Study the design and operation of Wind Energy System Interconnected with Utility Grid

Prof. Dr. Hassan H. EL-Tamaly
Faculty of Engineering, Minia University Elminia, Egypt Tamaly_minia@yahoo.com
Eng. Sultan I. EL-Ajmi
Faculty of Engineering, Minia University, Elminia Egypt Sultan735@hotmail.com

Abstract— This paper studies the design and operation of Wind Energy System, WES, interconnected with Utility Grid, UG,. It introduces a proposed computer program to determine the optimal design of WES to be interconnected with UG. The proposed computer program has been designed to determine the optimum number of Wind Turbine Generators, WTGs, needed to feed a certain load. Many WTG types have been introduced to the computer program to choose the best type of WTG. By using the proposed computer program the WES components can be completely designed to be interconnected with UG. This program has a subroutine which by using it the optimum operation of WES can be determined hour by hour through the year. Then, the monthly surplus energy, monthly deficit energy and yearly purchase from UG or selling energy to UG can be estimated. The decision from the computer program is based on minimum price of the generated kWh from the WES. The proposed computer program has been applied on two Egyptian sites. The first sit is Ras- Ghareb which located at coast of the Red sea and the second site is Ras- EL-Hekma which located at the coast of Mediterranean Sea.

Keywords—Wind Energy System; Wind Turbine Generator; Utility Grid; Deficit and surplus Energy

I. INTRODUCTION

Depletion of fossil fuels and the concomitant climate change have compelled nations to seek new, nonpolluting ways to produce energy. Consequently, renewable energies like wind, solar, biomass, and geothermal energies have been viewed as attractive solutions [1]. The total installed wind generation capacity worldwide is 47,000 MW in the year 2004. The wind generation in Europe alone is approximately 33,600 MW in the year 2004 [2]. Egypt targets to increase the installed capacity to reach 1750 MW by the end of 2017, more than 750 MW will be undertaken by private sector [3]. Wind energy is transformed into mechanical energy by means of a wind turbine that has several blades. It usually includes a gearbox, G.B., which matches the turbine low speed to the higher speed of the generator. Some turbines include a blade pitch angle control for controlling the amount of power to be transformed. The electrical generator transforms mechanical energy into electrical energy. The electrical generator can be synchronous or asynchronous [4].

II. DESIGN METHODOLOGY OF WES AT MAXIMUM POWER POINT

A. *Modification of Average Wind Speed to Hub Height*

Usually weather stations measure wind speed at 10-m or 24-m. If these heights do not match the hub height of a wind turbine it is necessary to extrapolate the wind speeds to hub height of the turbine [5]. This process can be done by the following equation:

$$u_h = u_{ho}\left(h/h_O\right)^{\alpha} \tag{1}$$

Where:

u_h is the wind speed at height h-m in m/s, u_{ho} is the wind speed at height ho-m in m/s, (h_o is usually 10-m), h is the height from the ground in m. α is the Exponent is usually 1/7. [7]

B. Calculation of Capacity Factor, CF and ANWTG

The capacity factor, CF, can be calculated by using the following Equation [1, 4]:

$$CF = \frac{Exp\left[-\left(u_c / C\right)^K\right] - Exp\left[-\left(u_r / C\right)^K\right]}{\left(u_r / C\right)^K - \left(u_c / C\right)^K} - Exp\left[-\left(u_F / C\right)^K\right] \quad (2)$$

Where;

u_c is the cut-in wind speed of the WTG, m/s, u_r is the rated wind speed of the WTG, m/s, u_F is the cut-off wind speed of the WTG, m/s, C and K are the scale and shape Weibull parameters respectively. These parameters can be calculated by using equations in reference [7].
The average electric power output form WTG, $P_{e,ave}$ can be estimated by using the following Equation [1,4]:-

$$P_{e,ave} = P_{rated}\ CF \quad (3)$$

Where;
P_{rated} is the rated electrical power output from the WTG, kW.
The average number of wind turbine generators, ANWTG, can be estimated by using the average load demand, $P_{L,ave}$, from the following Equation:-

$$ANWTG, N_w = \frac{P_{L,ave.}}{P_{e,ave.}} \quad (4)$$

The energy balance between the load and the output of WES should be carried out to compute the optimum number of WTG's, N_w. The hourly generated power, $P_{WTG,out}(t)$, and hourly load power, $P_{Load}(t)$, are compared with each other. If $P_{WTG,out}(t)$ is larger than the load power demand then there is an hourly surplus power, but if $P_{WTG,out}(t)$ is smaller than the load power demand then there is an hourly deficit power. At any value of N_w, if the summation of hourly surplus power approximately equals to the summation of hourly deficit power then this value of N_w represents the optimum number of WTG, ONWTG [8].

