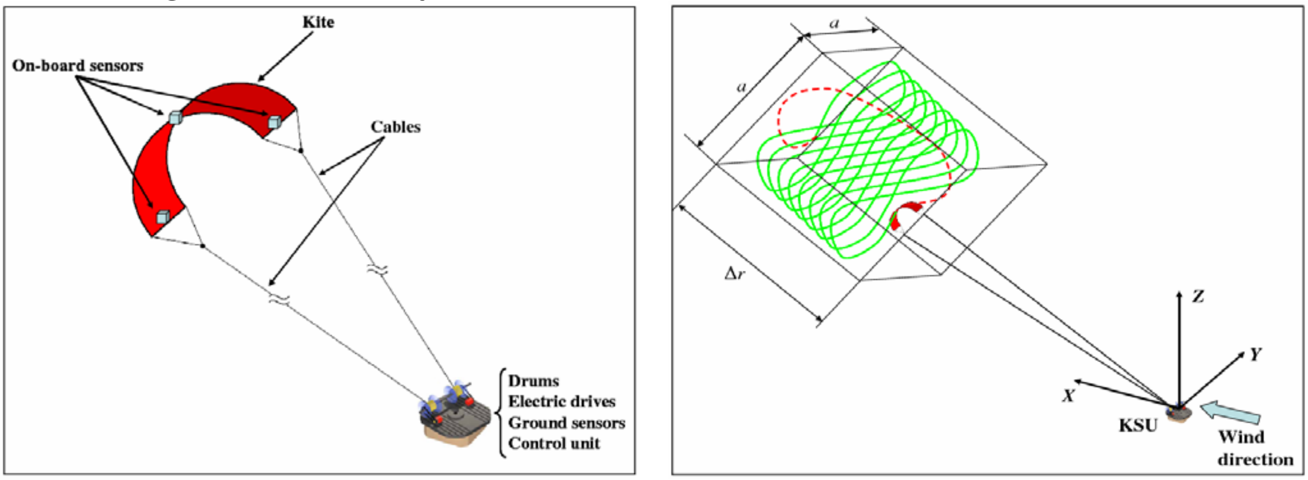
The kite flight is tracked and controlled using on-board wireless instrumentation (GPS, magnetic and inertial sensors) as well as ground sensors, to measure the airfoil speed and position, the power output, the cable force and speed and the wind speed and direction. Thus, the rotor and the tower of the present wind technology are replaced in KiteGen 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. As reported below, a kite generator of the same nominal power can be obtained using a 500-m^2 kite and cables 1000-m long, with a total weight of about 2 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 KiteGen technology.

The KSU can be employed in different ways to generate energy: two solutions have been investigated so far, namely the KG-yoyo and the KG-carousel configurations (7). In the KG-yoyo generator, wind power is captured by unrolling the kite lines, while in the KG-carousel configuration the KSU is also employed to drag a vehicle, moving along a circular rail path, thus generating energy by means of additional electric generators linked to the wheels. The choice between KG-yoyo and KG-carousel configurations for further developments will be made on the basis of technical and economical considerations, like construction costs, generated power density with respect to land occupation, reliability features, etc. In this paper, the focus is on the analysis of the potential of KG-yoyo generators to operate together in the same site, thus realizing large KG-farms in terms of maximum and average generated power per km^2 and energy production costs.

KG-yoyo wind generator

In the KG-yoyo configuration, the KSU is fixed with respect to the ground and the electronic control system can maneuver the kite by differentially pulling the two cables and changing their winding speed. Energy is obtained by continuously performing a two-phase cycle (depicted in Figure 2B): 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.



A B

Figure 2: KiteGen technology. (A) Scheme of a Kite Steering Unit (KSU). (B) KG--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. Δr is a design parameter imposing the maximum cable length variation during a single cycle. The value of a is related to the minimum trajectory radius of the kite and depends on its size.

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 fraction (less than 20%) of the amount generated in the traction phase. Such 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 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 presence of quite strong wind disturbance. In particular, the flight trajectory is kept inside a space region which is limited by a polyhedron of given dimension $a \times a \times \Delta r$ (see Figure 2B).
Table 1 shows the characteristics of the KG-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

Table 1: Numerical values of KG-yoyo model employed in the numerical simulations.

From such simulations, the power curve of the considered KG-yoyo has been also computed (see Figure 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 KG-yoyo with those of a commercial wind turbine with the same nominal power, whose power curve is reported in Figure 3 too.

