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Efficiency Analysis of an Installed Wind Farm

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Abstract

In this study, efficiency study of five wind turbines of a wind farm were performed using data of wind speed, wind direction, air temperature and electric generation of five turbines selected. Parameters effecting turbine efficiency were also examined.

Analysis of monthly and yearly dominant wind directions for selected turbines was performed. Performed analysis of turbines was also conducted considering the measured wind speed and direction. Aerodynamic characteristics of wind turbines were defined according to the variation of measured wind speeds. Annual energy production of turbines were calculated in order to obtain the most productive and efficient months.

Keywords: Efficiency, Electric generation, Wind turbine

Kurulu Bir Rüzgâr Çiftliğinin Verim Analizi

Özet

Bu çalışmada bir rüzgâr çiftliğine ait beş adet türbine ait rüzgâr hızı, rüzgâr yönü, güç üretimi ve hava sıcaklığı verileri kullanılarak ilgili türbinlerin verimlilik çalışması yapılmıştır. Türbin verimini etkileyen parametreler de ayrıca incelenmiştir.

Seçilen türbinler için aylık ve yıllık hâkim rüzgâr yönlerinin analizi yapılmıştır. Gerçek hızları ve yönleri dikkate alınarak türbinlerin performans analizi yapılmıştır. Rüzgâr hız değişimlerine göre, türbine aerodinamik karakteristik değerleri çıkarılmıştır. Türbinlerin yıllık enerji üretim değerleri hesaplanarak enerji üretiminin en fazla ve en verimli olduğu aylar belirlenmiştir.

Anahtar Kelimeler: Elektrik üretimi, Rüzgâr türbini, Verim

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1. INTRODUCTION

Energy usage is important in enhancing the quality of life besides providing physical comfort and surviving of life. Most of the energy used by humans was obtained from the sun until the discovery of nuclear energy. The sun energy is absorbed and stored up by plants with the specific activity named photosynthesis in order to provide energy found in foodstuff. Fossil fuels which are also derived from the sun were also produced of rotten plants lived million years ago. Energy generated by the sun develops wind formation in the atmosphere. This operates wind rotors for years. Nowadays, the world demand of energy grows rapidly and this demand will continue to grow substantially in coming years because of high growth of populations, social, economic and industrial developments. High rate of energy demand, rapid increase of oil price and negative impact of fossil fuels on the environment gave tremendous attention to wind energy all over the world. In order to convert wind energy into electricity one needs to use a wind turbine. Wind is an indirect product of the sun energy. There are lots of variations in wind speed from stagnant velocities to hurricanes.

The aim of the work is to study the performance of installed turbines in order to see the power produced on the feasibility basis.

Increase of the petrol cost and limitations in traditional energy sources enhanced interest to wind energy again. By the encouragements and formal research studies, lots of new turbine designs were accomplished. The equation demonstrating the relation between wind speed and generated power are given in equation 1. Change of wind potential with respect to the wind speed is depicted in Figure 1.

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

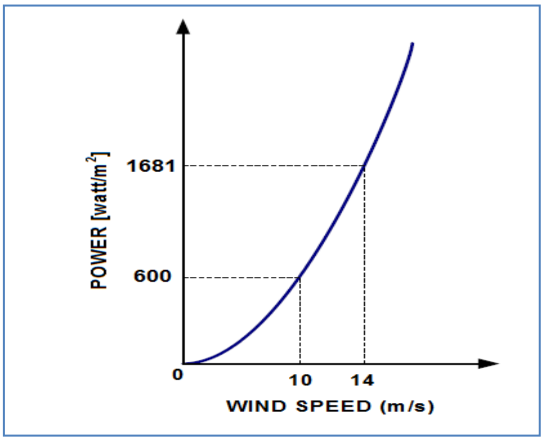

Figure 1. Relation of power with respect to the wind speed modified [1]