C. Calculation of Energy Cost Figure, ECF, [5, 6, 9, 10]

The ECF of WTG/UG can be estimated as follows:

Total cost of WTG, TCWTG= TW * ONWTG * R (5)

Microprocessor, TCMIC=TP* ONWTG *R (6)

Main substation, TCMS= TS* ONWTG *R (7)

Remote control modem cost, TCRC=TM* ONWTG *R (8)

Central station control cost, TCCC=TC* ONWTG *R (9)

Transmission line cost, TLC=TR* ONWTG *R (10)

TCC=TCWTG+TCMIC+TCMS+TCRC+TCCC+TLC (11)

Levalized annual cost of WTG, $LACw= K_w * TCC$ (12)

Where;

R is the rating of WTG in kW, TW is the Price of WTG in $/kW, TP is the price of microprocessor in $/kW, TS is the price of main substation in $/kW, TM is the price of modem for remote control in $/kW, TC is the price of central station control in $/kW, TR is the transmission line price in $/kW, TCC is the total Capital cost.

$$K_w = \frac{r*(1+r)^{n_w}}{(1+r)^{n_w}-1} \quad (13)$$

Operation and maintenance cost, $O\&MC=0.05*LAC_W$ (14)

Total levalized annual cost for WTG, $TLAC_W= (LAC_W+O\&MC)/0.9$ (15)

Energy cost figure, ECF, $/kWh

$=TLAC_W$/Total expected yearly energy generated. (16)

Where;

n_w is the life period of WTG in years and r is the interest rate of WTG.

III. RESULTS

A new proposed computer program has been designed depending on the above methodology for calculating optimum number of WTG. Fig. 1 shows the flowchart of the proposed computer program.

The input data of this program are:

1- Hourly wind speed, m/s. [11]

The hourly wind speed for the selected sites is the first data required for design of WES. The data has been obtained from the Egyptian Metrological Authority for Ras- Ghareb and Ras- EL- Hekma sites. Ras Ghareb site is located at Gulf of Suez (Red sea area), Egypt. It has the following data: Latitude: 28.33° N, Longitude: 33° E and Altitude: 56 m. Height of anemometer: 24.5 m above the ground. The surface consists mostly of sand and gravel with a roughness length of less than 0.01 m.

Ras- EL-Hekma site is located at Northwest Coast of Egypt (Mediterranean Sea area). It has the following data: Latitude: 31.2° N, Longitude: 24.87° E and Altitude: 23 m. Height of anemometer: 24.5 m above the ground.

Fig. 2 and Fig. 3 show the hourly wind speed over the year seasons as a sample data for months January, April, July and October for Ras- El-Hekma and Ras Ghareb sites respectively.

