High Altitude Wind Power Generation

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INFN, Laboratorio Nazionale di Frascati:
Frascati, November 19, 2008

Kite Gen project

- A radical innovation in wind technology, able 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.

Altitude	wind speed	wind power
800 m	7.2 m/s	205 W/m²
80 m	4.6 m/s	58 W/m²

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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

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The KiteGen solution

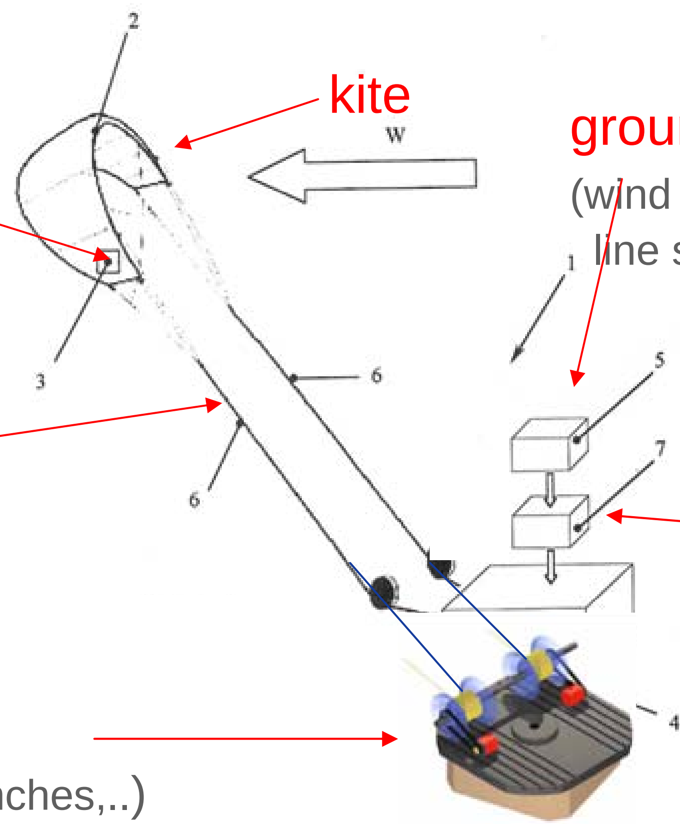
- **A radical shift of perspective:**

  no longer heavy and static structures,

  but a light, dynamic and intelligent machine.

KiteGen 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)

kite

ground sensors

(wind speed and direction, line strength ,….)

cables

control software

actuation unit

(electric drives, winches,..)

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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 special composite cables transmit the traction force and are differentially adjusted for manouvering.

Traction resistance:
10 tons / cm^2

Weight:
100 kg /km*cm2

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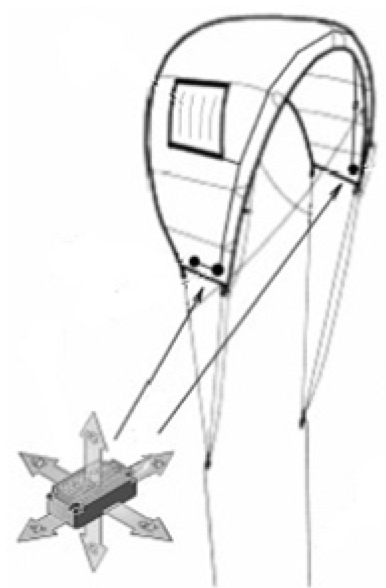
The intelligence

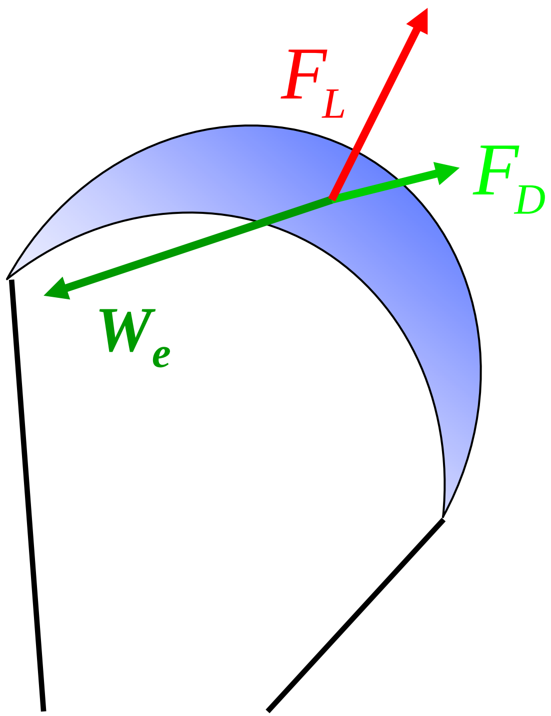
- At the very core of the project stays the **control flight system** that autonomously drives the kites, maximising the energy production.

