Preliminary Wind Turbine Assessment Using Urban Scaling Factors in Puerto Rico

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Abstract *— It is well known that wind energy applications are most effective in wide open areas. As shown in the literature, rather than completely discard the location of wind turbines in urban areas, the reduction in power generation for wind turbines near building structures can be estimated through the use of scaling factors. This paper explores the opportunity to incorporate wind energy alternatives at urban locations as well as the possibility of using such scaling factors to the design of small-scale wind energy systems in Puerto Rico. The project considers the development of an engineering design tool for the evaluation of the actual performance of wind turbines in proximity to building obstructions. The program predicts the expected wind energy production for a wind turbine in close proximity to a building. The user's input consists of the desired wind energy production, the average free-field wind velocity and the site characteristics. The output of the program provides a suggested wind turbine model and the estimated energy production.*

Key Terms *— Renewable Energy, Urban Scaling Factors, Wind Energy, Wind Turbine Selection.*

INTRODUCTION

For years society has seen how the environment has continued to change in a wrong way. Fossil fuels are the most used resource on the planet to generate electrical power. Because Puerto Rico does not have a source of fossil fuels, this makes it vulnerable to fluctuating fuel prices which in turn, affect the economics of the island.

Approximately 70% of the energy produced in Puerto Rico comes from petroleum derivatives [1]. In other words, the island is essentially linked to the petroleum producing countries and fluctuating gas prices. The economical factor is not the only problem. The use of fossil fuels produces dangerous gases that affect the environment, contributing to global warming (e.g., greenhouse gases) and to pollution.

Some alternatives have been proposed lately to deal with the problem of the energy cost and environmental pollution. In particular, due to the tropical characteristics encountered on the island, the use of wind as renewable energy is one of the most accessible alternatives to Puerto Rico. Since Puerto Rico is located in the path of the northeast trade winds, considered one of the most constant winds in the world [1], this makes the island an ideal place to implement wind energy.

It is well known that wind energy applications are most effective in wide open areas free of building obstructions. In particular, it is usually recommended not to place a wind turbine in close proximity of building structures. Nearby building structures generate turbulence effects that would have an adverse impact to the power generation from wind turbines. This requirement might impose a limitation for the implementation of wind energy applications in a densely populated territory such as Puerto Rico.

Through our literature research, it was found that rather than completely discard the placement of wind turbines in urban locations it is possible to estimate the reduction in power generation for wind turbines near building structures through the use of scaling factors [2].

This paper presents the possibility of using such scaling factors to the design of small-scale wind energy systems in Puerto Rico. This project considers the development of an engineering design tool for the evaluation of the actual performance of wind turbines in proximity to building obstructions. The program was developed in Excel and predicts the expected wind energy production (e.g., monthly or yearly) for a wind turbine in close proximity to a building. The user's inputs consist in the desired wind energy production, the average free-field wind velocity (i.e., without any building obstruction) and the site characteristics. The output of the program provides a suggested wind turbine model (out of a pre-programmed database) and the estimated energy production. In particular, the program selects the option that better matches the requirements of the user, expressed in the inputs at the beginning of the evaluation process. Finally, the output of the program shows the specifications of the selected turbine.

JUSTIFICATION

The goal of many researchers is to find a better way to get energy without exposing the environment to continued degradation. The United Nation's Intergovernmental Panel predicts that the average temperature will increase 5.8°C yielding the coverage of low land by the melting of the polar ice caps within the next century. This event will yield storms and changes in weather patterns [3].

The dependency of fossil fuel derivates, such as petroleum, is a problematic issue. As shown in Table 1, it is the main contributor to greenhouse gases by CO_2. This dependency puts the countries that use the petroleum as their only energy resource in a disadvantage.

