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INTEGRATION OF WIND TURBINE GENERATORS (WTG'S) AND SOLAR PHOTOVOLTAIC CELLS FOR POWERING LOADS IN REMOTE SITES

مشاركة تربينات الرياح للخلايا الكهروضوئية في تغذية أحمال المناطق البعيدة

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الخلاصة ـ يقدم البحث طريقة جديدة لحساب الجدوى الاقتصادية الناتجة من مشاركة الخلايا الشمسية الكهروضوئية لتربينات الرياح فى تغذية أحمال المناطق البعيدة وتحديد أنواع وأحجام تربينات الرياح والخلايا الكهروضوئية المستخدمة . وتعرض الدراسة طريقة عامة وبسيطة لتعيين :

١ ـ عدد مولدات تربينات الرياح الضرورية وأنواعها .
٢ ـ حجم مصفوفة الخلايا الكهروضوئية المطلوبة .
٣ ـ سعة بطاريات التخزين اللازمة لمعالجة الزيادة أو العجز فى القدرة المولدة .
٤ ـ تعيين معدل القدرة الضرورى فى تغذية الأحمال .

وتوضح الطريقة المقدمة أن القيم السابقة تعتمد أساسا على العوامل التالية :

أ ـ خصائص الموقع المقام عليه النظام والتى تمثل بشدة الاشعاع الشمسى الساقط على مصفوفة الخلايا الكهروضوئية وبسرعات الرياح المؤثرة على تربينات الرياح .
ب ـ شكل منحنى الحمل المطلوب تغذيته .
ج ـ كفاءة وتكلفة العناصر المكونة للنظام المقترح .

وتستخدم هذه الطريقة أيضا فى تحديد تأثير هذه العوامل على التصميم الأمثل لنظامى الشمسى والرياح اللذان تتحدد عناصرهما أساسا بهدف تحقيق أقل تكلفة ممكنة لوحدة الطاقة (الكيلووات . ساعة) المولدة . وتحديد التأثير الناتج عن الزيادة أو النقص فى كفاءة أو فى تكلفة أى عنصر على تكلفة وحدة الطاقة المستنتجة .

ويقدم البحث تطبيق عددى شامل يهدف الى توضيح صلاحية وامكانية تطبيق الطريقة المقترحة ودقتها فى تعيين حجم عناصر النظام المقترح وامكانية استخدامها فى التنبوء بتأثير الزيادة فى سعر أى عنصر أو كفاءته على تكلفة النظام وتكلفة الكيلووات . ساعة المولد . وقد أوضحت الدراسة أيضا تأثير شكل منحنى الحمل على التصميم الأمثل للنظام وتكلفة وحدة الطاقة حيث أنه قد تم اختيار خمسة أشكال لمنحنى الحمل مع الاحتفاظ بطاقة يومية ثابتة للمقارنة بينهما . ويقدم البحث فى نهايته النتائج والتوصيات الهامة المستنبطة .

CT - Integration of solar photovoltaic cells with wind turbine generators and utilizing stand alone renewable energy system for supplying the loads installed in the remote s the main subject of this paper. A suggested method is presented in this paper for dete ining:

1- The design of the stand alone system:
  a. Types and numbers of wind turbine generators.
  b. Size of solar photovoltaic cells.
  c. Battery storage capacity.
  d. Rating of the required power conditioner.

2- The price of the generated kilowatthour.

These two items are essentially dependent upon:

1- The characteristics of the site which are represented by:
  a. Solar radiation incident on the solar cells
  b. Wind speeds which affect the rotor blades of the wind turbine
2- Load curve shape
3- Costs and efficiencies of the elements consisting the system.

This method permits estimation of the effect of these characteristics on the design and the energy unit price. Impact of any change in the price and efficiency of any element can also be computed.

A numerical application is presented in this paper. This application demonstrates validity and accuracy of the proposed method. It illustrates also that by this method, the increase or decrease in kilowatt hour price due to present or future increase or decrease in cost of any element can be predicted. Impact of load curves shapes on the design and energy unit price is studied in details by taking five shapes of load curves with constant daily energy to facilitate the comparison, final executive results and recommendations are summarized at the end of this application.

1- INTRODUCTION

Each paper from the most pre-published ones studies only one form from the renewable energy systems. Few of them interested with the integrated renewable energy systems. This paper is concerned with evaluating the avail obtained from integration of more forms of renewable energy systems. This paper interested with solar photovoltaic cells integrated with wind turbine generators, battery storage and power conditioner to form a stand alone energy system. This paper presents a method for determining the types and numbers of wind turbine generators that interconnects with a specific sizes of solar cells to power a certain load installed at a given remote site.

2- DESIGN OF THE INTEGRATED WIND-SOLAR POWER SYSTEMS FOR POWERING LOADS INSTALLED IN REMOTE SITES.

Solution procedures of the method proposed for determining the design of the integrated solar-wind power system shown in Fig. 1 are demonstrated in the flow chart shown in Fig. 2.

