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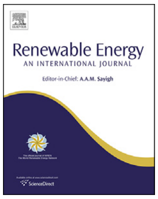

Airborne wind energy: Optimal locations and variability

Cristina L. Archer[a,*], Luca Delle Monache[b], Daran L. Rife[c]

[a] College of Earth, Ocean, and Environment, University of Delaware, Newark, DE 19716, United States
[b] National Center for Atmospheric Research, Boulder, CO, United States
[c] GL Garrad Hassan, San Diego, CA, United States

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ABSTRACT

This paper explores the global wind power potential of Airborne Wind Energy (AWE), a relatively new branch of renewable energy that utilizes airborne tethered devices to generate electricity from the wind. Unlike wind turbines mounted on towers, AWE systems can be automatically raised and lowered to the height of maximum wind speeds, thereby providing a more temporally consistent power production. Most locations on Earth have significant power production potential above the height of conventional turbines. The ideal candidates for AWE farms, however, are where temporally consistent and high wind speeds are found at the lowest possible altitudes, to minimize the drag induced by the tether. A criterion is introduced to identify and characterize regions with wind speeds in excess of 10 m s^{-1} occurring at least 15% of the time in each month for heights below 3000 m AGL. These features exhibit a jet-like profile with remarkable temporal constancy in many locations and are termed here "wind speed maxima" to distinguish them from diurnally varying low-level jets. Their properties are investigated using global, 40 km-resolution, hourly reanalyses from the National Center for Atmospheric Research's Climate Four Dimensional Data Assimilation, performed over the 1985–2005 period. These wind speed maxima are more ubiquitous than previously thought and can have extraordinarily high wind power densities (up to 15,000 W m^{-2}). Three notable examples are the U.S. Great Plains, the oceanic regions near the descending branches of the Hadley cells, and the Somali jet offshore of the horn of Africa. If an intermediate number of AWE systems per unit of land area could be deployed at all locations exhibiting wind speed maxima, without accounting for possible climatic feedbacks or landuse conflicts, then several terawatts of electric power (1 TW = 10^{12} W) could be generated, more than enough to provide electricity to all of humanity.

1. Introduction

1.1. Background

Airborne Wind Energy (AWE) is a relatively new branch of the wind energy field that deals with airborne devices, rather than ground-based or offshore wind turbines (hereafter referred to as "conventional"), to extract a portion of the wind's kinetic energy and convert it to electricity [1,2]. All AWE systems use tethers to connect an airborne device to a ground station, which could be mounted on land, an anchored buoy, an offshore platform, or a boat. The tethers are constructed of strong, lightweight, durable, synthetic fibers; some tethers also contain a conductive material, such as aluminum. There are currently two types of AWE systems: the first having an on-board electric generator, and the second employing a ground-based generator. In the latter case, the AWE devices operate on cycles that involve reeling in and out of the tether, resemble kites [3–5], do not have rotating blades, are made of light fabrics, and generally take advantage of cross-wind flight [6]. If using on-board generators, the AWE systems include, separately or in combination, gas-filled aerostats [7], a rigid wing, or a frame with rotating blades [8].

Although no commercial AWE system is available on the market as of mid-2013, AWE is a proven concept [5–7] and over 100 AWE-related patents have been filed in the US alone (http://patft.uspto.gov). The AWE community has been growing rapidly in the past five years and it includes now over twenty startups worldwide with different designs, energy outputs, and flying altitudes (http://www.awec2011.com).

AWE systems are intended to be flown either at low altitudes (e.g., below 600 m over US land and waters), in special-use airspace, or in the open international airspace outside of territorial waters, to prevent interference with normal aircraft operation. They cannot be operated during thunderstorms or severe weather conditions.

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* Corresponding author.
E-mail address: carcher@udel.edu (C.L. Archer).

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Additional challenges that AWE faces include: sophisticated control systems to achieve fully-autonomous operation take time to develop; stronger, lighter weight, more durable tether materials at lower costs are needed to reduce altitude constraints and future cost of operations and maintenance; time and cost of testing and validations can delay commercialization; development of rigorous standards of operation and safety take time but are needed to gain support from the public, sponsoring agencies, and investors; and little favorable legislation and policy currently exist at both the local and federal levels.

Despite these challenges, there are many potential advantages of AWE, including:

1. higher capacity factor (i.e., ratio of actual to maximum possible wind power output) than conventional wind turbines, because they can reach higher altitudes with generally stronger, temporally consistent, and less turbulent winds;
2. lower cost of electricity generation than conventional wind turbines, because they do not need expensive foundations or towers, and they are generally made of cheaper and lighter materials;
3. low visual and acoustic impacts, because they typically fly at altitudes greater than 200 m AGL, where they are less visible and audible to humans than conventional wind turbines.

Given the promise of AWE, we employ a unique dataset to explore the global distributions of winds in the low troposphere to identify the optimal locations for AWE deployment.