2. PREVIOUS STUDIES

Bilgili et al. (2004) researched wind energy potential in eastern regions of Turkey such as Iskenderun and Antakya regions [2]. In this study, Wind Atlas Analysis and Application Program WAsP software package was used in order to obtain wind map for the related regions. Whole wind map of this region was constructed by Sahin et al. (2005) using Wasp package program [3]. Data of hourly wind speeds and wind directions obtained in regions of Antakya, İskenderun, Karataş, Yumurtalık, Dörtyol, Samandağ and Adana, Turkey were used for this work. Also, wind characteristics and energy potential of Belen-Hatay regions of Turkey was researched by Sahin and Bilgili (2009) and statistical analyses were performed [4].

Bilgili and Sahin (2009) investigated wind energy density in the southern and southern west region of Turkey through using Weibull and Rayleigh probability density functions, and the Wind Atlas Analysis and Application Program (WAsP) [5]. Also, Bilgili and Sahin (2010) investigated wind energy density in the western region of Turkey by using Weibull and Rayleigh probability density functions, and the Wind Atlas Analysis and Application Program (WAsP) [6].

Bilgili et al. (2009) analyzed statistically wind energy potential in the regions of Akhisar, Bababurnu, Belen, Datça, Foça, Gelendost, Gelibolu, Gökçeada and Söke located in south, south-west and west coasts of Turkey [7].

3. CALCULATION of WIND POWER AND EFFICIENCY

Maximum wind power that is available to be converted into electric power is expressed by the following equation [8];

$$P = \frac{1}{2} \rho A V_i^3 \tag{2}$$

Theoretical power determined by equation (2) is multiplied by Betz–Limit in order to obtain maximum turbine power [8];

$$P_{TH} = \frac{1}{2} \rho A V_i^3 \; x \; 0.59 \tag{3}$$

By using the wind speed data, U_∞, free-stream of the rotor power efficiency (C_p) are calculated with following equation [9].

$$c_p = \frac{P_r}{\frac{1}{2} \rho U_\infty{}^3 \pi R^2} \tag{4}$$

Where P_r designates real power obtained from wind turbine, ρ is the air density, U_∞ is the free-stream wind speed and R is the radius of the rotor.

Flow induction factor (a) is determined using the following equation;

$$4a(1-a)^2 \text{ - } C_P = 0 \tag{5}$$

At wind speed on the rotor, U_D to be given initially rather than wind speed in front of the rotor (free-stream), U_∞ and equations 6 and 7 are used to determine flow induction factor.

$$a = \frac{X}{X+4} \tag{6}$$

Where, X is determined by,

$$X = \frac{P_{real}}{0.98.0.97.\frac{1}{2}.\rho.A U_D^3} \tag{7}$$

Relation of thrust coefficient (C_T) with respect to the flow induction factor (a) is expressed as follows [8].

$$C_T = 4a(1-a) \tag{8}$$

Wind speed before rotor (U_∞), and far on the wake (U_W) are related with equation (9) [10].

$$\lambda = \frac{U_W}{U_\infty} \tag{9}$$

Where, wind speed on the rotor (U_D) and wind speed far on the wake (U_W) are defined as [8],

$$U_D = U_\infty (1-a) \tag{10}$$

$$U_W = U_\infty (1-2a) \tag{11}$$

Thrust of wind is given by equation (12) [9].

$$T = 2 \rho A_D U_\infty^2 a (1-a)^2 \tag{12}$$

4. IDENTIFICATION of WIND DIRECTIONS FOR TURBINES

With considering the data presented in Table 1, Figure 2 was constructed. This figure demonstrates yearly wind blowing directions for all turbines. Monthly distributions of wind direction for turbines T01, T02, T03, T04 and T05 are presented in Figures 3 and 4. During the procurement of these figures, numbers of hourly wind direction data used in these directions estimations are numbered on these figures.

Data determined in Table 1 refers the processed wind speed, air temperature, power generation and wind direction by eliminating wind speeds below cut-in speed (4 m/s) where turbine starts power generation, eliminating zero and negative values of power generation and unrecorded wind direction data.

