High Altitude Wind Generation: Renewable Energy cheaper than oil

Mario Milanese
Politecnico di Torino

HAWP Conference
Chico-Oroville (CA), November 5-6, 2009
The need

• At present, about 80% of the world electric energy is produced from thermal plants making use of fossil sources (oil, gas, coal).

• The economical, geopolitical and environmental problems related to such sources are becoming everyday more and more evident.

• Is it possible to invert the percentage split between non-renewable and renewable sources with the present renewable technologies?
Limits of present renewable technologies

• High production costs → incentives are required for their installations
• Large occupation of land

• Without significant breakthroughs, even reaching the objectives posed by many countries (e.g. 20% for 2020 in EU) is a difficult challenge
Kitenergy project

• A radical innovation in wind technology, aimed to generate renewable energy at cost lower than from oil

• Exploiting a renewable energy source, the altitude wind, available anywhere

• Channelled through arrays of automatically controlled tethered airfoils (kites).
Altitude vs. ground wind

- Wind power is already extremely promising at approx. 800 meters, where the average wind speed is estimated at 7.2 m/s.
- The related wind power is almost 4 times the one globally available for wind towers.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>wind speed</th>
<th>wind power</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 m</td>
<td>7.2 m/s</td>
<td>205 W/m²</td>
</tr>
<tr>
<td>80 m</td>
<td>4.6 m/s</td>
<td>58 W/m²</td>
</tr>
</tbody>
</table>
The problem

- Wind at 800 m is out of the reach of current and future aerogenerating towers, already struggling at 100 m.
- The structure holding up the rotors becomes exponentially heavier, more unstable and expensive.
The Kitenergy solution

• A radical shift of perspective: no longer heavy and static structures, but a light, dynamic and intelligent machine.
Kitenergy key technology

- The core is the system of automatic control of the kite flight, called KSU (Kite Steering Unit):

  on board sensors
  (kite position and speed)

  ground sensors
  (wind speed and direction, line strength, ...)

  cables

  actuation unit
  (electric drives, winches, ...)

  kite

  control software
Kitenergy key technology

- In wind towers, the outermost 20% of the blades contributes for 80% of the power.

- The kite acts as the outermost part of the blades without requiring the heavy tower.
In the air: power kites

- In the air, to extract energy from the wind, power kites, air foils with high aerodynamic efficiency automatically driven.
In the air: light cables

- Connecting each power kites to the units at ground level for power generation, 2 composite cables transmit the traction force and are differentially adjusted for manoeuvring.

**Traction resistance:**
10 tons / cm²

**Weight:**
100 kg / km* cm²
The intelligence

- At the very core of the project stays the control flight system that autonomously drives the kites, maximising the energy production.

- modeling, control and sensors fusion techniques have been one of the main KiteGen focus of research.
• A FMPC (Fast Model Predictive Control) method is used based on dynamic model of kites

\[
F_L = \frac{1}{2} C_L A \rho |W_e|^2
\]

\[
F_D = \frac{1}{2} C_D A \rho |W_e|^2
\]

\( W_e \): kite speed wrt wind

\( A \): kite area

\( \rho \): air density

\( E = \frac{C_L}{C_D} \)  Aerodynamic efficiency
Kite modeling and control

\[
\begin{align*}
    r\ddot{\theta} - r \sin (\theta) \cos (\theta) \dot{\phi}^2 + 2\dot{\theta} \dot{r} &= \frac{F_\theta}{m} \\
    r \sin (\theta) \ddot{\phi} + 2r \cos (\theta) \dot{\phi} \dot{\theta} + 2 \sin (\theta) \dot{\phi} \dot{r} &= \frac{F_\phi}{m} \\
    \ddot{r} - r \dot{\theta}^2 - r \sin^2 (\theta) \dot{\phi}^2 &= \frac{F_r}{m} \\
    F_\theta &= \sin (\theta) mg + F_\theta^{aer} \\
    F_\phi &= F_\phi^{aer} \\
    F_r &= - \cos (\theta) mg + F_r^{aer} - F^c
\end{align*}
\]

\[u = \psi = \arcsin \left( \frac{\Delta l}{d} \right)\]
Kite modeling and control

Model equations are of the form:

\[ \dot{x} = g(x, u, W_w) \]

- kite position and speed in spherical coordinates \( \theta, \phi, r \)
- wind speed
- differential length of lines
Fast Model Predictive Control (FMPC) strategy

- The on-line solution of the optimization problem cannot be performed within the required sampling times (100 ms).
- For each phase, the control law is a nonlinear static function of several variables:
  \[ \psi(t_k) = f(x(t_k), W_0(t_k), \dot{r}_{\text{ref}}(t_k))^T = f(w(t_k)) \]

- A “Fast” implementation of Model Predictive Control is obtained by means of Set Membership nonlinear function estimation using a suitable number of off-line MPC solutions. (Canale and Milanese, IFAC World Congress, Prague 2005)

- Set Membership nonlinear function estimation methology provides an approximation \( f^* \) of the function \( f \) with the following properties:
  1. passivity constraints satisfaction
  2. computational time independent of the MPC horizons and suited for the employed sampling periods
  3. \( \text{FMPC} \rightarrow \psi(t_k) = f^*(w_t(t_k)) \)
KE-yoyo configuration

Energy is generated by actuation of two phases:

- **Traction**: the kite pull the lines making the KSU electric drives generate electric energy

- **Recovery**: the lines are recovered by spending 1/20 of energy generated in the traction phase
How much energy is generated?

