The potential of the sea breeze for wind energy generation in peri-urban coastal areas using small wind turbines

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Abstract

This work investigates the potential of the sea breeze for wind energy generation with small wind turbines. For this purpose, we used wind data recorded in the Llobregat Delta (NE of the Iberian Peninsula) from 1993 to 2010 and turbine power curves obtained from QBlade, FAST and AeroDyn freeware tools, and from the manufacturer. The HP-600W turbine, with hub-height 8 m, would deliver 126 kWh in a year (53 kWh during the sea breeze period, i.e., March 1 to September 30, 10 to 19h LT), with average power of 14 W (27 W). The results for the entire year agree with data measured *in situ* in 2015, but it is not the case for the sea breeze period. Therefore, more research is necessary to validate completely the proposed approach, and to confirm the real potential of the sea breeze for micro-generation in a peri-urban coastal area like the one under study, where large wind farms are not feasible.

1 Introduction

Wind energy is one of the most promising renewable energy, obtained usually from wind farms installed in areas with significant synoptic winds (i.e., winds associated with the meteorological macroscale). These wind farms typically use large wind turbines (tower height ≥80 m), with high efficiency in converting kinetic energy of horizontal synoptic wind into

electricity. However, urban and suburban areas –where local, weaker winds (thermal winds) are generally dominant– are receiving increasing attention as potential sites for wind energy generation using small wind turbines (SWT). Recent investigations on local wind regimes [1]–[4] and wind farms in coastal sites [5]–[7] have enabled better assessment of the wind resource. However, simulations of wind energy generated from local winds are scarce. An exception is a work comparing the sea breeze in the US Middle Atlantic Bight with synoptic winds from data for 18 years [8], concluding that, while the average wind speed was below 5.7 m s^{-1}, the sea breeze is suitable for daily energy generation in the studied coastal area.

The objectives of this work are: 1) investigate the potential of the sea breeze for wind energy generation; 2) quantify the power production by SWT in the Llobregat Delta (NE of the Iberian Peninsula); 3) compare the production during the sea breeze period (March 1 to September 30, 10 to 19h LT) with that for a reference year; and 4) validate the performance of QBlade, FAST and AeroDyn simulation tools.

1.1 The sea breeze

The sea breeze is a thermal circulation showing diurnal cycle in the local scale [9]–[13]. It appears in coastal areas due to the differences between the air over the land and the sea during daytime, particularly in warmer months: the air over the land is heated faster, and gains altitude, while the air over the sea moves inland forming a cold front. The air over the land that gained altitude travels hundreds of kilometers offshore, where a subsidence occurs, closing the thermal cycle. The sea breeze layer thickness ranges from 50 m (at dawn) to 300–400 m [9]. The sea breeze is usually weaker than synoptic winds, but features larger periodicity and high predictability, which is most interesting. The direction of the sea breeze rotates due to the Coriolis force (in the northern hemisphere, it turns clockwise). In the Llobregat Delta, the sea breeze blows from the SE (SW) at the beginning (end) of the day. At night, a reversed thermal circulation appears (the land breeze, usually less intense).

2 Methods and materials

Two coupled freeware tools from the National Renewable Energy Laboratory were used to obtain the turbine power curves: FAST v7.01, a dynamics analysis code for

computing the loads on horizontal-axis wind turbines (HAWT) [14]; and AeroDyn v13.00, an aerodynamics analysis code that, together with a dynamics code, computes aerodynamic loads on blade elements [15] and the behavior of control and protection systems and structural dynamics of HAWT [16]. FAST and AeroDyn have been applied in many investigations [16]; namely, these codes were assessed by *Germanischer Lloyd WindEnergie* and found adequate for design and certification of onshore HAWT [17]. These tools require input data like the wind conditions and blade parameters. The latter can be obtained from technical data by the manufacturer or from measuring physical components, e.g., by 3D digitalization of a blade.

