Assessment of Wind Energy Potential for Shanghai, China

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Abstract: - Because of its geographical advantage as a coastal port Shanghai has grown over the past several decades into a major metropolis. In this study, the energy needs of this region and the potential for wind turbines in meeting some of the needed energy are explored. A wind turbine farm, customized for the region, has been designed and modeled. A coefficient of power around 0.5 was realized. An economic analysis has been conducted, and it has been determined that wind power is a viable alternative to other sources of energy in this region. Environmental impact of the wind turbine farm has been assessed. While wind turbine noise and power fluctuations due to wind speed variations were not of major concern, migratory pattern of birds in this area suggests that the location of the wind farms must be carefully chosen.

Key-Words: - wind resources, wind turbine modeling and design, cost of energy, avian and noise issues

1 Introduction

Over the past several decades, Shanghai, China, has grown into a megacity because of its geographical advantage as a coastal port. Due to the growing population and increasing of the urban area, the energy need of the city and the suburbs has also grown. The household electricity consumption was around 1618 kWh per year per household in 2000 [1] and rose to 2480 kWh per year per household in 2004. The total energy consumption in Shanghai is shown in Figure 1.

The sources of energy that are being used to meet the energy needs are depicted in Figure 2. It is seen that much of the energy production relies on fossil fuel plants. The environmental impact of these power plants in terms of pollution and greenhouse gases is significant.

Figure 3 shows the wind power density and a few of the major wind energy plants in China [3]. It is seen that Shanghai's wind resources are equivalent to those regions where wind turbines are already in operation. Table 1 below shows the wind speeds in the Shanghai – Chongming – Beiyan region [4].

2 Wind Turbine Design

Given the good wind potential of the Shanghai region, the feasibility of a wind form made of 750 KW turbines has been explored in this research. The power produced from a wind turbine may be estimated from

$$P_{rated} = \eta_{DT} \cdot C_p \cdot 0.5\rho\left(V_{rated}\right)^3 \cdot \pi \cdot \frac{D^2}{4} \tag{1}$$

Here D is the rotor diameter, η_{DT} is the efficiency of conversion of energy from mechanical energy to electrical power, and C_P is the nominal power coefficient which may be estimated to be 0.5 based on existing commercial wind turbines.

The rated wind speed V_{rated} may be found from the velocity measured by an anemometer at a height of 10 meters as follows.

$$V_{mean} = V_{10m\_height} \cdot \left(\frac{h_{hub}}{10}\right)^{0.143}$$

$$V_{rated} = 1.5V_{mean} \tag{2}$$

The hub height (or the tower height) is assumed to be 1.3 times the rotor diameter D based on industry practice [5, 6]. Given these equations, a preliminary estimate of the hub height and tower height could be established.

A three-bladed rotor configuration was assumed. A root cut out radius of 1 m was assumed, since this gives adequate space in the hub region for the power generator enclosed by the nacelle, and for the pitch control mechanisms.

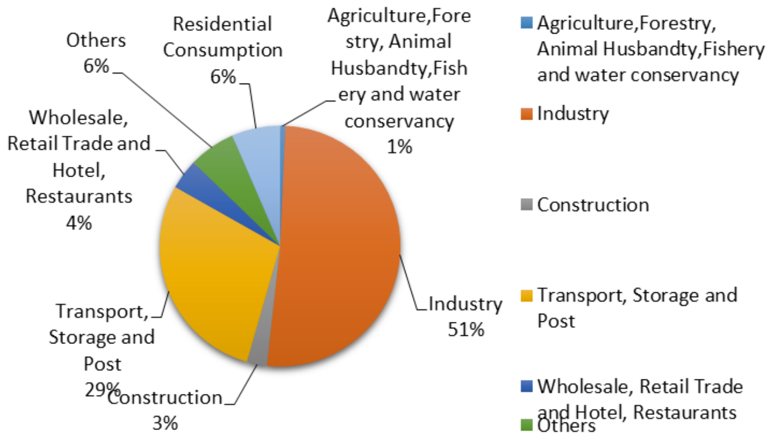

Fig. 1 Total Energy Consumption of Shanghai [2]