- A single KE-yoyo with:
  - kite area $A = 500 \text{ m}^2$
  - kite efficiency $E = 12$
  - wind speed $W_e = 15 \text{ m/s}$
  - $a = 300 \text{ m}; \Delta r = 50 \text{ m}$

- A KE-farm can be realized by suitably displacing several KE-yoyo’s in order to avoid kite collision and aerodynamic interferences

10 MW power

KE-farm
KE-farm
KE-farm

• Using 10MW KE-yoyo with:
  » $L = 300$ m
  » $r_1 = 1150$ m
  » $r_2 = 850$ m

- power density: 160 MW/km$^2$

• power density of actual wind towers: $\approx 12$ MW/km$^2$
Energy availability anywhere

- Exploiting altitude wind simplifies the issue of where to localize the plants: on average every point on the planet’s surface 800 meters on its vertical has enough power available ($\approx 200 \text{ W/m}^2$).

- Existing wind towers has lower operative range and needs a more accurate and severe selection of the possible favourable sites.
Due to wind variability, a wind generator is able to produce in average only a fraction of its rated power, called “Capacity Factor”:

\[ P_{av} = P_{max} \cdot CF \]

*Wind tower power curve taken from http://www.vestas.com*
Capacity Factor examples

<table>
<thead>
<tr>
<th>City</th>
<th>Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linate (IT)</td>
<td>0.006</td>
</tr>
<tr>
<td>Buenos Aires (AR)</td>
<td>0.18</td>
</tr>
<tr>
<td>Misawa (JP)</td>
<td>0.11</td>
</tr>
<tr>
<td>Leba (PO)</td>
<td>0.32</td>
</tr>
<tr>
<td>Brindisi (IT)</td>
<td>0.31</td>
</tr>
<tr>
<td>De Bilt (NL)</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Capacity factors of wind tower (black) and of KE-yoyo (orange) in some locations

Wind data taken from the NOAA/ESRL Radiosonde Database: http://raob.fsl.noaa.gov/
Scalability and energy cost

Production cost of energy vs. Kitenergy plant size

€/MWh

Current wind turbines

Fossil fuels

100
90
80
70
60
50
40
30
20
10
0

10 MW 100 MW 1.000 MW

60
27
10

10 MW 100 MW 1.000 MW
The KSU drives the flight of the kites in order to rotate the turbine and maximize the exerted torque.

The turbine transmits the rotation to electric generators.
• The turbine rotates with tangential speed of 20-50 km/h, depending on wind speed
• The kite flies “lying eight” at high speed (200-250 km/h), exploiting the aerodynamical lift force: “lift machine”
Flight paths

kite speed: 50-100 km/h

kite speed: 200-300 km/h
Current status

- Extensive computer design and simulations have been performed using sophisticated aerodynamical models of kites and control strategies.

- A first operating prototype in yo-yo configuration, codename KSU1, has been realized by Politecnico di Torino and partial support of Regione Piemonte.
KSU1 prototype
Mobile KSU1 prototype while operating a commercial power kite
Current status

- The prototype has been tested to produce energy in KE-yoyo configuration
  - max power: 40 kW
  - lines length: 1000 m
  - kite area: up to 20 m²

- The prototype allowed to experimentally confirm the computer simulation results
- Experimental test movies can be viewed at:
  - www.kitenav.com
  - http://lorenzofagiano.altervista.org/movies/Casale_test.wmv
Test performed in Sardegna (IT), in September 2006. Turbulent wind of about 3-4 m/s at ground level. Kite effective area: 5 m², maximum line length: 300 m
Test performed near Casale (IT), in January 2008. Wind of about 1-2 m/s at ground level. Kite effective area: 10 m$^2$, maximum line length: 800 m
Future plans

• To build in 18 months a new yo-yo prototype with a power of 1-2 MW.

• This prototype will demonstrate the feasibility of building in further 18 months a wind farm with a power of 10 MW with energy production costs lower than from oil.
References


M. Canale, L. Fagiano, M. Milanese and M. Ippolito, Control of tethered airfoils for a new class of wind energy generator, in Proc. 45th IEEE CDC, San Diego, CA, 2006


More information:

mario.milanese@polito.it

Thank you!