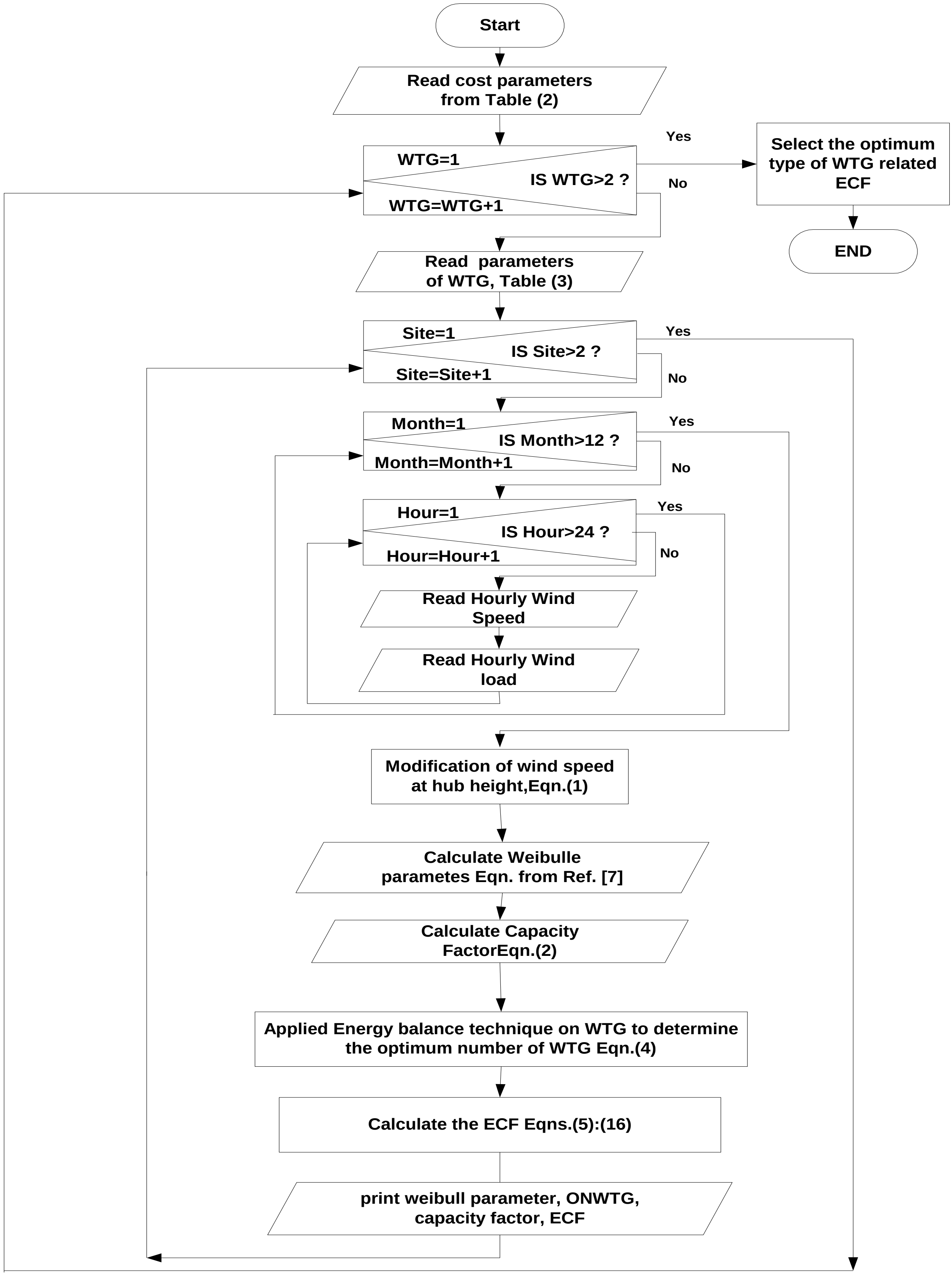

Fig.1 Flowchart of the Proposed Computer Program

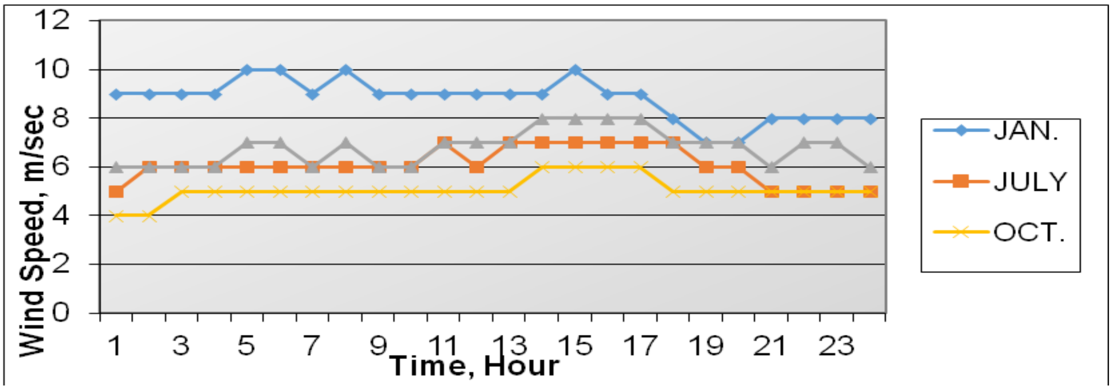

Fig. 2 Hourly Wind speed during January, April, July, and October for Ras-El-Hekma site, Egypt