- Patented software control techniques and avionic on board kites sensors have been one of the main KiteGen focus of research.



Kite modeling and control

A MPC (Model Predictive Control) method is used based on a aerodynamic 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

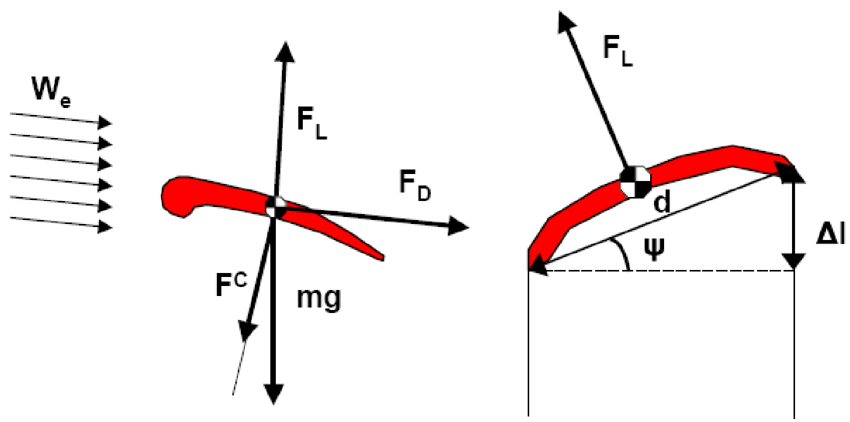
$\rho = 1.2$

$E = C_L / C_D$ ← **Aerodynamic efficiency**

Kite modeling and control

$$
\begin{cases}
r\ddot{\theta} - r\sin(\theta)\cos(\theta)\dot{\phi}^2 + 2\dot{\theta}\dot{r} = \dfrac{F_\theta}{m} \\
r\sin(\theta)\ddot{\phi} + 2r\cos(\theta)\dot{\phi}\dot{\theta} + 2\sin(\theta)\dot{\phi}\dot{r} = \dfrac{F_\phi}{m} \\
\ddot{r} - r\dot{\theta}^2 - r\sin^2(\theta)\dot{\phi}^2 = \dfrac{F_r}{m}
\end{cases}
$$

$$
\begin{cases}
F_\theta = \sin(\theta)mg + F_\theta^{\text{aer}} \\
F_\phi = F_\phi^{\text{aer}} \\
F_r = -\cos(\theta)mg + F_r^{\text{aer}} - F^c
\end{cases}
$$



$$u = \psi = \arcsin\left(\frac{\Delta l}{d}\right)$$

Kite modeling and control

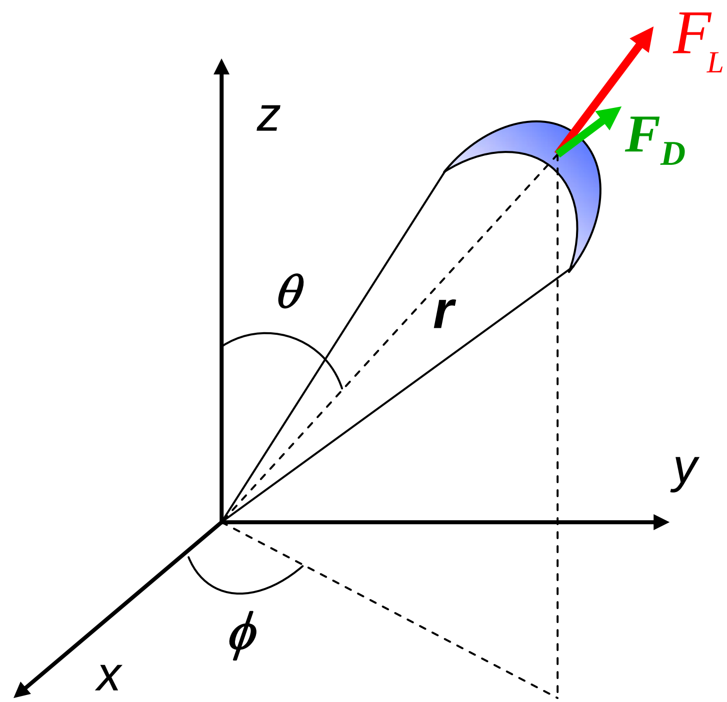
Model equations are of the form:

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

kite position and speed in spherical coordinates θ,ϕ,r

wind speed

differential length of lines



Spherical coordinate system

Kite modeling and control

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. FMPC $\rightarrow \psi(t_k) = f^*(w_t(t_k))$

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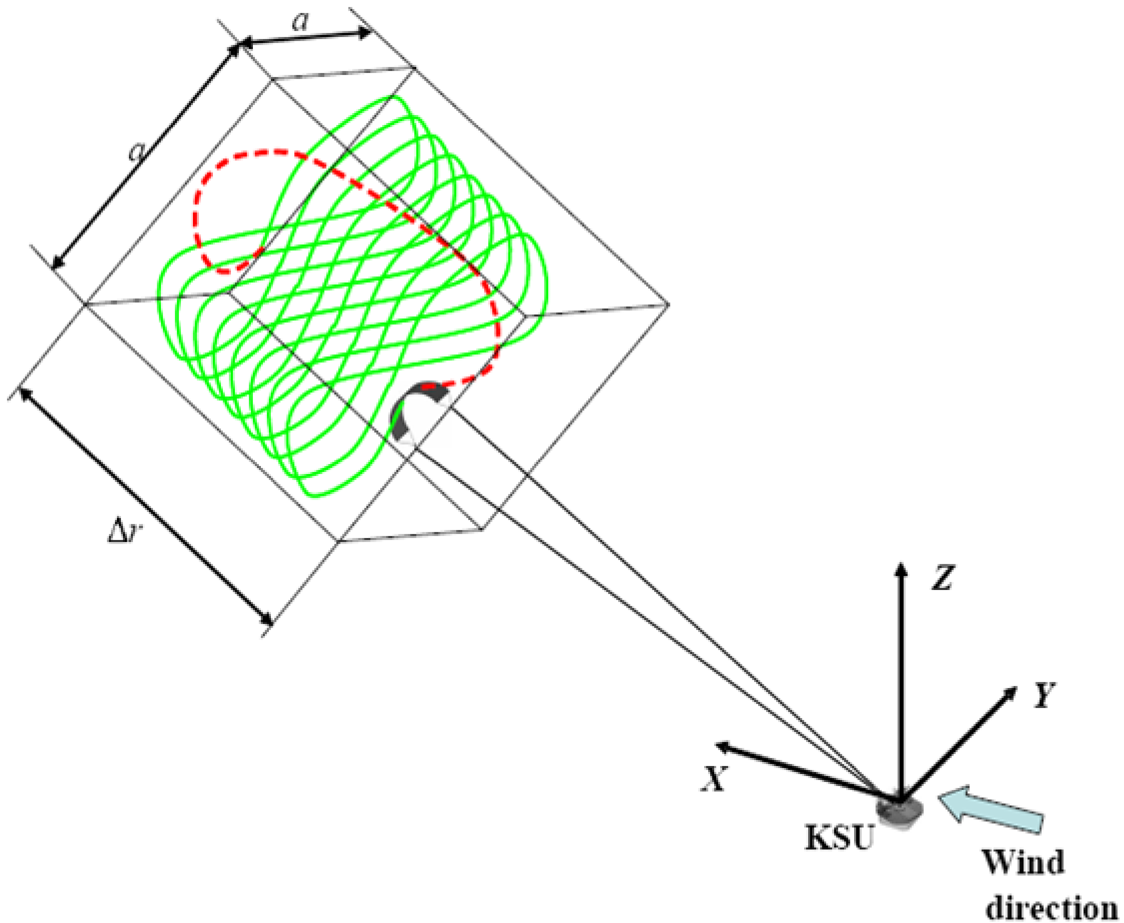
KG-yoyo configuration

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 KG-yoyo with:
  - »kite area A= 500 m^2
  - »kite efficiency E= 12
  - »wind speed We= 15 m/s
  - » a= 300 m; Δr= 50 m