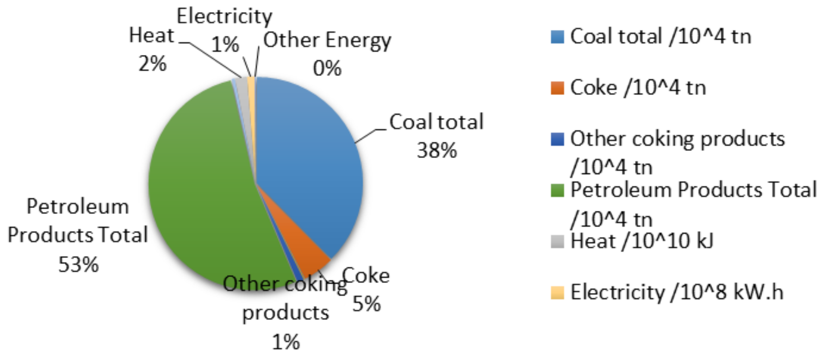

Fig. 2 Energy Sources in Shanghai [2]

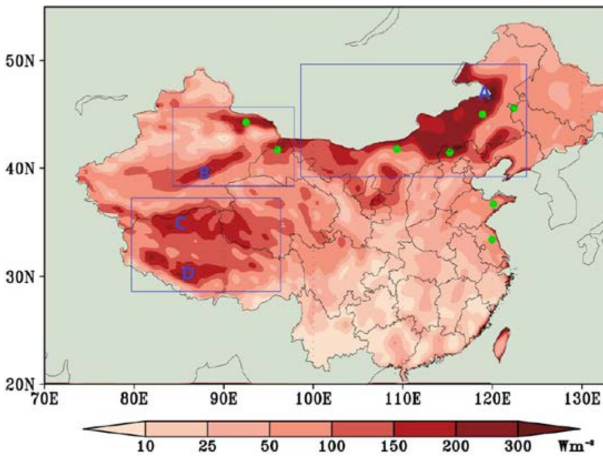

Fig. 3 Distribution of Wind Power Density (Watts per square meter of wind turbine cross section) in China [3]

Table 1 Average Wind Speed Observed in Chong Ming Meteorological Station [4]

Month	The average wind speed in	Available Power at the
May	6.18	208.135
Jun	5.78	166.182
Jul	6.83	298.856
Aug	7.33	379.633
Sep	7.46	401.448
Oct	6.74	285.056
Nov	6.02	189.9
Dec	7.26	368.003
Jan	6.05	193.167
Feb	7.17	353.184
Mar	6.69	277.527
Apr	6.28	220.493

TABLE 2 Preliminary Sizing of a 750 KW Wind Turbine

Rotor Diameter	m	57.6
Hub Height	m	75
Rotor Speed Tip Speed	m/s	65
Rated Wind Speed	m/s	10

TABLE 3 Specification of the Airfoil Family [7]

	r/R	Re. No.	t/c	c_{lmax}	c_{dmin}	c_{m0}
S817	0.95	3.0	0.160	1.1	0.007	-0.07
S816	0.75	4.0	0.210	1.2	0.008	-0.07
S818	0.40	2.5	0.240	1.3	0.012	-0.15

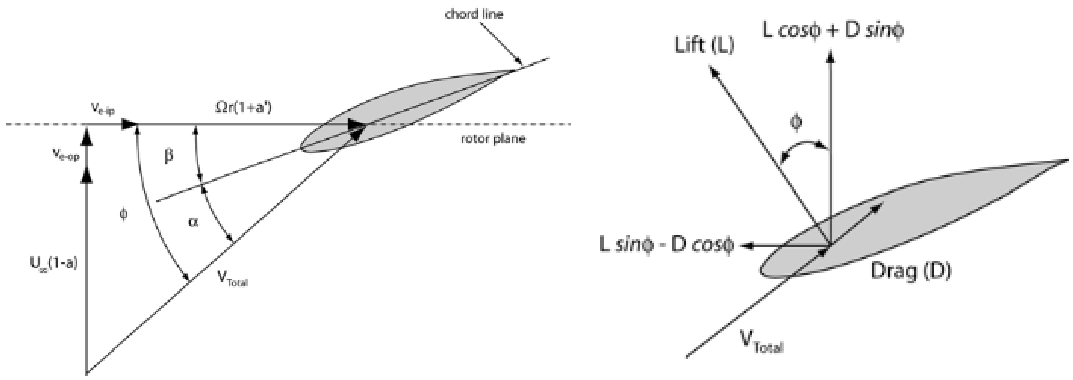

Fig. 4 Local Flow Velocities, Flow Angles, and Sectional Lift [8]