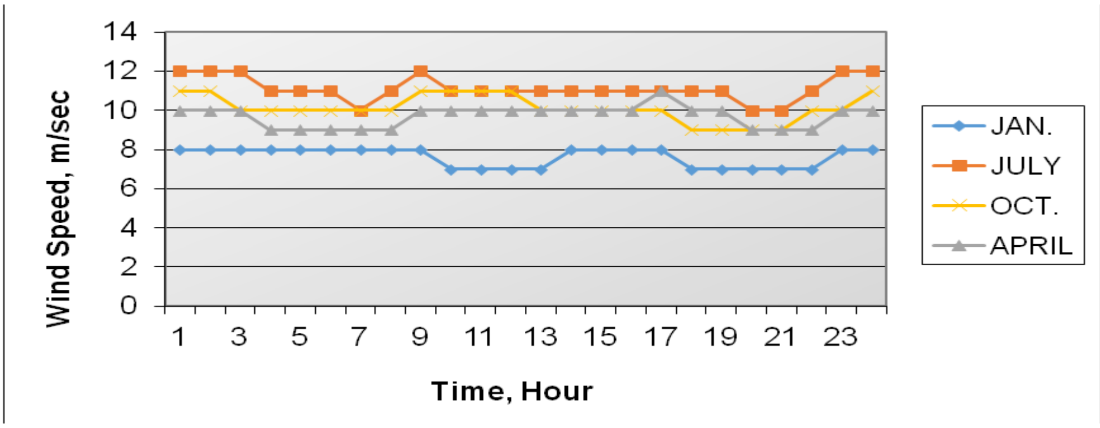

Fig. 3 Hourly Wind speed during January, April, July, and October for Ras Ghareb site, Egypt

2- Characteristics of each WTG type

In this study, two different selected types of WTG's have been used. The characteristics of these WTG's are revealed in Table (I)

Table (I) Characteristics of the selected WTG's

Type of WTG / Characteristics	N90/2500 HS	S52-600 kW
Rated Power (kW)	2500	600
H (m)	100	75
D (m)	90	52
Swept Area (m^2)	6362	2124
u_c **(m/s)**	3	4
u_r **(m/s)**	13	13
u_f **(m/s)**	25	25
Generator Type	Double-fed asynchronous generator	Single speed induction generator
Output voltage (V)	660 V	690 V AC (phase to phase)
Frequency (Hz)	50/60	50
No. of Blades	3	3
Power regulation type	Pitch regulation	Pitch regulation

3- Hourly load demand, kW.

It is assumed here that the load demand varies monthly. This means that each month has daily load curve different from other months. Therefore, there are twelve daily load curves through the year. Hourly load demand is shown in Fig. 4 for months January, April, July and October.