Table 1
Stack Emissions Comparison [3]

Stack emissions of coal, gas, and wind power plants (kg/GWh, t/GWh for CO2			
Pollutant	Conventional coal	Gas (CCGT)	Wind
Sulfur oxides	630 – 1370	45 – 140	2 – 8
Nitrogen oxides	630 – 1560	650 – 810	14 – 22
Carbon dioxide	830 – 920	370 – 420	10 – 17

As the years go by, the population increases, and the need of alternate sources of energy emerge to comply with these needs, whereas the finiteness of fossil fuels reserves and the negative environmental impact that the use of those energy sources produce is ever more evident.

There are renewable alternatives that could be seen as answers to solve the problems related with the energy in Puerto Rico. Wind energy is one of the alternatives proposed to produce energy in the island.

In Puerto Rico the main competitor to wind energy is solar energy. Comparing both in terms of the cost, for standalone solar systems, the cost per kW is $14,000/kW against $2000/kW for wind energy [4]. These figures make the wind alternative cheaper than the solar alternative, putting in disadvantage solar considering the payback period.

WIND TURBINE

Wind is air in movement caused by solar energy. Rays from the sun hit the earth and simultaneously the surface is heated, which warms the air that is lying above it. This air becomes less dense allowing those particles to rise in the atmosphere. Cooled air, being denser, takes the place of the warmed air raised by the rays of the sun [5]. This makes a cycle called convection cells as seen in Figure 1. By the effect of convection cells, the wind can be considered as renewable energy.

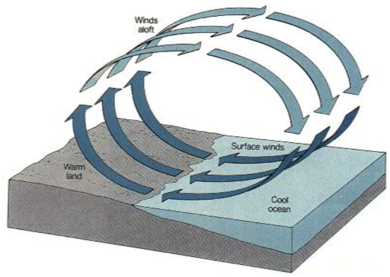


Figure 1
Convection Cell [6]

A wind turbine is a machine that converts the kinetic energy of the wind into mechanical energy. The wind hits the blades producing a difference in pressure by the geometry of the blades. The impact generates a lift effect on the blade imparting a torque to a shaft that is connected to the generator. That torque produce rotation, hence electricity. By transmission lines this electricity is transferred to buildings, homes, commercial establishments, among others.

WIND POWER

The wind power production is based on the cubed wind speed and projected swept area of the rotor. The description of the instantaneous available power in the wind is given by

$$P_w = \frac{1}{2}\rho A U^3, \tag{1}$$

where the air density is taken from sea level (15^{o}C), ρ = 1.225 kg/m^3, A is the rotor swept area and U is the wind speed at the wind turbines hub height. For the variation in wind speed, the average wind power is given by

$$\overline{P_w} = \int_0^\infty \mathrm{P_w(U)p(U)dU}, \tag{2}$$

where $P_w(U)$ is the power known from the power curve of the wind turbine and $\mathrm{p(U)}$ represents the wind speed probability density function.

The wind turbine rotor power can be calculated as

$$P_{rotor} = \frac{1}{2}\rho A U^3 C_p, \tag{3}$$

where *Cp* is the rotor power coefficient. In the ideal case of a wind turbine without considering the effect of wake rotation, this takes the value of 16/27. This case ignores the effect of flow rotation behind the wind turbines rotor and is known as the Betz limit. For the case of a practical wind turbine design, it is necessary to contemplate the rotational effect of the flow behind the rotor and the Cp is much lower than the Betz limit [3].

The overall output power is a function of the rotor power (Cp) and mechanical (η) efficiency (drive train efficiency) as:

$$P_{out} = \frac{1}{2}\rho A U^3 C_p \eta. \tag{4}$$

A typical power curve is shown in Figure 2.

WIND ENERGY

Considering the fluctuation of the wind, from equation 4 we can calculate the energy proportional to the period of time selected (e.g., 24hr daily, 730hr monthly, 8760hr yearly) as

$$E = (\overline{P_w})\mathrm{(t)} = \mathrm{(t)}\int_0^\infty \mathrm{P_w(U)p(U)dU}. \tag{5}$$

The importance of the result calculated in equation (5), allows the prediction of how much energy can be extracted from the wind energy system before incurring in the investment.

