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Artículo Original

Techno-Economic Feasibility Study of Small Wind Turbines in Havana city

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Abstract

Cuba has an ambitious program to develop its renewables to satisfy 24% of the electricity demand. The vision for 2030 is to increase investment in clean energy production. This work explores the wind energy potential in Havana at 10 and 30 m. The statistical wind speed, the wind rose and the power density were obtained. This study is also part of the techno-economical assessment of turbines of 1, 2.5, 3.5 and 5 kW according to the analysis of annual energy produced (AEP), capacity factor (CF) and leveled cost of energy (LCOE). The results showed that despite of the low wind potential in the zone it is likely to implement and develop the urban wind energy sector. According to the economic assessment, the 2.5 kW WES Tulipo wind turbine is the best option, producing power at the lowest price of 0.22 and 0.09 USD/kWh at 10 and 30 m height respectively.

Keywords: small wind turbines, wind data, wind energy, renewable energy

1. Introduction

The demand for energy is constantly increasing in the world. The consumption of fossil fuels is still overload and will continue for next decades accompanied by risks and negative environmental impacts. To ensure continuity in economic development, power plants using renewable energy sources should be increased. In this sense, small wind turbines (SWT) are designed and installed to contribute to meeting the local energy needs in many places in the world. Although used since ancient times, the wind energy has recently gained particular attention as an attractive source of renewable energy. Electricity production using wind turbines has versatile applications, being wind farm the most popular. However, this is not the only mean by which wind can be used to produce electricity; the application of SWT for the decentralized use of energy is a popular option for isolated grids, rural or urban electrification, and also in hybrid systems.

Characterizing the wind speed at a specific location or area is extremely important for wind energy projects. The best way for it is to perform “in-situ” measurements, which should last several years [1]. This task is complex due to the random nature of wind, which does not exactly follow any known statistical distribution. This behavior is reflected, to a certain extent, in the power delivered by a wind turbine generator (WTG) [2]. The wind prospect for small wind energy projects might be done with a two-parameter Weibull probability distribution [1, 3]. The Weibull distribution is termed as the most suitable as well as the extensively used in wind power estimation. Besides it is also used in commercial software packages specialized in wind energy resources, national atlas of wind energy resources [4], international standards [5], simulations of WTG behavior [6], development of site-matching approaches [5, 7-9], etc.

Wind is a source of energy with relatively high potential over many areas. It is originates from the atmospheric air pressure differences and the primary source of it is the solar radiation. Cuba has just a few places with relatively good wind potential. There are just 511 km^2 of area with good-to-excellent wind resource. These windy areas represent solely the 0.5% of its total land area of 110.860 km^2. If additional areas with moderate wind resources potential are considered, the estimated total windy area increases to 4.281 km^2. Then, this amount of windy area represents the 3.9% of Cuba's total territory and could support 21.000 MW of installed capacity [4, 9]. For accurate wind power resource estimation, wind speed prospect is the best practice recommended by experts. In this study, using the software WAsP [10], a ten-year wind speed data was analyzed. On the other hand, researches in wind turbines design, modeling and connection to the grid are reported for the case of Cuba [11-13].

The aim of this work is to estimate the wind potential in the center of Havana city, far from the shore area, beside to assess the viability of the implementation of SWT in this site, with poor wind resources. The study weighs the total annual energy output and the capacity factor of the selected turbines. Also, the economic assessment has been carried out by comparing the LCOE (USD/kWh) of all of the SWT models analyzed.

2. Data and Methodology

The method used in this study is outlined in three stages as is shown in Fig.1. The wind data used in the analysis was collected over a period of 10 years (2001 to 2011), at 10 and 30 m height. Two-parameter Weibull distribution function for each 10 and 30 m height was used. Eight commercially available wind turbines were tested and compared. The method described is general and can be adopted in assessing the wind potential of any location once the wind speed data is known [14-17].