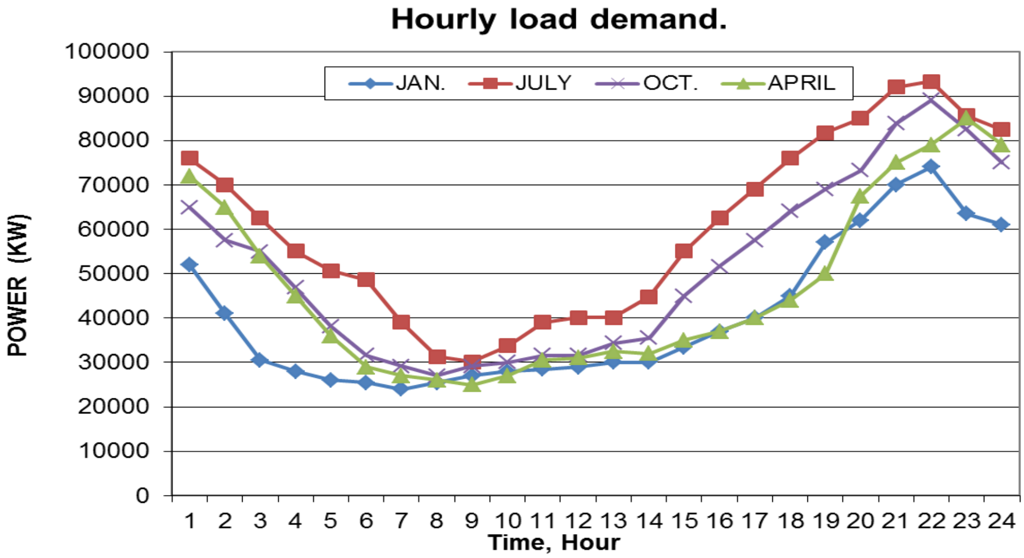

Fig. 4 Hourly load demand

4- The Price of Each Component of WTG's is displayed in Table (II).

The outputs of this program are:
Optimum number for each type of WTG's, Cost of kWh generated for each type of WTG's in $/kWh, Optimum type for each type of WTG’s based on its ECF, Monthly surplus energy in kWh, Monthly deficit energy in kWh, Yearly purchase or selling energy to or from UG in kWh.
Table (III) revels some of the results from computer program such as Weibull parameters, capacity factor, optimum total number of WTG’s and energy cost figure, ECF, for each type of the selected WTG's and for each selected site. From this Table it can be seen that the N90/2500 HS WTG type has lower ECF than the type of S52-600 kW for the two selected sites. On the other hand, the WTG type of N90/2500 HS has CF value greater than the CF value of S52-600 kW WTG for the two selected sites. This is can be seen in Figs 5 and 6. For these reasons it can be concluded that the N90/2500 HS WTG type is the more suitable WTG type for the two selected sites.

Table (II) Price of Each Component of WTG's [12]

Item	TW	TP	TS	TM	TC	TR
Price, $/kW	600	2.5	11	3	4.2	1.8

Table (IV) displays the monthly surplus energy, monthly deficit energy and the difference between them when the WTG 2500 HS type used at Ras- El-Hekma site. Also, Fig. 7 shows the monthly difference between surplus energy and deficit energy (monthly Net energy) for Ras- El-Hekma site when the WTG 2500 HS type used. From Table (IV) it can be seen that the yearly surplus energy sent selled to the UG equal to (117097.2374 MWh) and the deficit energy taken purchased from the

Table (III) Parameters of the Selected WTG's for the two selected sites. [13], [14].

Modes	Ras Ghareb site		Ras EL- Hekma site	
	N90/2500 HS	S52-600 kW	N90/2500 HS	S52-600 kW
Rated Power kW	2500	600	2500	600
C , m/s	9.024	9.024	6	6
K	2.506	2.506	2.25	2.25
C.F	0.3519276488	0.3362136173	0.1471285796	0.1257836854
ONWTG, No.	25	102	46	223
Total Capital Cost, $	38906249.985	38096999.9	71587499.9	83290199.
Levalized Cost, $	2862789.94	2803243.91	5267533.50	6128660.72
O&MC, $	143139.499	140162.196	263376.679	306433.040
Yearly Energy (kWh), $	15509904	14609050	14556575	14552473
ECF ($/kWh)	0.215	0.2238	0.4222	0.4913
Total Levalized annual cost for WTG,TLACW,$	3339921.61	3270451.23	6145455.92	7150104.37

