ELECTRICITY GENERATION AND WIND POTENTIAL ASSESSMENT IN REGIONS OF COLOMBIA

GENERACIÓN ELÉCTRICA Y EVALUACIÓN DEL POTENCIAL DE ENERGÍA EÓLICA EN REGIONES DE COLOMBIA

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Received for review April 26 th, 2011, accepted July 1th, 2011, final version July, 27 th, 2011

ABSTRACT: In this work, mathematical modeling and simulation of electricity generation from wind was carried out in regions which are not connected to the national electrical system grid, and have an annual mean wind velocity higher than 4 m/s at an altitude of 10 m. Seven different types of power turbines between 6 and 2,750 kW were studied in order to analyze their technical and economic feasibility. The Gachaneca (Boyaca) and the Sesquicentenario (San Andres Island) stations have an energy potential of 5,106 and 3,823 MWh/year, respectively, using a 2,750 kW turbine at an altitude of 70 m. The production cost of kWh for the two regions was found to be less than US$0.10 for turbines with a capacity higher than 1.0 MW. The energy produced can satisfy the electricity needs of Colombian islands such as San Andres or Providencia.

KEYWORDS: wind energy, renewable energy, wind potential

RESUMEN: En este trabajo, modelación y simulación matemática de la generación de electricidad a partir del viento fue realizado en regiones que no están conectadas al sistema eléctrico nacional, y tienen velocidad promedio anual mayor que 4 m/s a una altitud de 10 m. Siete diferente tipo de turbinas de potencia entre 6 y 2,750 kW fueron estudiadas para analizar su factibilidad técnica y económica. Las estaciones de Gachaneca (Boyacá) y Sesquicentenario (Isla de San Andrés) tienen un potencial de energía de 5,106 y 3,823 MWh/año, respectivamente, usando turbina de 2,750 kW a una altitud de 70 m. El costo de producción de kWh para dos regiones fue encontrado ser menor que US$0.10 para turbinas con capacidad mayor a 1.0 MW. La energía producida puede satisfacer las necesidades eléctricas de islas Colombianas, como la de San Andrés o Providencia.

PALABRAS CLAVE: energía eólica, energía renovable, potencial eólico

1. INTRODUCTION

The use of fossil fuels (e.g., oil and coal) as an energy source has many negative environmental impacts, such as the release of pollutants and resource depletion. A high consumption rate of fossil-fuels will result in an increase in environmental pollution during the next century, due to the emission of CO_2 and other gases that cause global warming through what is known as the greenhouse effect [1,2]. In order to reduce CO_2 emissions and oil dependency, each country in the world is responsible for improving the quality of its energy sources. If possible, each country could start to replace a percentage of consumption of fossil fuels (coal and oil) with renewable alternatives such as wind and solar energy. Colombia has to make meaningful decisions in relation to its energy sector for remote regions and islands where the national electrical grid fails to cover. This is due, among other reasons, to geographical factors, the lack of infrastructure for electricity distribution, and social problems [3]. Colombia has abundant coal and hydroelectric potential, limited gas reserves, and crude oil, along with important solar and wind energy resources [4,5]. How to make efficient use of these resources is a strategic question that needs to be answered within the context of climate change, reduction in CO_2 emissions, and sustainable development.

Before proceeding with the installation of a renewable wind energy system, and in order to analyze the competitiveness and environmental impact of the wind power in terms of fossil fuels, it is necessary to conduct research based on the mathematical modeling, simulation, economic study, and potential reduction of CO_2 emissions [6]. Countries with high growth in solar and wind power, like Algeria and Australia, have conducted mathematical modeling studies before proceeding to construct and install renewable energy systems. Algeria proposes exporting 6,000 megawatts of solar electricity to Europe by the year 2020 [7].

In Latin America, research and development programs on renewable sources of energy are limited. Brazil and Venezuela have carried out simulations of hydrogen production from renewable sources: including hydroelectric and solar [8–11]. Meanwhile, in Colombia, the development of wind and solar energy is minimal and is represented respectively by the wind farm Jepirachi [12] and small systems of photovoltaic cells [13,14] with a capacity of 2 MW. Pinilla et al. [12] present some technical details and lessons learned on the effect of high temperature, in small electronic control circuitry, that caused the uncontrolled and frequent stoppage of turbines.