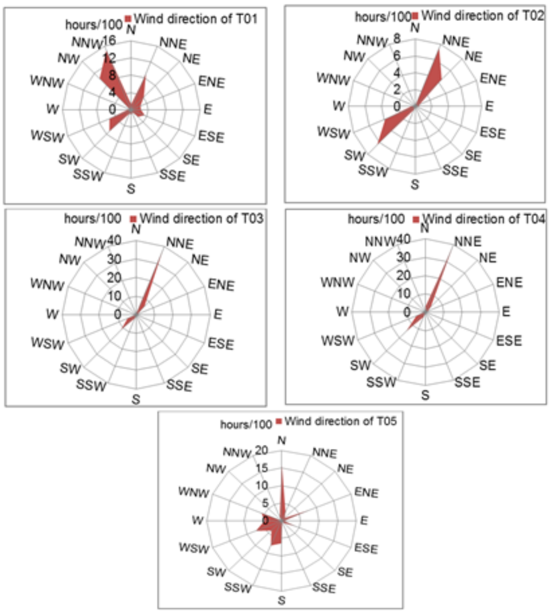

Figure 2. Distributions of wind directions for turbines T01, T02, T03, T04 and T05

Figures 3 and 4 involve average wind directions of T01, T02, T03, T04 and T05 for each month shown with blue numbers. Green patterns inside the figures indicate the amount of data used in determining the monthly wind direction for each discrete turbines. In Figure 3 (Top, right), all hourly wind directions measured for months between June and December were unfortunately unrecorded.

Similarly, these unrecorded wind directions were also designated with bluish color in Table 1.

5. INTRODUCTION OF CUT-IN AND CUT-OUT SPEEDS

Average data in Table 1 are acquired with the consideration of cut-in and cut-out speeds, elimination of zero and negative values of power generation, and elimination of unrecorded wind directions (using boundary values). Maximum wind powers were obtained using wind speeds presented in Table 1 and equation 2 was used for calculations. Theoretical wind powers were determined according to the wind speed data given in Table 1 with the utilization of equation 3. Efficiency calculations were performed by equation 4. Real powers were directly taken from Table 1 which were computed by taking average values of hourly data.

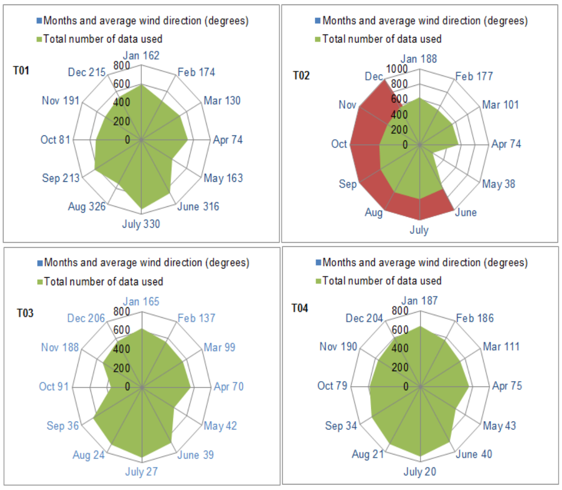

Figure 3. Monthly distributions of wind direction for turbines T01, T02, T03 and T04

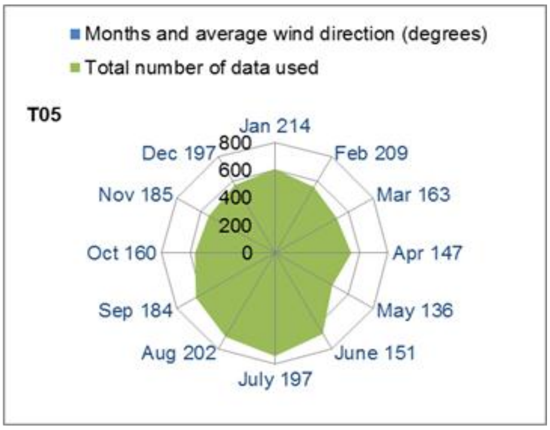

Figure 4. Monthly distributions of wind direction for turbine T05

These estimations were given for each discrete turbines distributed for each months of 2010 year. Table 2 contains related computed data for turbines T01, T02, T03, T04 and T05.