⇒ **10 MW power**

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

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KG-farm

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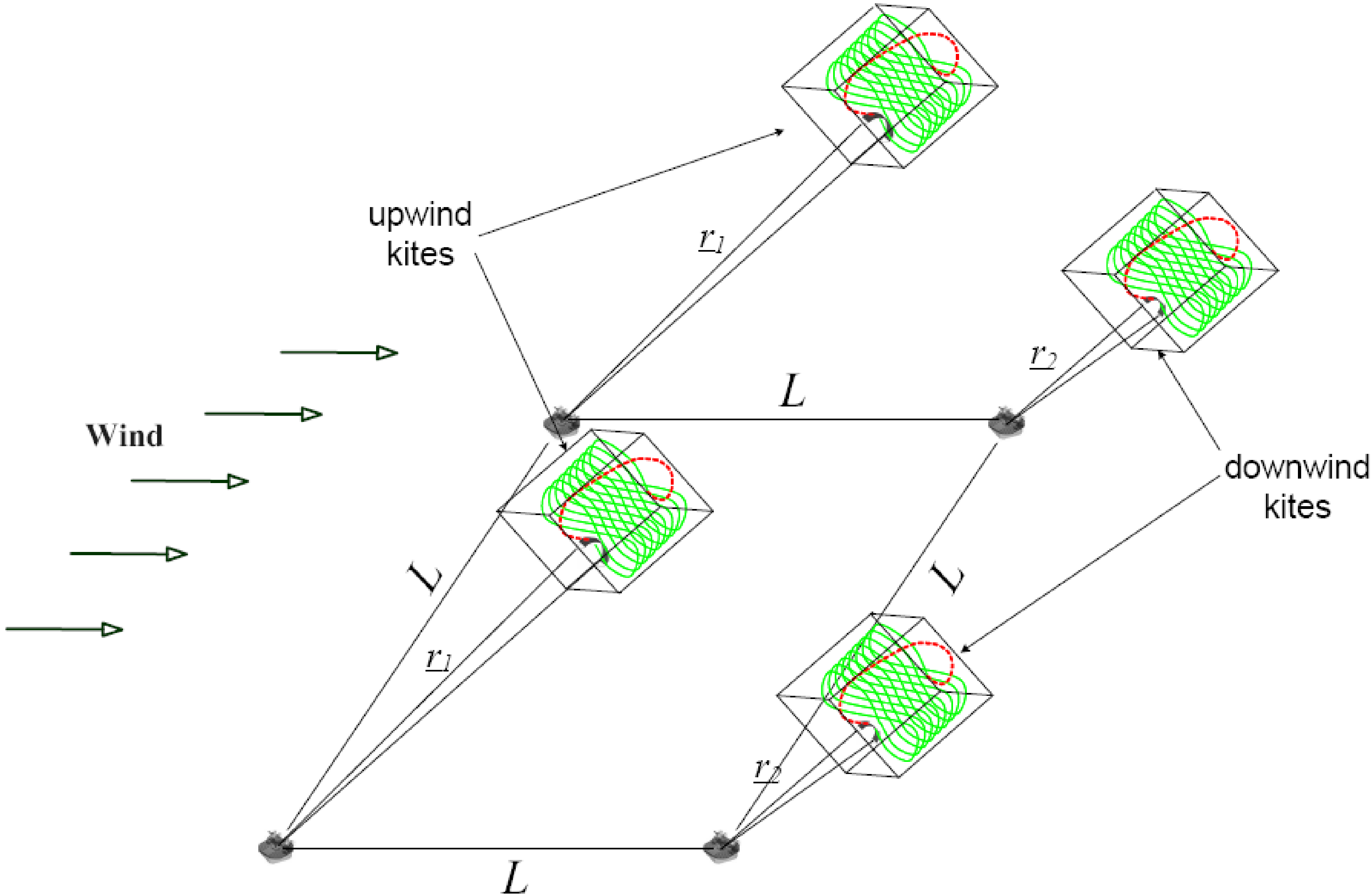
KG-farm



