Preliminary Cost Assessment for Offshore Wind Energy in Puerto Rico

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Abstract*– The high cost of energy in Puerto Rico (e.g., $0.27/kWh in September 2014) due to its dependence on fossil fuels (i.e., 61% of electricity production) has become a direct burden on individuals and a critical barrier on economic development in the Island. To alleviate the cost of energy and reduce environmental pollution and greenhouse effects, the Puerto Rico Electric Power Authority (PREPA) is seeking to establish over 380 MW of electrical power from wind sources as part of its renewable energy portfolio. However, contrary to a wind energy study that indicates that the greatest potential for wind power extraction in Puerto Rico resides offshore, all PREPA's wind energy projects are onshore. This investigation considers a preliminary assessment for the use of offshore wind energy in the eastern region of Puerto Rico. A theoretical model was used to calculate the wind power and levelized cost of energy (LCOE) for three typical offshore wind turbines with nominal output power of 2,300 kW, 3,000 kW, and a 3,600 kW. The results suggest that a smaller wind turbine will be more cost effective in the offshore region of Puerto Rico. As shown in the results, the LCOE could be as low as $0.20/kWh for the 2,300 kW turbine and as high as $0.36/kWh for the 3,600 kW turbine.

Keywords*— Image Compression, ANN, HIS energy, wind, offshore, cost, Puerto Rico.

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Keywords— energy, wind, offshore, cost, Puerto Rico.

I. INTRODUCTION

It is well known that Puerto Rico (PR) is experiencing an energy crisis. The cost of energy is not only a direct burden on individuals, but also a critical barrier on economic development in the Island. The high cost of energy in PR has been largely attributed to its dependence on fossil fuels. Approximately 99 percent of the generated energy in PR is coming from fossil fuels. According to the Puerto Rico Electric Power Authority (PREPA), 61% of the electricity in PR is currently produced by oil burning plants. Natural gas and coal represent 24% and 14%, respectively, and only 1% of the electricity is being produced by renewable sources [1].

Minimizing the dependence on fossil fuels will also reduce its contribution to environmental pollution and greenhouse effects. A 2010 law in PR established that 12% of the energy produced must be generated through renewable sources by 2015 [2]. As also noted in the law, the percentage shall increase to 15% by 2020 and 20% by 2035. With only 1% of electricity currently produced by renewable sources, meeting the requirements of this law has become more than a steep challenge to the Island.

Renewable energy sources span from solar, wind, nuclear, hydroelectric, bioenergy, and geothermal sources, among others. No single renewable source will provide the much needed cost reduction and allow meeting the environmentally-driven renewable source targets. To improve its renewable energy portfolio, PREPA is in the process to establish over 1,640 MW of electrical power from various renewable sources [1]. As shown in [1], PREPA is expecting to generate over 380 MW from wind sources. To date, the two most significant wind energy projects in PR are the 75MW wind farm in Santa Isabel and the 23MW wind farm in Naguabo. None of the existing or future projects consider an offshore wind energy farm.

Offshore wind farms have been increasingly developed across the world. Most of the projects of the approximately 7 GW in installed offshore wind farms are in northwestern Europe and China. The U.S. is getting ready to complete its first three projects in New Jersey, Virginia, and Oregon with key funding from the Department of Energy (DOE) and will serve as pilots with the goal that many others that are currently at advanced stages will follow [3]. According to the DOE, the U.S. will need about 54 GW of offshore wind in order to meet a critical goal of having 20% of its electricity coming from wind by year 2030 [4].

The increasing trend to consider offshore wind energy systems is driven by the improved wind resource conditions far from the shore. Offshore provides vast open spaces, reduced impact on the environment, and higher energy densities [5]. Incidentally, according to a wind resource study developed by the National Renewable Energy Laboratory (NREL), the greatest potential for wind power extraction in PR resides offshore [6]. As shown in the study, the best wind resources in PR are in the northern and eastern ocean areas.