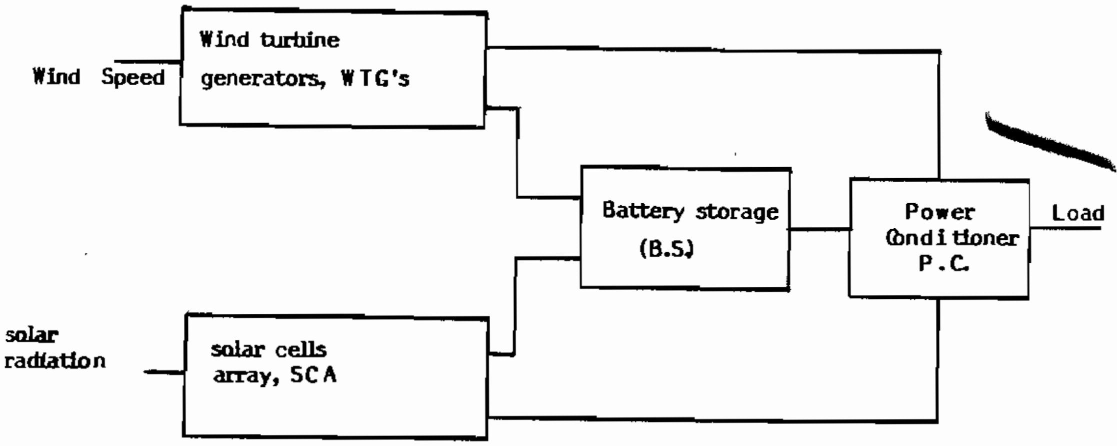


Fig.1. Wind-solar integrated power system.