Table 4. Variation of Rotor Blade Chord and Twist along the Radius

r (Meters)	Chord c (Meters)	Twist, degrees	C_L	Angle of attack, □
7.200	3.62	19.072	1.768	9
7.920	3.49	16.866	1.768	9
9.360	3.36	13.306	1.768	9
10.80	3.23	10.573	1.768	9
12.240	3.11	8.418	1.768	9
13.680	2.98	6.680	1.768	9
15.120	2.85	5.250	1.768	9
16.560	2.72	4.055	1.768	9
18	2.60	5.043	1.241	7
19.440	2.47	4.174	1.241	7
20.880	2.34	3.421	1.241	7
22.320	2.21	2.762	1.241	7
23.760	2.08	2.181	1.241	7
25.200	1.96	3.164	0.894	5.5
26.640	1.83	2.702	0.894	5.5
28.080	1.70	2.287	0.894	5.5

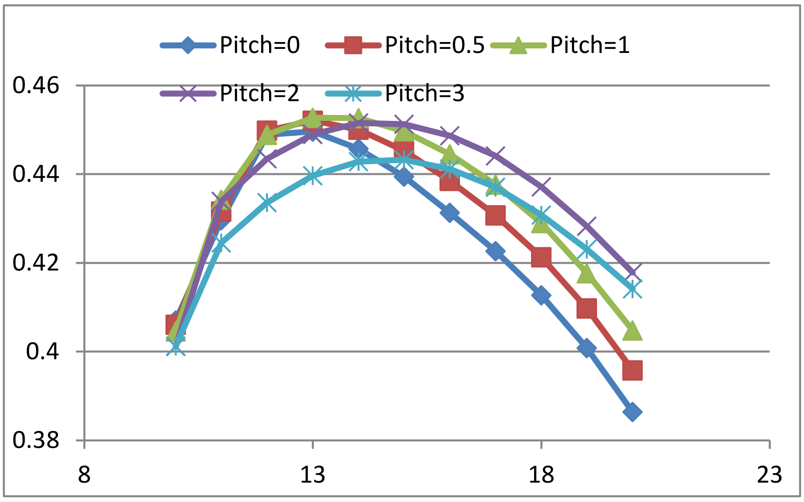

Fig. 5 Variation of Power Coefficient with Tip Speed Ratio at several blade Pitch Angles

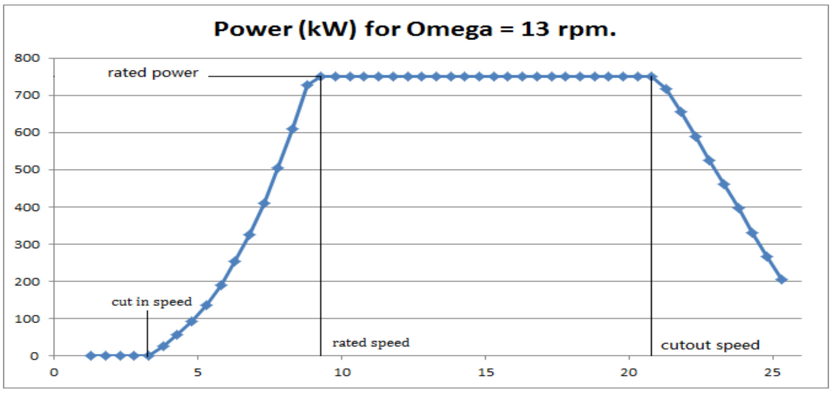

Fig. 6 Variation of Power vs. Wind Speed (m/sec)

Table 5. Breakdown of Component Cost

Component	Cost, in 2002 dollars
Rotor	$ 248,000
Drive Train + Nacelle	$ 563,000
Control System	$ 1,000
Tower	$ 101,000
Foundation	$ 49,000
Transportation	$ 51,000
Road & Civil Work	$ 79,000
Assembly & Installation	$ 51,000
Connection with the Grid	$ 127,000
Permits, Engineering	$ 33,000
Project Uncertainty	$ 162,000
Total	$ 1,465,000

Table 6 Migration Altitude Distribution of the Birds in Chong Ming [10]

Wind turbine	65m
Waders of small size	50-250
Waders of middle size	100-300
Waders of large size	150-400
Egret and heron	150-600
Storks	350-750
Cranes	300-700
Ducks	150-500
Geese including swans	350-12000

A set of airfoils recommended by the National renewable Energy laboratory (NREL) for this class of wind turbines was chosen and placed along the radius as shown in the Table 3.