The benefits of offshore wind energy in PR were previously recognized in a University of Puerto Rico study in 2008 [7]. The study presented a preliminary assessment of offshore wind energy potential and concluded that offshore wind energy could provide more than 13,700 MW of power. According to the study, even if only 10% of the available potential is used, offshore wind energy could produce over 2,600,000 MWh per year (i.e., enough energy to supply electricity to over 272,000 residential customers). A similar study considered a specific site in the eastern side of the Island with wind speeds in the 7.0-7.5 m/s range and shallow waters in the range 14 to 17 meters in depth [8].

Although highly encouraging, the previous studies did not include enough details about the cost of energy from an

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offshore wind plant in PR. The present work considers a detailed analysis of the levelized cost of energy (*LCOE*) for offshore wind energy in the eastern portion of Puerto Rico. According to the results, the *LCOE* for an offshore wind energy installation will be in the \$0.20/kWh-\$0.36/kWh range.

II. OFFSHORE WIND ENERGY

Offshore wind turbines are becoming viable option to wind energy installations. The reduced availability of land resources on densely populated areas and increased wind energy availability in the ocean has pushed the development of these projects towards offshore regions. Offshore wind farms have become extremely attractive due to several factors such as: (1) large available area with limited environmental impact, (2) relatively higher mean wind speeds, (3) lower wind shear, (4) lower wind turbulence effects, and in many cases (5) closer proximity to high population regions [9].

Figure (1) shows the basic components of an offshore wind turbine [10]. As shown in the figure, the key components are the rotor-nacelle assembly and the support structure. In particular, the support structure consists of the tower, the sub-structure and the foundation. Support structures are based on the water depth in which they will be installed. Offshore wind turbines are commonly found in shallow waters which account for a depth of up to 30 meters. Transitional water depth ranges from 30 and 60 meters and more than 60 meters of depth can be considered deep water scenario as seen in Figure (2) [11]. As the water depth increases it is more likely for the support structures to increase in complexity, thus elevating the cost of setting up the wind turbine.

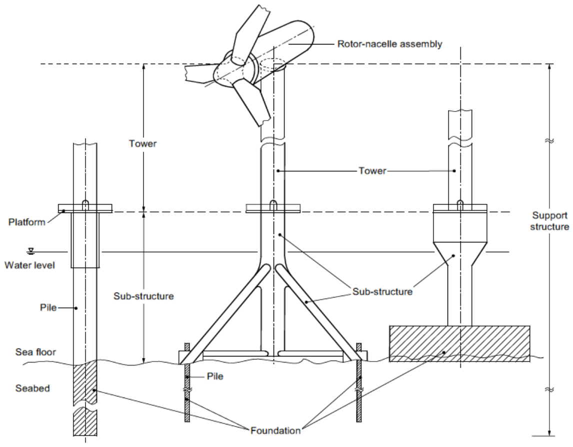

Figure 1. Components of an offshore wind turbine [10].

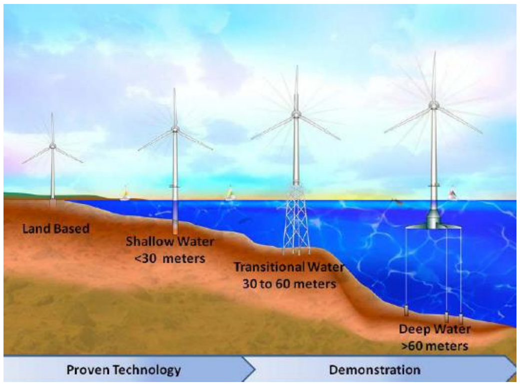

Figure 2. Status of the Offshore Wind Energy Technology [11].

Early offshore installations were "marinised" versions of land based wind turbine designs. The first offshore wind farm was built in Denmark in 1992 near the town of Vindeby. The wind farm is still in operation and has eleven 450 kW wind turbines. Since the early beginnings, offshore wind farms have been increasingly developed across the world. In a recent development, the largest offshore wind farm has been approved to be constructed on the United Kingdom. The new development will have approximately 240 wind turbines with an installed capacity of 1200 MW and is expected to be generating electricity by 2020 [12].