QBlade, an open source software for design and simulation of HAWT, distributed under the GNU General Public License, was also used. XFOIL, integrated within QBlade, allows airfoil design and performance analysis. In addition, QBlade allows for extrapolation of airfoil performance data to 360° angle of attack, turbine blade design, realization of rotor and turbine simulations, structural blade design, modal and static load analyses using QFem solver, generation of turbulent windfields, and realization of FAST simulations.

Two off-grid SWT (the IT-PE-100 and HP-600W; see the technical specifications in Table 1) were selected for this research because: 1) the start-up[1] wind speed, V_{su}, and cut-in[2] wind speed, V_{ci}, are relatively low (3 and 3.5 m s^{-1}), which makes them suitable for weak winds like the sea breeze; 2) their size is relatively small, which makes them suitable for urban/suburban areas, and areas close to an airport; and 3) we installed the HP-600W in the studied area, and we plan to install also the IT-PE-100.

The IT-PE-100 was designed by ITDG for communities in remote areas of developing countries following the appropriate technology philosophy [18], [19]. The IT-PE-100 is not patented, and manuals, design specifications, and technical data are open-access [20], [21]. The blades and the hub are made of glass fiber reinforced polymer, and thus are light but with good structural properties. The turbine operates at high rotational speeds, which allows direct connection of the rotor shaft to the generator shaft without a heavy transmission system [22]. The nacelle, a cylindrical piece of steel in the tower's upper end to which the generator-rotor system is attached, allows rotation around the vertical axis, facilitating the alignment with the incident wind.

[1] The start-up speed is the wind speed at which an unloaded rotor starts turning.
[2] The cut-in speed is the wind speed at which a wind turbine starts pushing power into the battery bank or the grid.

The HP-600W, developed by Hopeful Energy, is light, compact and smaller than most low-wind speed turbines and SWT. The blades are made of nylon and glass fiber reinforced polymer coated to prevent problems due to corrosion, high temperatures, water, salinity, dust and sand. It works at higher nominal wind speed and rotational speed than the IT-PE-100, but both have axial-flux permanent magnet synchronous generator [22], [23].

3 Results and discussion

3.1 Wind speed distribution and prevailing wind direction

A weather station of the Catalan Weather Service (MeteoCat) has been measuring wind data in the Llobregat Delta since 1993. Every 10 min, the station averages and records the wind speed at 2 m high. The data available to the users are the hourly averages of these records[3]. Assuming a stable atmosphere and a roughness length z_0 of 0.25, corresponding to open landscape and areas with scattered shelter belts [24], the wind speed at 8, 10 and 15 m was computed from the weather station data using the potential wind equation (Eq. 1):

$$V_H = V_{2m} \frac{\ln(\frac{H}{z_0})}{\ln(\frac{2}{z_0})} \quad (1)$$

where V_H is the velocity at a height H, and V_{2m} is the wind speed at 2 m. The Weibull probability density function was fitted to the extrapolated data from 1993 to 2010. Fig. 1 and Fig. 2 show, respectively, the Weibull distributions for the wind speed at 10 m for the entire year and for the sea breeze period. The former (latter) has a shape factor, k, of 1.51 (1.80)[4] and a scale factor, C, of 3.01 (4.23); the probability for $V_H > 3$ m s^{-1} is 36.9% (58.4%), that is 3232 hours per year and 1250 hours during the sea breeze period.

Finally, wind directions ranging from NW to NE represent 45% of the total measurements for the entire year in the Llobregat Delta, while wind directions ranging from SW to SE represent 38%. Considering the sea breeze period, the dominant direction is SW,

[3] If abundant reliable measurements of wind speed in the geographical area of study were not available, an alternative is to use wind speed predictions using the well accepted tools for micro-scale wind resource assessment [30], [31], like WRF or also NEWA, in the short-term future. The use of these tools is a de-facto standard, for example, in wind farm design [32].
[4] $k \approx 2$ is usual in north European sites, e.g., in good rural and high rise sites [25].

clearly corresponding to the sea breeze circulation. Thus, it can be assumed that the wind energy generated during the sea breeze period is basically due to the sea breeze.