WIND SHEAR

Once the equations to get the power extracted from the turbine are defined, is important to incorporate a tool that permits the prediction of the wind at the wind turbine's hub height based on the available wind speed information. The wind speed from a reference height to another desired height can be computed from the log law as

$$U(z) = U(z_r)\frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)}, \tag{6}$$

where z_r is a reference height, z_0 is the surface roughness length, and z is the new height of interest. Table 2 shows typical values for z_o.

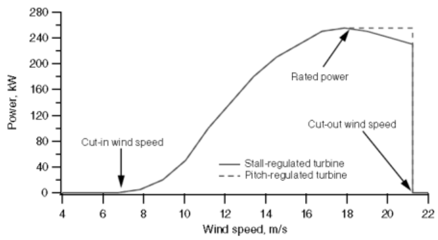


Figure 2
Power Curve [3]

Table 2
Terrain Description [3]

Terrain description	z_0 (mm)
Very smooth, ice or mud	0.01
Calm open sea	0.20
Blown sea	0.50
Snow surface	3.00
Lawn grass	8.00
Rough pasture	10.00
Fallow field	30.00
Crops	50.00
Few trees	100.00
Many trees, hedges, few buildings	250.00
Forest and woodlands	500.00
Suburbs	1500.00
Centers of cities with tall buildings	3000.00

WIND DATA ANALYSIS

The probability that a specific wind speed is between U_1 and U_2 is given as

$$p_r(U_1 < U < U_2) = \int_{U_1}^{U_2} p(U)dU, \quad (7)$$

and in the case of Rayleigh distribution

$$p(U) = \frac{\pi}{2}\left(\frac{U}{\bar{U}^2}\right) e^{-\frac{\pi}{4}\left(\frac{U}{\bar{U}}\right)^2}. \quad (8)$$

The cumulative distribution represents that probability wind speed is equal or smaller to the given wind speed (i.e. $(U' \leq U)$) [3]

$$F(U) = \int_0^U p(U')dU', \quad (9)$$

and for a Rayleigh distribution

$$F(U) = 1 - e^{-\frac{\pi}{4}\left(\frac{U}{\bar{U}}\right)^2}. \quad (10)$$

EFFECT OF WIND TURBULENCE

Before installing a wind turbine, some considerations are recommended. One of them is directly related with the turbulence generated by obstructions. As a rule of thumb for small turbines, the entire rotor should be at least 30 feet above any obstruction within 300 feet of radius [5]. This restriction is shown in Figure 3. As shown in the figure, the shadow represents the region of turbulence that generally is avoided by classic designers.

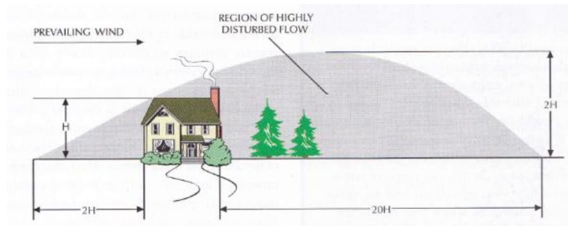


Figure 3
Shadow Region [5]

At a glance, to detect turbulence in a potential site, just elevate a kite preferable over obstructions (e.g., trees, houses, hills, etc.) as seen in Figure 4 and observe the behavior. The test is to see if the kite remains stable or starts swirling by the instability of the stream. If the kite remains stable, in the same way the wind will beat the rotor, but the turbine will work with less vibration minimizing the probability of a failure. Once detected, the turbine may be installed in the site without the effect of turbulence on the rotor.

A more formal assessment on the effect of turbulence can be conducted either through a Computational Fluid Dynamics (CFD) analysis or through wind tunnel testing. However, a less accurate but perhaps more practical method is the use of scaling factors to predict the behavior of the wind into the turbulence region.