The U.S. is getting ready to complete its first three projects in New Jersey, Virginia, and Oregon. The projects have key funding from the Department of Energy (DOE) and will serve as demonstrative with the goal that many others will follow. The DOE interest in funding the demonstration projects not only seeks to maximize the usage of available offshore wind resources but also stimulate economic development through manufacturing jobs creation. It is expected that the offshore wind industry could support up to 200,000 jobs in the U.S. [3].

The transition from inland to offshore wind turbines is not one without challenges. Offshore wind turbines tend to be significantly more expensive than inland installations. Higher project costs are due to several factors that involve specialized equipment for construction, maintenance and operation. Offshore projects require special considerations to survive extreme conditions such as high winds, hydrodynamic loads and corrosive environments. Similarly, underwater support structures and long distance power transmission require special considerations. Furthermore, the maritime environment represents a special set of challenges since the characteristics of the seabed, currents and marine sanctuaries must be considered.

III. EXPECTED WIND ENERGY PRODUCTION

Wind turbines convert wind power into electrical power. Most large wind farms have horizontal axis wind turbines (HAWTs). For a given HATW, the available wind power is given as [5]

$$P_W = \frac{1}{2}\rho A U^3, \qquad (1)$$

where A is the wind turbine's area, ρ is the air density and U is the available wind speed. However, physical constraints and inefficiencies prevent a wind turbine to produce the available wind power.

A practical wind turbine configuration has an output power given as [5]

$$P_O = \eta C_p P_W, \qquad (2)$$

where the factors η and C_p are the efficiency and coefficient of power, respectively. In practice, both factors are less than 1. The efficiency factors account for mechanical and electrical losses while the coefficient of power is directly related to the aerodynamic design of the wind turbine. The maximum realizable wind power is limited by the well-known Betz limit of $C_{p,max}$=0.596 [5]. Equations (1) and (2) are fundamental to understand the mechanical to electrical energy conversion from the available wind power. In particular, both equations show the strong dependence on the wind speed to maximize power generation.

In practice, a well-designed wind turbine will produce an output power in the order of 40% to 45% of the available power. Figure (3) shows the comparison between the available power and the realizable output power for a hypothetical wind turbine. The lower curve in Figure (3) resembles a practical power curve for a wind turbine. Output power curves are usually available from original equipment manufacturers.

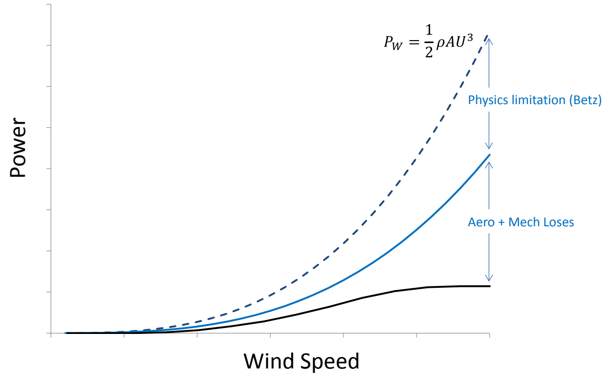

Figure 3. Wind power curves.

The energy production from a wind turbine is determined from the product of instantaneous power and time. Depending on the available wind speed information the expected energy production can be estimated using direct or statistical methods. Wind data is typically gathered over a long-period of time (e.g., a year) and averaged over time intervals Δt. In the presence of wind data, the energy estimate can be obtained as

$$E = \sum_{i=1}^{N} P_o(U_i)\Delta t\ , \qquad (3)$$

where N is the total number of wind speed observations each averaged over a time interval Δt.

An accepted practice, if only mean wind speeds and standard deviations are available, is to assume that the wind speeds follow a Weibull statistical distribution. Using this approach, the gross expected energy production over a period of time t is given as

$$E = \bar{P}_O t, \qquad (4)$$

where the average wind output power for a given wind turbine is given as [5]

$$\bar{P}_O = \int_0^\infty P_O(U) p(U) dU. \qquad (5)$$

The total number of hours to estimate the energy production in a year is t=8,760 hours. The average power in (5) is a function of the output power evaluated at wind speed U and the probability density function for the wind resource. As shown in the literature, (5) can also be re-written as

$$\bar{P}_O = \int_0^\infty P_O(U) dF(U), \qquad (6)$$

where the Weibull cumulative density function is given as [5]