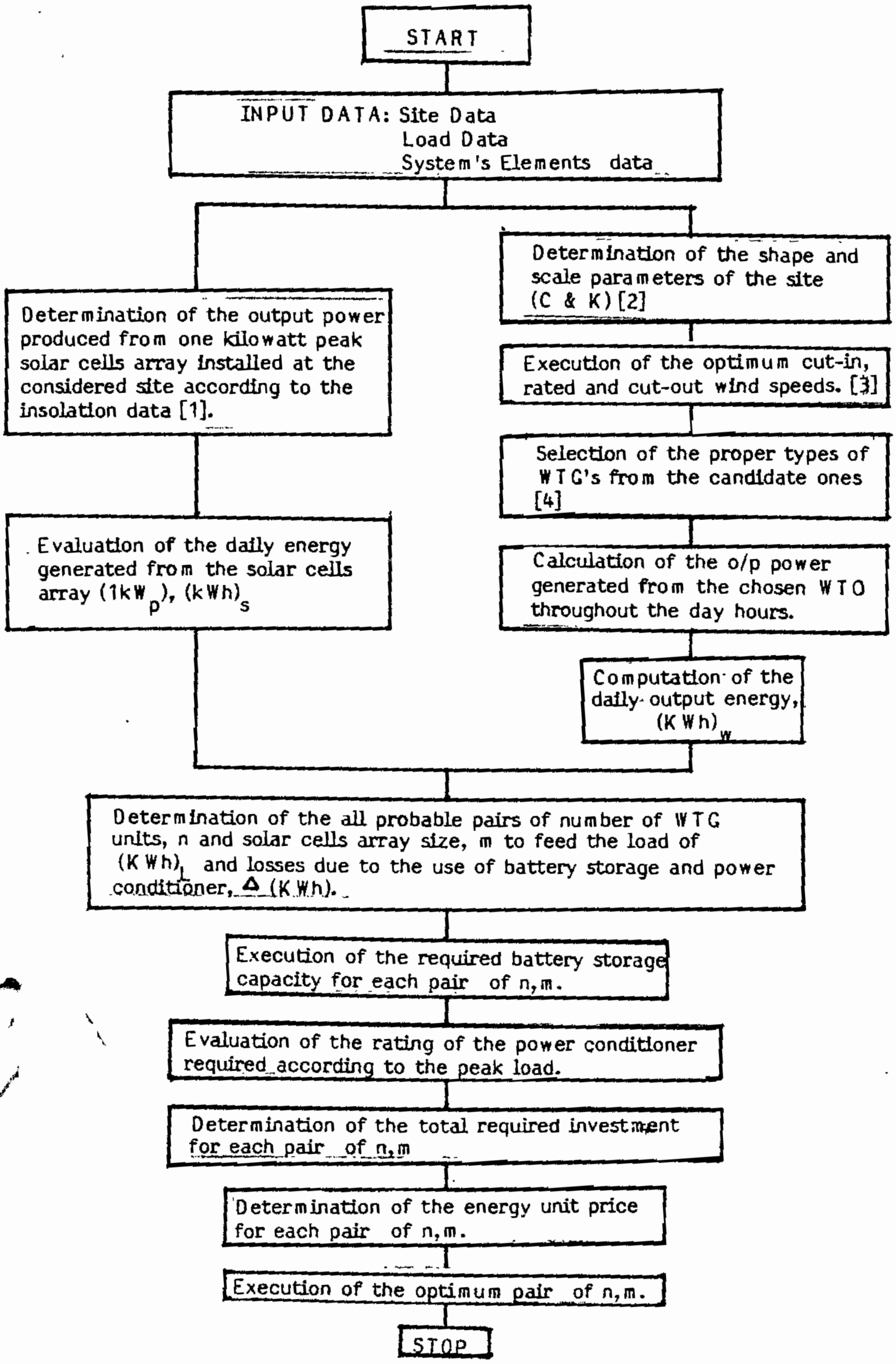


Fig. 2. Determination of the optimum design of the integrated wind-solar power system.

Types and numbers of WTG's, solar cells size, battery storage capacity and rating of power conditioner can be determined in a simple manner. The data necessitated for this method are:

1- Site data

The site considered is represented by:

a. Wind speed occured throughout the day hours for the site at which the system will be installed. The wind speed is measured at a certain height and can be modified for another height [3].

b. Solar radiation intensity incident along the day hours on the solar cells.

2- Load data:
Total kilowatt hours required along the day hours for the loads to be supplied

3- System's elements data: system's elements data are:

a. Characteristics of the solar cells are:
current-voltage relation-conversion efficiency-price/kilowatt peak of solar cells.

b. Specifications of WTG's are

performance coefficient-rotor blade diameter-transmission efficiency-generator rating and its efficiency-cost per square meter of rotor swept area-cost per kilowatt rating of the generator-cut-in, rated and cut-out wind speeds of the WIG.

c. Characteristics of the battery storage and the power conditioner; their efficiencies and prices; and depth of discharge of the battery.

On determining the design of an integrated wind-solar power system, the following statements are carried out:

I. From the wind speed data presented in Fig3, scale and shape parameters, c and k of the site are computed [2]. These parameters are considered as indicies showing the properness of this site for installing WIG's.

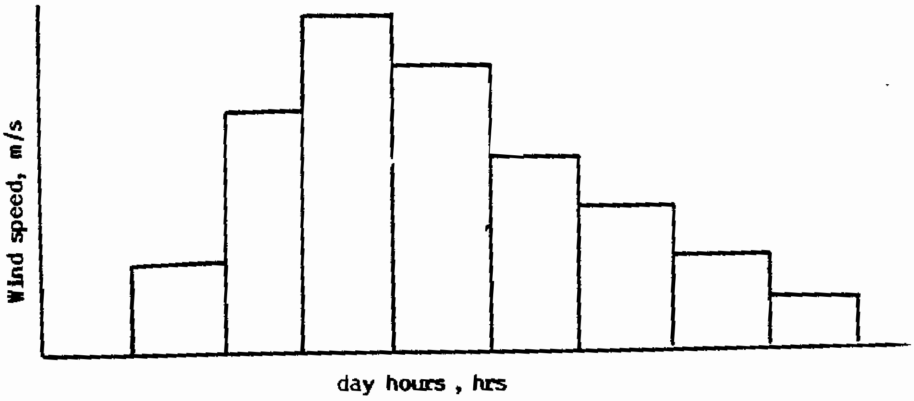


Fig.3. Wind-speed curve

II. From c and k, estimate the optimum cut-in, rated and cut-out wind speeds (V_C, V_R and V_F respectively) demonstrated in Fig.4[2]. Practically, cut-in and cut-out wind speeds are taken as half and twice of the rated wind speed.

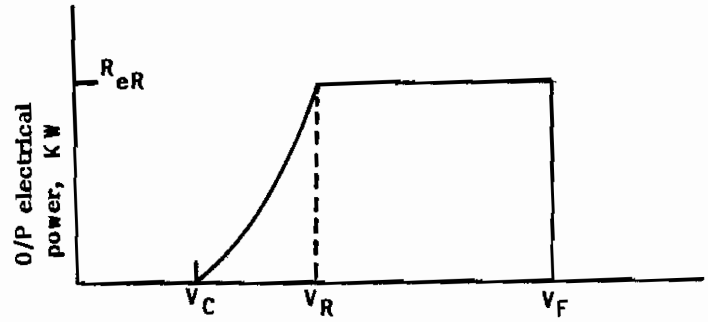


Fig.4. O/P power-wind speed relation of WTG.

III. According to the optimum cut-in, rated and cut-out wind speed, select the proper WIG'S types from the actually found ones in the markets [4].

IV. Computation of the Power output from the selected WTG'S. The output power at various wind speeds ranged between V_C and V_F is [3]:

$$\begin{array}{ll} P = 0 & V < V_C \\ P = 0.647\ \eta_o\ A\ V^3 & V_C \leq V \leq V_R \\ P = P_{eR} & V_R \leq V \leq V_F \\ P = 0 & V > V_F \end{array} \qquad \ldots (1)$$

Where, P_{eR} is the rated electrical power, W ,
η_o is the overall efficiency,
A is the rotor blade swept area, m² and
V is the wind speed, m/s.