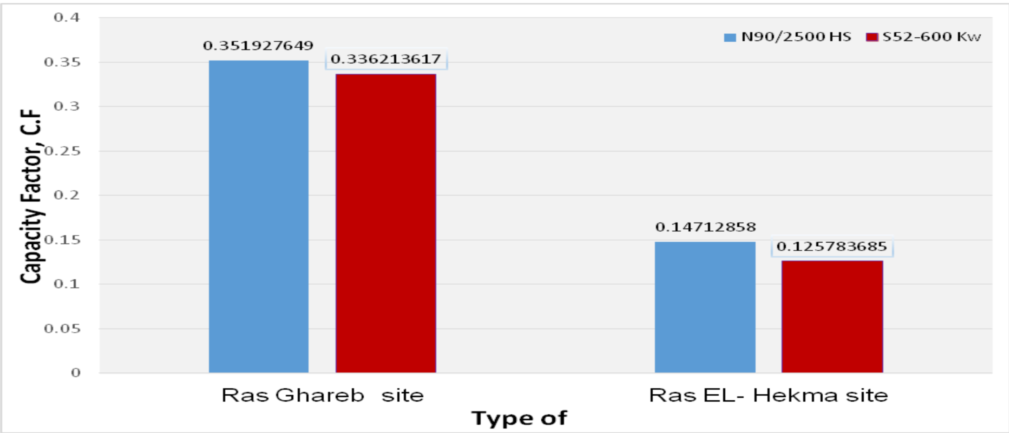

Fig. 5 The Capacity Factor of selected WTG's for Ras Ghareb site and Ras EL- Hekma site, Egypt.

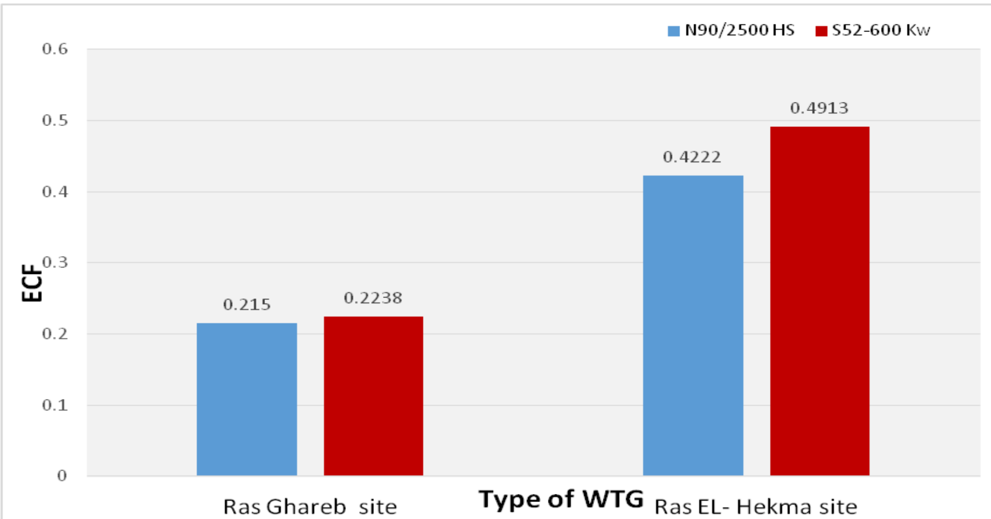

Fig. 6 Energy Cost Figure of selected WTG's for Ras Ghareb site and Ras EL- Hekma site, Egypt.

UG equal to (115746.0825 MWh). From Fig.7 and Table (IV) it can be concluded that there is yearly income fund from the UG to the WES. This income fund represents the price of the net surplus energy which equal to (1351.154889 MWh) yearly.

Table (IV) Monthly Net Energy for WTG 2500 HS for Ras El-Hekma site, Egypt.

Monthly	Surplus Energy, MWh	Deficit Energy, MWh	Surplus - Deficit, MWh
Jan.	41114.29209	328.5703427	40785.72175
Feb.	21952.07376	3697.463169	18254.61059
March	10823.43726	6426.501765	4396.935495
April	11352.861	6333.8475	5019.0135
May	2334.205409	10225.9173	-7891.711891
June	3000.419433	12994.852	-9994.432567
July	1686.12659	15601.401	-13915.27441
Aug.	1660.750936	14229.59418	-12568.84324
Sept.	330.4711999	17672.52945	-17342.05825
Oct.	0	18666.4141	-18666.4141
Nov.	12397.27913	3622.857213	8774.421917
Dec.	10445.32056	5946.134459	4499.186101
Summation	117097.2374	115746.0825	1351.154889