$$F(U) = 1 - e^{\left[-\left(\frac{U}{c}\right)^k\right]}. \qquad (7)$$

The factors c and k in (7) are the well-known Weibull scale and shape factors, respectively. The shape factor can be approximated as [5]

$$k = \left(\frac{\sigma_U}{\bar{U}}\right)^{-1.086}, \qquad (8)$$

where $\bar{U}$ and σ_U are the mean value and standard deviation of the wind speed. Similarly, the scale factor can be estimated as [5]

$$c = \bar{U}\left(0.568 + \frac{0.433}{k}\right)^{-\frac{1}{k}}. \qquad (9)$$

The integral in (6) is usually approximated as a summation

$$\bar{P}_O \cong \sum_{j=1}^{N_B}\left[F(U_j) - F(U_{j-1})\right]P_O\left(\frac{U_j+U_{j-1}}{2}\right), \tag{10}$$

where the integral is substituted by a summation of discretized N_B wind speed bins. The term in brackets in (10) represents the probability that a wind speed between U_{j-1} and U_j will be present in a given site. In this project a bin size of 1 meter-per-second was assumed.

A typical measure of the energy production for a given turbine in a specific site is the gross capacity factor

$$CF = \frac{E}{E_{rated}}, \tag{11}$$

where E_{rated} assumes that the turbine is operating at its rated power through the entire time span. The gross *CF* in (11) does not consider typical energy losses from array impacts, availability, or inefficiencies in power collection and transmission. The net capacity factor is given as

$$CF_{net} = \frac{E_{net}}{E_{rated}}, \tag{12}$$

where E_{net} is the reduced energy production due to the expected losses. The losses for land-based projects could be estimated in the range of 17% while this number increases to 18% for offshore projects [14].

IV. COST OF WIND ENERGY

An accepted practice to quantify the cost of wind energy production is to calculate *LCOE* (i.e., in \$/kWh). The *LCOE* has been widely used by the DOE to evaluate the cost of energy generation projects. *LCOE* includes initial capital costs and operational costs. It is important to mention that *LCOE* does not include transmission expenses, the expenses of integrating wind power into the grid, or indirect environmental costs [15]. Therefore, the final cost to the end consumer will be higher than the *LCOE*.

LCOE represents the cost per-kilowatt-hour (kWh) of building and operating the energy generation plant by equating the financial life to the lifetime of the system. For wind energy projects this is typically a 20-year lifespan. The approach to calculate the *LCOE* in this project has been taken from a recent NREL report and is calculated as [16]

$$LCOE = \frac{(FCR \times ICC) + AOE}{(8760 \times CF_{net})}, \tag{13}$$

where *FCR* is the fixed charge rate, *ICC* is the initial capital cost in \$/kW, *AOE* is the annual operating expenses in \$/kW per year. Notice in (13) that *ICC* and *AOE* are normalized by the size of the wind turbine (i.e., the rated power) and is given in \$/kW.

The *FCR* represents the amount of revenue per dollar of investment that must be collected each year to pay the carrying charges such as return on debt and equity, income and property tax, book depreciation, and insurance [17]. The *FCR* has been recently estimated for offshore wind energy projects with 20-year lifespans in the U.S. as 11.8% [14].

The *ICC* considers the contribution of the turbine system cost, the balance of station costs, and additional "soft" costs in constructing a wind energy project. Table 1 shows a typical percentage breakdown of the installed costs for an offshore wind energy project. As can be observed in the table, a significant portion of the initial costs in an offshore wind turbine project goes to the balance of station sub-components.

Estimation of *ICC* is simpler in the presence of an extensive history of similar projects. This is the case for land-based wind turbines in the U.S. where more than 40,000 MW of wind capacity has been installed at the end of 2010 [16]. However, due to the lack a single completed offshore wind energy project in the U.S., the available estimates carry a greater level of uncertainty. NREL developed an estimate for offshore wind energy projects based on a parallel assessment of (1) global market data, (2) published literature, and (3) interviews with active offshore wind energy developers in the U.S. Using this information, the reference average *ICC* for large (i.e., > 50 MW) fixed-bottom U.S. projects in 2011 was estimated to be \$5,600/kW (with a range between \$2,500/kW-\$6,500/kW) [13].