3.2 Power curves

Fig. 3 and Fig. 4 show the power curves obtained from QBlade, FAST and AeroDyn and the manufacturer for the IT-PE-100 and HP-600W, respectively, and the Weibull curves from Sect. 3.1. The relative error between power curves (associated with inaccuracies and limitations of the models used by FAST and AeroDyn, the turbine models, and the power curves from the manufacturer) is 10.1 ± 13.3% for the IT-PE-100 and -28.4 ± 2.9% for the HP-600W, for which the simulated power is lower than the manufacturer data (suppliers of commercial turbines typically provide over-optimistic performance data of their products). From the simulations, the IT-PE-100 produces more power than the HP-600W at low wind speeds, while the contrary occurs if we consider the manufacturer data. The average error is larger for the HP-600W, as expected, since less design and technical data for the proper modeling of this commercial turbine was available. The power curves agree more closely with manufacturer data at low wind speeds, while a tailing off is observed at high wind speeds [25]. The power curve from QBlade shows deviations from the manufacturer data, with power being underestimated (overestimated) below (above) a wind speed of ≈6 m/s.

3.3 Average power and overall energy produced

Among the methods to obtain the probability distribution of the power produced, the static method is the simplest, as it ignores non-stationary effects, i.e., losses due to changes in wind direction and maintenance periods [26]. It assumes that the probability density function of the power produced is a Weibull curve identical to that corresponding to the wind speed distribution. Hence, the probability for the turbine to provide a given power comes from superposing the power curve, $P_{turb}(V)$, and the Weibull distribution of the wind speed, $f(V)$, as shown in Fig. 3 and Fig. 4. The average power, P_{ave}, computed with the static method (Eq. 2; where V_{ci} and V_{co} are the cut-in and cut-out speeds from Table 1) and overall energy, E, produced by the SWT in the entire year and in the sea breeze period are shown in Table 2.

$$P_{ave} = \int_{V_{ci}}^{V_{co}} P_{turb}(V) f(V) dV \quad (2)$$

The values in Table 2 are similar to those from the Warwick Wind Trials Project [25], which measured the energy generated by building-mounted, grid connected SWT in 26 different sites [27]. The average wind speed ranged from 1.7 to 6.7 m s^{-1}, and the average annual energy produced per turbine was 78 kWh. If not taking into account the periods with the turbines switched off, the average was 230 kWh per year (94 kWh per year if omitting the results for the best site and highest buildings). The turbine in the poorest site produced 15 kWh per year in average, less than the energy consumed by the turbine's electronics.

In Table 2, the results for the entire year using the simulated power curve of the HP-600W and the wind speed measured from 1993 to 2010 agree with the *in situ* measurements in 2015, as shown in Table 3; namely, the average power is 14 vs 13 W and the produced energy is 126 vs 100 kWh. These data are statistically significant because in 2015 the data acquisition system was operative 292 days, i.e., 80.0% of the year. However, the *in situ* measurements in 2016 are not representative because the data acquisition system has been operative only 126 days, i.e., 34.5% of the year, all of which are within the spring and the summer, not homogeneously distributed throughout the year. If using the manufacturer power curve instead of the simulated curves, the results in 2015 overestimate a little more the power and energy (this is expected since manufacturer power curves are typically over-optimistic). However, it is important to recall that, since the measured wind speed data and manufacturer power curves are often not very accurate, it is not uncommon to obtain energy predictions with errors larger than ±25% if data is not significantly pre-processed; e.g., energy outputs overestimated by a factor between 1.7 and 3.4 have been reported in previous works [25].

Unfortunately, the *in situ* measurements for the sea breeze period in both 2015 and 2016 are significantly below our predictions. In this case, the data acquisition system was operative 207 and 126 days, i.e., 96.7% and 58.9% of the sea breeze period, respectively. Thus, more research and longer data series are necessary to establish the real potential of the sea breeze in the studied location.

