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Economic assessment of small-scale kite wind generators

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ABSTRACT

The concept of extracting wind energy from high altitudes by means of pumping Kite Wind Generator (KWG) is considered. Basic formulas for evaluating the power output of the small-scale KWG and its optimal parameters are presented. Comparison of the KWG wind energy converter efficiency with the efficiency of conventional small-scale wind turbines is given. The ultimate conclusions are: 1) Specific ex-works cost of small-scale KWG increases with the kite area, and 2) Cost per installed capacity per kW increases with the rated power of the KWG. It is shown that kite wind generators are effective for stand-alone applications in remote or detached territories which have no access to electricity grid. In particular, the economic justification of the concept of using the KWG for water pumping is discussed.

1. Introduction

The replacement of non-renewable types of energy resources with renewable energy systems is currently an important social and economic issue. Wind energy generation is one of the most powerful and promising renewable and environmentally friendly energy sources with no fuel costs. According to American Wind Energy Association (AWEA), the cost of electricity from utility-scale wind systems has dropped by more than 80% over the last 20 years. At present, wind power plants at excellent sites can generate electricity at less than 5 cents/kWh. Technology changes have played a critical role in driving down costs [1]. Costs are continuing to decline slowly as more and larger wind turbine plants are built and advanced technology is introduced.

It is well known [2] that the power available in the wind flow for the generation by traditional wind turbines does not merely increase linearly with wind speed, but rather by the cube of the wind speed. It is this fact that has lead many researchers to propose various concepts for extracting electricity from high altitudes (1–10 km) by means of attempting to locate wind turbine systems at high altitudes [3]. In recent years several designs have been also proposed to collect wind energy at high elevations by means of kites [4]. The global wind power potential of airborne wind energy was assessed in Refs. [5,6].

In this paper, the so-called pumping kite generator concept for extracting the wind energy available in the elevated altitudes is considered (see Fig. 1). The concept's operating principle is to mechanically drive a groundbased electric generator using a tethered kite, instead of attempting to locate a wind turbine system at high altitudes. On the groundstation the lower portion of the tether is wound around a drum connected to the generator. Energy is extracted from high altitude by letting the kite fly at a lying-eight orbit with high crosswind speed. During the fast crosswind motion the kite develops a large pulling force, and thus the generator generates electricity while the kite pulls the tether out of the groundstation. Then the kite is controlled so, that the pulling force is reduced, and the lower part of the tether is wound back onto the drum using the generator as a motor. This cycle is repeated, and thus the system is called a pumping kite generator. It should be emphasized that the requirement for energy generation with this system is that the kite dynamics must be controlled to get large and small pulling force alternately [7,8].

The key question in economic evaluation of a new wind energy technology associated with kite wind generators is how much energy can be extracted from the wind flow at a specific height (for instance, at 150 m from the ground) and thus the power generated by such wind energy conversion systems. To answer this question, the mathematical modeling approach based on both the equilibrium model of the kite crosswind motion [9] and the structural optimization model [10] was developed in Ref. [11] and used in the present paper. Practical aspects of efficiency of small-scale KWGs

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Nomenclature

E_{wind}	wind energy
P_{wind}	wind power
A_{swept}	swept area
P_M	mechanical power output
A_{kite}	kite characteristic area
ϑ_*	average inclination angle
$C_\perp$	tether drag coefficient
$V_\parallel$	wind speed along tether
z_*	maximum operating height
W_*	groundstation weight
V	wind speed
ρ_a	air density
C_p	power coefficient
C_L	lift coefficient
C_D	drag coefficient
d	tether diameter
G_e	effective glide ratio
l	tether length
V_*^{max}	maximal wind speed
c_{s1}, c_{s2}	coefficients of safety