The *AOE* for offshore wind projects in the U.S. include three major categories: (1) levelized replacement cost (i.e., expected costs of replacing major components); operations and maintenance (O&M) such as labor, vessels, equipment, scheduled/unscheduled maintenance, onshore support, project administration, etc.; and (3) outer continental shelf (OCS) lease payments to the Bureau of Ocean Energy Management. NREL estimated average *AOE* to be \$107/kW [14].

Table 1. Table 1. ICC break-down for fixed-bottom offshore wind turbines [14].

Cost Component	Cost Sub-Component	%
Turbine System	Rotor, Nacelle, Tower, etc.	32
Balance of Station	Assembly, Transportation, and Installation	20
	Electrical Infrastructure	10
	Port and Staging	1
	Support Structure	18
	Project Management	2
	Development	1
Soft	Insurance	2
	Bond	3
	Contingency	8
	Construction and Finance	3

V. OFFSHORE WIND FARM IN PUERTO RICO

As shown in (13), the *LCOE* for a given site is highly dependent on the wind resource characteristics of the site through CF_{net}. For this study we will reference to the wind resource assessment in [6]. The study was part of a collaborative effort between the DOE/NREL Wind Powering America Program, AWS Truewind and the Commonwealth of Puerto Rico. The study considered a comprehensive modeling and validation process that led to the development of detailed wind resource maps with a special resolution of 200 m. The modeling component included the use of a numerical weather model with climatic data and a wind flow model to produce preliminary maps. The preliminary maps were validated to determine 50-m annual average wind resource maps using available high quality data. The final maps were the result of a revision of the preliminary maps with the validation results. The study also included 70-m and 100-m maps that were extrapolated from the validated 50-m maps. Besides showing wind resource maps with average wind speeds at different heights, the study concluded that Weibull shape factors in PR are in the range of k=2.5 to k=3.5. As shown in (10), the Weibull factors are extremely useful to estimate the wind energy production.

Figures (4) and (5) show the wind speed maps at 70-m and 100-m. As shown in Figure (4), offshore wind speeds were estimated in the 7.0 m/s to 9.0 m/s range at a 70-m height. Figure (5) shows even better average wind speeds at 100-m height. At similar heights, the estimated average wind speeds in the location of the existing wind farms in Santa Isabel (southern shore of the Island) and Naguabo (eastern shore of the Island) are in the 5.5 m/s to 6.5 m/s range. For the sake of comparison, since wind power varies proportional to the cube of the wind speed, an offshore wind turbine in PR could more than double the generated wind power versus an on-shore turbine. Furthermore, since offshore winds generally blow more strongly and consistently than onshore winds, offshore wind turbines operate at higher capacity factors than in-land turbines. Similarly, offshore wind speed profiles tend to be higher during the day and correspond better to periods of high electricity demand [11].

Current offshore wind turbine technology requires the turbines to be placed in relatively shallow waters. This depth requirement seeks the turbines to be placed in waters less than 30-m deep [5]. Figures (6) and (7) shows a modified map with the 70-m wind speed date that only considers the shallow water region in the surroundings of PR. The wind speed contours in the figures are for the water region that has a depth less than or equal than 30-m. In particular, the contoured area in the eastern offshore portion of the Island (i.e., in the ocean area within the main island and the smaller islands Vieques and Culebra) comprehends approximately 900 km^2.

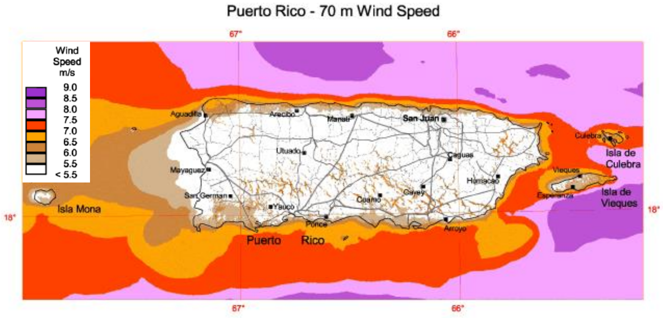

Figure 4. Wind speed map at 70-m [6].