SCALING FACTORS

There are urban areas where the wind speed is suitable, but the space for installation is not, considering the installation into the region where the turbulence is present, as shown in Figure 3. This fact brings a new challenge to the investigation about the effects of irregularities (e.g., houses, trees, buildings) at heights that coincide with the rotor; for example, when the turbine is located in the center of the city where it has buildings around, traffic in the streets, trees in the sidewalk, but it is windy. All these aspects have a minimizing effect on the wind speed by the obstructions encountered in the path. Therefore, the power generation will be less.

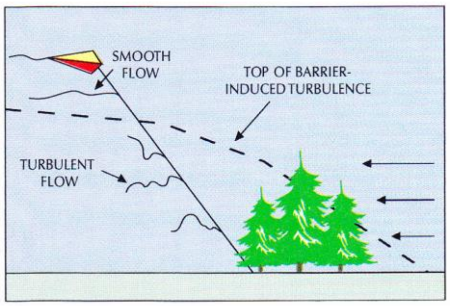


Figure 4
Simple Turbulence Detector [5]

These obstructions generate an irregular surface that can be described in terms of terrain categories.

Researchers in United Kingdom have worked to develop scaling factors that take into consideration the fact of producing energy, not above the turbulence region (Figure 3) but, instead, where the turbine is within the flow disturbed by the obstacles [4]. The Microgeneration Installation Standard (MIS) explains in detail the requirements for installations of small wind turbines in the UK [2]. As mentioned in the standard, the scaling factors are selected from a matrix that combines the terrain categories (described in Table 3) and types of obstructions (described in Table 4) [2]. The site is compared with the description of the terrain categories, and is matched with one of them. The significant obstruction near the location is evaluated according to Figure 5. The figure shows the perimeter around the wind turbine where the obstruction is considered significant. Once both parameters have been selected, they are combined in an adjusted matrix that considers the effects of the combination of both to deliver the best scaling to the wind.

The scaling factors are based on multiple data collectors localized at different points with similar characteristics, approximately at the same height (i.e. 10m for these scaling factors) to then be compared with the data estimated at macro levels (e.g., wind maps). The scaling factors estimate the wind speed at the location as [2], [7]-[8]

$$s_u = \frac{\overline{u_m}}{\overline{u_e}} \qquad (11)$$

Table 3
Terrain Category Description [2]

Terrain Categories	Description
1	Flat grassland, parkland or bare soil, without hedges and only a few isolated obstructions.
2	Gently undulating countryside, fields with crops, fences or low boundary hedges and few trees.
3	Farmland with high boundary hedges, occasional small farm structures, houses and trees etc.
4	Woodland or low rise urban/suburban areas (e.g. Domestic housing).
5	Dense urban areas and the center of cities (e.g. Buildings of four-stories or higher).

where $\overline{u_m}$ and $\overline{u_e}$ are the mean wind speeds measured at the location and mean estimated from the maps respectively. Before using the equation (11) is important that the investigator takes the average wind speed from the wind reference height to a height of 10m, see equation (6). This requirement is so, because the scaling factors were calculated at a height of 10m considering the effect of the obstructions with similar characteristics (e.g. trees, edges, buildings, among others) but at different scenarios (i.e. terrain categories explained in table 3). Scaling factor covers from a height as low as 1m (3.28ft) to 100m (328ft). The results fluctuate between 0.05 and 1.32 depending of the terrain category and the configuration of the significant obstruction in the system.

Significant Obstructions

As explained in MIS [2], a significant obstruction is defined as any solid item (e.g., building, wall, etc.) or semi-permeable item (e.g.

trees) that is at least 0.5m in the widest part and reaches more than 25% of the hub height into the zone marked by the obstruction perimeter in Figure 5. To determine a significant obstruction, do not forget that the zone of obstruction is relative to the position of the obstruction's height and the hub's height as also indicated in Figure 5. To configure the category that best describes the surroundings of the turbine location, it is necessary to define other parameters as shown in Table 4. In particular, ho is the height of the highest significant obstruction, ht is the height of the turbine's hub, hb is the combination of the turbine height mounted in the roof of the building plus the height of the building and hc is a factor used to identify the scaling factor in a table together with the category of the terrain.