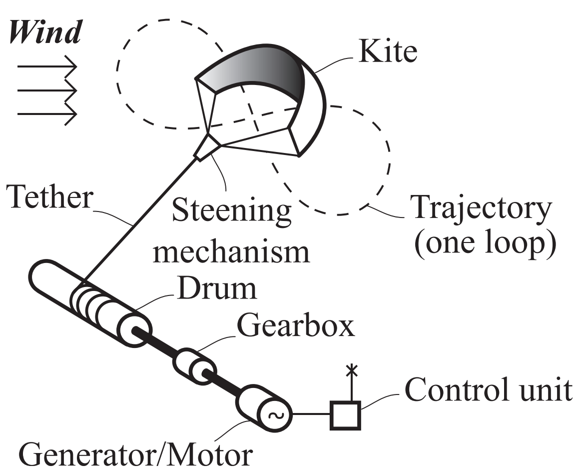

Fig. 1. Pumping kite wind generator concept.

are considered in Ref. [12].

Very recently the economic assessment of large-scale pumping kite generator systems was given by Heilmann and Houle [13] on the basis of established methods for conventional wind energy conversion systems. In particular, for the baseline values of 150 m^2 for the projected kite area and 500 m for the maximum tether length, it was shown that large-scale pumping KWGs can be competitive under European market conditions. Our interest in this paper is to assess the economic efficiency of small-scale KWG (of kite area about less than 25 m^2). The preliminary estimates show that the net cost of wind energy generated by the small-scale KWG can be cheaper than that produced by a small-scale wind turbine of the same rated power.

The remainder of this paper is organized as follows. Section 2 introduces the basics of wind energy. This section is a necessary prerequisite for understanding the concept of kite wind energy conversion introduced in Section 3. Section 4 describes the theoretical framework used to evaluate the performance of the so-called small-scale kite wind generators whose operating height is restricted by aviation rules. Section 5 combines the results concerning economic efficiency of KWGs. Finally, Section 6 presents our conclusions.

2. Wind energy

2.1. Wind power density

Wind energy is determined by the kinetic energy of moving air masses in accordance with the formula

$$E_{wind} = \frac{1}{2} m_{air} V^2, \quad (1)$$

where V is the wind speed (m/s), m_{air} is the mass of moving air.

The rate at which wind energy is transferred is called the wind power. For a uniform wind flow, the energy transferred in time t is

$$P_{wind} = \frac{E_{wind}}{t}. \quad (2)$$

Recall that the unit of power is the watt (W).

During time t, the wind flow of speed V passing through a swept area A_{swept} will carry the air mass as much as

$$m_{air} = \rho_a A_{swept} V t, \quad (3)$$

where ρ_a is the air density (kg/m^3).

Thus, collecting Eqs. (1)–(3), one can easily obtain the following formula for evaluating the wind power:

$$P_{wind} = \frac{1}{2} \rho_a A_{swept} V^3. \quad (4)$$

Practically, it is preferable to operate with the wind power density (W/m^2) defined as the wind power per vertical unit swept area:

$$\frac{P_{wind}}{A_{swept}} = \frac{1}{2} \rho_a V^3. \quad (5)$$

Formulas (4) and (5) show that doubling the wind speed increases the available wind power by eight times. It should be emphasized that the concept of swept area refers to traditional wind turbines and parachute devices. The corresponding modification for KWGs is not trivial, because the kite performers a variable crosswind motion, and is not further considered, as it is not needed for the purpose of this paper.

2.2. Variation of wind speed with altitude

The prevalence of wind at altitude is due to the fact that the Earth's surface creates a boundary layer effect so that winds generally increase with altitude according to a power-law at low-altitudes. A typical form of this variation is given by

$$V(z) = V_0 \left(\frac{z}{z_0} \right)^{\alpha}, \quad (6)$$

where $V(z)$ is the wind speed at altitude z, V_0 is the known speed at the reference level z_0 (10 m), and α is a surface friction coefficient which is called the wind shear exponent [14].

The graph that describes the relation between height above ground level and wind speed is called the vertical profile of wind speed [15]. Fig. 2 shows the profiles determined by Eq. (6) for