V. Representation of the generated power throughout the day hours as depicted in Fig.5

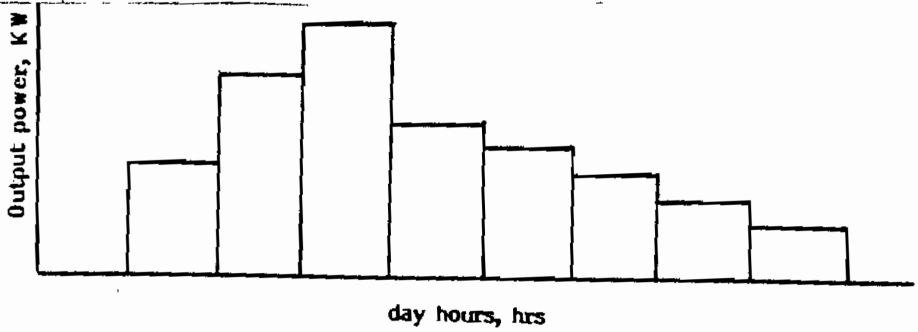


Fig.5. Output power-dayhours relation

VI. Execution of the daily energy generated from the WTG, $(KWh)_W$. From Fig.5, t the generated energy is:

$$(K\ Wh)_W = \sum_{i=1}^{n} P_i \times \Delta t \qquad \ldots (2)$$

where, P_i is the output power, KW at the ith wind speed, V_i, and

Δt is the period of time through which P_i is maintained constant, hr

VII. The WTG that produces the largest amount of energy is the relevant WTG from the above selected ones.

VIII. Determination of the electrical output power from one kilowatt peak $(1K.W_p)$ solar cells array installed at a certain site as shown in Fig.6. The electrical output power

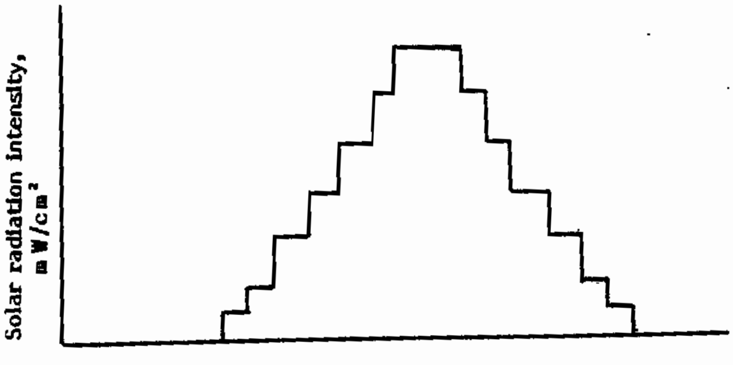


Fig.6. Output Power Vs. day hours.

at a specific solar radiation intensity, SRI_i m W/cm²) is:

$$(P_e)_{SRI_i} = 1\ (KW) \times \frac{SRI_i}{100} \ KW \qquad \ldots$$

Overall solar cells array efficiency, η_o is assumed to be constant at all solar radiation sities to facilitate the calculations.

IX. Estimation of the daily energy generated from one kilowatt peak solar cells arra, $(KWh)_s$ The daily generated energy is:

$$(KWh)_s = \sum_{i=SRSRL}^{SSSRL} (P_s)_i \cdot \Delta t \qquad \ldots (4)$$

where, SRSRL is the sunrise solar radiation level intensity, m W/cm²

SSSRL is the sunset solar radiation level intensity, m W/cm².

P_i is the power output at the ith. solar radiation level, KW, and
Δt is the period of time during which P_i is constant.

X- On computing number of WTG's, n and the rating of SCA, m required to meet the load, $(KWh)_L$, the following expression must be verified:

$$n\,(KWh)_W + m\,(KWh)_S = (KWh)_L + \Delta(KWh) \qquad \ldots (5)$$

where,

$(KWh)_L$ is the energy required for the load
$\Delta(KWh)$ is the energy required to supply the losses due to the use of the battery storage and the power conditioner.

XI. Determination of the battery storage capacity required for compenating the deficit and the surplus in the energy. For a selected paire of (n,m) the battery storage required can be determined from Table 1.

Table 1: Determination of the battery storage capacity.

