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An assessment of the sea breeze energy potential using small wind turbines in peri-urban coastal areas

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ABSTRACT

From wind speed data recorded hourly at 2 m high during 18 years (1993–2010) in the Llobregat Delta (15 km south of Barcelona city; northeast of the Iberian Peninsula), wind speed distributions at 10 m high were computed for the whole year and for the sea breeze period (from March 1 to September 30, from 10 to 19 local time). Weibull probability density functions fitted to the distributions were used to assess the wind energy generated by two off-grid small wind turbines: the IT-PE-100 and the HP-600W. Results from FAST and AeroDyn simulation tools were compared with those obtained by applying measured wind speeds to manufacturer power curves. Using manufacturer data, the IT-PE-100 would deliver 132 kW h during the whole year (70 kW h during the sea breeze period). From the simulations, the IT-PE-100 would deliver 155 kW h during the whole year (80 kW h during the sea breeze period). It is concluded that the sea-breeze is an interesting wind energy resource for micro-generation, not only in the Mediterranean basin but in other areas of the world with similar wind regimes, and particularly in peri-urban coastal areas where large-scale wind farms cannot be implemented.

1. Introduction

In the last decades, wind energy has become the most attractive renewable energy resource worldwide. Wind farms are widespread in areas where climatic conditions and topography features allow for their development. Traditionally, wind farms are installed in remote areas, where synoptic winds (i.e., winds associated to the meteorological macroscale) are significant. The large wind turbines used in typical wind farms, with tower heights that can be larger than 80 m, have high efficiency in converting kinetic energy of horizontal synoptic wind into electric energy. However, more recently, interest in urban and suburban areas has raised as potential wind energy generation zones using small wind turbines. These areas are generally dominated by local winds (thermal winds) and are characterized by a lower potential productivity. Knowledge of the wind speed patterns in these areas is essential for enabling good assessments of wind energy generation. For this purpose, in the last years, research on the local regimes of winds has been intense (Bivona et al., 2003; Carta and Ramirez, 2007; Celik et al., 2010; Dahmouni et al., 2010). There are also many investigations in the literature regarding wind farms in coastal sites (Dalton et al., 2008; Montlaur et al., 2012; Mason et al., 2010). Nevertheless, research on the simulation of potential wind energy generation from local winds is still scarce. Garvine and Kempton (2008) investigated issues related to quantification of wind energy generated from the sea breeze. These researchers analyzed hourly wind records for a period of 18 years from meteorological stations in the US Middle Atlantic Bight, comparing areas of coast, estuary, and open shelf, and evaluating wind intensity at turbine hub-height due to the sea breeze compared with synoptic winds. These researchers concluded that the sea breeze regime is suitable for daily energy generation in the studied coastline regions, where the average wind speed is lower than 5.7 m s^{-1}. They also found that, as expected, the wind energy generated from the sea breeze was larger offshore compared to onshore. Finally, to the authors knowledge there is no research in the literature on wind energy generation from the sea breeze in the Mediterranean basin.

The objective of this work is to analyze the wind energy generation from the sea breeze in the Llobregat Delta (15 km south of Barcelona city; northeast of the Iberian Peninsula), as an example of a regular and weak local wind regime, and to assess the potential of small wind turbines in the west Mediterranean basin. Ultimately, this research will clarify whether the sea breeze is adequate for energy generation using small wind turbines, what percentage of the produced annual wind energy would correspond to the sea breeze, and which types of small wind turbines are appropriate for wind energy generation from the sea breeze. In addition, the performance of FAST and AeroDyn simulation tools will be tested.

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1.1. The sea breeze regime

The sea breeze is a thermal circulation exhibiting diurnal cycle within the local scale. Its dynamics have been studied by many researchers (Simpson, 1994; Rotunno, 1983; Estoque, 1961; Steyn and Kallos, 1992; Arritt, 1993). This circulation develops in coastal areas during daytime, caused by the differences between the air over the land (warmer) and the air over the sea (cooler). During daytime, especially around noon in the warm period (from March to September), the air over the land is heated faster (and therefore becomes less dense) than the air over the sea. The former gains altitude, while the air over the sea moves inland forming a cold front over the land. The air mass over the land that gained altitude travels hundreds of kilometers offshore, where a subsidence occurs, closing the thermal cycle. At night, the air over the land is cooled faster than the air over the sea, and another thermal circulation appears but reversed: the air over the land (cooler) travels offshore, while the air over the sea (warmer) gains altitude. This is the so-called land breeze circulation, much less intense than the sea breeze.

The sea breeze is generally less intense than synoptic winds. However, it features a larger periodicity, and thus a priori it could be suitable for energy generation with small wind turbines. Effectively, in many warm tropical areas the sea breeze shows high regularity and maximum wind velocities around 7–8 m s^{-1} can be expected at low levels at noon and early afternoon (Simpson, 1994). Right after dawn and in the early morning, the sea breeze is weak and blows in a relatively thin atmosphere layer, having less than around 50 m. Above this layer, the land breeze blows in the opposite direction. As the land–sea thermal difference increases during daylight, the thickness of the sea breeze layer increases, reaching 300–400 m. The direction of the sea breeze exhibits diurnal rotation, especially on coastal zones, as a consequence of the Coriolis force. For instance, in the northern hemisphere, this force turns the sea breeze clockwise. In the Llobregat Delta, from March to September, the sea breeze blows from the southeast at the beginning of the day, while it blows from the southwest at the end of the day (see Section 3.1). Following this introduction, Section 2 is devoted to describe the methodology used in this research. Results are presented and discussed in Section 3. Finally, the conclusions are exposed in Section 4.