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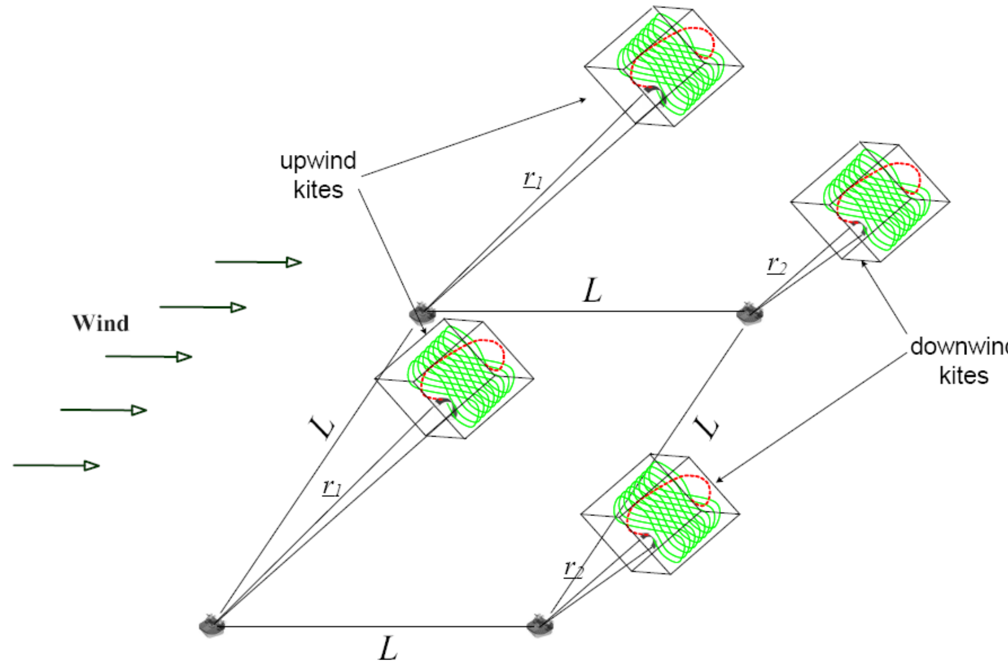
KG-farm

- Using 10MW KG-yoyo with:
  - »kite area $A = 500\ m^2$
  - »$a = 300$ m; $\Delta r = 50$ m
  - » $L = 300$ m
  - » $r_1 = 1150$ m; $r_2 = 850$ m



power density: 160 MW/km²

power density of 2MW wind towers : 12 MW/km²

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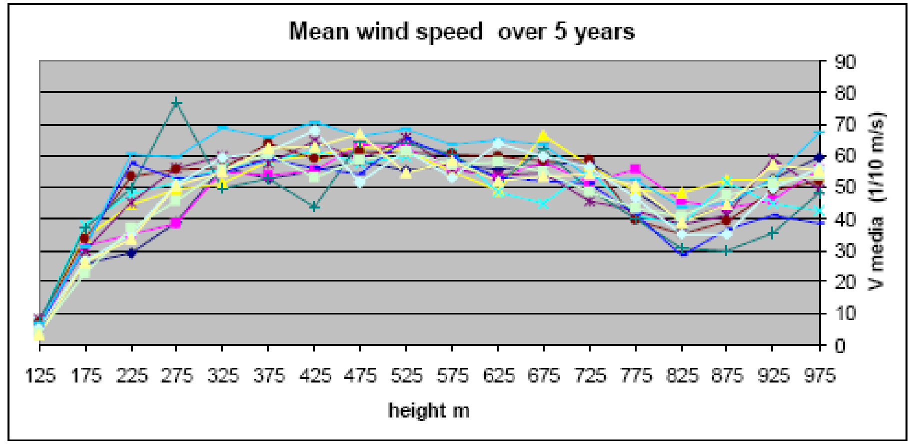
Energy availability anywhere

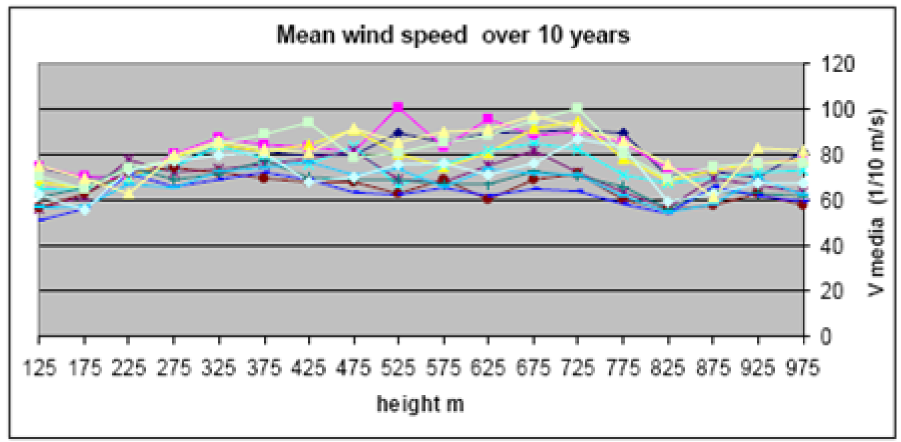
- Exploiting altitude wind simplifies the issue of where to localize the plants: on average every point on the planet's surface 800 meters on its vertical has enough power available (≈200 W/m^2).
- Existing wind towers has lower operative range and needs a more accurate and severe selection of the possible favourable sites.