Day hours	1	2	3	.....	24
Solar radiation intensity, mW/cm²	SRI_1	SRI_2	SRI_3		SRI_{24}
Wind speed, m/s	V_1	V_2	V_3		V_{24}
Load demand, W	PL_1	PL_2	PL_3		PL_{24}
O/P from WTG's, W	PW_1	PW_2	PW_3		PW_{24}
FROM SCA, W	PS_1	PS_2	PS_3		PS_{24}
surplus/deficit energy	E_1	E_2	E_3		E_{24}
accumulative surplus/ deficit energy	$\sum E_1$	$\sum E_2$	$\sum E_3$		$\sum E_{24}$

Where,

$$E_1 = (PW_1 + PS_1) - PL_1$$
$$E_2 = (PW_2 + PS_2) - PL_2$$
$$\text{-------------------}$$
$$E_{24} = (PW_{24} + PS_{24}) - PL_{24}$$

$$\sum E_1 = (PW_1 + PS_1) - PL_1$$
$$\sum E_2 = (PW_1 + PS_1) + (PW_2 + PS_2) - PL_1 - PL_2$$
$$\text{-- -- -- -- -- -- -- -- -- --}$$
$$\sum E_{24} = \sum_{i=1}^{24} (PW_i + PS_i) - PL_i = \text{initial charge of the battery}$$

The maximum value of the accumulative surplus or deficit energy determines the necessary battery storage capacity

XI. Determination of the maximum number of WTG's required:
In determining the maximum number of WTG's, it is assumed that the load is supplied only from the WTG's. Hence, the maximum number of WTG's, n_{max} is:

$$n_{max} = \frac{(KWh)_L + \Delta(KWh)}{(KWh)_W} \text{ WTG's} \qquad \ldots (6)$$

XII. Determination of the maximum size of SCA:
On determining the maximum size of SCA, m_{max} it's assumed that the load is fed only from the solar cells. Then, the maximum size of solar cells array, m_{max} is:

$$m_{max} = \frac{(KWh)_L + \Delta(KWh)}{(KWh)_S} \text{ kW}_p \qquad \ldots (7)$$

XIII. From the above two statements, all the probable pairs of n , m can be chosen.

IIII . For each probable pair of (n,m), total investment is computed including the investment of:

WTG's (their electrical and mechanical parts), solar cells array, battery storage, power conditioner, installation, project management, operation, maintenance, battery replacement, etc.

IIII . The price of the generated energy unit; properness index; is executed. The paire of (n,m) that achieves the minimum energy unit cost assigns the optimum number of WTG's and solar cells array size, associated in meeting the load demand. Therefore, the av obtained from the integration of the solar cells with the wind turbine generators formi a stand alone renewable energy source is developed.

3- NUMERICAL APPLICATION

Objective:

It is required to determine the optimum design of the integrated wind-solar power system necessitated to feed a load, the load curve is shown in Fig.7.

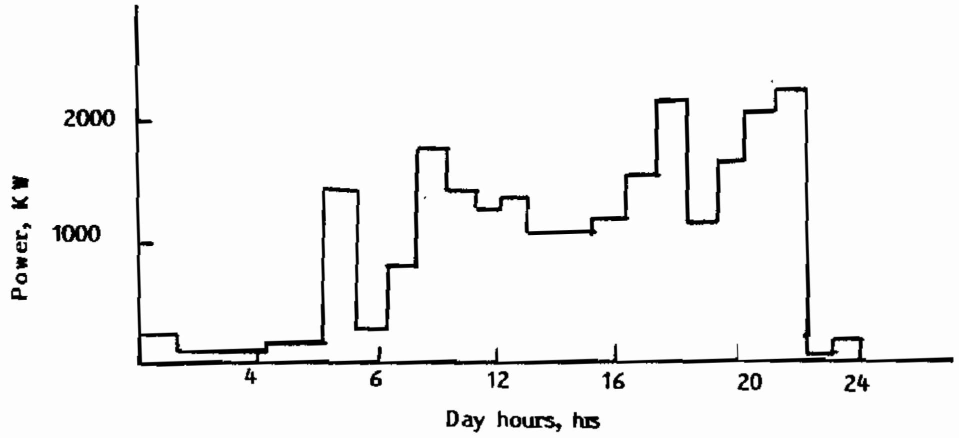


Fig.7. Original load curve

The average incident insolation and the wind speed occured throughout the day hours of the site considered are presented in Table 2.

Table 2: Average insolation and wind speed throughout the dayhours of the considered site

dayhours, hrs	1	2	3	4	5	6	7	8		10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Average insolation, m W/cm²	0	0	0	0	0	5	13	24		42	49	51	44	44	35	22	11	4	2	0	0	0	0	0
Average wind speed, m/sec	11	11	12	12	11	12	14	15	15	15	14	11	11	11	11	11	10	10	9	10	10	9	10	9

From the load curve and the site data presented, the following factors are executed:

1- Total daily kilowatt hour required for the load is:
22106.4 KWh.

2- Scale and shape parameters of the site are:
7.06 and 2.3, respectively.

3- Optimum rated wind speed is : 12.5 m/s

4- The proper wind turbine generators have the following characteristics:

a. V_C = 4 m/s , b. V_R = 12.5 m/s
c. V_F = 30 m/s , d. R_D = 15 m and
e. P_{eR} = 55 KW

The output power from each wind turbine generator is depicted in Fig.8. The total daily energy produced from the WTG, $(KWh)_w$ is 1079.8 KWh.