4 Conclusions

This work investigates the potential of the sea breeze for wind energy generation with SWT (the IT-PE-100 and HP-600W), using as case study the Llobregat Delta (NE of the Iberian Peninsula). For this purpose, we applied the static method using wind data recorded *in*

situ from 1993 to 2010 and turbine power curves obtained from QBlade, FAST and AeroDyn freeware tools, and from the manufacturer. The following conclusions are drawn:

- The predicted annual energy ranges from 111 to 312 kWh, depending on the wind turbine, the hub-height and whether we use the manufacturer power curve or the simulated power curve.
- 42% to 55% of this energy is generated during the sea breeze period (March 1 to September 30, 10 to 19h LT), which is 22% of the total time in a year.
- The results for the entire year agree with data measured *in situ* in 2015, but it is not the case for the sea breeze period. Thus, more research and longer data series are necessary to validate completely the proposed approach, and to confirm the real potential of the sea breeze for micro-generation in a peri-urban coastal area like the one under study, where large wind farms are not feasible.
- This work tested the suitability of FAST and AeroDyn for simulation of SWT operating in low-wind speed conditions. For the IT-PE-100, the simulated power curve and the manufacturer power curve compare well. It may not seem so for the HP-600W, but many technical data essential for the proper modeling of the turbine was lacking.
- The Llobregat Delta is a suburban area, characterized by presence of farms, secondary roads and paths between cities, and a 20 km long promenade following the coastline. The SWT have small rotor diameters, and hub-heights equivalent to a street light, and thus could be installed in lighting systems besides roads, paths and the long promenade. Besides feeding the lighting systems, the energy could be used for many purposes, like feeding electric pumps for farmers to extract water from the aquifer to water crops [28], [29].

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1 Table 1. Summary of technical data of the IT-PE-100 and the HP-600W wind turbines.

Concept	IT-PE-100	HP-600W
Rated output power	100 W	600 W
Rotor configuration	3 blades, upwind, HAWT	3 blades, upwind, HAWT
Control	Variable speed, furling tail	No information available
Blades	Fixed-pitch, NACA 4412 airfoils	No information available
Drive train	High speed, direct coupling	No information available
Rotor diameter	1.7 m	1.5 m
Blade length	0.7 m	0.68 m
Hub diameter	0.3 m	0.14 m
Hub-height	8 – 10 m	8 – 10 m
Start-up wind speed	3 m s^{-1}	3 m s^{-1}
Cut-in wind speed	3.5 m s^{-1}	3.5 m s^{-1}
Rated wind speed	6.5 m s^{-1}	12 m s^{-1}
Maximum wind speed	12 m s^{-1}	25 m s^{-1}
Rated rotor rotational speed	420 rpm	810 rpm

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Table 2. Average power, P_{ave}, and energy, E, obtained with the static method (using a power curve from the manufacturer or FAST and AeroDyn) for the IT-PE-100, HP-600W and SP-500 for the sea breeze period (March 1 to September 30, 10 to 19h LT) and the entire year.

Power curve (turbine)	Period	Height 8 m		Height 10 m		Height 15 m	
		P_{ave} [W]	E [kWh]	P_{ave} [W]	E [kWh]	P_{ave} [W]	E [kWh]
Manufacturer	Sea-breeze	28	53	33	63	43	83
(IT-PE-100)	Entire year	14	123	15	132	21	180
Simulations	Sea-breeze	28	53	35	67	48	93
(IT-PE-100)	Entire year	13	111	14	121	21	180
Simulations	Sea-breeze	47	90	56	108	75	144
(IT-PE-100)[a]	Entire year	24	213	26	208	36	312
Manufacturer	Sea-breeze	37	71	45	86	62	119
(HP-600W)	Entire year	18	157	19	170	28	242
Simulations	Sea-breeze	27	53	33	63	43	83
(HP-600W)	Entire year	14	126	15	134	21	182
Manufacturer	Sea-breeze	28	53	33	63	43	83
(SP-500)[b]	Entire year	13	111	14	121	21	180

[a] These results correspond to the IT-PE-100 operating constantly at its peak power coefficient (≈0.37) thanks to the simple open-loop control algorithm developed *ad hoc* by Colet-Subirachs et al. [18].