Availability examples

- Pianura Padana (Linate):
  - »Wind tower (90 m rotor diameter: 70 h/y
  - »KiteGen (200-800 m op. height): 3100 h/y

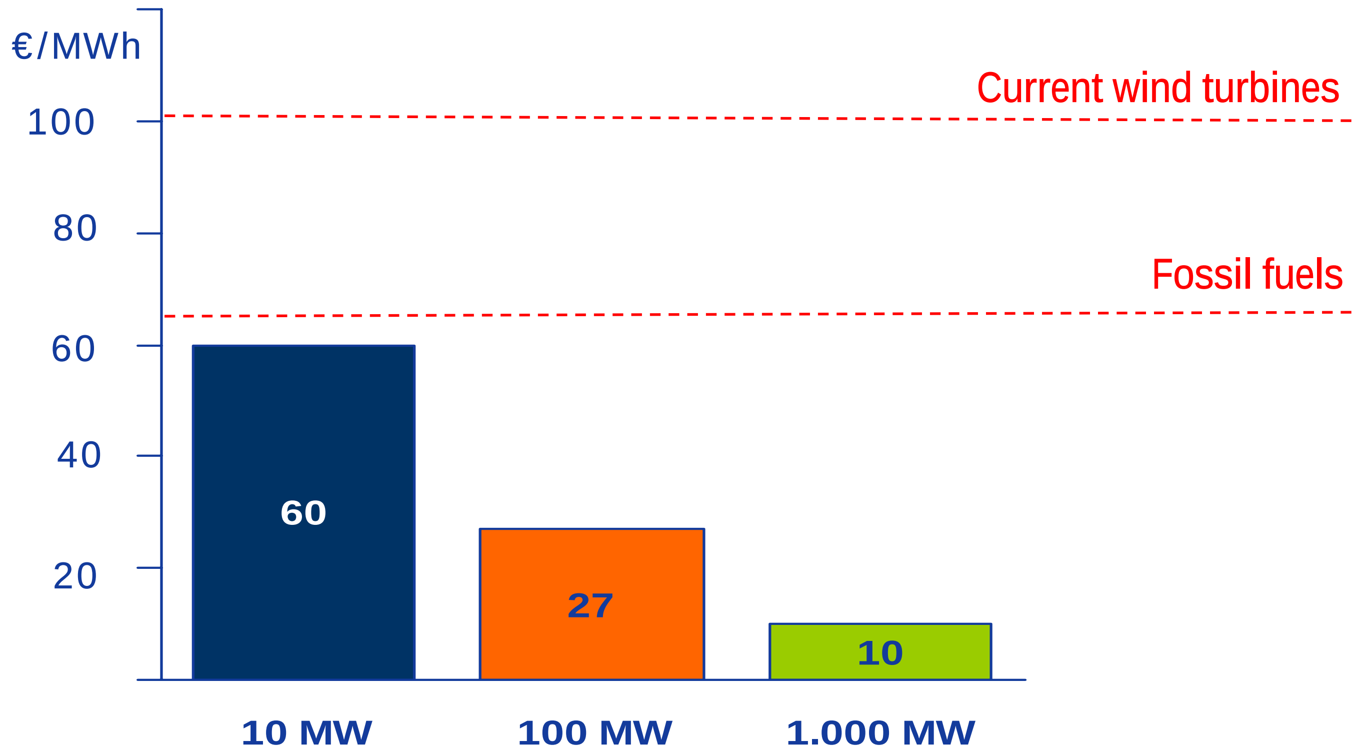


- South Italy (Brindisi):
  - »Wind tower (90 m rotor diameter: 2350 h/y
  - »KiteGen (200-800 m op. height): 5200 h/y