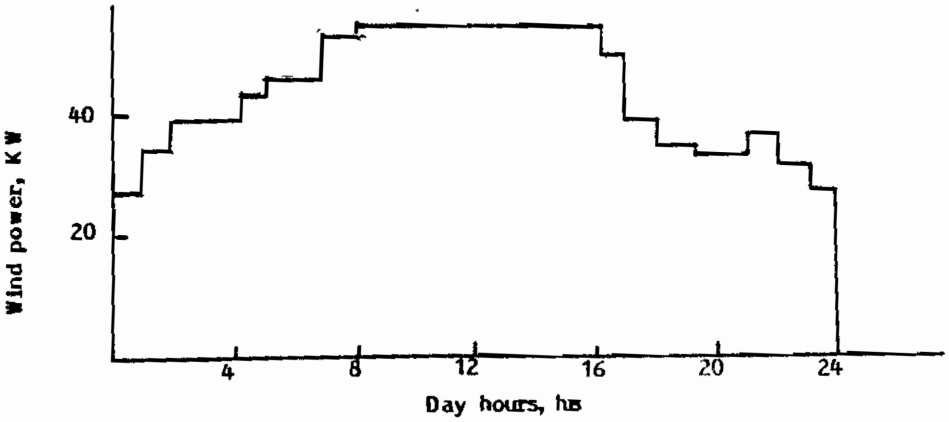


Fig.8. Output power from a WTG.

The output power produced from a one kilowatt peak (1 KW_p) solar cells array is illustrated in Fig.9. The total output energy, $(KWh)_s$ is 3.794 KWh.

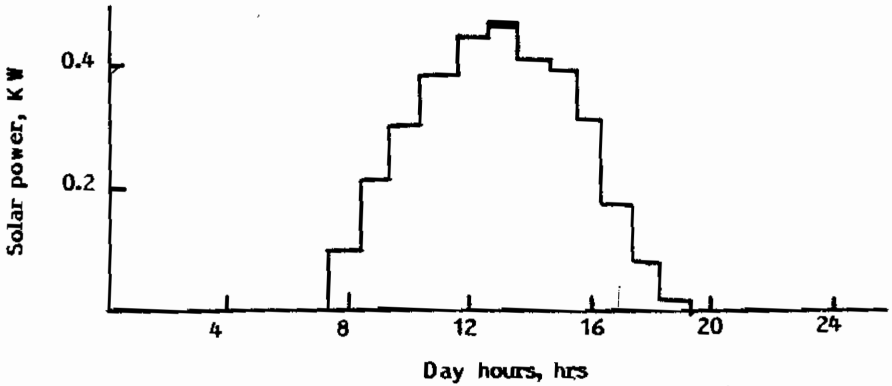


Fig.9. Output power from 1 KW_p SCA

determining the maximum number of wind turbine generators, n_{max}., the load is assumed be supplied from the wind turbine generators only. Hence the value of n_{max} is:

$$n_{max} = \frac{\text{Total load KWh}}{\text{KWh obtained from each WTG}} \qquad \ldots (8)$$

Then, $n_{max.} = \frac{22106.7}{1079.8} = 20$ WTG,s

The value of n_{max}. is modified to achieve the following Equation:

$$\text{Surplus KWh } (P_+) \text{ X Battery efficiency } (\eta_B) = \text{deficit KWh } (P_-) \qquad \ldots (9)$$

The number of WTG's achieved the above equation is 23 WTG as revealed in Table 3.

Table 3: Determination of the maximum number of WTG's and the battery storage required

day hours, hrs	1	2	3	4	5	6	7
O/P of WTG's, P_w	774	896	1022	1163	1234	1230	1241
$\eta^*_{pc} \times P_w$, KW	697	807	920	1047	1110	1107	117
P_L , KW	165	70	70	70	90	90	1376
ΔP^{**} , KW	+532	+737	+850	+977	+1020	+1017	-259

day hours, hrs	[illegible]	9	10	11	12	13	14	15	16	17
O/P of WTG's, P_w	[illegible]	1265	1265	1265	1265	1265	1265	1265	1265	1265
$\eta^*_{pc} \times P_w$, KW	[illegible]9	1139	1139	1139	1139	1139	1139	1139	1139	1139
P_L , KW	200	712	1695	1335	1200	1218	1030	1040	1080	1470
ΔP^{**} , KW	+939	+427	-557	-197	-62	-79	+109	+99	+59	-332

day hours, hrs	18	19	20	21	22	23	24
O/P of WTG's, P_w	1040	977	879	901	979	820	701
$\eta^*_{pc} \times P_w$, KW	937	825	791	811	881	738	631
P_L , KW	2030	1120	1650	1965	2180	85	165
ΔP^{**} , KW	-1094	-295	-859	-1154	-1199	+653	+466