The main objective of this work is to model and simulate the wind energy potential in remote regions and islands of Colombia. This mathematical model permits us to analyze the effect of the type and height of a turbine on electricity generated by wind.

2. INFORMATION AND ANALYSIS OF WIND DATA

Colombia is located in South America. It has a land surface of 1.141.748 km^2 and a population of 45 million inhabitants, according to the last population census recorded [15]. The regions selected have different topographies and are located in different points in Colombia. San Andres and Providencia are islands on the Caribbean sea of Colombia, at an altitude of 1 m, that are not connected to the national electrical system grid and have had a high increment in population in the last decade. The Guajira peninsula is located in the north zone of Colombia, on the Caribbean Sea. Huila and Boyaca are situated in the center of the country at an altitude of 1,475 m and 2,600 m, respectively. Nariño is located in the south-west at an altitude of 2,710 m.

The wind speed and direction were measured using an anemometer. The data was obtained each hour at 10 m of altitude during the 1987/2001 period by the Institute of Hydrology, Meteorology, and Environmental Studies in Colombia (IDEAM). Table 1 shows the geographical coordinates and an annual mean wind speed of the meteorological stations [16].

Figure 1 demonstrates that the wind speeds in all the stations presented the same behavior, with maximum values in June/July and minimum values in October. For example, the Gacheneca station has a maximum value of 6.7 m/s in June and July, and the Almirante Padilla station has a minimum value of 2.93 m/s in October. This behavior in Colombia is due to variations of climatology and relief [17]. Also, it is due to the circulation of the *Alisios wind*, caused mainly by the unequal heating between the equatorial zone and the rest of the planet. This type of wind is intensified during the period of June to August because of a high incidence of solar radiation that increases the heating of the earth.

Table 1. Geographical coordinates of the meteorological stations.

Station name	Department	Coordinates		Altitude (m)	Annual mean wind speed (m/s) at a height of 10 m
		Latitude	Longitude		
Gachaneca	Boyaca	5°26'	73°33'	2375	5.51
Sesquicentenario Airport	San Andres Island	12°35'	81°43'	1	4.99
La Legiosa	Huila	3°20'	74°44'	1475	4.15
El Embrujo Airport	Providencia Island	13°22'	81°21'	1	3.97
Almirante Padilla Airport	Guajira	11°32'	72°56'	50	3.8
Villa Carmen	Boyaca	5°32'	73°30'	2600	3.96
Obonuco	Nariño	1°11'	77°18'	2710	3.59

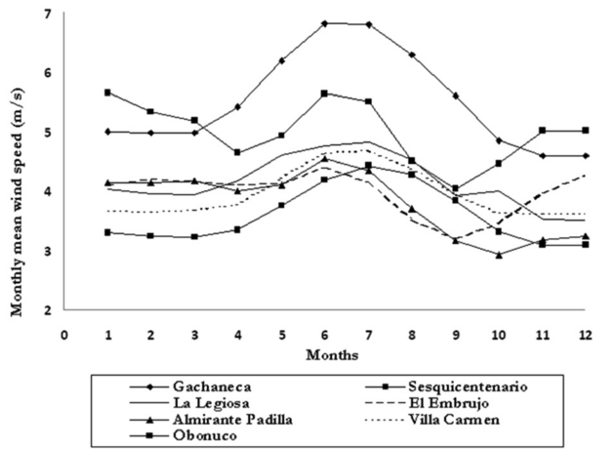

Figure 1. Monthly variation of wind speed for each Colombia region at 10 m altitude

2.1 Weibull Distribution and Annual Energy Output from a Wind Turbine

The Weibull function describes the general pattern of wind speed variations [18–19]. It is very important to the wind industry for designing wind turbines. This distribution is characterized by two parameters: the shape parameter (α) (dimensionless) and scale parameter (β, m/s), deduced from the experimental wind data.