Scalability and energy cost

Production cost of energy vs. Kite Gen plant size



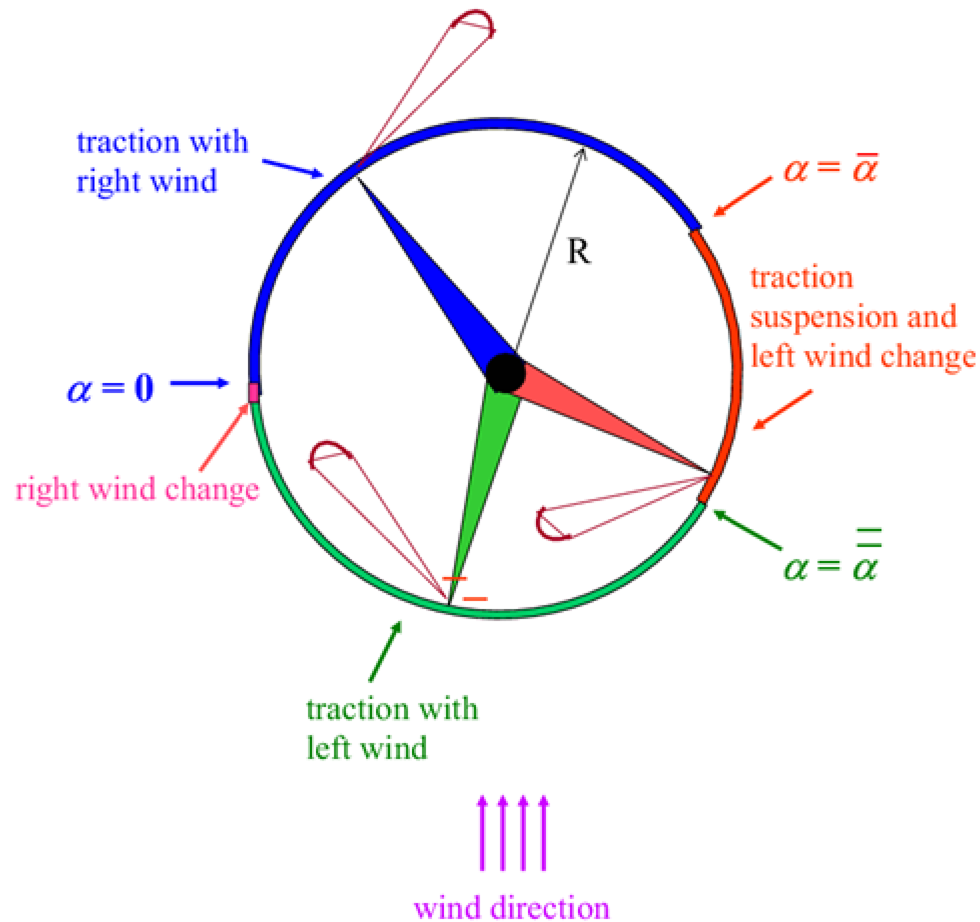
Carousel configuration

• The KSU drives the flight of the kites in order to rotate the turbine and maximize the exerted torque.