Table 1. Monthly average wind data (Considering boundary values)

	Hourly Wind Data (m/s)					Hourly Generation Data (kWh)					Hourly Wind Direction Data (°)					Hourly Temperature Data (C°)				
Turbine no	T01	T02	T03	T04	T05	T01	T02	T03	T04	T05	T01	T02	T03	T04	T05	T01	T02	T03	T04	T05
Date	Hourly Average Wind Speed (m/s)	Hourly Average Wind Speed (m/s)	Hourly Average Wind Speed (m/s)	Hourly Average Wind Speed (m/s)	Hourly Average Wind Speed (m/s)	Hourly Average Generation (kWh)	Hourly Average Generation (kWh)	Hourly Average Generation (kWh)	Hourly Average Generation (kWh)	Hourly Average Generation (kWh)	Hourly Average Wind Direction (°)	Hourly Average Wind Direction (°)	Hourly Average Wind Direction (°)	Hourly Average Wind Direction (°)	Hourly Average Wind Direction (°)	Hourly Average Temperature (C°)	Hourly Average Temperature (C°)	Hourly Average Temperature (C°)	Hourly Average Temperature (C°)	Hourly Average Temperature (C°)
January	8.15	8.97	8.82	10.00	9.25	934.99	1129.00	1044.95	1336.83	1163.70	161.65	187.76	164.64	187.26	214.10	7.51	7.55	8.14	8.15	7.38
February	9.10	9.94	9.65	10.85	10.03	1130.39	1407.07	1237.43	1564.24	1334.85	174.15	177.18	136.97	185.52	209.32	7.89	7.93	8.70	8.61	7.87
March	7.75	8.28	7.97	8.57	8.18	787.02	919.22	838.46	966.28	860.72	129.55	100.63	98.83	110.54	162.64	12.08	12.06	12.70	12.15	11.82
April	6.99	7.64	6.98	8.01	7.43	604.97	745.74	615.47	801.98	668.22	73.83	74.18	70.41	74.70	146.54	14.15	14.21	14.63	13.93	13.67
May	7.80	9.05	7.87	8.91	8.33	813.02	1144.56	907.04	1070.66	909.49	163.21	38.20	42.38	43.33	136.26	17.38	16.17	17.88	17.02	16.75
June	8.82	10.02	9.03	10.09	9.49	1083.59	1393.10	1241.85	1431.59	1231.07	315.84	1000.00	39.08	39.57	151.12	20.06	20.23	20.75	19.58	19.48
July	10.70	12.60	11.26	12.88	12.05	1605.48	2094.98	1922.58	2136.12	1934.50	329.80	1000.00	27.29	20.48	196.88	21.91	21.67	22.58	21.13	21.03
August	8.62	10.02	8.75	9.73	9.23	1019.48	1375.24	1161.50	1303.19	1142.37	326.25	1000.00	24.05	20.92	202.14	27.04	25.42	25.52	24.49	24.34
September	7.98	9.15	8.30	9.41	8.91	878.57	1190.30	1058.07	1298.62	1119.85	212.78	1000.00	36.07	33.71	183.73	25.67	22.39	22.73	21.70	21.77
October	6.54	7.25	6.66	7.26	6.80	513.03	645.44	549.92	678.96	543.78	80.85	1000.00	90.86	78.76	160.32	21.66	18.42	19.52	18.04	18.00
November	6.18	6.79	6.22	7.26	6.69	392.67	508.15	412.73	658.33	506.74	191.47	1000.00	188.49	190.34	184.65	20.21	16.80	17.37	16.96	16.86
December	8.12	9.05	8.31	9.65	8.76	881.44	1054.35	922.99	1250.19	1033.13	215.40	1000.00	206.07	203.94	197.49	12.08	9.74	10.28	10.41	9.74
Yearly	8.06	9.06	8.32	9.38	8.76	887.05	1133.93	992.75	1208.08	1037.37	197.90	115.59	93.76	99.09	178.77	17.30	16.05	16.73	16.02	15.73