The cumulative distribution function for the Weibull distribution is:

$$W(v) = 1 - e^{-\left(v/\beta\right)^{\alpha}} \quad (1)$$

The parameters are calculated by mean linearization of Eq. 1 using natural logarithms as described below:

$$\ln[-\ln[1 - W(v)]] = \alpha \ln v - \alpha \ln \beta \quad (2)$$

The wind speed is extrapolated to a different height with the *Lysen* profile [20], Eq. 3; after the parameters of Weibull function are calculated again for each height chosen.

$$v(h) = \frac{v(h_r) \times \ln\left(\frac{h}{h_0}\right)}{\ln\left(\frac{h_r}{h_0}\right)} \quad (3)$$

where $v(h_r)$ is the wind speed at reference altitude (h_r) and parameter h_0 is the ruggedness longitude. The parameter h_0 depends principally on the elevations of the earth's surface as described by Lysen (1983). The elevation type on the earth surface of each zone where the station was localized was given by the Geographical Institute of Colombia Agustin Codazzi.

The Weibull probability density function [21], $F(v)$, is used to calculate the electric energy (E) produced by the turbine over the period of a year; using Eq. 4.

$$E = N_h \int_{vm}^{vM} P_{wind}(v) g(v) F(v) dv \quad (4)$$

where P_{wind} is the wind potential and $g(v)$ is the efficiency curve of the turbine given by the manufacturer, N_h is the number of hours over the year, and *vm* (cut in wind speed) and *vM* (cut off wind speed) are the minimum and maximum mean air speeds at which the turbines generate electricity. The wind potential per area unit perpendicular to the wind stream is calculated using the following relationship:

$$P_{wind} = \frac{1}{2} \rho \bar{v}^{-3} \quad (5)$$

where the standard of air density is ρ and $\bar{v}$ is the mean wind speed.

2.2 Turbine Characteristics

The wind turbine converts mechanical energy into electrical energy. Generally, these generators provide electric power of between 6 and 2,750 kW. Table 2 shows the characteristic properties of wind turbines used in this work. The efficiency curve indicates that turbines generate electricity from low values of wind speed (*vm*). The converted wind electricity quickly increases, then it takes its maximum value at the nominal wind speed (*vn*) and this slowly decreases for higher wind speeds until reaching the value of *vM* at which the turbines can continue to work without any risk of destruction.

3. RESULTS AND DISCUSSIONS

3.1 Annual Energy Output from a Wind Turbine

The annual energy output is estimated by using Eq. 4 for the turbines given for each of the regions selected. The results are shown in Fig. 2 for Gacheneca (Boyaca), the Sesquicentenario (San Andres Island), and El Embrujo (Providencia Island) stations. The annual mean energy increases with the increasing of the height and the turbine capacity for all regions. The yearly energy production for a small turbine (6 kWh) is low since it lies between 400 and 6,400 kWh/year while the bigger turbines (2,750 kWh) produce approximately 350 times more.

Figure 2 indicates that energy production is according to the wind profile of each region. For example, the Gacheneca (Boyaca) and the Sesquicentenario (Island of San Andres) stations present the highest mean annual energy output with 5,106.02 and 3,828.07 MWh/year at an altitude of 70 m, respectively; while El Embrujo station (Island of Providencia) has the lowest mean annual energy output with 1,899.92 MWh/year. The previous results were obtained for the turbine NEG Micon 2,750 kW.

Annual energy production in different regions of Colombia is similar to those obtained in other countries with a turbine of the same type and of a similar height and with a similar wind profile. For example, the Sirocco turbine produces 14,550 and 11,020 kWh/year in the Boyaca and San Andres regions respectively, while regions of Algeria such as Tindouf and Tamanrasset produce approximately 10,000 kWh/year [22].