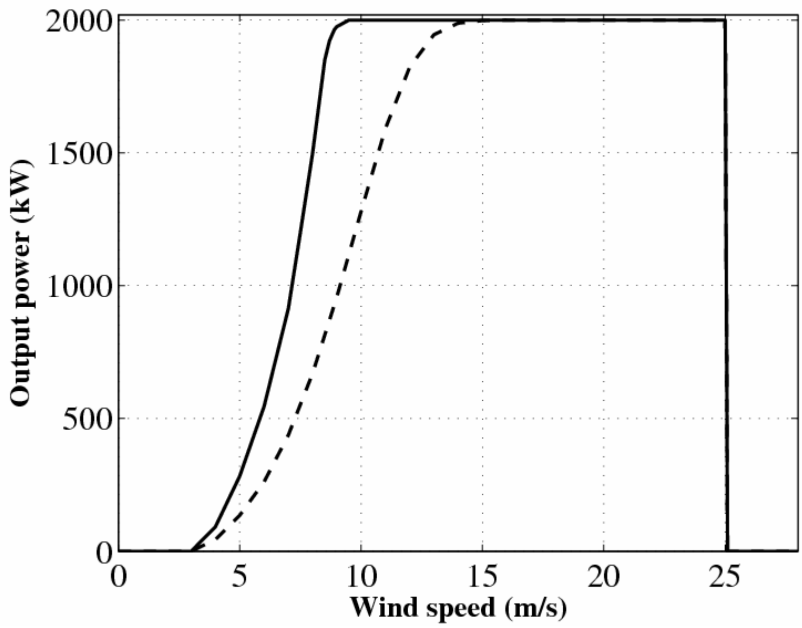


Figure 3: Comparison between the power curves of a typical wind tower (dashed) and of a KG-yoyo (solid), both with the same nominal power of 2 MW. Due to the possibility for a kite to sweep a bigger area than the one intercepted by the blades of a turbine, the KG-yoyo can produce the nominal power already with a wind speed value of 9 m/s, while 15-m/s wind speed is necessary for a wind tower to produce the same amount of power.

In particular, it can be noted that a net power value of 2 MW is obtained by the KG-yoyo with 9-m/s wind speed, while a commercial wind tower can produce only 1 MW in the same conditions. Note that 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 cut--out wind speed of 25 m/s has been also considered for structural safety reason, as it is done for wind turbine.
The numerical simulation analyses also show how the generated power of a KG-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. Thus, for example, using a kite with the characteristics reported in Table 1 and a cable diameter of 4.2 cm, a KG-yoyo can generate a net power of 10 MW with 15 m/s wind speed.
In the KiteGen project, a small-scale KG-yoyo prototype has been built (see Figure 4), capable of generating 40-kW peak power, driving the flight of 10-15-m^2 kites with cables more than 1000 m long, which allow to capture wind power up to 600-700 m above the ground. A movie of the experimental tests performed near Torino, Italy, is available on the web-site (*10*). The good matching between measured data and simulation results gives a good confidence level in the latter. Thus, the developed numerical simulation methods can be employed to perform a realistic study of the energy generation potential of large power plants, denoted as KG-farms, composed of several KG-yoyo generators.

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

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 nominal power.

For a given wind generator on a specific site, the CF can be evaluated knowing the probability density distribution function of wind speed. In Table2, the CFs of a KG-yoyo and of a wind tower with the power curves of Figure 3 are reported, considering some Italian sites and one location in The Netherlands.

	Linate	Pratica	Cagliari	Trapani	Brindisi	De Bilt
wind tower	0.006	0.23	0.31	0.30	0.31	0.36
KG-yoyo	0.33	0.49	0.56	0.56	0.60	0.71

Table 2: Capacity factors of 2-MW nominal power wind tower and KG-yoyo at Linate, Pratica, Cagliari, Trapani and Brindisi, in Italy, and at De Bilt, in The Netherlands, evaluated from daily wind measurements of sounding stations.

Figure 5 shows, for each considered site, the estimated probability density distribution function 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 KG-yoyo can operate. Such estimates have been computed using the daily measurements of sounding stations collected over 11 years (between 1996 and 2006) and available on the database RAOB (RAwinsonde OBservation) of the National Oceanographic and Atmospheric Administration.