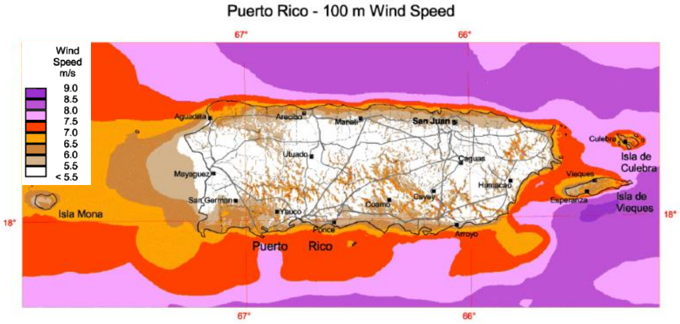

Figure 5. Wind speed map at 100-m [6].

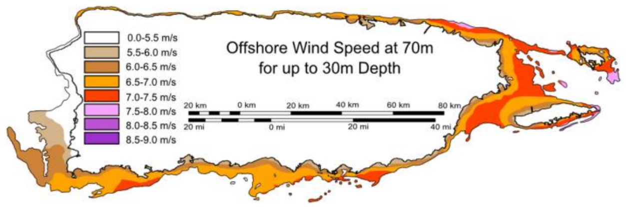

Figure 6. 70-m offshore wind resource map in the shallow water region.

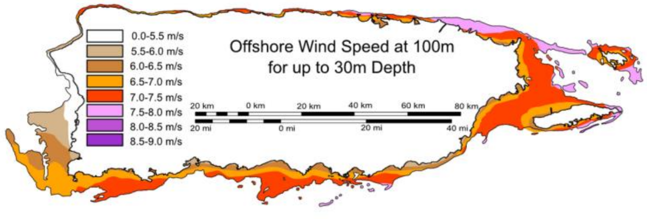

Figure 7. 100-m offshore wind resource map in the shallow water region.

VI. RESULTS

The present study considers the installation of a wind farm in the eastern offshore region of the Island. The study compares the performance of three typical offshore wind turbines with nominal power capacities of 2,300 kW, 3,000 kW, and 3,600 kW. The selected turbines are similar to the ones referenced in [17], [18], and [19]. Typical output power curves for these turbines are shown in Figure (8). The power generation from wind turbines will be maximized when the wind speeds reach or exceed their rated wind speeds (i.e., required wind speed to obtain the rated output power). As shown in Figure (8), the power curves for all three systems indicate rated wind speeds above 10 m/s.

The analysis for energy production and *LCOE* considered the offshore regions where the average wind speeds at 70-m is in the 7.0-7.5 m/s range as shown in Figure (6). In the analysis, these wind speeds were extrapolated to a 90-m hub height (i.e., typical for offshore wind energy applications) using the power law [5] with a wind shear exponent α=0.14 as recommended for normal offshore operation in [10]. Therefore, the expected average wind speeds at 90-m will be in the range of 7.25-7.77 m/s.

Comparison of the power curves with the estimated average wind speeds in the offshore region in PR indicate that the available wind speeds are significantly lower than the typical rated wind speeds in the offshore wind turbines in Figure (8). As indicated in Section III in this article, an accepted practice to determine the energy production from wind turbines is to assume that the wind speeds follow a Weibull statistical distribution. In our case, the analysis considered a wind speed variation following a Weibull distribution with shape factors in the range of *k*=2.5 to *k*=3.5 as recommended in [6].

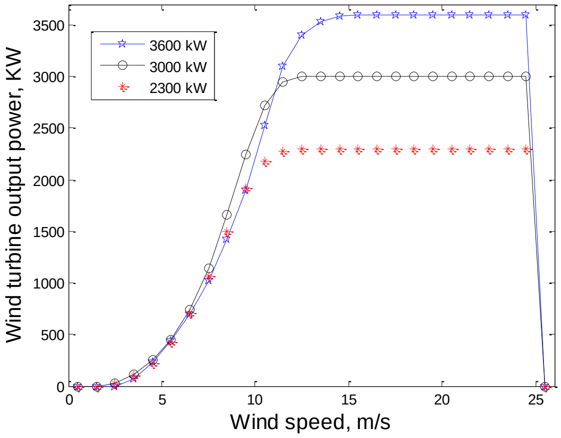

Figure 8. Power curves for considered cases.