* η_{pc} is the efficiency of the power conditioner

** $\Delta p = P_W \cdot \eta_{pc} - P_L$

notice that:

$$P_+ \cdot \eta_{pc} + P_- = \text{initial charge}$$

The battery storage capacity, BSC = 7773.529 KWh

P_+ is the surplus power, KW

P_- is the deficit power, KW

On determining the maximum rating of the solar cells array, $(SCA)_{max.}$, the load is assumed to be fed from the solar cells only. The maximum solar cells array is developed from:

$$\text{Maximum rating of SCA, } kW_p = \frac{\text{Total load KWh}}{\text{produced KWh from 1 KW}_p} \qquad \ldots (10)$$

$$\text{Then, } (KW_p)_{max.} = \frac{22106.4}{3.794} = 5826.7 \ KW_p$$

This rating is modified to the value that achieves Eq. g,as demonstrated in Table 4.

Table 4: Determination of the maximum size of the SCA and the associated battery storage capacity (KW_p = 7227).

day hours, hrs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
O/P from SCA, P_s	0	0	0	0	0	0	363	938	1744	2357	3045	3565	3683	3204	3173	2533	1560
$P_s * \eta_{p.c.}$	0	0	0	0	0	0	327	344	1570	2122	2740	3209	3314	2884	2856	2279	1404
P_L, KW	165	70	70	70	90	90	1376	200	712	1595	1335	1200	1218	1030	1040	1080	1470
Δp, KW	-65	-70	-70	-70	-90	-90	-1049	-1049	644	858	426	1405	2009	2096	1854	1816	1199

18	19	20	21	22	23	24
771	325	142	15	0	0	0
694	293	128	13	0	0	0
2030	1120	1650	1965	2180	85	165
-66	-1336	-828	-1952	-218	-85	-165

From the above results, it is found that the number of WTG's and the size of SCA ranges from 0 to 23 WTG's and from o to 7227 KW_p, respectively. If the predescribed load is powered from an integrated wind-solar power system, solar cells array size, number of WTG's, the associated battery storage capacity and the price of the generated energy unit are presented in Table 5. This load is sited at the site predescribed above.

Tables 5: Probable pairs of n and m, the associated battery storage capacity and the energy unit price.

n, WTG's	0	1	2	3	4	5	6	7
m, KW_p	7227	6874	6521	6218	5915	5562	5259	4956
Bsc, KWh	9318	9148	8978	8791	8610	8453	8325	8198
$/KWh	0.2407	0.2309	0.2208	0.2122	0.2035	0.1934	0.1848	0.1764

n, WTG's	8	9	10	11	12	13	14	15	16	17
m, KW_p	4633	4299	3996	3693	3390	3087	2784	2421	2128	1825
Bsc, KWh	069	7959	7832	7704	7576	7448	7320	7210	7082	6954
$/KWh	0.1678	0.1579	0.1493	0.1409	0.1322	0.1236	0.162	0.1054	0.0967	0.0881

n, WTG's	18	19	20	21	22	23
m, KW_p	1521	1218	900	600	300	0
Bsc, KWh	6826	6698	6898	7170	7467	7773
$/KWh	0.0797	0.0703	0.0629	0.0552	0.0478	0.0401

The price of the energy unit is computed on the base of:

Cost of 1 W_p of the solar cells is	\$ 2.5
Cost of KWh of battery storage is	\$ 150
Cost of 1 W of the power conditioner is	\$ 1.0
Cost of the WTG = $C_1 \times A + C_2 \times P_{eR}$	
Where, C_1 and C_2 are constants	19

These costs are selected only to demonstrate the validity of the proposed method. The price of the energy unit cost resulted due to other costs of the system's elements is computed without any difficulties.

On computing the impact of load curve shape on the design of the wind-solar integrated power system and the energy unit price, five shapes of load curves are chosen. The areas under these are maintained constant and equal the energy provided from the load curve shown in Fig.7. These curves are illustrated in Fig.10, and the results obtained are presented in Table 6.

Table 6: Number of wind turbine generators, rating of solar cells array and capacity of battery storage necessitated for the different shapes of load curves and the resulted energy unit cost.

1 st. Load curve.

n (WTG,s)	m (KW_p)	BSC (KWh)	\$ / KWh
0	6827	4873	0.2198
2	6221	4733	0.2030
4	5563	4679	0.1850
6	4959	4648	0.1766
8	4353	4870	0.1524
10	3746	5317	0.1368
12	3140	6110	0.1219
14	2584	6770	0.1082
16	2028	7430	0.0946
18	1471	8117	0.0761
20	950	8731	0.0682
22	350	9627	0.0538
24	0	9714	0.0444

2 nd. Load curve:

0	7277	8835	0.2311
2	6521	7799	0.2095
4	5865	6887	0.1908
6	5159	5851	0.1692
8	4503	4939	0.1385
10	3796	3900	0.1186
14	2484	2140	0.0785
16	1778	2231	0.0605