Original Picture Source: http://www.shutterstock.com/pic-17679673/stock-vector-isometric-view-house-with-solar-panel-and-wind-turbine.html

Figure 5
Significant Obstruction Zone

Table 4 gives more and better information on to know how to incorporate the height of the turbine mounted in a building based on the options and restrictions described. It is important to point out that Figure 5 is just an illustration that considers the representation of obstructions (e.g., the house in this case).

The analysis in this section applies to obstructions inside the lines shown in Figure 5. Also, it is important to note that the wind turbine's orientation is with respect to the prevalent wind direction.

Table 4
Cases of Obstruction [2]

Obstructions Cases	Description
1	Where there is no significant obstruction according to the before mentioned. hc = ht
2	Where there is one or more significant obstruction(s). hc = ht - 0.8*ho
3	Special case for turbines (micro/small) installed on the roof of isolated tall buildings. hc = hb Requirements to apply case 3. ✓ Building height (hb) exceeds 20m. ✓ There is no other building within the zones marked in Figure 5. ✓ The lowest point of the turbine blades is at least 0.1*hb. note: if the requirements are not completed, use case 2

Scaling Factors in Puerto Rico

In Puerto Rico, as in other locations, the knowledge about micro-generation is not clear. The process to collect data and make a good approximation in presence of nearby obstructions to the installation of a turbine is not available in Puerto Rico. This project adopted the scaling factors calculated in the UK to incorporate it to a similar scenario in Puerto Rico. These factors help to predict the impact of obstructions in the wind speed.

Given the case that in Puerto Rico these experiments have not been developed yet, these scaling factors were implemented into a program that evaluates what alternatives (i.e., turbines) match with the energy required to give a better idea of what they can expect from a specific scenario at urban scale.

PROGRAM EVALUATOR

An interface was developed in Excel based on the Rayleigh PDF, to incorporate all the aspects discussed through this paper. The program has a database with 21 models of small turbines with their respective power curve and all the information of each one (e.g., rated power, turbine and tower price, rotor diameter, weight, etc.) as presented in Achievable Renewable Energy Targets for Puerto Rico's Renewable Energy Portfolio Standard [9]. The program requires data related with the elements that describe the general behavior of the system. This data is detailed in Table 5.

Once the requirements are entered into the program, a scaling factor is chosen from the combination of the selections between the terrain category and the case of obstruction. This scaling factor, that considers the effect of the obstruction in the wind, is used to correct the mean wind speed in equation 11. Later, the log law in equation 6 is applied to take the mean wind speed adjusted to the desired hub height. Afterward, as part of the process the equation 10, is used to get the probability of how many times a velocity is repeated. Then each velocity probability is multiplied by a point in the power curve of the machine that makes reference to the power at that particular velocity. Later, all multiplications are summed giving as result the estimated average power of the machine in study. Depending on the lapse of time selected (i.e. monthly or yearly), the energy production is extracted in kWh/mo or kWh/yr as shown in Figure 6. The program estimates the energy production for all turbines with and without scaling factor.

CASE STUDY

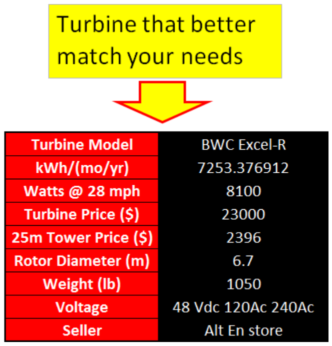
A hypothetical case was taken from a residence located in Fajardo. This selection was based on the proximity (i.e., 150m approximated) between the turbine and a wind data collector located at a met (meteorological) station in Fajardo. By the distance approximation it is assumed that the wind speed is basically the same for both points: turbine location and the met station.