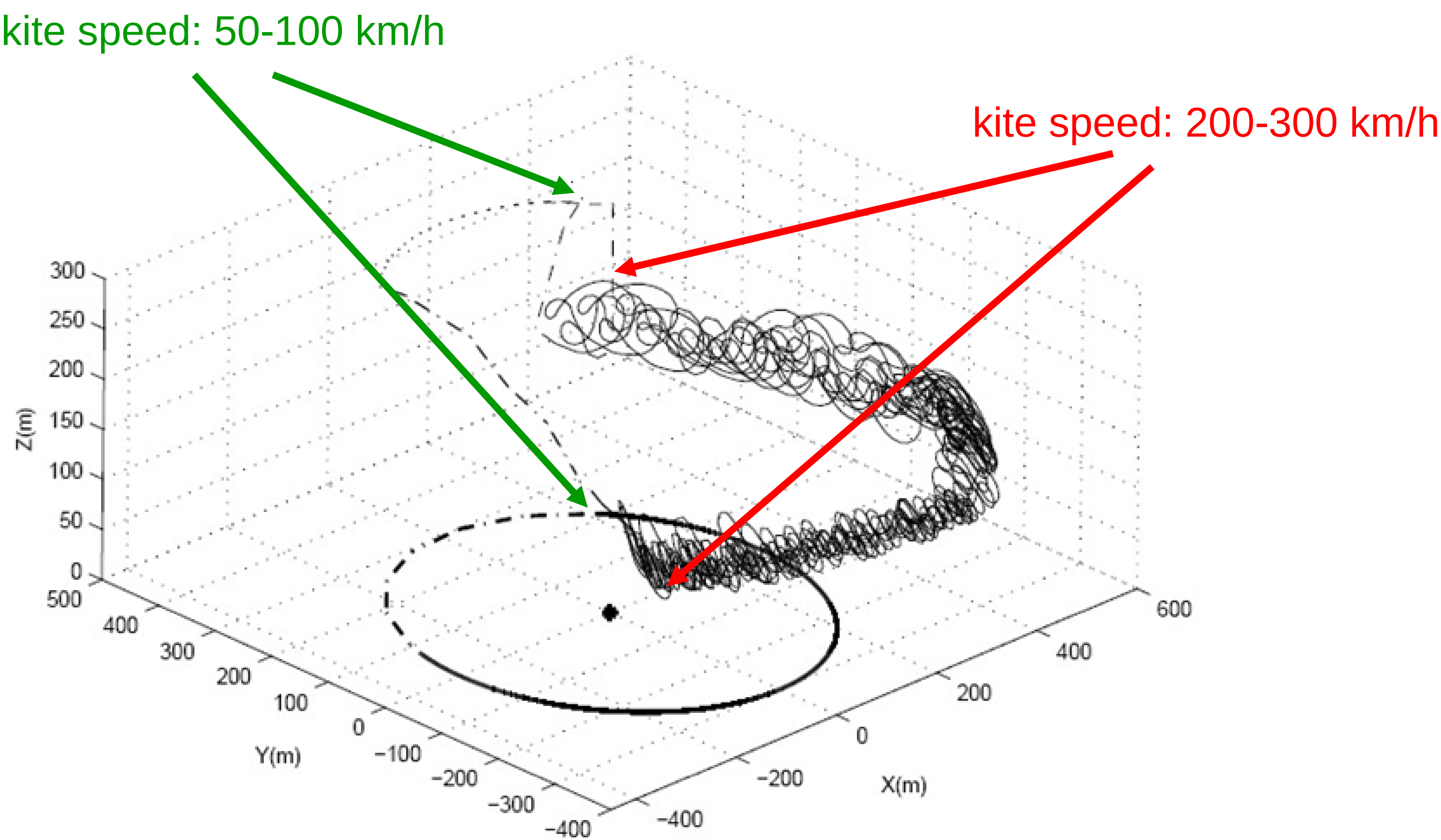
• The turbine transmits the rotation to electric generators

Carousel configuration

- 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



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Current status

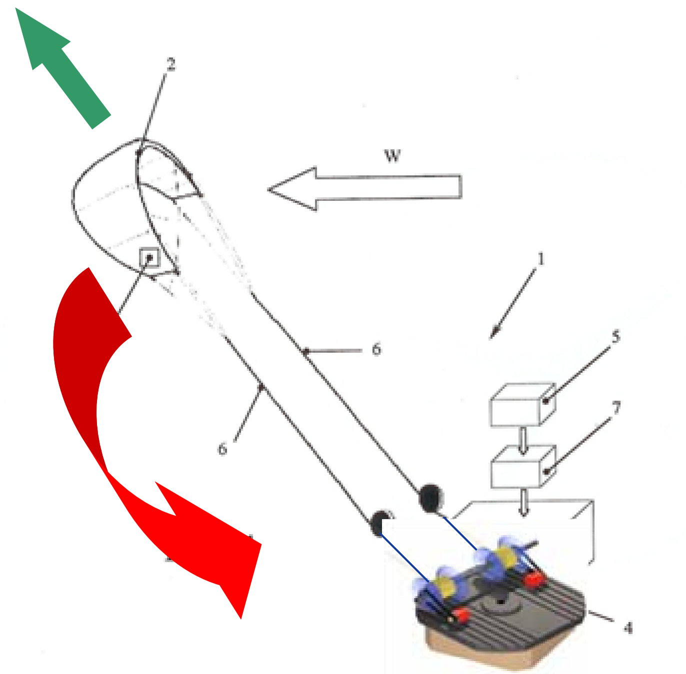
- Extensive computer design and simulations have been performed using sophisticated aerodynamical models of kites.
- **9 patents have been deposited.**
- **A a first operating prototype in yo-yo configuration, codename KSU1, has been realized in collaboration with Politecnico di Torino and partial support of Regione Piemonte.**

KSU1 prototype

Current status

- The prototype allowed to experimentally confirm the computer simulation results

- The prototype has been tested to produce energy in KG-yoyo configuration
- max power: 40 kW
- lines length: 1000 m
- kite area: up to 20 m^2



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KSU1 prototype

Mobile KSU1 prototype while operating a commercial power kite

Future plans

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

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

- To build in 36 months a prototype with carousel configuration, demonstrating all the functionalities of a 50 MW plant on a circular structure of 500 m radius

More information on

www.kitegen.com

Thank you!