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Harvesting high altitude wind energy for power production: The concept based on Magnus' effect

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HIGHLIGHTS

- ▸ High altitude wind energy as a great potential for energy source in the near future.
- ▸ Magnus' effect can be used for harvesting high altitude winds for energy production.
- ▸ We showed a theoretical feasibility study of Magnus' effect as a concept for harvesting high altitude winds.

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ABSTRACT

High altitude winds are considered to be, together with solar energy, the most promising renewable energy source in the future. The concepts based on kites or airfoils are already under development. In this paper the concept of transforming kinetic energy of high altitude winds to mechanical energy by exploiting Magnus effect on airborne rotating cylinders is presented, together with corresponding two-dimensional per-module aerodynamic and process dynamics analysis. The concept is based on a rotating airborne cylinder connected to the ground station with a tether cable which is used for mechanical energy transfer. Performed studies have shown the positive correlation between the wind speed and mechanical energy output. The main conclusion of this work is that the presented concept is feasible for power production.

1. Introduction

1.1. Motivation and the potential of high altitude winds for power production

The constant need for reduction of emissions and dependency on oil has made research, development, production and installation of renewable energy sources economically viable during the past decades [1–3]. In addition to solar and hydro, one of the most relevant renewable energy sources is wind. All feasible concepts for exploiting wind for power production are currently restricted to terrestrial winds. World's largest wind turbine reaches top height of little less than 200 m (Enercon E-126 with rated capacity of 7.58 MW). Wind power density in these areas is generally under the influence of relief (mountains, hills, valleys), ground thermic (thermal capacity of different soils and water) and coverage type (vegetation) [4]. It is clear that in higher regions wind is less influential by those parameters. They become steadier, more persistent and of higher velocity magnitude [5]. This means that development of concepts which aim to harvest winds on these heights may result in new and powerful category of renewable energy sources. These concepts are called high altitude wind energy (HAWE) or high altitude wind power (HAWP) systems. Wind power density which stands on disposal for power production is a function of air density and wind velocity. Profile of wind power density with respect to height, covering average for the entire world as well as some large cities, was assessed for the first time by Archer and Caldeira in 2009 [6] for altitudes between 500 and 12,000 m. However, distribution over the Earth's surface shows significant difference over the longitude and latitude, see Fig. 1.

Wind power density in work of Archer and Caldeira [6] is based on reanalysis data from the National Centers for Environmental Prediction (NCEP) and the Department of Energy (DOE) [7]. In this work the same data for the approximation of wind profile is used. The same dataset can be used for estimating wind power on terrestrial level (example of 10 m above ground level in Hagspiel et al. [8]).

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Nomenclature

Latin	
A	cylinder cast surf. (m^2)
C	model coeffi.
CF_L	lift force coeff.(–)
CF_D	drag force coeff.(–)
CM_Z	moment coeff(–)
D	cylinder diameter (m)
E	model constant (–)
E_{net}	net energy (J)
F_c	cable force (N)
F_g	net weight on ABM (N)
$F_{g,c}$	cable weight (N)
$F_{g,ABM}$	ABM weight (N)
$F_{g,EM}$	EM weight (N)
F_l	net lift on ABM (N)
$F_{L,Ar}$	buoyant lift force (N)
F_w	wind force (N)
$F_{w,D}$	wind force, drag (N)
$F_{w,L}$	wind force, lift (N)
g	gravitation const. (m/s^2)
K	model constant (N s/m)
k_p	first-node turbulence (m^2/s^2)
L	cylinder length (m)
L_c	cable length (m)
M_{fr}	friction moment (N m)
M_{el}	moment of el. motor (N m)
n	freq. of cylinder rot. (1/s)
n_{max}	maximum allowable n (1/s)
$\vec{n}$	normal vector (–)
p	pressure (N/m^2)
P_c	cable power (W)
P_{EM}	EM power (W)
P_{net}	net power (W)
$q_{g,c}$	spec. cable weight (N/m)
$q_{g,cast}$	spec. cast weight (N/m^2)
R	cylinder radius (m)
t	time (s)
U_p	first-node velocity (m/s)
U_w	cylinder wall velocity (m/s)
V	cylinder volume (m^3)
v	ABM velocity (m/s)
$\vec{v}'_c$	thresh. velocity (m/s)
v_{rel}	relative velocity (m/s)
v_w	wind velocity (m/s)
v_{II}	ABM velocity comp. (m/s)
$\vec{x}$	ABM horiz. pos. (m)
X	spin ratio (–)
X_{opt}	optimum spin ratio (–)
$\vec{y}$	ABM vert. pos. (m)
y^*	friction length (–)
y_p	first-node distance (m)
Greek	
α	angle (rad)
α'	critical angle (rad)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
τ	process time (s)
$\tau_{wall,shear}$	wall shear stress (N/m^2)
ω	cylinder rotation (1/s)
ω_{max}	maximum allowable ω (1/s)