1.2. Airborne wind energy and wind speed maxima

Although the highest winds and wind power densities on Earth are found at the jet stream cores [9,10], reaching such high altitudes with AWE systems can be difficult. Tethers would need to be very long, increasing weight and drag of the AWE system; they would interfere with aviation air space; and intense winds at the jet level could damage the AWE systems. As such, only a few AWE companies are considering reaching the jet streams and most AWE systems target altitudes between 200 and 3000 m AGL.

In this altitude range, 200–3000 m AGL, wind speed generally increases monotonically with height, with higher gains (shear) in the boundary layer and more modest increases above it [3–5,10]. However, a variety of weather phenomena can invalidate the general rule-of-thumb that better AWE resources are available at higher altitudes, for example low-levels jets (LLJs). LLJs are narrow, nocturnal wind speed maxima with cores centered below 1000 m that form at a several locations worldwide due to a favorable combination of synoptic conditions, regional topography, and local stability [11], discussed later. Here we include LLJs as a subset of the broader category of *wind speed maxima* (WSM), defined as jet-like wind profiles centered below 3000 m regardless of the formation mechanism and diurnal variation. Our hypothesis is that locations with WSM are ideal for AWE applications because wind speed and wind power densities near the WSM are as high or higher than those normally found elsewhere at greater elevations, but at much lower altitudes. The height of 3 km is not based on physical properties of the atmosphere, but rather on practical limitations of current and near-future AWE systems. Since tethers longer than 5–6 km can weigh more than a ton, flying altitude will unlikely exceed 3 km as tether angles remain lower than 30°. As such, only jets that are located below 3 km are of practical interest for AWE applications and are therefore the focus of this paper.

The most well-known WSM are the nocturnal LLJs that form below 1 km AGL (and often below 500 m) at several locations worldwide [11,12], both inland [7,13–16] and along coasts [8,17–25]. The most common formation mechanism of inland nocturnal LLJs is an inertial oscillation of the ageostrophic wind vector occurring near the top of the boundary layer at night (under clear skies) as radiational cooling near the ground reverses the sign of the heat flux, which reduces vertical mixing and eventually causes the decoupling of the friction layer from the layer aloft by the formation of a nocturnal inversion and a geostrophic (or even super-geostrophic) jet near it [5–7,13]. However, additional phenomena, such as barrier effects [26–28] or mass adjustments induced by upper-level waves [29,30], can overlap or replace this basic mechanism depending on the location and characteristics of the inland LLJ. Along coasts, LLJs can form due to the thermal wind process associated with land-sea differential heating [20,22]. Coastal topography can have an influence on LLJs by enhancing wind speeds near the inversion level [31,32]. One of the most detailed global studies of nocturnal LLJs is that by Rife et al. [33].

Regardless of their formation mechanism, WSM are a cause of concern for conventional wind farms because their strong wind shear enhances turbulence above and near the tops of wind turbine rotors [34]. By contrast, WSM can represent a significant and yet untapped source of energy for AWE systems for two reasons. First, WSM have stronger wind speeds than the surrounding environment but at altitudes that are too high for conventional wind turbines, but reachable by AWE systems. Second, AWE systems can dynamically adjust their flying altitudes to coincide with the WSM core, where wind speed is highest and vertical shear is nearly zero (thus turbulence is also negligible).

This study uses a recently-created, 21-year, 40-km horizontal resolution reanalysis dataset to construct global maps of WSM properties. This dataset is ideal to study WSM because its fine horizontal and vertical resolutions are necessary to resolve the WSM features. The reanalyses are also available at high temporal resolution (hourly), which allows us to document the diurnal and seasonal characteristics of WSM worldwide. Such information is needed by the AWE industry to identify the best locations for AWE exploitation and to quantify how much wind energy can be expected and when.

2. Methods

2.1. Dataset

This study uses the National Center for Atmospheric Research's Climate Four Dimensional Data Assimilation (CFDDA) reanalyses, in which the meteorological model MM5 [35] and standard surface and upper-air measurements are blended together to create a retrospective analysis of the hourly, three-dimensional, global atmosphere for the years 1985–2005, with a horizontal resolution of 40 km and 18 vertical sigma levels in the lowest 3 km (28 in total with model top at 30 hPa). This dataset has been described in detail in Rife et al. [33] and validated specifically for low-level jets [33,36].

2.2. Algorithm for identifying wind speed maxima

The algorithm used here to identify WSM differs from that used by Rife et al. [33]. Their criterion was designed specifically to identify LLJs with a significant diurnal variation (i.e., jet core winds must be stronger at local midnight than at local noon). Such a constraint is not imposed here because all WSM are of interest to AWE, particularly those with winds that consistently blow throughout the daily cycle.

We employ a similar criterion to Rife et al. [33] to identify WSM by requiring a difference of at least 5 m s^{-1} between the WSM's core wind speed, which may vary its vertical position, and the wind speed at the sigma level directly above 3 km (located at