Distribution of $C_p - \lambda$ for four turbines regarding equations (4) and (9) is given in Figure 5, whereas, $C_T - \lambda$ variation of the same turbines is shown in Figure 6 with using equations (8) and (9).

Figure 7 presents change of power efficiency, C_p with respect to the flow induction factor, a by considering equations (7), (6) and finally (5) respectively.

Figure 7 presents change of power efficiency, C_p with respect to the flow induction factor, a by considering equations (7), (6) and finally (5) respectively.

As it is mentioned above, thrust coefficient (C_T) and flow induction factor (a) are related by equation 8. This relation considering four turbines is given in Figure 8.

Wind speed far on the wake, (U_W) and wind speed in front of the rotor, U_∞ are related through exploitation of equation 11 as demonstrated in Figure 9.

For determination of data presented in Figure 10, equation 10 was used in order to relate wind speed on the rotor (U_D) and in front of the rotor, U_∞.

By using equation 10, free-stream velocity, U_∞ was estimated. Generated real powers were given in table 2. Consequently, variation of real power generation with free-stream velocity, U_∞ are presented in Figure 11. When this figure is carefully analyzed, it is observed that through approaching cut-in and cut-out speeds, power generations either stop or approach to a limit. Equation 12 gives the relation between thrust force, T and free-stream wind speed, U_∞ for all turbines considering twelve months and obtained results are shown in Figure 12.

Variations of actual power generation and trust force, T with free-stream wind speed, U_∞ for all turbines throughout twelve months are more or less same.

Table 2. Power efficiencies of turbines T01, T03, T04, and T05 turbines.