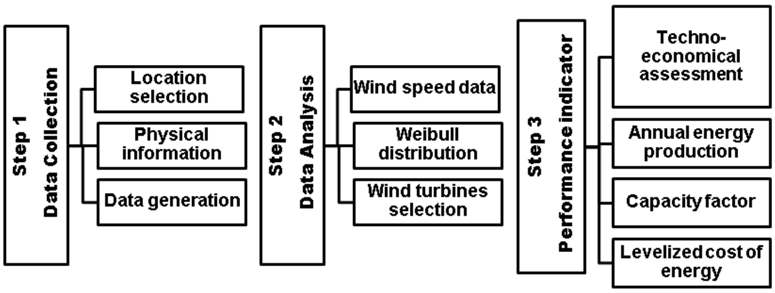

Fig.1 Outline of the method used in the study

Description of the site

Havana is a coastal city located in the west region of Cuba between 23.53º N and 82.35º W. It is the 15th province of Cuba by extension with an area of 727.4 km^2, representing 0.7% of the total Cuban territory. The urban site of this case study is located in the Casa Blanca Meteorological Station which is on the east side of the harbor at 51 m above sea level and at the Belen Neighborhood in the west side of the Havana harbor, 5 m above sea level and 1 km from Casa Blanca Meteorological Station [18]. Morphologically the urban site is very compact with narrow and orthogonal streets oriented NNW-SSE and ENE-WSE. Two to four-floor buildings with average height of 10-15m are clustered, leaving no open spaces inside the block except the inner courtyards. The wind energy resource map for Cuba at 50 m height was also used for this study [5]. Besides using the Global Wind Atlas (GWA), it was possible to check the average wind speed and wind power density on 5 height levels (10, 50, 100, 150 and 200 m) with a spatial resolution of 1x1 km, showing average wind speed map at 10 and 50 m using GWA web page. For developing wind applications, exploration, prospection and pre-feasibility evaluation of wind resources are important issues.

The wind potential in Havana can be classified as poor (wind power class one). Two measurement campaigns with duration of four weeks each were made in order to compare them with the meteorological station; the first one in summer 2003 and then in winter (December 2003-January 2004).

Also for this study the wind data in a period of 10 years from the Casablanca Meteorological Center of Havana was collected. It revealed that the seasonal weather variability in the area has not been significant between 2001 and 2011. The average (Av), coefficient of variation (CV) and standard deviation (SD) of temperature (T), relative humidity (RH), and wind speed (WS) have been low during that period, as in shown in Table 1. The weather in the site can be classified as tropical wet with two climatic seasons: a dry autumn-winter period (October-April) and a wet spring-summer period (May-September). Both seasons have approximately equal duration and relatively few differences of temperature and relative humidity.

Table 1. Values of the climatic parameters

Climatic parameters	Average	SD	CV (%)
RH (%)	76.1	6.4	8.4
t (°C)	25.3	2.4	9.4
WS (10m) m/s	3.4	1.3	38.2
WS (30m) m/s	4.8	2.1	43.7

Assessment of wind data

Wind resources assessment includes the estimation of the wind power density (WPD). The WPD helps in the conversion of kinetic energy of wind into a useful form of energy production. Wind is a highly changing atmospheric parameter in time. To estimate the wind conditions at a specific site, the Weibull distribution can be used. So far, this tool is working well for simple landscapes but forests or hills are considered to be complex terrain. Similar to a forest, a city can be described in terms of a canopy, seen by the wind as a single roughness. Cities cannot be described accurately with such macro wind climate tools, because they have micro climate zones that are very complex and influenced by different kind of parameters. One method to determine the wind conditions at a certain urban location is to take intensive wind measurements on the spot [2]. This method is very accurate, but could be very expensive and should last several years, and does not resolve the wind flow pattern in a city district. Another method, besides wind tunnel measurements, is the computational fluid dynamic (CFD) simulation of the wind field [7, 19-21]. However the prevailing literature is showing that two-parameter Weibull distribution is often used to rather evaluate the wind power assessment in a city [22-30].

Table 2 shows the performance measures equations for wind resource analysis. Wherein the Weibull probability density function (f(v)), cumulative distribution function (F(v)), power density (PD), energy density (ED), the average power output (Pe, ave), capacity factor (CF), and annual energy output (AEP) are shown. Then these quantities will be used to describe the performance of the eight SWT and their energy production in relation to the wind potential and wind characteristic of the site studied.

3. Results and Discussion

Wind measurements and parameters

The mean wind speeds (Vm) are found to be 3.4 and 4.8 m/s at 10 and 30 m respectively. It is found that wind speed increases with altitude as is expected. Fig.2 shows the monthly average wind speed in a whole year corresponding to the zone in study. The monthly hour wind speed registered at both altitudes are also shown in Fig.3 and Fig.4, corresponding to the monthly hourly wind speed contour map and the wind rose at 10 and 30 m height respectively. The typical wind speeds for a single day at 10 m is shown in Fig.5. The highest number of wind speeds measurement is witnessed in autumn and winter season and the lowest in summer at both heights. Accordingly, the highest values of average wind speed of 5.3, 5.4 and 5.6 m/s were found at 30 m in January, February and March respectively.