18	1121	2253	0.0415
20	500	2292	0.0264
22	0	2347	0.0206

3 rd Load curve:

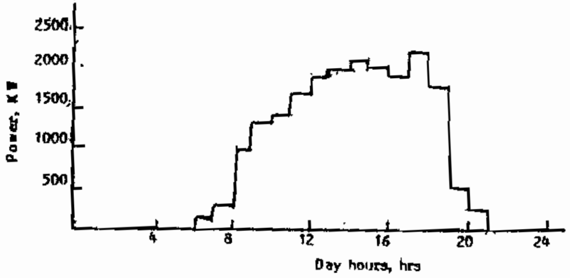
0	6827	3227	0.2174
2	6171	2648	0.1982
4	5465	2126	0.1778
6	4909	2137	0.1598
8	3847	2429	0.1344
10	3243	2741	0.1186
12	2687	3477	0.1048
14	2131	4246	0.0914
16	1573	5039	0.0792
18	1018	5845	0.0648
20	500	6526	0.0521
22	0	7150	0.0398

4 th Load curve:

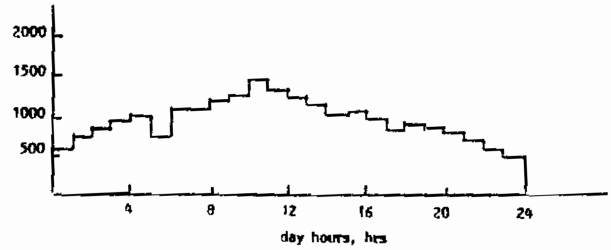
0	7427	13130	0.2532
2	6721	12554	0.2316
4	6065	12009	0.2124
6	5409	11469	0.1944
8	4753	10928	0.1752
10	4096	10467	0.1562
12	3490	9986	0.1387
14	2834	9539	0.1198
16	2178	9091	0.1008
20	900	8176	0.0641
22	250	8024	0.0458
23	0	7920	0.0389

5 th Load curve:

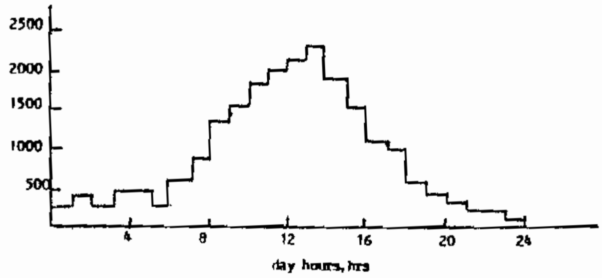
0	7459	10942	0.2436
2	6803	10585	0.2254
4	2147	10228	0.2071
6	5491	7870	0.1888
8	4834	9593	0.1706
10	4228	9310	0.1538
12	3572	9166	0.1361
14	2966	9024	0.1195
16	2359	8883	0.1032
18	1703	8793	0.0857
20	1100	8775	0.0694
22	500	8766	0.0533
24	0	8612	0.0391



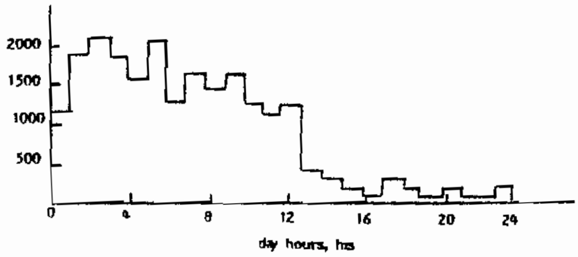
a- 1st load curve



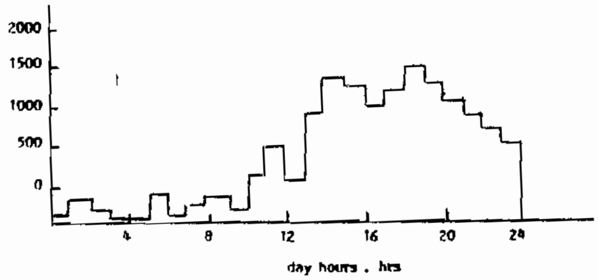
b - 2 nd. load curve



c - 3 rd . load curve



d - 4 th . load curve



e - 5 th. load curve

Fig.10 . The Deffirent Load Curves.

4- CONCLUSTONS

This paper is concerned with evaluating the avail obtained from using wind-solar power systems in powering loads installed in remote sites. This method shows that, there are several factors must be investigated carefully on determining the design and the energy unit price. These factors are:

1. load curve shape.
2. wind speed and solar radiation intensity throughout the day hours for the site considered.
3. technical and economical constraints imposed on the use of these systems.
4. cost of each element involved.

These factors have important role in determining:

a. Number and types of wind turbine generaters
b. proper size of solar cells array
c. battery storage capacity required to compensate the surplus and deficit power
d. produced energy unit price
e. rating of the power conditioner

All the presented results in this research varies from site to site and from load to another.

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