Figure 3 indicates the energy produced by each mean wind speed considering its annual frequency for two turbines (Turbine 1: 300 kW and Turbine 2: 2750 kW) and three stations. All stations present low wind energy for a wind speed below 3 m/s (a typical cut in wind speed for the turbines). Stations like Sesquicentenario and Almirante Padilla of intermediate and low wind speeds, present the energy bulk in wind speeds between 4 and 9 m/s, and a maximum annual energy at wind speed of 7 m/s for both turbines; in these stations, the wind speed profile matches the characteristics of the two turbines. The Gachaneca station presents the energy bulk between 5 and 12 m/s, and it has maximum of annual energy at wind speeds of 8 and 10 m/s for turbines of low and high power, respectively; in this station, the wind speed profile matches the characteristics of the high-power turbine.

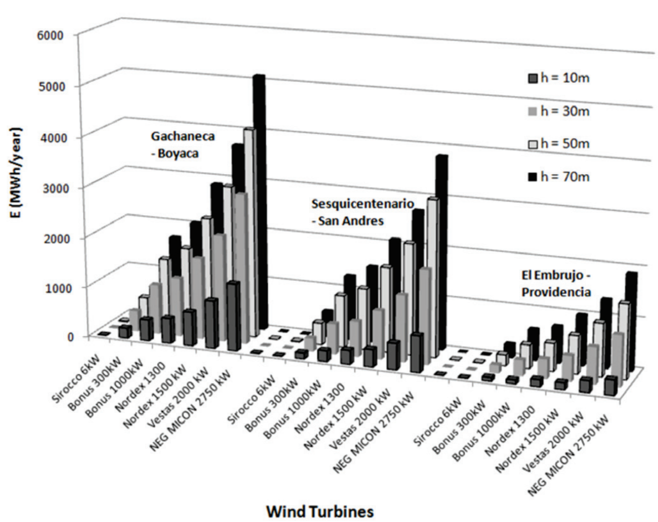

Figure 2. Annual mean energy at Gachaneca, Sesquicentenario, and El Embrujo stations using seven different turbines

Table 2. Characteristics of the selected wind turbines

Turbine model	Eoltec Sirocco 6kW	AN Bonus 300kW	AN Bonus 1000 kW	Nordex N60 1300 kW	Nordex s70 1500 kW	Vestas v80 2000 kW	NEG Micon 2750 kW
Rated power (kW)	6	300	1,000	1,300	1,500	2,000	2,750
Hub height (m)	30	30	50	60	70	60–100	70
Rotor diameter (m)	5.6	33.4	54.2	60	70	80	92
Swept area (m^2)	24.7	876	2,300	2,828	3,848	5,027	6,648
Number of blades	2	3	3	3	3	3	3
Cut in wind speed, *vm* (m/s)	4	3	3	3	3.5	4	4
Nominal wind speed, *vn* (m/s)	12	14	15	15	13	15	14
Cut off wind speed, *vM* (m/s)	25	25	25	25	25	25	25
Price (US$)	39,739.8	1,086,222	1,390,894	1,722,060	1,589,593	2,119,458	3,973,984

3.2 Cost Analysis

Over the last 10 years, wind systems have resulted in a drop in the cost of electricity. These costs continue diminishing as more plants, larger plants, are built and advanced technology is introduced. Also, selection of a suitable site with high wind velocity is a key for the economics of wind energy. In general, a wind speed exceeding 5 m/s is required for cost-effective application.

The economic factor is important for determining the viability of wind energy. The cost of electricity by kWh produced for each turbine in all regions is shown in Fig. 4, and it was calculated from the present value of costs (PVC). The assumptions for calculating the PVC of electricity are similar to those used by Alnaser [23], Habali et al. [24], and Ahmed and Hanitsch [25-27]. Investment (I) includes the turbine price plus its 20 %. The operation maintenance and repair costs (C_{om}) were considered to be 25% of the annual cost of the turbine (machine price/lifetime). The interest rate (r) and inflation rate (i) were taken to be 10 % and 7 %, respectively. Scrap value (S) was taken to be 10 % of the turbine price, and the lifetime of the machine (t) was assumed to be 20 years. The PVC is calculated by using Eq. 6, and the electricity cost per kWh is obtained by dividing the PVC by the total kWh produced for each wind turbine over its lifetime, see Fig. 4.