Table 2. Summary of performance measures equations for wind resources analysis

Performance measures	**Definition**	**Eq.**
Wind speed vertical variation	$V(Z_R) = V(Z)\ln[(Z_R/Z_0)/\ln(Z/Z_0)]$	(1)
Probability density function (PDF)	$f(V) = (k/c)(V/c)^{k-1}e^{-(v/c)^k}$	(2)
Cumulative distribution function (CDF)	$F(V) = 1 - e^{-(v/c)^k}$	(3)
Most probable wind speed (V_F)	$V_F = C((k-1)/k)^{1/k}$	(4)
Wind speed carrying maximum energy (V_E)	$V_E = C((k+2)/k)^{1/k}$	(5)
Power density (P_D)	$P_D = {}^1/_2\, \rho V_m{}^3$	(6)
Energy density (E_D)	$E_D = P_D\, T$	(7)
Weibull shape parameter (k)	$k(h) = k_0\,[1 - 0.088\ln(h_0/10)]/[1 - 0.088\ln(h/10)]$	(8)
Weibull scale parameter (c)	$c(h) = c_0(h/h_0)^n$	(9)
Exponent *n*	$n = [0.37 - 0.088\ln(c_0)]/[1 - 0.088\ln(h/10)]$	(10)
Average power output (PE_{ave})	$P_{E_R}\left\{\left\{\left[e^{-(V_c/c)^k} - e^{-(V_r/c)^k}\right]/[(V_r/c)^k - (V_c/c)^k]\right\} - e^{-(V_f/c)^k}\right\}$	(11)
Capacity factor (C_f)	$c_f = P_{E_{ave}}/P_{E_R}$	(12)
Annual energy production (AEP)	$AEP = c_f\,(P_{E_R})\,t$	(13)

On the other hand, to locate the best position of the wind turbines, proper knowledge of the dominant wind direction is sensitive. The wind rose diagram is used to find out the predominant wind direction. In Fig.4, it is observed that the wind blows from east almost all the time. This agrees with Casablanca's climate data that indicate a dominance of east and northeast winds direction for most time of the year in Havana. The presence of vegetation and built structures in the urban area could cause turbulence effects and affect the wind profile. This effect is expected to increase with increasing buildings height due to the drag by surface roughness elements [21]. However, it was not a problem in this study because Havana city has just a few tall building and the vegetation does not create enough turbulence to distort wind gusts. So there is no evidence to suggest that these factors distorted the wind data reviewed, measured at the height of 10 and 30 m. This is confirmed by an almost identical wind rose pattern at the 10 and 30 m heights, as is observed in Fig.4.

Fig.6 (a) and (b) shows the probability density function and cumulative distribution function for 10 and 30 m height. The probability density function and Weibull cumulative density function are given in Equations (2) and (3) respectively, as is shown in Table 2. The values of shape and scale parameters are 2.4 and 3.9 m/s for 10 m height and 2.3 and 5.5 m/s for 30 m.

The probability density curve indicates that the most frequent wind speed is from 3 to 4 m/s with a probability of 26.2% for 10 m height and 4 to 5 m/s with 19.6% probability for 30 m. Table 3 shows the monthly mean wind speed (Vm), VF, VE and the c and k parameters of the wind over the analyzed time interval; also the wind power density (PD) and energy density (ED) for a period of a year. The VF and VE values were obtained using Equations (4) and (5) and the PD and ED were obtained according to the equations (6) and (7) in Table 2.