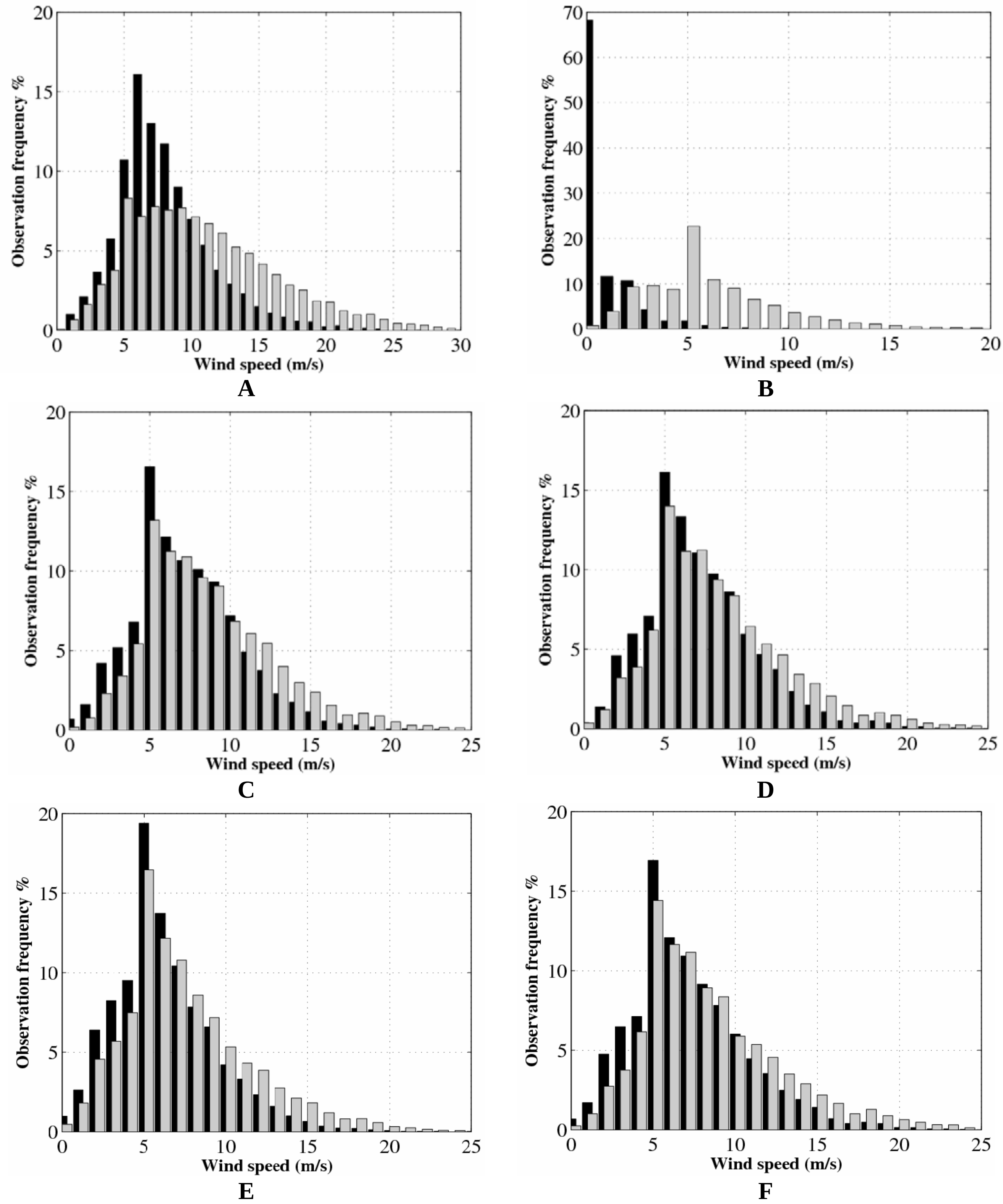


Figure 5: Probability density distributions of wind speed between 50 and 150 meters above the ground (black) and between 200 and 800 meters above the ground (gray). Data collected at (A) De Bilt (NL), (B) Linate (IT), (C) Brindisi (IT), (D) Cagliari (IT), (E) Pratica di mare (IT), (F) Trapani (IT).

Interesting economical considerations can be drawn from these results. 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 KiteGen technology obtains a CF values 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 nominal power of a KG-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 KiteGen 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 KG-yoyo could give a CF greater than that of a wind tower in the good site of De Bilt.