2. Methodology

The quantification of the wind energy was obtained by means of several tools. First, two coupled software tools developed by the National Renewable Energy Laboratory (NREL) for aeroelastic simulation of horizontal-axis wind turbines (HAWT): FAST v7.01, a dynamics analysis code, and AeroDyn v13.00, an aerodynamics analysis routine capable of interfacing with FAST. In particular, the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) code "is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of two- and three-bladed HAWT" (Jonkman and Buhl, 2005). AeroDyn is an element-level wind-turbine aerodynamics analysis routine that, when used in conjunction with dynamics software (e.g., FAST, YawDyn or SymDyn wind turbine dynamics analysis codes, or ADAMS® commercial dynamics analysis package), allows computing the aerodynamic loads on the blade elements of HAWT (Laino and Hansen, 2002). For this purpose, AeroDyn uses essentially two wake models: the blade element momentum (BEM) theory, and the generalized dynamic-wake theory, a model for skewed and unsteady wake dynamics (Laino and Hansen, 2002). Both models are used basically to calculate the axial induced velocities from the wake in the rotor plane, taking into account the influence of tip losses, hub losses and skewed wakes. AeroDyn uses also a dynamic stall model based on the semi-empirical Beddoes–Leishman model, and a tower shadow model based on potential flow around a cylinder and an expanding wake (Moriarty and Hansen, 2005). Since FAST and AeroDyn incorporate models of controller (servo) dynamics and structural (elastic) dynamics, they enable also simulation of the behavior of the control and protection systems and the structural dynamics (Jonkman and Matha, 2011). It is worth to note that FAST and ADAMS®, together with AeroDyn, were evaluated in 2005 by *Germanischer Lloyd WindEnergie* and found adequate for computation of loading of onshore wind turbines for design and certification (Manjock, 2005).

FAST and AeroDyn were used in this research due to several reasons. First, these are well-known, well-accepted codes, applied successfully in many previous investigations (Jonkman and Matha, 2011). Second, FAST and AeroDyn are freeware (open access software), and it is possible to periodically download improvements of these tools. Finally, FAST and AeroDyn provide much flexibility in simulating modifications for optimizing wind turbine design, which is one of our future research objectives for the IT-PE-100.

These tools require several input files containing diverse data like, for example, the wind-inflow conditions, and physical and aerodynamics parameters of the wind turbine blades. The first step of this research was to characterize the small wind turbines selected for this study and to build the input files requested by FAST and AeroDyn. This was done using the information and technical data provided by the manufacturers, and data measured from physical components, e.g., by 3D digitalization of the blades. For the aerodynamic, structural and/or control system properties lacking proper definition, the corresponding input data for the simulations were based on educated guesses.

QBlade was also used for double-checking the results obtained with the previous tools for the IT-PE-100. QBlade is open source software for design and simulation of HAWT, distributed under the GNU General Public License. Its integration in XFOIL allows airfoil design and airfoil performance analysis. QBlade allows also for extrapolation of airfoil performance data to 360° angle of attack, turbine blade design, and realization of BEM simulations of the rotor and turbine. Finally, this tool allows structural blade design, modal and static loading analyses using QFem solver, generation of turbulent windfields, and realization of FAST simulations.

The off-grid small wind turbines selected for this research were the IT-PE-100 and the HP-600W. A summary of technical data is presented in Table 1. Both are 3-bladed upwind HAWT, and were selected mainly for the following reasons: 1) their start-up[2] and cut-in[3] wind speeds are relatively low (3 and 3.5 m s^{-1}, respectively, for both), which makes them suitable for weak winds like the sea breeze; 2) their dimensions are relatively small (10 m tower height; 1.7 and 1.5 m rotor diameter respectively), which makes them suitable for urban and suburban areas, and areas close to an airport and 3) we have recently installed the HP-600W in the area of study, and we plan to install also the IT-PE-100. The latter is a 100 W wind turbine developed by Practical Action-Intermediate Technology Development Group (ITDG) to provide access to electricity to communities in rural or remote areas in developing countries. The turbine is especially suited to operate at low wind speeds, and was designed following the appropriate technology philosophy, i.e., it was intended to be simple, low-cost, robust, reliable, easy to maintain and, above all, producible by local workshops or microenterprises using a minimum of imported materials and components (Ferrer-Marti et al., 2010, 2012; Ferrer-Marti et al.,). As an open access technology, the IT-PE-100 is not patented, and the design specifications, manuals and technical data by the manufacturers are available online (Piggott, 2001; Sanchez et al., 2001). The blades and the hub are made of glass fiber reinforced polymer, and thus are light and with good structural properties. The turbine operates at high

[2] The start-up speed is the wind speed at which an unloaded rotor starts turning.

[3] The cut-in speed is the wind speed at which a wind turbine starts pushing power into the battery bank or the grid.