Turbine no	Wind speed (m/s)	Maximum Power (kW)	Theoretical Power (kW)	Real Power (kW)	Efficiency
T01	4.8542	445.6982	264.1174	115.8390	0.2599
	6.0351	856.5000	507.5556	251.3872	0.2935
	7.1572	1428.5968	846.5759	426.2730	0.2984
	8.2743	2207.3699	1308.0710	661.6781	0.2998
	9.4016	3238.0499	1918.8444	974.3245	0.3009
	10.4749	4478.5340	2653.9461	1329.9973	0.2970
	11.5412	5990.0773	3549.6754	1701.8768	0.2841
	12.4639	7544.7621	4470.9701	2008.2902	0.2662
	13.4355	9450.2355	5600.1395	2285.4070	0.2418
	14.3531	11521.6548	6827.6473	2497.6512	0.2168
	15.2248	13751.0976	8148.7986	2673.9116	0.1945
	16.1984	16561.4152	9814.1720	2724.9523	0.1645
	17.0716	19386.5748	11488.3406	2798.0730	0.1443
	17.8630	22209.8284	13161.3798	2864.3308	0.1290
	18.7791	25805.0456	15291.8789	2884.7340	0.1118
T03	4.9233	464.9877	275.5483	134.7493	0.2898
	6.0929	881.3775	522.2978	276.0047	0.3132
	7.2370	1476.8998	875.1999	464.1775	0.3143
	8.3490	2267.7116	1343.8291	718.9983	0.3171
	9.4530	3291.4989	1950.5179	1040.5259	0.3161
	10.5174	4533.2110	2686.3473	1398.1634	0.3084
	11.5628	6023.8053	3569.6624	1780.7973	0.2956
	12.5354	7675.2377	4548.2890	2097.2404	0.2732
	13.4731	9529.8545	5647.3212	2359.2805	0.2476
	14.4110	11661.7551	6910.6697	2598.4248	0.2228
	15.3588	14117.2667	8365.7877	2751.5994	0.1949
	16.2030	16575.5669	9822.5582	2815.4732	0.1699
	17.2275	19922.5552	11805.9586	2917.2658	0.1464
	18.1135	23157.4471	13722.9316	2894.9068	0.1250
	19.0480	26929.7331	15958.3603	2930.7750	0.1088
T04	4.8807	453.0365	268.4661	122.4706	0.2703
	6.0234	851.5431	504.6181	248.5066	0.2918
	7.1199	1406.3880	833.4151	405.8159	0.2886
	8.2053	2152.6312	1275.6333	611.2681	0.2840
	9.3222	3156.7560	1870.6702	886.1574	0.2807
	10.3743	4350.6705	2578.1751	1193.7902	0.2744
	11.4162	5797.5271	3435.5716	1521.2887	0.2624
	12.4037	7435.9902	4406.5127	1817.1450	0.2444
	13.3638	9299.6407	5510.8982	2083.4820	0.2240
	14.3495	11513.0491	6822.5476	2348.4563	0.2040
	15.2871	13920.4128	8249.1335	2591.5827	0.1862
	16.2272	16650.0439	9866.6927	2792.9743	0.1677
	17.1461	19641.7550	11639.5585	2925.3417	0.1489
	18.0498	22913.7882	13578.5411	2957.9491	0.1291
	19.0750	27044.1911	16026.1873	2982.0494	0.1103
T05	19.8078	30282.4839	17945.1757	2977.9515	0.0983
	20.8706	35423.2427	20991.5512	2983.6730	0.0842
	21.9236	41059.6220	24331.6278	2978.8525	0.0725
	4.8353	440.4980	261.0359	111.9293	0.2541
	6.0091	845.4752	501.0223	235.7734	0.2789
	7.0869	1386.9045	821.8693	384.7237	0.2774
	8.1803	2133.0148	1264.0088	585.6881	0.2746
	9.2691	3103.0995	1838.8738	850.4058	0.2741
	10.3372	4304.1979	2550.6358	1155.1794	0.2684
	11.3677	5723.9545	3391.9730	1470.3233	0.2569
	12.3900	7411.3334	4391.9013	1789.1887	0.2414
	13.3765	9326.2484	5526.6657	2055.6961	0.2204
	14.3002	11394.7150	6752.4237	2293.1810	0.2012
	15.2531	13827.9953	8194.3676	2514.0166	0.1818
	16.1750	16489.7061	9771.6777	2711.1743	0.1644
	17.0856	19434.4234	11516.6953	2821.0584	0.1452
	18.0232	22812.7127	13518.6446	2901.7680	0.1272
	19.1645	27426.6182	16252.8108	2971.9598	0.1084