KG-farm

The problem of suitably allocating several KG-yoyo generators on a given territory is now considered, in order to maximize the generated power per km^2 while avoiding collision 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 KG-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, to maximize the generated power density per km^2 of the KG-farm, it is important to keep the distance between the KSUs as short as possible. A basic unit of 4 KG-yoyos, placed at the vertices of a square with sides of length L, is now considered (see Figure 6). 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 flight.

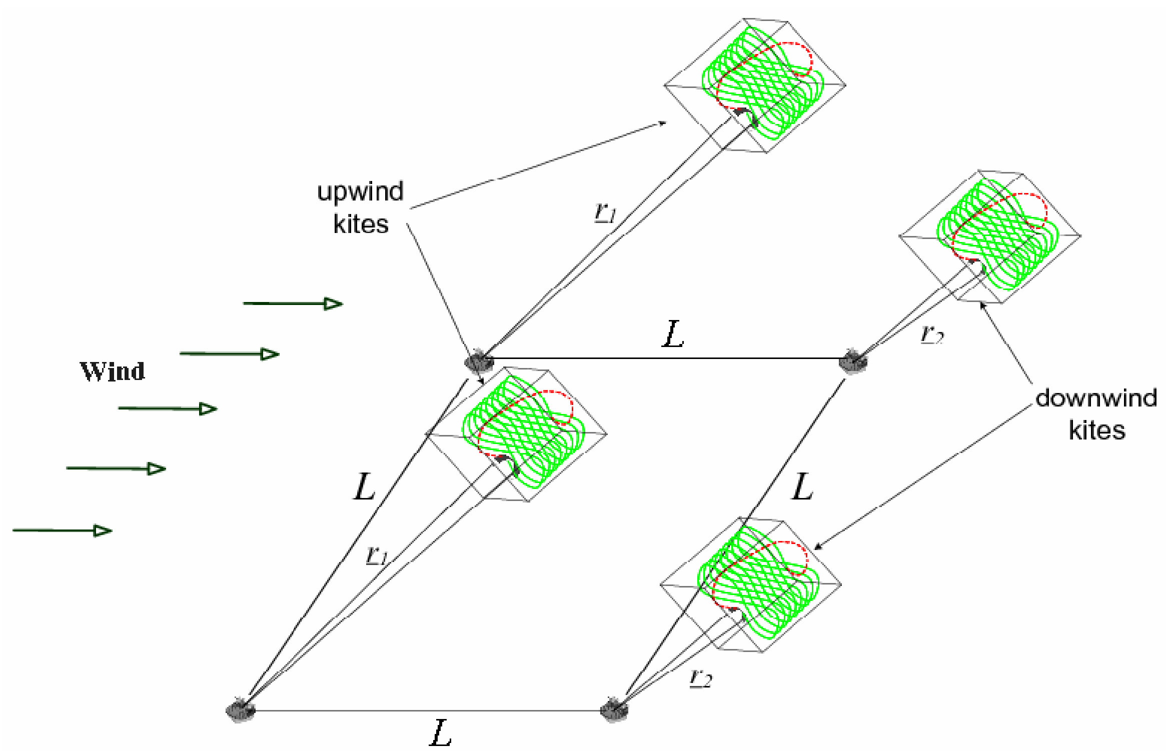


Figure 6: Basic unit of 4 KG-yoyos placed on the vertices of a square land with sides of length L. The maximal flight elevation of the two downwind kites is lower than the minimal elevation of the upwind ones and the space regions in which the kites fly are kept separated, to avoid collisions and aerodynamic interferences.

For a given wind characteristic, the values of $L, \underline{r}_1, \underline{r}_2, \Delta r$ can then be chosen to maximize the overall net power generated by the four KG-yoyo generators, subject to the constraint that the polyhedra that limit 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. For example, using 2-MW, 500-m^2 KG-yoyos with the characteristics reported in Table 1 and the power curve reported in Figure 3, with a limiting polyhedron of dimensions $(300 \times 300 \times 50)$ meters, at the De Bilt site the values $L = 300m, \underline{r}_1 = 1150\,m, \underline{r}_2 = 850\,m, \Delta r = 50\,m$ are obtained, with consequent kite flight elevation of