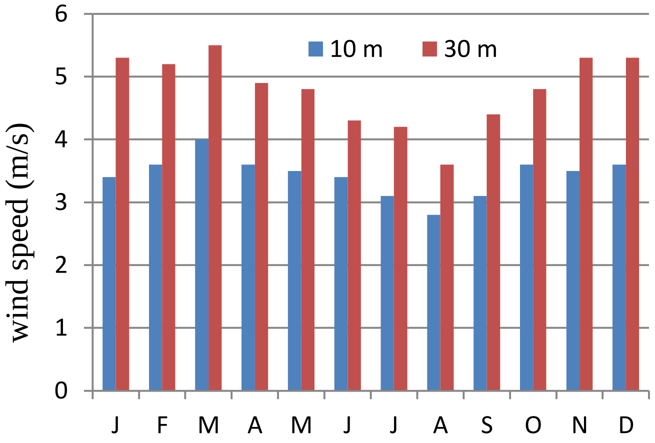

Fig.2 Monthly average wind speed measurements at 10 and 30 m altitude

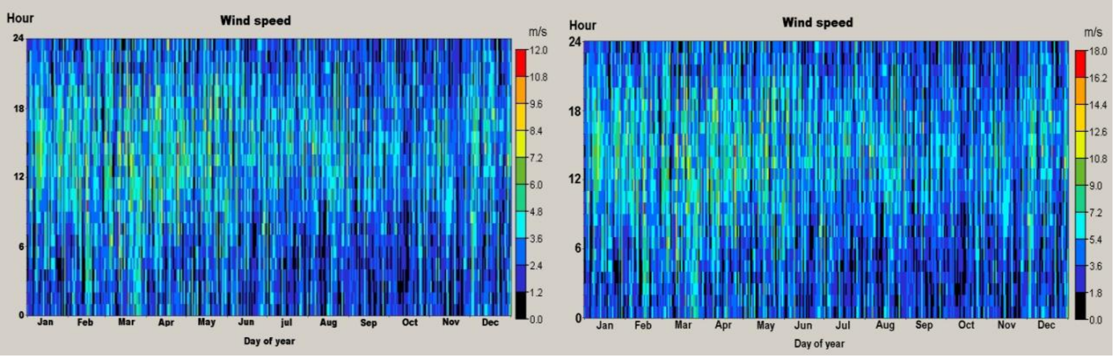

Fig.3 Monthly hourly wind speed contour map at 10 and 30m height

Table 2. Summary of performance measures equations for wind resources analysis

Performance measures	Definition	Eq.
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Power density (P_D)	$P_D = {}^1\!/_2\,\rho V_m{}^3$	(6)
Energy density (E_D)	$E_D = P_D\,T$	(7)
Weibull shape parameter (k)	$k(h) = k_0\,[1 - 0.088\ln(h_0/10)]/[1 - 0.088\ln(h/10)]$	(8)
Weibull scale parameter (c)	$c(h) = c_0(h/h_0)^n$	(9)
Exponent n	$n = [0.37 - 0.088\ln(c_0)]/[1 - 0.088\ln(h/10)]$	(10)
Average power output (PE_{ave})	$P_{E\,R}\left\{\left\{\left[e^{-(V_c/c)^k} - e^{-(V_r/c)^k}\right]/[(V_r/c)^k - (V_c/c)^k]\right\} - e^{-(V_f/c)^k}\right\}$	(11)
Capacity factor (C_f)	$c_f = P_{E\,ave}/P_{E\,R}$	(12)
Annual energy production (AEP)	$AEP = c_f\,(P_{E\,R})\,t$	(13)

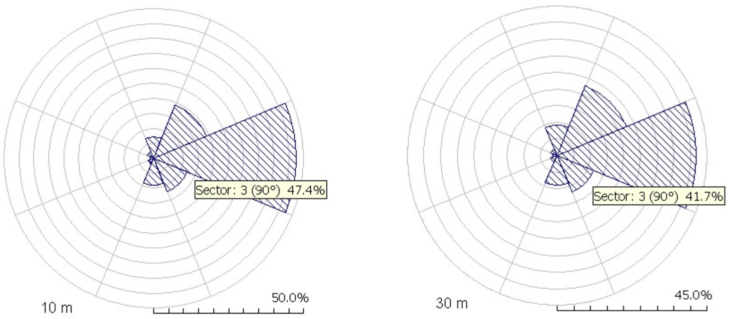

Fig.4 Wind rose for 10 and 30m height

Wind turbines characteristics and performance

To investigate the feasibility of harvesting the wind power at the location, eight commercially SWT from different manufacturers were selected to estimate their performance. Their rated electrical power (PeR) are 1; 2.5; 3.5 and 5 kW. The eight wind turbines have technical parameters of Swept Area (SA) in square meters and cut-in (Vi), rated (Vr) and cut-off (Vo) wind speed in meters per second given in Table 4; also showing the SA/PeR quotient. The technical data and the price of turbines and data of vendor's brochures have been gathered from [31, 32].