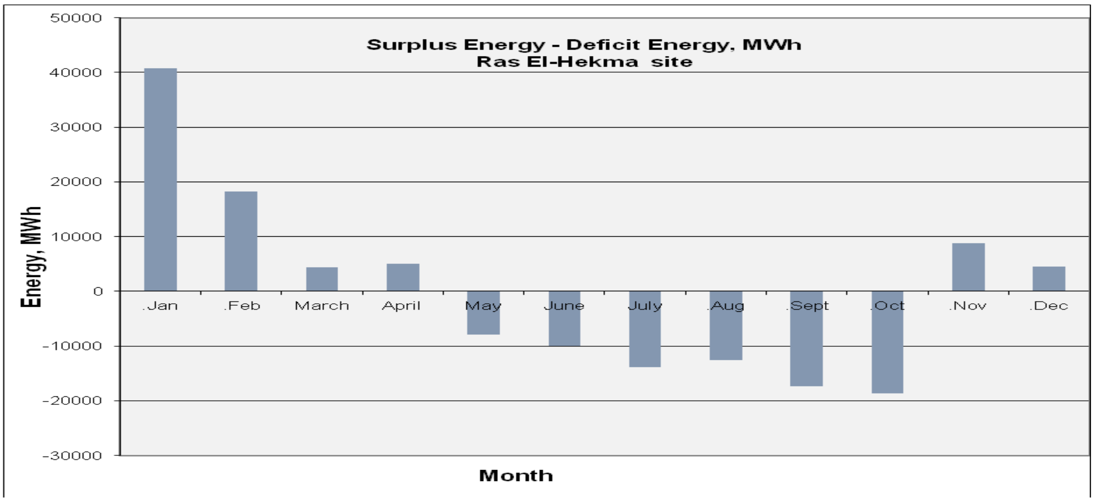

Fig. 7 Monthly Net Energy for WTG 2500 HS for Ras El-Hekma site, Egypt.

Table (V) reveals the monthly surplus energy, monthly deficit energy and the difference between them when the WTG 2500 HS type used at Ras- Ghareb site. Also, Fig. 8 shows the monthly difference between surplus energy and deficit energy (monthly Net energy) for Ras- Ghareb site when the WTG 2500 HS type used. From Table (V) it can be seen that the yearly surplus energy sent selled to the UG equal to (97223.88453 MWh) and the deficit energy taken purchased from the UG equal to (66891.54714 MWh). From Fig.8 and Table (V) it can be concluded that there is yearly income fund from the UG to the WES. This income fund represents the price of the net surplus energy which equal to (30332.33739 MWh) yearly.

Table (V) Monthly Net Energy for WTG 2500 HS for Ras- Ghareb site, Egypt.

Monthly	Surplus Energy, MWh	Deficit Energy, MWh	Surplus - Deficit, MWh
Jan.	5084.266904	7927.404007	-2843.13710
Feb.	4734.072051	7027.397699	-2293.3256
March	12787.93164	3403.985153	9383.94648
April	13191.68776	3421.91224	9769.77552
May	12236	3082.27806	9153.72194
June	8542.4	4453.6	4088.8
July	7365.920267	5663.520093	1702.40017
Aug.	7363.792102	6399.199768	964.592334
Sept.	8104.336353	4204.928455	3899.40789
Oct.	11201.18391	3933.84836	7267.33555
Nov.	2663.171558	10408.4681	-7745.2965
Dec.	3949.121982	6965.005206	-3015.8832
Summation	97223.88453	66891.54714	30332.3373