$550 \div 700$ m for the upwind kites and $385 \div 540$ m for the downwind kites. Similar values are obtained also for the other sites considered in Table 2. Then, several of such basic units can be placed at a distance of 300 meters one from the other, so to avoid collisions among kites of adjacent basic units. With such a 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 600 meters, with limited expected aerodynamic interferences. This way, it is possible to realize KG-farms with nominal power density of 32 MW per km^2. Note that a wind farm realized with 2-MW, 80-m diameter wind towers has a nominal power density of 12 MW per km^2 (4,5). Indeed, as previously noted, the same 500-m^2 kite can be used to obtain a 10 MW nominal power KG-yoyo, without significant cost increases, except for the electric equipments. Then, a KG-farm using such 10-MW KG-yoyo would have a nominal power density of 160 MW per km^2.
Finally, considering also the different capacity factors of the two technologies, even greater improvements in terms of average yearly generated power density are obtained, ranging from 7 to 13 times the value obtained by wind towers, for the 2-MW and 10-MW KG-yoyo respectively.

Energy cost analyses and conclusions

From the analyses presented so far, it results that, even in a good site for the actual wind technology, the average yearly generated power density of KiteGen technology may be up to 13 times greater. The energy production costs for both 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 KiteGen. Thus, the main differences between the two technologies are related to their structures, foundations and required land, whose costs are significantly lower for KiteGen. In fact, the heavy tower and the rotor of a wind turbine are replaced by light composite fiber cables and the kite in a KG-yoyo. Given the same nominal power, the foundations of a KG-yoyo have to resist to significantly lower strains and the required site dimension may be up to 10 times lower. A reliable estimate of the energy production costs of a KG-farm certainly requires more experimentations. However, for all the aspects discussed so far, a conservative estimate can be obtained by assuming that the overall costs are similar to those of an actual wind farm with the same nominal power. In a site with CF $\approx$ 0.3, a present wind farm has energy production costs of about 150 $/MWh. In the same location a KG-farm has CF $\approx$ 0.6, i.e. it can generate twice the energy with the same nominal power. Then, a conservative estimate of energy production cost of about 75 $/MWh is obtained. Note that the actual costs of energy production from fossil sources are in the range 60-90 $/MWh, according to the different types of source (coal, oil, gas). Moreover, the presented analyses show that a suitably designed KG-farm may generate an average power density from 7 to 13 times greater than that of an actual wind farm. Thus, scale factors may positively affect the production costs of KiteGen technology, leading to estimates of about 50 $/MWh for a 100 MW KG-farm and 15 $/MWh for a 500 MW KG-farm.
In conclusion, from the results obtained so far, including numerical simulations, prototype experiments and wind data analyses, the KiteGen technology, 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 a cost even lower than that of fossil energy.
Moreover, such a significant reduction of the dependence on fossil sources could be realized in a relatively short time. Indeed, the industrialization of KiteGen technology may require from 3 to 5 years, since no more basic research or technological innovations are needed, but only the fusion of advanced competencies already available in different engineering fields, such as modelling and control, aerodynamics and flight mechanics, materials and mechatronics.

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References

1. U. S. Energy Information Administration (EIA), *International Energy Outlook 2008 -- Highlights* (2008). (Available online: http://www.eia.doe.gov/oiaf/ieo/).

2. U. S. Energy Information Administration (EIA), *Solar Thermal and Photovoltaic Collector Manufacturing Activities 2006* (2007). (Available online: http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solar.html).

3. Global Wind Energy Council, *Global wind 2007 report* (2008). (Available online: http://www.gwec.net/fileadmin/documents/test2/gwec-08-update FINAL.pdf).

4. C. L. Archer, M. Z. Jacobson, *J. Geophys. Res.* **110, D12110** (2005).

5. G. M. Masters, *Renewable and Efficient Electric Power Systems* (Wiley, 2004).

6. M. L. Loyd, *Journal of Energy* **4**, 106 (1980).

7. M. Canale, L. Fagiano, M. Milanese, *IEEE Conrol Systems Magazine* **27**, 25 (2007).

8. A. Ilzhöfer, B. Houska, M. Diehl, *International Journal of Robust and Nonlinear Control* **17**, 1590 1599 (2007).

9. B. Lansdorp, R. Ruiterkamp, W. Ockels, *AIAA Atmospheric Flight Mechanics Conference and Exhibit* (Hilton Head, CA, 2007).

10. Complex Systems Modeling and Control group website: http://www.modelingcontrol.polito.it/