Considering the nearness between the turbine and the NOAA Met station in Fajardo [10] (i.e. Figure 7), the mean wind speed is 4.1 m/s from data reported in 2010 for whole year with a reference wind height of 6.4m to be extrapolated to a desired hub's height of 12m. The Puerto Rico Electric Power Authority (i.e. AEE) estimates that the energy consumed, residentially, is of 800 kWh/mo and 9,600 kWh/yr [9].

This hypothetical case will be evaluated as if the user would want to cover all the expense of his energy bill (i.e., 9,600 kWh/yr) in a year. Then, setting the terrain category for domestic housing near the beach shore as seen in Figure 7 and the case of obstruction for case 2 (i.e., where there is one or more significant obstruction into the lines marked in black and highest significant obstruction of 3m represented in the Figure 5 by the residence), the program yields a velocity scaling factor of 0.84.

Table 5
Inputs and Selections (Dropdown Menu) to the Program

Description	Unit	Input	Dropdown Menu
Mean wind speed	m/s	x	
Energy desired per (Month/Year)	kWh/(mo/yr)	x	
Selection of the time of prediction	Monthly or Yearly		x
Wind height reference	m	x	
Desired hub height	m	x	
Selection of the surface roughness described in table 2	m		x
Selection of the terrain category that better depicts the site described in table 3	n/a		x
Selection of the case of obstruction described in table 4	n/a		x
If the case 2 is selected, need the height of the highest significant obstruction (ho)	m	x	
If the case 3 is selected, need the combination of the turbine height mounted in the roof of the building plus the height of the building (hb)	m	x	



Turbine Model	BWC Excel-R
kWh/(mo/yr)	7253.376912
Watts @ 28 mph	8100
Turbine Price ($)	23000
25m Tower Price ($)	2396
Rotor Diameter (m)	6.7
Weight (lb)	1050
Voltage	48 Vdc 120Ac 240Ac
Seller	Alt En store

Figure 6
Program that Provides the Better Option Based on the Requirements Evaluated Using Scaling Factors

Figure 7
Wind Turbine Location [11]

This scaling factor is used in equation 11 to get the velocity fixed, after that, equation 6 has been used to adjust the velocity from the reference height to the height used to calculate the scaling factors (i.e., 10m for these scaling factors). Once the velocity is fixed from the reference height where the scaling factors were calculated, it is readjusted to the height desired by the user (i.e., hub heights) and this calculation is included in the scaling factor. Table 6 shows all the program inputs and selections previously mentioned in a simple form.

The configuration exposed, considering the scaling factors, based on the obstructions frequently found on the residential area near the beach shore and farms, the energy generated yearly for the better choice found (i.e., a BWC Excel-R) that match with the energy expected (i.e., 9600 kWh/yr) by the client is 7,253 kWh/yr, against 12,951 kWh/yr that did not consider the obstructions that really absorb energy from the wind dissipating it through many forms to the surrounding.

DISCUSSION

Figure 8 shows, graphically, how the distribution of the wind, with the scaling factor that includes the effect of the air flow behavior through obstacles represented by trees and homes, in this case, against the wind behavior that, did not consider the obstructions. This evaluation is in agreement with the use of scaling factors. Although they were calculated for another region, (i.e. UK), the same scaling factors can be used in any site with similar characteristics. The purpose is to predict if the location meets the requirements for the installation of a wind turbine and if it will really produce energy. The histogram in blue represents the number of occurrences with the application of the scaling factor, showing that, although the energy production is less because the representative quantity is running at lower speeds, it still generates a good concentration of energy.