[b] The results for the SP-500 wind turbine, which is currently under development by ITDG, are only for informative purposes, since this large turbine is less appropriate than the IT-PE-100 for weak, low-speed wind regimes. The SP-500 is a 3-bladed, upwind HAWT, with rotor diameter 3 m and rated power 500 W at a rated wind speed of 8 m/s and rated rotational speed of 300 rpm. The SP-500 is also an open access technology, like the IT-PE-100.

Table 3. Average power, P_{ave}, and energy, E, obtained from *in situ* measurements in the Agròpolis of Viladecans, in the Llobregat Delta, for the HP-600W for the sea breeze period (March 1 to September 30, 10 to 19h LT) and the entire year.

Year of tests (turbine)	Period	Height 8 m	
		P_{ave} [W]	E [kWh][a]
Year 2015 (HP-600W)	Sea-breeze	9	14
	Entire year	13	100
Year 2016 (HP-600W)	Sea-breeze	10	19
	Entire year	5	42

[a] Since neither in 2015 nor 2016 we have *in situ* measurements of power for the entire year or for the entire sea breeze period, the energy reported in this table is obtained assuming that, in the missing days for the corresponding time period, the power is equal to the average power computed from the available data for that period.

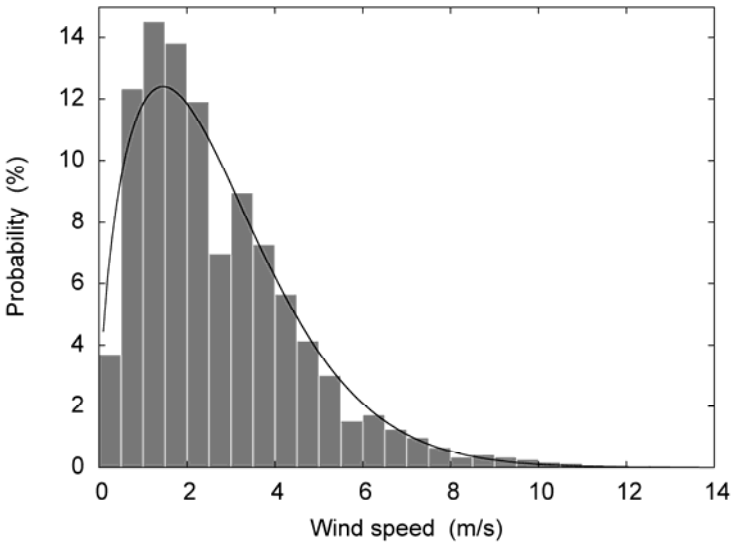

Figure 1. Wind speed distribution and fitted Weibull probability density function for the entire year (January 1 to December 31, 00 to 24 LT) as obtained from wind speed data measured in the Llobregat Delta from 1993 to 2010.