1.2. Short overview of HAWE concepts

Bronstein in 2011 made a positive correlation between advancement in development of high altitude wind energy (HAWE) systems to the price of oil [4]. Same author stated that present state of development in concepts for capturing high altitude wind power still encounters many technical and policy difficulties. The best proof for this is that, by authors' knowledge, only the Magenn's air rotor system [9] is available for ordering on the market. Up to date, all concepts for harvesting high altitude winds for power production are currently in research and development stage, with some in the prototype phase. Lansdorp and Ockels in 2005 compared laddermill and pumping mill concepts by weight criteria [10]. Roberts et al. in 2007 presented a 240 kW concept of tethered rotorcraft [11]. High altitude kites are one of the prevailing concepts in the literature. Loyd in 1980 performed calculations for power production by using the kite concept and validated the results against simple analytical models [12]. Argatov et al. in 2009 made an estimation of the mechanical energy output [13] and Argatov and Silvennoinen in 2010 introduced the performance coefficient [14] for the same concept. Thesis of Fagiano in 2009 [15] showed that tethered airfoil concept (KiteGen) can be successfully used in power production on almost all locations in the world with costs lower than fossil energy. Kite concept is also explored by Canale et al. in 2009 [16]. Argatov et al. in 2011 presented analytical model of wind load on a tether constraining a power kite performing a fast crosswind motion [17]. Dirigible based rotor (DBR) are also under research, with Magenn air rotor system (M.A.R.S.) as most advanced example [9].

1.3. HAWE systems and energy planning

From the energy planning point of view, all HAWE systems are producing power in discontinuous cycles, having the production and recovery phase. This gives additional importance to energy storage systems, besides the ones arising from possible intermittency of the wind source or limitations of the grid. Krajačić et al. in 2011 related development and use of energy storage systems with feed-in tariffs [18]. Therefore, in the case of HAWE systems feed-in tariffs can play significant role, despite higher energy potential from high winds. Since up to date there are no analyses dealing with potential of power production from HAWE systems, it is unknown what would be the impact of incorporating these systems into energy systems throughout the world. However, motivation for that could be the increase in fossil fuel price, as well as CO_2 price. Since operating costs of the conventional systems rise with the increase in CO_2 price [19], the larger penetration of RES is allowed, possibly also with HAWE systems. HAWE systems could be used during the planning of electricity and/or integrated electricity and water supply. For example, they could be incorporated into the Renewislands methodology (Chen et al. in 2007 [20], Duić et al. in 2008 [21]), and the widely-used H2RES and EnergyPLAN models [22–26], by possibly using the same analogy with terrestrial winds. The difficulties are, though, in finding the real power potential from high winds and unknown response of HAWE systems to available wind potential, since the latter it still known only from modelling and simulation. In this work modelling of such response is done for HAWE concept based on Magnus' effect.