Table 6
Inputs and Selections for Case Study

Input/Selections	Description
4.1 m/s	Mean wind speed
9600kWh/yr	Energy desired per year
One year	Selection of the prediction time
6.4m	Wind height reference (zr or hr)
12m	Desired hub height (ht)
0.25m	Selection of the surface roughness (many trees, hedges, few buildings)
Terrain Cat. # 3	Selection of the terrain category (Farmland with high boundary hedges, occasional small farm structures, houses and trees ect)
Obstruction Case # 2	Selection of the case of obstruction (Where there is one or more significant obstruction(s))
3m	Highest significant obstruction (ho)

The energy extracted (i.e., 7,253 kWh/yr for a BWC Excel-R) considering obstructions at an urban scale are enough to comply with the average yearly energy consumed residentially in Puerto Rico for a machine installed at 12m (40ft approximated) with a rotors diameter of 6.7m (22ft approximated). Some other alternatives can be considered, as an Inclin 6000 that produces 12,769 kWh/yr, depending of the need of the client and the budget available to spend on this technology.

To give to the client a prediction, on how long it takes for the initial investment to be recovered, simple payback analysis was applied. The installed capital cost (*Cc*) for this turbine is approximately $30,400, the annual energy production (*Ea*) is 7,253kWh/yr and the price of electricity (*Pe*) in Puerto Rico is $0.28/kWh [12], resulting in approximately 15 years, without the consideration of the 60% of the initial investment absorbed by the governmental incentives for urban scale that are taxable [13]. If the client applies for the incentives, then the initial investment will be absorbed in just 6 years. Covering the energy bill annually completely against 6 years of payback, definitively the investment is paid up in a short time, comparing it with the benefit that the client will receive after this period.

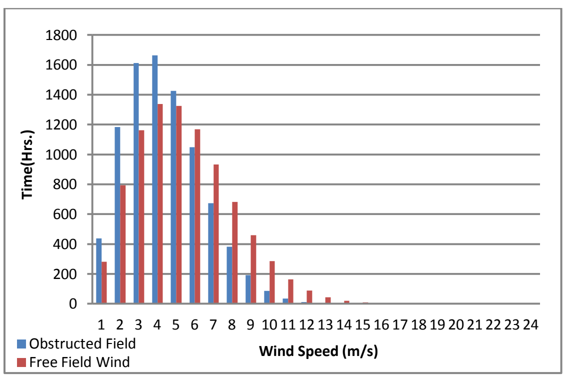


Figure 8
Comparison between the Wind with and without Scaling Factor Applied

CONCLUSIONS

This paper presents basic concepts, such as the interaction of the wind with the turbine to generate electric power and a brief explanation of the advantages of wind power. The paper includes important aspects about the environmental pollution and the instability of fuel prices that affect the everyday life of the citizens. The use and explanations of design tools that allow the designer to predict the power extracted from the combination of the correct turbine in the adequate location have been expounded. The incorporation of the correction factors, enables to take the tools available reviewed in this article to a scenario that can be used to predict energy at domestic heights, giving the people the opportunity to participate of this technology. A program was developed to put into a correct perspective the fact that although the scaling factors are unknown in Puerto Rico, these can be implemented, while at the same time, presenting a useful tool that can effectively predict the power obtained at an urban scale. Also, an example that gives a real perception of how these tools are used to predict the behavior of a turbine, is that in a zone where the turbulence generated by the obstructions are unavoidable. With the information described in this paper, any person is able to conclude that the technology is available to be incorporated. Not only will it help with the reduction of the energy bill, which is so important in PR, but also it will reduce the negative impact of the emissions generated by the fuel combustion over the environment.

RECOMMENDATIONS

Taking into consideration the limitations for validating the results of a particular site using scaling factors, to be compared against real historic data collected at sites with the same conditions, it is recommended to use a CFD model to compare it with the results of the scaling factors based on the same scenario to see how compatible the results can be. As a final suggestion, another recommendation would be to distribute several turbines at the same height, having similar obstructions conditions, in order to evaluate them and obtain correction factors from empirical data right here, in Puerto Rico. Following the example given from the UK, the Administration of Energy Issues (i.e. AAE) [13] and the corresponding agencies, should try to implement projects similar to the one discussed, to give to Puerto Rico tools to obtain more knowledge on the real possibilities to be participants as users of renewable energy and promote the improvement of the whole environment.

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