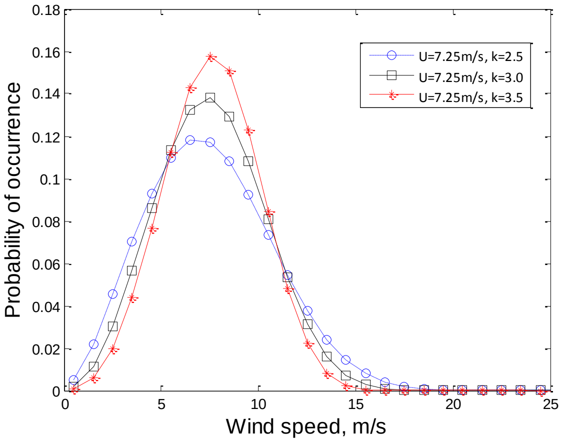

Figure 9. Weibull wind speed distributions for different shape factors.

Figure (9) shows the probability of occurrence for different wind speeds when the average wind speed is 7.25 m/s (i.e., lower bound of expected wind speed) and the Weibull shape factor varies from *k*=2.5 to *k*=3.5. As shown in the results, a smaller shape factor results in a greater spread of the wind speed range and therefore an increase probability of reaching the rated power during operation (i.e., wind speeds greater than the corresponding rated speed of the wind turbine). Conversely, assuming a shape factor *k*=3.5 results in a conservative assessment of energy production.

The wind speeds assuming the Weibull distribution and in combination to the power curves in Figure (8) are used then to estimate the net capacity factors using equation (12). The analysis considered average wind speeds in the 7.25-7.77 m/s range and Weibull shape factors in the 2.5-3.5 range. As shown in equation (13), the capacity factor is an important parameter for the calculation of net output power and hence the *LCOE*.

Figure (10) illustrates the variation in net capacity factors for the three turbines as a function of average wind speed and shape factor. As shown in the figure, the best capacity factors are for the wind turbine with the lowest rated power. This result is mainly due to the relative low average wind speed (i.e., 7.25-7.77 m/s) in comparison to the rated speeds for the considered wind turbines (i.e., above 10 m/s). As can be inferred from Figure (8), all three machines generate similar output power in the low-speed regime (i.e., below 10 m/s). Therefore, the energy generation for the three considered wind turbines will be similar. The capacity factor, for a given wind turbine, involves a normalization of the energy generation with respect to its maximum energy generation (i.e., at rated power). Therefore, a smaller machine will result in a larger capacity factor. Figure (10) also indicates that the difference

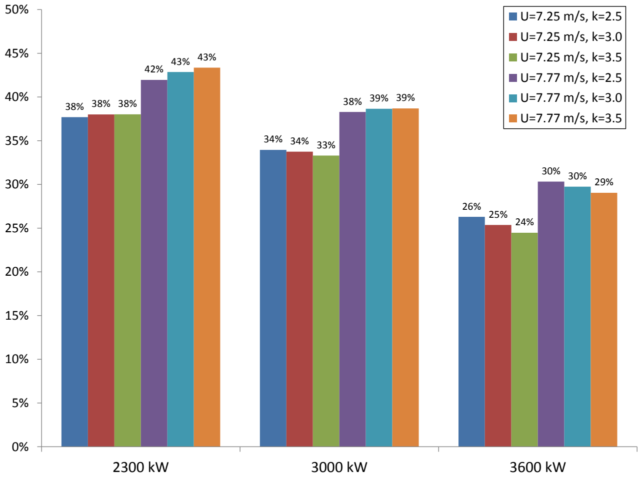

Figure 10. Net capacity factors.

in the results for the different Weibull shape factors is negligible.