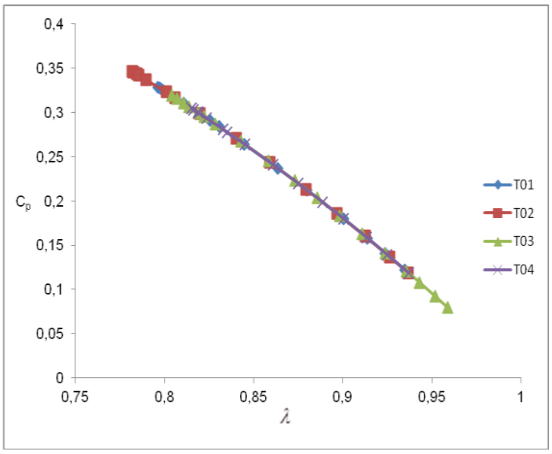

Figure 5. C_p- λ distribution

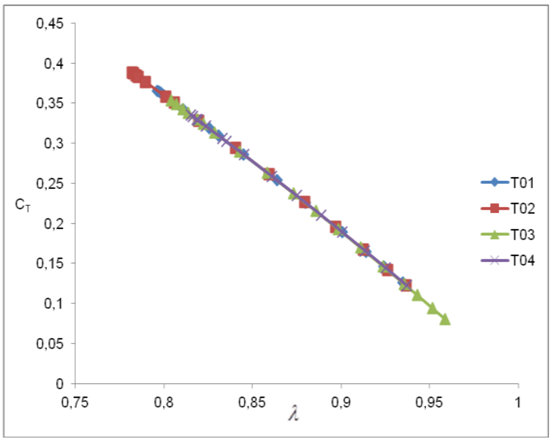

Figure 6. C_T - λ distribution

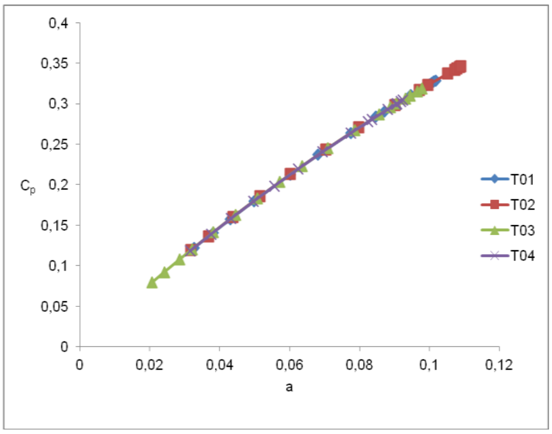

Figure 7. C_p-a distribution

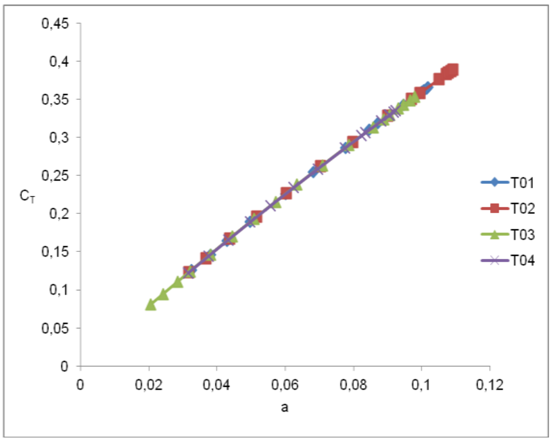

Figure 8. C_T-a distribution

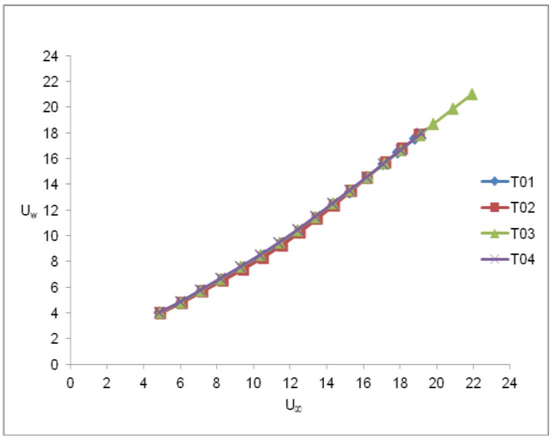

Figure 9. U_w-U_∞ distribution

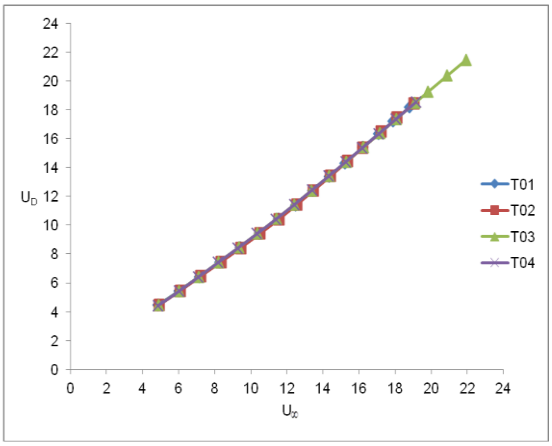

Figure 10. U_D-U_∞ distribution

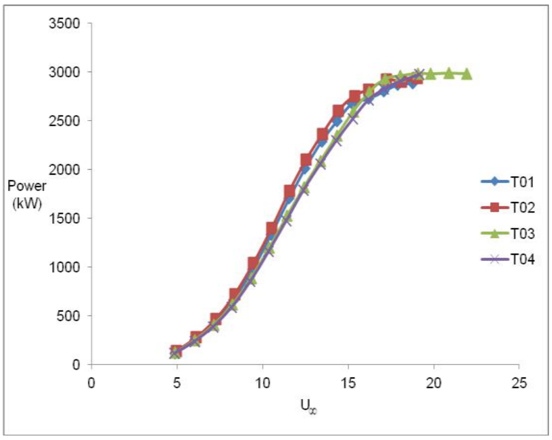

Figure 11. Power-U_∞ distribution

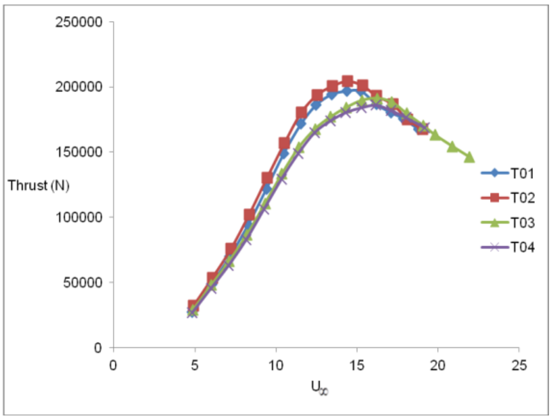

Figure 12. Thrust-U_∞ distribution

Figure 13 refers to total energy generation of five turbines with an average wind speed throughout twelve months. It can be seen that all turbines generates electricity throughout twelve months. The highest power generation occurs in July.

6. CONCLUSIONS

According to the data obtained from wind farm, firstly analyses were performed without taking cut-in and cut-out speeds into consideration. Monthly averages wind data were used in estimations of related parameters. At very low speeds, turbine cannot generate electricity where it is expressed in its specifications as cut-in speed. Maximum power and real power generally increase with increasing free-stream wind speeds (U_∞) when cut-in speeds are considered, however efficiencies decreases to a meaningful values.