Figure 4 shows that the cost of each kWh for all stations decreases by increasing the turbine rated power until the 2,000 kW turbine (Vestas v80); this result indicates that the 2,000 kW turbine is more appropriate for the zones studied. Also, the maximum costs of kWh were obtained at Obonuco station for all turbines due to the low wind speeds.

$$PVC = I + C_{om}\left[\frac{1+i}{r-i}\right]x\left[1-\left(\frac{1+i}{1+r}\right)\right]-S\left(\frac{1+i}{1+r}\right)^{t} \qquad (6)$$

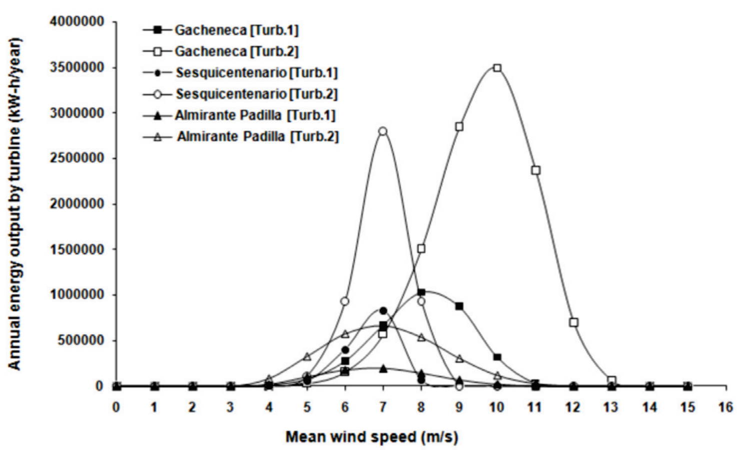

Figure 3. Energy output by turbine as function of mean wind speed at 70 m

The minimum cost of producing each kWh of electricity using a 2000 kW wind turbine was US $0.037 at Gacheneca while the maximum was US$0.134 at Obonuco. The minimum cost of electricity produced using a 1,300 kW wind turbine was US$0.050 /kWh at Gachaneca while the corresponding maximum cost was US$0.196 kWh at Obonuco. It is recommended to make a cost analysis with several turbines of capacity higher than 2750 kW for finding the optimal minimum cost. The cost results are similar to those [28] obtained in other countries with similar wind profiles and using turbines of the same power capacity ratings.

Figure 5 indicates that the payback periods for Gachaneca and Sesquicentenario stations were found to be less than the lifetime of the machine. On the other hand, the payback periods for the other regions were higher than 20 years.

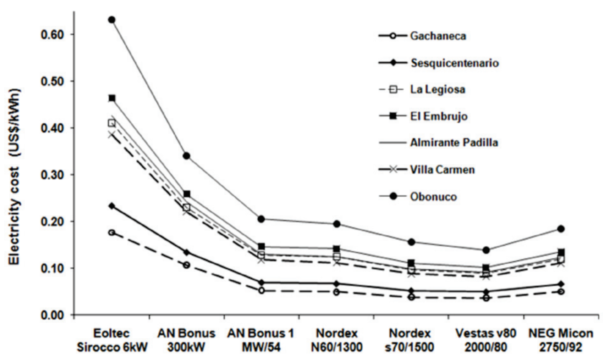

Figure 4. Cost of wind energy for all stations using seven types of turbines at a height of 70 m

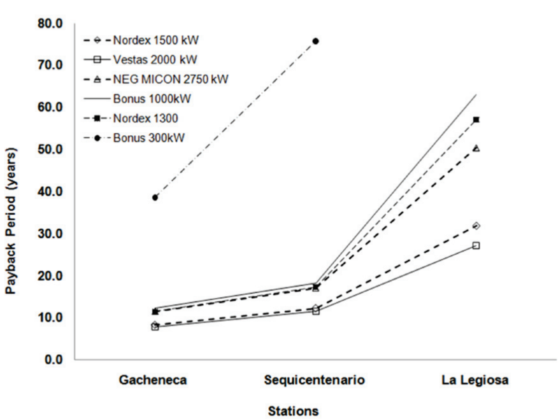

Figure 5. The payback period for turbines located in Gachaneca, Sesquicentenario, and La Legiosa stations

4. CONCLUSIONS

This work is an analysis of the electrical energy produced from wind on islands and in remote regions of Colombia, with the purpose of discovering their potential. The annual mean wind speeds at a height of 10 m were calculated as 5.51 m/s, 4.99 m/s, and 4.15 m/s for Gachaneca, Sesquicentenario, and El Embrujo stations, respectively.