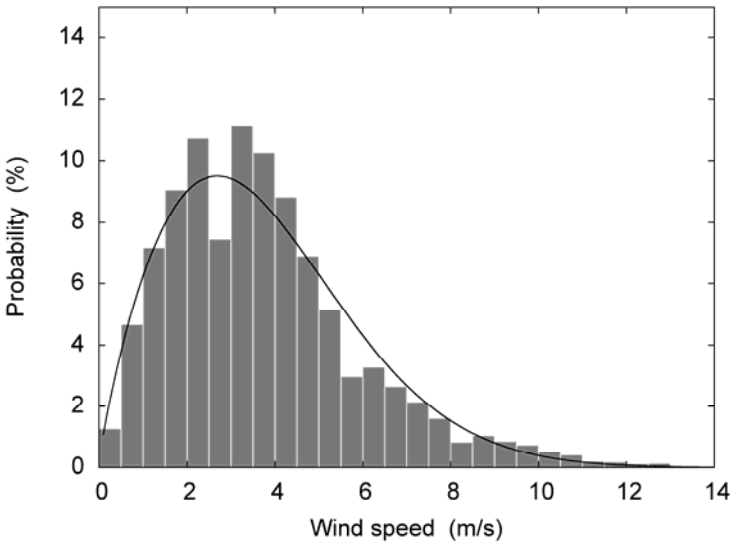

Figure 2. Wind speed distribution and fitted Weibull probability density function for the sea breeze period (March 1 to September 30, 10 to 19 LT) as obtained from wind speed data measured in the Llobregat Delta from 1993 to 2010.

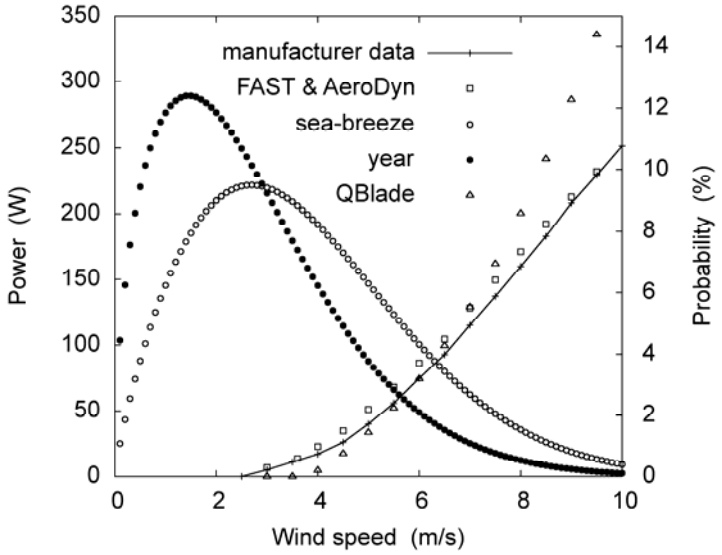

Figure 3. For the IT-PE-100: manufacturer power curve and power curves obtained from FAST and AeroDyn, and from QBlade, together with Weibull distributions for the entire year and the sea breeze period (March 1 to September 30, 10 to 19 LT) as obtained from wind speed data measured in the Llobregat Delta from 1993 to 2010.

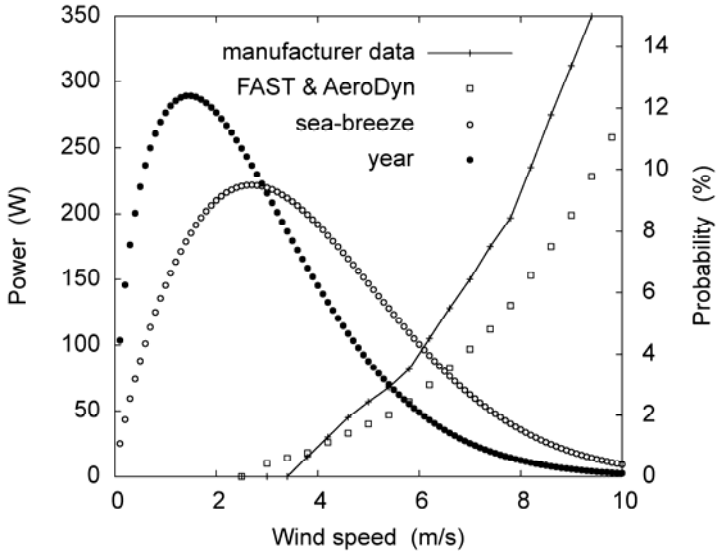

Figure 4. For the HP-600W: manufacturer power curve and power curve obtained from FAST and AeroDyn, together with Weibull distributions for the entire year and the sea breeze period (March 1 to September 30, 10 to 19 LT) as obtained from wind speed data measured in the Llobregat Delta from 1993 to 2010.