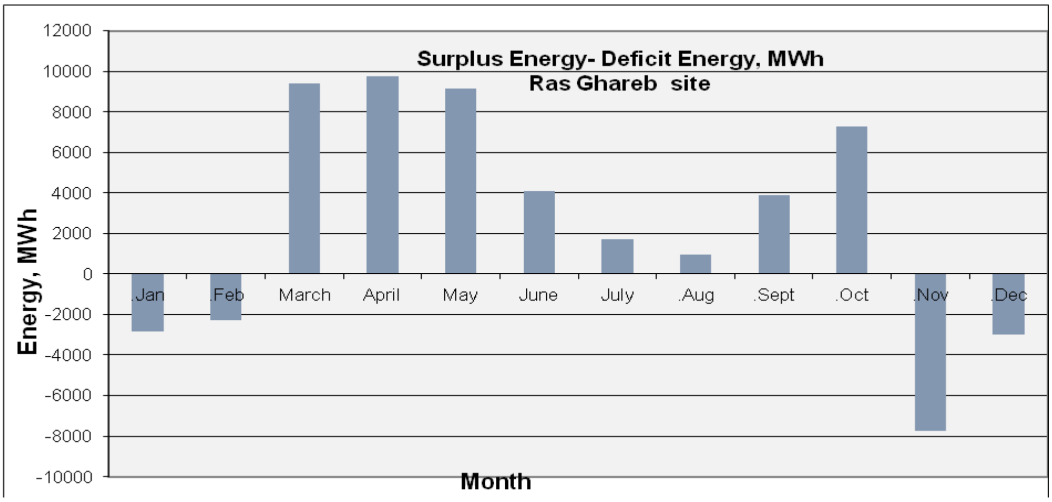

Fig. 8 Monthly Net Energy for WTG 2500 HS for Ras Ghareb site, Egypt

V. CONCLUSION

Considering Ras- EL- Hekma site and from Table (IV) and Fig. 7 it can be concluded that there is surplus energy fed to the UG through the months of Jan., Feb. ,March , April , Nov, and Dec. Also, there is energy taken from the UG to overcome the deficit energy of the load demand during the months of May, June, July, Aug., Sept., and Oct.

Considering Ras- Ghareb site and from Table (V) and Fig. 8 it can be concluded that there is surplus energy fed to the UG through the months of March, April, May, June, July, Aug., Sept. and Oct. Also, there is energy taken from the UG to overcome the deficit energy of the load demand during the months of Jan., Feb., Nov. and Dec.

REFERENCES

[1] Harri Vihriala, "Control of Variable Speed Wind Turbines ", Ph. D Thesis, Tampere University of Technology Department of Electrical Engineering, Institute of Electromagnetic, October 29, 2002.

[2] F. W. Koch, L Erlich, "Dynamic Interaction of large Offshore Wind Farms with the Electric Power System", IEEE Bologna power Tech, Bologna, Italy, June 23-26,2003.

[3] New & Renewable Energy Authority, Egypt, "Implementation of Renewable Energy Technology-Opportunities Barriers Egypt Country Study", UNEP Collaborating Center on Energy and Environment, RisǾ National Laboratory, ISBN: 87-550-30114, Denmark, 2001, pp. 1-133.

[4] Aleksandar Radovan, "Transient and Dynamic Stability o Wind Farms", M. Sc., Department of Electrical and Communications Engineering, Hel sinki, University of Technology, Power Systems Laboratory , March, 3td 2003.

[5] Manwell, J. F., Mc Gowan, J. G., & Rogers, A. L. " Wind energy explained: theory, design and application" 2nd edition, Wiley, England. 2009.

[6] H. H. El-Tarnaly and F. M. El-Kady, "Optimizing the Integration of Photovoltaic / Wind System with Electric Utility", Proceeding of Al Azhar Engineering sixth International Conference, Sept. 1- 4-2000, pp. 69-80.

[7] GARY L. JOHNSON, MAHATTAN, KS, "WIND ENERGY SYSTEM ", BOOK, ELECTRONIC EDDITION, 2006.

[8] Dafrose Camille, M. Bajaro and Mahatma Gandhi, "Horizontal and Vertical Axis Wind Turbines ", color the earth turquoise files. Wordpress.com /2012/03/ horizontal-and- vertical – axis – wind - turbines 1.pdf.

[9] Tsang-Jung Chang, Yu-Ting Wu , Hua-Yi Hsu Chia-Ren Chu , Chun-Min Liao," Assessment of wind characteristics and wind turbine characteristics ", in Taiwan (2002).

[10] H. H. EL-Tamaly, "Techno-Economical Analysis for Different Concepts of Renewable Electric Energy Systems and Applications", Bulletin of the Faculty of Engineering, Elminia University, Vol. 12, No. 2, Sept. 1993.

[11] Meteorological Authority of Arab Repuplic of Egypt.

[12] Hassan H. EL-Tamaly and Ahmed M. Abd-ElWhab, "Fult Calculations of the WES / PEM Fuel Cell Electrical Hybrid System", 17th International Middle East Power Systems Conference, Mepcon, 2015, Faculty of Engineering, Mansoura University,EL-Mansoura Egypt, December 15-17,2015, Conference Procceding.

[13] WWW.VROONOFFSHORE.COM

[14] WWW.SUZLON.COM