Figure 7 illustrates the power curve from each wind turbine (indexed from 1 to 8) and the Coefficient of Power (CP) across a range of wind speeds. All data was processed with an Excel spreadsheet. For each model, annual energy production (AEP) was calculated for 10 m and 30 m height values of the wind speed, using Weibull distribution.

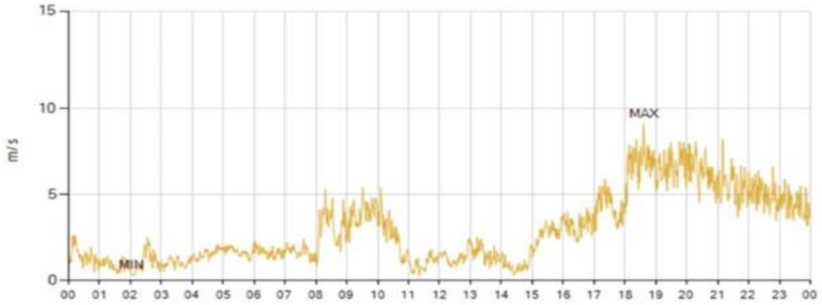

Fig.5 Typical wind speed contour for one day at 10 m

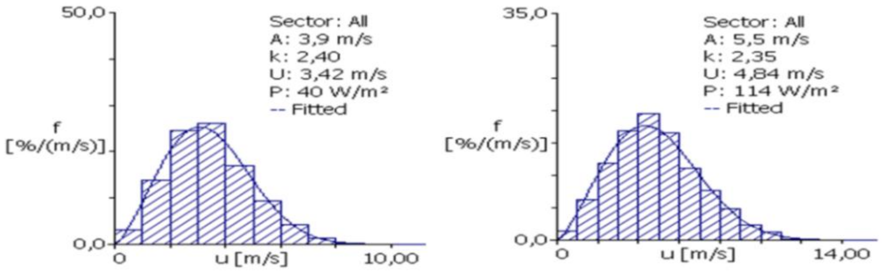

Fig.6 Probability density and cumulative distribution functions: (a) 10 m, (b) 30 m

Table 3. Analysis of wind speed characteristics in Havana

Altitude	Vm (m/s)	c (m/s)	k	VF (m/s)	VE (m/s)	PD (W/m^2)	ED (kwh/m^2/y)
10 m	3.4	3.9	2.4	3.1	5.0	40.0	350.4
30 m	4.8	5.5	2.3	4.3	7.2	114.0	998.6

Table 4. Technical details of selected SWT

Index	PeR	Model	Manufacturer	SA	PeR	SA/PeR	Vi	Vr	Vo
1	1	Aeolos (H)	Aeolos	8.0	1.0	8.0	1.5	10.0	50.0
2	1	Aeolos (V)	Aeolos	5.6	1.0	5.6	2.0	10.0	50.0
3	2.5	WES Tulipo (H)	WES b.v.	19.6	2.5	7.8	3.0	10.0	35.0
4	2.5	Ropatec (V)	Ropatec S.p.a.	7.3	2.5	2.4	2.0	14.0	40.0
5	3.5	Raum (H)	Raum energy	12.6	3.5	3.6	3.0	12.0	22.0
6	3.5	Tornado (V)	Technowind	16.0	3.5	4.6	3.5	11.0	18.0
7	5	Iskra (H)	Prowind	22.9	5.0	4.6	3.0	11.0	50.0
8	5	Aeolos (V)	Aeolos	22.3	5.0	4.6	2.5	10.0	55.0

The CP coefficient is the ratio of power produced by the turbine to the available energy in wind. According to the Betz limit, a wind turbine cannot physically convert more than 59% of the kinetic wind energy into mechanical energy turning the blades, so the maximum CP is 0.59. Also as can be seen from Fig.7 and Table 5, the results show CP from 24% minimum to 44% maximum. For instance, the Aeolos 1 kW (H) horizontal axis wind turbine (HAWT), indexed as 1, has a CP of 0.25 from 5 to 7 m/s wind speed, and the Aeolos 1 kW (V) vertical axis one, indexed as 2, has a CP of 0.37 also from 5 to 7 m/s. It means that the first one extracts 25% of the 0.59, maximum Betz limit energy from the wind, and the second one 37%. In this case, the vertical axis wind turbine extracts more quantity of the available kinetic wind energy than the horizontal one. This behavior is similar to the rest of the turbines, because vertical axis wind turbines have better adaptable characteristics to the unsteady urban wind condition. Also these turbines can produce electricity with any wind blow direction and they have relatively low cut-in wind speed [33, 34], except in the case of WES Tulipo. In the case of 2.5 kW WES Tulipo HAWT, the power curve is different from the other turbines' curves. Also, in spite of the rated power of 2.5 kW, its SA is 19.6 m^2 which is more or less the same value of the 5 kW turbines, thus it's SA/PeR quotient is higher than those of the 5 kW. This is why at low wind speeds the efficiency of this turbine is performing so well.