The data observed shows that the maximum wind speeds for all sites are during June/July. The highest potentials in terms of wind energy were estimated at Gachaneca (Boyaca) and Sesquicentenario (San Andres Island), with 5,106 and 3,828.07 MWh/year at 70 m altitude.

The production cost of kWh of electricity in the station with higher annual wind speed, Gachaneca station,—using wind turbines with rated power of 1,000, 1,300, 1,500, 2,000, and 2,750 kW—were 0.053, 0.050, 0.039, 0.037, and 0.050 US$, respectively. Meanwhile, in regions of intermediate annual wind speeds, such as San Andres Island, the cost of each kWh,—using wind turbines with nominal potencies of 1000, 1300, 1500, 2000, and 2750 kW—were 0.070, 0.068, 0.053, 0.050, and 0.067 US$.

The payback periods indicated that the Gachaneca and Sesquicentenario stations are economically viable for the construction of wind parks with turbines of rated power higher than 1000 kW. The payback periods for these stations were found to be less than the lifetime of the machine (20 years) for turbines of power rated higher than 1000 kW. This is compared to the payback periods for other regions, which were higher than 20 years; thus indicating that electricity production from wind is not yet an economical option for various regions of Colombia. It is necessary an appropriate political framework around tax incentives and research to decrease the generation cost and payback period of wind energy, and therefore to make a wind park an economically viable option.

ACKNOWLEDGMENTS

The authors would like to acknowledge the commitment of the personal of Energy Laboratory and to give special thanks to Yeison Venecia and Luis G. Ricardo. The authors also acknowledge the financial support provided by the University of Cartagena to carry out this work (resolution #3555, 2008). Thanks also to the IDEAM institute, which submitted the wind data.

REFERENCES

[1] Veziroglu TN. Hydrogen technology for energy needs of human settlements. International Journal of Hydrogen Energy. 12:99. 1987

[2] Ryde´n Magnus, Lyngfelt Anders. Using steam reforming to produce hydrogen with carbon dioxide capture by chemical-looping combustion. International Journal of Hydrogen Energy. 31:1271–83. 2006

[3] Mantilla, J. M., Duque, C. A., C. H. Galeano., Análisis del esquema de generación distribuida como una opción para el sistema eléctrico colombiano. Rev. Fac. Ing. Univ. Antioquia. 44, pp. 97-110, 2008.

[4] Rodríguez, J., Energía, Sus Perspectivas, Su Conversión y Utilizaciones en Colombia, First ed., Bogotá, 2000.

[5] Ministerio de Minas y Energía. Unidad de Planeación Minero Energética – UPME, 200. Plan Energético Nacional, Contexto y Estrategias 2006–2025. Bogotá D.C. Abril 2007.

[6] Turkenburg, W., Beurskens, J., Faaij, A. P., Fraenkel, I., Fridleifsson, E., Lysen, D., Mills, J., Moreira, L., Nilsson, A., Schaap, W., Sinke, World Energy Assessment. Capitulo 7: Renewable energy technologies. World Energy Assessment. Goldemberg, J. Washington, DC, UNDP pp. 220–272, 2000.

[7] Argelia Exportará energía solar en dos años, ABC.es. Available at: http://www.abc.es/20080728/nacional-sociedad/argelia-exportara-energia-solar-20080728.html, 2008.

[8] Contreras, A., Posso, F., Nejat Veziroglu, T., Modeling and simulation of the production of hydrogen using hydroelectricity in Venezuela. International Journal of Hydrogen Energy. 32, pp. 219–1224, 2007.