Figure (11) shows the *LCOE* for the three studied wind turbines at the minimum (i.e., 7.25 m/s) and maximum (i.e., 7.77 m/s) average wind speeds. The results in Figure (11) show that the expected *LCOE* in the studied range is as low as \$0.20/kWh and as high as \$0.36/kWh. The results suggest that the turbine with the lowest capacity will results in a lower *LCOE*. The results in Figure (11) are a direct consequence of the effect of net capacity factor on *LCOE*. Therefore, in the case of Puerto Rico, where the mean wind speeds at 90-m is in the range of 7.25-7.77 m/s, a smaller wind turbine will be more cost effective than a larger machine.

VII. CONCLUSIONS

The proposed analytical model was successfully used to compute the wind power and *LCOE* for the eastern offshore region in Puerto Rico. The study also includes the results of the bathymetry of the region to show potential shallow-water areas where the installation of offshore wind turbines is possible. This study revealed that the eastern offshore region has an approximate area of 900 km^2 with shallow depth (i.e., less than 30m) that can be used for offshore wind power.

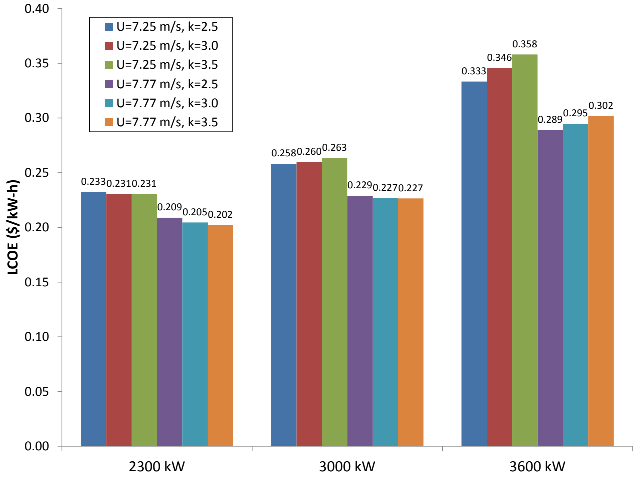

Figure 11. *LCOE* results.

The *LCOE* calculations considered three typical offshore wind turbines with capacities of 2,300 kW, 3,000 kW, and 3,600 kW. The analysis considered a reference average *ICC* of \$5,600/kW, average *AOE* of \$107/kW, array losses of 18%, and a *FCR* of 11.8% [13]. The results for the studied configurations indicated that the *LCOE* for offshore wind energy could be as low as \$0.20/kWh for the 2,300 kW machine and as high as \$0.36/kWh for the 3,600kW turbine. The results indicate that, in the case of Puerto Rico, the smaller the wind turbine the lower the *LCOE*. Since the mean wind speeds in Puerto Rico are in the low side of operation for current offshore wind energy technologies, a smaller machine will result in a higher net capacity factor and therefore a lower *LCOE*.

In terms of the economic assessment, the *LCOE* is closer to the cost of energy to the wind power provider than to the end consumer. *LCOE* omits costs such as transmission expenses, integration of wind power to the grid, and various indirect costs [14]. Therefore, including the additional costs to produce offshore wind energy, the expected end cost of energy due to offshore wind energy production in Puerto Rico could reach similar to the current cost of energy in the Island. Therefore, it is unlikely that offshore wind energy is a viable near term option to the solution of the energy crisis in Puerto Rico. However, the potential of offshore wind energy as a long term alternative comes along with the recent interest of the U.S. in developing the offshore wind energy industry. The DOE's strategic roadmap for offshore wind energy seeks to develop an offshore wind industry able to achieve 10GW of offshore wind energy at a cost of energy of \$0.10/kWh by the year 2020 and over 50GW at a cost of energy of \$0.07/kWh by the year 2030 [20]. Therefore, offshore wind energy may become a viable alternative in the next decade in Puerto Rico.

Not included in the analysis and matter of future work includes the consideration of environmental and social impacts in the development of an offshore wind farm in PR. Additional research has to be done in order to verify the depth and composition of the sea bottom as well as maritime, aerial and avian migration routes. Similarly, the effect of inclement weather (i.e., hurricane conditions) and seismographic activity (i.e., earthquakes) will need to be evaluated further to complement the results in the preliminary cost assessment in this work.

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