The annual electricity production was calculated for all turbines according to the two considered wind speeds at 10 and 30 m height. The higher wind speed regime (4.8 m/s annual average) was found at 30 m height and assuming the same 30 m hub height. For the lower wind speed regime at 10 m (3.4 m/s annual average) a 10 m hub height was set. These two cases were designed to test the importance of the average wind speed on the turbine's behavior. Both the annual production in kWh/y and the estimated Capacity factor (Cf) are the two performance indicators analyzed of the turbine's generation capacity.

In order to estimate the energy produced of a given turbine, it is necessary to calculate the average power and then multiply it by the time T for which the energy needs to be calculated. Then, the capacity factor is calculated as a ratio of the amount of energy produced and the amount of output that would be produced in case the turbine is operated at the full nominal capacity for the entire period T. Equations (8-12) and the Weibull distribution function were used to calculate the monthly power output from each turbine. The results are presented in Table 5.

Table 5 represents how naturally the yearly electricity production varies with nominal power. Also that the annual electricity production with 4.8 m/s average wind speed is higher than that of 3.4 m/s average speed, but the energy production is quiet similar for every pair of SWT at the same rated power. However, surprising is the difference in electricity production between the pair of turbines with 2.5 kW rated power. The annual 3122.27 kWh/y produced by the WES Tulipo is 4 times higher than the 776.85 kWh/y produced by Ropatec turbine at 10 m. The result is similar at 30 m height. This is a very significant difference and the cause was previously explained.

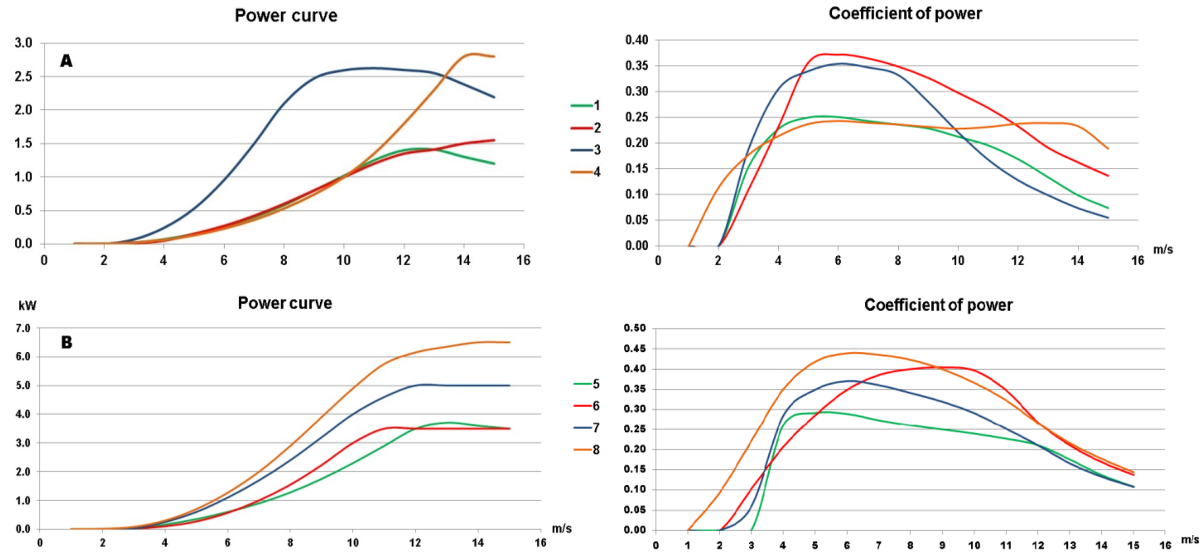

Fig.7 Power curves and CP of the selected SWT, indexed from 1 to 4 (A) and from 5 to 8 (B)