[9] De Souza, Hydrogen energy as a possibility of utilization of the secondary energy of brazilian hydropower plant of Itaipu. Proceedings of the 13th world hydrogen energy conference. Beijing, China, pp. 116–21, 2000.

[10] De Lima L, T. Veziroglu, Long-term environmental and socio-economic impact of a hydrogen energy program in Brazil. International Journal of Hydrogen Energy. 26, pp. 39–45, 2001.

[11] Da Silva, E., Marin, A., Ferreira, P., Camargo, J., Apolinario, F., Pinto, C. Analysis of hydrogen production from combined photovoltaics, wind energy and secondary hydroelectricity supply in Brazil. Solar Energy 78, 670–7, 2005.

[12] Alvaro Pinilla, Luis Rodríguez, Rodrigo Trujillo, Performance evaluation of Jepirachi Wind Park. Renewable Energy 34, 48–52, 2009.

[13] Unidad de Planeación Minero Energética (UPME). Plan Energético Nacional 2003–2020, Bogotá, 2003.

[14] Pérez Bedoya, E., Osorio Osorio, J., Energía, Pobreza y Deterioro Ecológico en Colombia: Introducción a las Energías Alternativas. Todográficas. Medellín, Colombia, 2002.

[15] DANE Colombia, Censo General 2005, Resultados Población Conciliada. Available at: http://www.dane.gov.co/daneweb_V09/index.php?option=com_content&view=article&id=307&Itemid=124, 2005.

[16] IDEAM, Databases of wind, solar and hydrological. Available at: http://institucional.ideam.gov.co/jsp/loader.jsf?lServicio=Publicaciones&lTipo=publicaciones&lFuncion=loadContenidoPublicacion&id=993, 2011.

[17] Mesa, O., Poveda, G., Carvajal, L. F.,Introducción al clima de Colombia, First ed., Imprenta Universidad Nacional, Medellín, 1997.

[18] Vogiatzis N, Kotti K, Spanomitsios S, Stoukides M. Analysis of wind potential and characteristics in North Aegean, Greece. Renewable Energy. 29, pp. 1193–208, 2004.

[19] Justus, C., Mikhail Amir. Height variation of wind speed and wind distributions statistics. Geophysical Research Letters. 3 (5), pp. 261–4, 1976.

[20] Lysen H., Introduction to wind energy. Consultancy Services, Wind Energy, Developing Countries (CWD), 82-1, May, 2nd Edition, The Netherlands, pp. 36–47, 1983.

[21] Weibull, W., (1951). A statistical distribution function of wide applicability. J. Appl. Mech.-Trans. ASME **18** (3), pp. 293–297, 1951.

[22] Youcef F., Abd El Hamid, Mohamed Lassaad, Nabila Bouzergui. Comparative simulation of wind park design and siting in Algeria. Renewable Energy. 33, pp. 2333–2338, 2008.

[23] Alnaser W., Assessment of the possibility of using three types of wind turbine in Bahrain. Renewable Energy. 3 (2–3), pp. 179–84, 1993.

[24] Habali S, Hamdan MAS, Jubran BA, Zaid AIO. Wind speed and wind energy potential of Jordan. Solar Energy. 38 (1), pp. 59–70, 1987.

[25] Ahmed, A., Shata, R. Hanitsch., Evaluation of wind energy potential and electricity generation on the coast of Mediterranean Sea in Egypt. Renewable Energy. 31, pp. 1183–1202, 2006.

[26] Ahmed A., Shata, R. Hanitsch., The potential of electricity generation on the east coast of Red Sea in Egypt. Renewable Energy. 31, pp. 11597–1615, 2006.

[27] Ahmed A., Shata, R. Hanitsch., Electricity generation and wind potential assessment at Hurghada, Egypt. Renewable Energy. 33, pp. 141–148, 2008.

[28] Rehman S., Halawani, T., Mohandes, M., Wind power cost assessment at twenty locations in the kingdom of Saudi Arabia. Renewable Energy. 28, pp. 573–583, 2003.