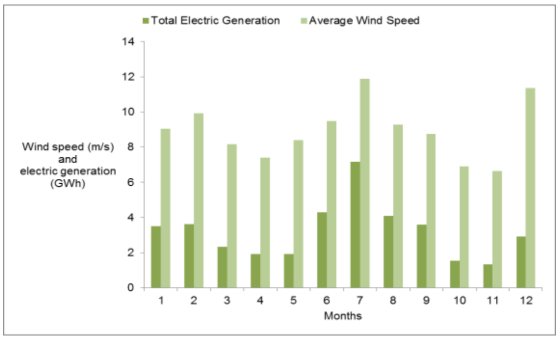

Figure 13. Monthly total electric generations and average wind speeds

It is observed that maximum power generations occur in July for all turbines, when average wind speed (U_∞) is maximum and air temperature is also high compared with other months for all turbines. In addition, non-stop generations take place in this month for all turbines. The total electric generation of five turbines was 38.09 GWh in the year of 2010. Turbine T04 generated 9.03 GWh electricity. The maximum power was generated by turbine T04, on the other hand, turbine T01 generated 6.12 GWh electricity. Although both turbines are installed in the same wind farm, the difference of electric production in between turbine T01 and T04 is 33% in the year of 2010. This wind farm is situated in the valley containing many hills, crests and roughness. This topographic condition of the farm effects wind directions and magnitude of wind speed, U_∞.

7. REFERENCES

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