The next step is to determine the blade chord and twist distribution as a function of radial location. At a given radial location r, the flow properties and the forces acting on the rotor section are shown IN Figure 4.

Here a´ is the swirl induction factor, and is negligibly small. The axial induction factor ‘a’ was assumed to be 1/3, based on Betz analysis of an actuator disk that produces the best power. Since we know axial induction factor, angular velocity Ω, the radial position r, and the wind speed U_∞, we can compute the local flow angle ϕ as follows.

$$tan\emptyset = \frac{U_\infty(1-a)}{U_\infty} \tag{3}$$

At each radial location r, the angle of attack α was chosen so that the lift to drag ratio was maximized, based on measured airfoil lift-drag data for the airfoils shown in Table 3. Knowing the local flow angle ϕ and the angle of attack α, we can find the local blade twist distribution β as follows:

$$\beta = \emptyset - \alpha \tag{4}$$

The local chord at each radial location may be computed by comparing the sectional force normal to the rotor disk, over a radial segment of width dr, from the momentum theory to the corresponding forces from blade element theory. Here B is the total number of blades.

$$dT = B\frac{1}{2}\rho V_{total}^2\left(C_l\cos\varphi + C_d\sin\varphi\right)chord_r dr$$
$$dT = 4\pi r\rho U_\infty^2(1-a)dr \tag{5}$$

The equations above will yield a nonlinear planform where the chord varies nonlinearly with the radial location. A linear regression fit was used to approximate the planform with a trapezoidal planform. Table 4 shows the final design.

3 Performance of the Wind Turbine

Once the rotor was designed, its performance could be analyzed using classical blade element momentum theory. A parametric variation of the blade pitch angle, and wins speed (or alternatively tip speed ratio) was done. Figure 5 shows the predictions for the coefficient of power CP as a function of tip speed ratio, for various blade pitch angles. It is seen that a value of 0.5 was realized over a broad range of wind speeds. This value is representative of commercial wind turbines.
Figure 6 shows the power production. The blade pitch was adjusted so that the generated power never exceeds the rated power of 750 KW.

4 Cost of Energy

Given the rotor diameter, rated power, the hub height the component costs (blade, turbine, tower, foundation) and other costs such as construction, transportation of parts, legal and engineering fees, and the cost of annual maintenance, repair, and overhaul (MRO) may be estimated using a cost model developed at NREL [9] as shown on Table 5. Assuming a cost of financing of 11.5% per year, that includes bank loans and expected return on equity, the annual cost of financing the wind turbine could be estimated.

Assuming a Weibull distribution of the probability of wind speed, the annual energy production for this region was computed as 4400 MW-Hours. The cost of energy based on the annual cost and annual production is 4.72 cents per KW hours in 2002 dollars. Allowing for inflation, the cost of energy in 2018 dollars is 6.8 cents per KW hour. This figure is considerably lower than the nominal cost of 10 cents per KW hour charged by utility companies in the Shanghai region.

3 Environmental Factors

Chongming Dongtan National Birds Nature Reserve is located in the Yangtze River estuary. It is located on the migratory path of birds between East Asia to the central part of Australia. The flight altitude of the various species is listed below in Table 6. For the present design with a hub height of 75 m and rotor diameter of 57.6 m, only waders of small size would be vulnerable to the presence of the turbines. Placing the wind turbines away from ponds and wetlands would reduce the impact of wind turbines on avian population further.

Noise is also an important consideration for large wind turbines. For the class of wind turbines considered here, the nose level drops below 50 dB in areas that are at least 200 meters away from the wind turbine. Thus, noise is not expected to be a major factor.

Finally, power quality is another consideration. It is important to reduce the variations in power production, voltage, frequency and current fluctuations, and various forms of electrical noise (e.g. flicker or harmonic distortion) on the electrical grid. For the wind turbine farm in this study, the total install capacity would be 30 MW, and there would be 40 wind turbines evenly distributed in 230km^2. Compared to a single wind turbine, the stability would be improved a great deal since fluctuations among the individual turbine plants would tend to average out. As a result, power quality is not expected to be a major issue.

5 Conclusion

The feasibility of operating a wind turbine farm in Chong Ming island region, in the vicinity of the city of Shanghai, China, has been studied. A wind turbine has been designed specifically for this site, and the energy production computed using a physics based model. The cost of wind energy is very competitive with local utility rates. It is concluded that this site is favorable for operating a wind turbine farm. The production of renewable energy would be a good way to reduce the pollution of Shanghai, due to emission of industrial pollutants.

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