Table 5. Annual energy production, CP and CF of the SWT

SWT Index	PeR	CP	10 m		30 m	
			CF	AEP	CF	AEP
1	1.0	0.25	9.92	868.90	25.86	2265.60
2	1.0	0.37	9.36	819.67	25.82	2262.01
3	2.5	0.35	14.26	3122.27	34.40	7534.13
4	2.5	0.24	3.17	776.85	9.62	2106.14
5	3.5	0.29	6.17	1891.63	16.59	5086.23
6	3.5	0.40	5.64	1729.71	18.01	5520.63
7	5.0	0.37	7.71	3378.64	20.81	9112.75
8	5.0	0.44	9.36	4098.80	24.98	10941.15

Wind turbines costs

The analysis in this study is conducted for an urban energy consumer who wants to generate electricity from wind to supply his household. The consumer would accepts initial costs related to the purchase and installation of the turbine, but later, during its operation time, only minor repairs or an inverter replacement (in the case of a direct current turbine) are accepted. The operation and maintenance cost (O&M) is around 2% of purchased price and is accumulated once over the entire operation period of the turbine. The detailed costs for each device (USD) are quoted in Table 6.

When considering investments in electric facilities, one of the most important input data is the cost of the electricity produced. The so-called levelized cost of energy (LCOE) is defined as the average cost of a unit of electricity produced during the entire lifetime of a power plant. This method considers the total electrical energy that the power plant produces in its lifetime, usually 25 years for wind turbines, divided by the total costs in that period.

In this work, to calculate the LCOE of each SWT model, the cost of producing electricity for wind speed at 10 and 30 m height is implemented. The result is also presented in Table 6. Hereafter, the calculated LCOE by the analyzed turbines significantly differs again for the case of 2.5 kW in pairs; WES Tulipo seems as the best option. The cost of energy per kWh shown in Table 6 is in agreement with those reported by [33], in a study developed for more than forty turbines.

Table 6. Investment costs for the selected turbines

SWT Index	1	2	3	4	5	6	7	8
PeR	1	1	2.5	2.5	3.5	3.5	5	5
Costs								
Turbine	3850.00	4685.00	12950.00	10750.00	12460.00	10500.00	12150.00	11200.00
Mast	1660.00	1800.00	2000.00	2500.00	3500.00	4000.00	5500.00	4800.00
Inverter	1500.00	1500.00	0.00	0.00	0.00	0.00	2000.00	2500.00
Install	1450.00	1300.00	1600.00	1500.00	2500.00	3000.00	4500.00	5000.00
Other	375.00	250.00	250.00	345.00	350.00	200.00	350.00	300.00
Total	8835.00	9535.00	16800.00	15095.00	18810.00	17700.00	24500.00	23800.00
O&M	132.53	143.03	252.00	226.43	282.15	265.50	367.50	357.00
Investment	8967.53	9678.03	17052.00	15321.43	19092.15	17965.50	24867.50	24157.00
Invest./kW	8967.53	9678.03	6820.80	6128.57	5454.90	5133.00	4973.50	4831.40
Levelized cost of energy (USD/kWh)								
LCOE 10m	0.41	0.47	0.22	0.79	0.40	0.42	0.29	0.24
LCOE 30m	0.16	0.17	0.09	0.29	0.15	0.13	0.11	0.09

4. Conclusions

In this study, the wind energy prospective and an eight small turbines performance analysis were carried out in Havana. Ten years wind speed data at 10 and 30 m height were subjected to Weibull k and c parameters and other statistical analyses. Although the study site experienced low wind speeds, the site provided a suitable wind conditions for small wind applications. The typical Weibull wind distribution was skewed toward lower speed values, resulting in low average wind speed. The most important outcomes were that monthly mean wind speed at 10 and 30 m height was 3.42 m/s and 4.87 m/s respectively. The annual mean energy and power densities values were 40.0 W/m^2 and 350.4 kWh/m^2/y at 10m and 114.0 W/m^2 and 998.6 kWh/m^2/y at 30m respectively. The 2.5 kW WES Tulipo model had the highest capacity factor of 14.26% and 34.40% for 10 and 30m height respectively. The results demonstrated that Havana city has a potential to develop SWT applications.

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Conflicto de Intereses

Los autores declaran que no hay conflictos de intereses.

Contribución de los autores

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Análisis de los resultados y revisión del manuscrito.