FEASIBILITY STUDY FOR USING RENEWABLE ENERGY SYSTEMS FOR THE ELECTRIFICATION OF A REMOTE SETTLEMENT IN SAUDI ARABIA

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ABSTRACT

The majority of the electric energy consumers in Saudi Arabia are concentrated in the major cities and towns. However, some electric loads are scattered in many small isolated settlements far away from the major load centers. Small generating units burning Diesel are used in such locations. The cost of fuel and fuel transportation make the cost of the generated energy very high.

A study for supplying a remote village in Saudi Arabia with electric energy using an alternative energy sources is being conducted at King Fahd University of Petroleum and Minerals. The study considers the use of several options comprising of standalone diesel, wind and solar standalone systems. In addition the study also considers the use of hybrid diesel/wind/solar systems. The study is sponsored by King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia.

In this paper, a review of the existing wind and solar data in the region will be presented. The survey of the currently available wind and solar energy systems will be summarized. The design parameters and system selection criteria will be highlighted. The paper will present results of the feasibility study including the cost of production of electric energy from the various systems.

Keywords: *Renewable, Wind, Solar, Diesel, Electrification.*

الملخص

إن الأغلبية الساحقة لمستهلكي الطاقة الكهربائية في المملكة العربية السعودية تتمركز في المدن الرئيسية والمراكز الحضرية ولكن في المقابل هنالك مجموعات متفرقة تسكن في أماكن نائية معزولة عن الشبكات الكهربائية. تستخدم مولدات الديزل وباحجام مختلفة من أجل تغذية هذه المجموعات بالتيار الكهربي. إن تكلفة وقود الديزل ونقله لهذه المناطق النائية تسبب في ان تكون تكلفة إنتاج الطاقة الكهربائية عالية جدا بالمقارنة مع الشبكات وعليه فان البحث في وسائل أخرى لإنتاج الطاقة مطلوب. ومن هذا المنطلق فان دراسة قد تمت في جامعة الملك فهد للبترول والمعادن من أجل استخدام وسائل أخرى لأنتاج الطاقة لقرية نائية. إن الدراسة تبحث في استخدام طاقة الرياح ، الطاقة الشمسية ومقارنة ذلك باستخدام الديزل. هذه الدراسة مدعومة من مدينة الملك عبد العزيز للعلوم والتقنية - الرياض.

تتضمن هذه الورقة مسح عن إمكانية استخدام طاقة الرياح والطاقة الشمسية في المنطقة المختارة وذلك بتحليل المعلومات المتوفرة. كذلك تناقش الورقة مكونات التصميم المقترح ومن ثم تقدم الورقة ملخصا اقتصاديا عن تكاليف انتاج الطاقة المختلفة في القرية المختارة.

1. INTRODUCTION

The majority of the electric energy consumers in Saudi Arabia are concentrated in the major cities and towns. However, some electric loads are scattered in many small isolated settlements far away from the major load centers. To extend the electric services to these settlements from the main grid is, in many cases, uneconomical and technically unviable. Small generating units burning Diesel are used in such locations. The cost of fuel and fuel transportation make the cost of the generated energy very high.

A study for supplying a remote village in Saudi Arabia with electric energy using alternative energy sources was conducted at King Fahd University of Petroleum and Minerals. The study considered the use of several options comprising standalone diesel, wind and solar standalone systems. In addition the study also investigated the use of hybrid diesel/wind/solar systems. The study was sponsored by King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia.

The technology of the wind machines has improved dramatically over the last decade and their prices have dropped substantially. These technical improvements have resulted in an increase in the production capacity of wind machines. Machines in the range of 2 MW are commercially available. The rate of increase in installed capacity worldwide during the last ten years is 30 per cent per annum. It is expected that more than 100,000 MW of wind power will be installed in Europe alone by the year 2030. The cost of producing one kWh of electricity from wind energy systems has dropped to become competitive with conventional energy sources [Wind Energy Facts 1998], [World Wind Energy.., 1999], [The Wind Energy Pioneer, 1999], [Wind Energy Facts, 1999], [Laali et al., 1998].

The generation of electricity through the use of photovoltaic (PV) systems has also grown in a dramatic manner. Today, there are thousands of villages and remote settlements throughout the world that are supplied by PV systems. The global PV market has grown at an average rate of 16 percent per annum over the last decade. In many instances, the life-cycle costs for PV systems are less than those of non-renewable energy systems [Standalone, 1980], [Groumpos et al., 1987].

Standalone wind and solar (photovoltaic) systems, because of their intermittent nature, are not economically competitive to conventional sources of electrical energy since they will require a large storage capacity to meet the load demand. Hybrid systems of wind, solar, and diesel are finding acceptance and being widely used in rural electrification [Eric, 1999], [Nordex,1999]. Worldwide wind/diesel, wind/PV/diesel and PV/diesel hybrid systems are now commercially available. They represent an economical alternative to diesel generators that are being used to meet the electrical load demand of many remote villages and settlements.

The major objective of this study was to investigate the technical and economical feasibility of utilizing renewable energy sources to meet the electrical energy requirement of isolated villages and settlements in Saudi Arabia. Specifically the wind, solar, and hybrid systems were investigated. The merit of each option was evaluated with regards to its size, operational requirements, investment cost, maintenance, and support availability. An economic analysis of the above options was performed and their costs were compared with the use of diesel generator to generate the required power and the connection of the village to the nearest utility grid.

2. SITE SELECTION

A remote isolated village was selected for the project study. The village is Al-OWEIQELA in the north east of Saudi Arabia. It is located at an almost equal distance from the towns of Arar and Al-Jouf. The wind and solar data are available for these two towns and may be used as a representative data for Al-OWEIQELA. The village was selected because of the availability of solar and wind data close to it and the availability of the required electrical load data for at least one calendar year.

Diesel units currently supply the village and it has an operational electrical grid. Eleven diesel generators power the village electrical system. The installed generation is 8 MW of diesel units [General, 1999]. The generators vary in size from 0.6 MW to 2.3 MW. Table 1 shows some of the features of the load for the year 1998. The number of customers is more than1200. The peak load in 1998 was 4.34 MW.

Table 1 Al-OWEIQELA Electrical load Monthly Statistics-1998

Month	Max Load (MW)	Min. Load (MW)	Energy (GWh)	Load Factor
Jan.	3.25	1.38	1.617150	0.67
Feb.	3.25	1.15	1.305995	0.60
Mar	2.60	0.87	1.109695	0.7
Apr	2.60	0.84	1.002255	0.64
May	3.33	1.05	1.555520	0.63
Jun.	3.87	1.60	2.041962	0.72
Jul.	4.09	1.94	2.179127	0.72
Aug.	4.34	2.56	2.566705	0.79
Sep.	4.22	1.41	1.992264	0.66
Oct.	2.86	0.85	1.137954	0.53
Nov.	2.07	0.87	0.914803	0.61
Dec.	2.92	0.88	1.321558	0.61

3. WIND DATA

Hourly wind speed data at 20, 30 and 40 meters height for Arar was obtained from KACST [KACST, 1999]. The monthly average wind speed data are shown in table 2 for 1997. The data indicated that the wind speed measured at 40 m height was higher than those measured at

30 m height. The data presented in Table 2 show that the wind speed during the summer months (March to August) is relatively higher than those of the winter months (October to February). The percentage wind speed frequency distribution for Arar at 40-meter height is shown in Table 3 for the year 1997. It is clear from the results that wind machines installed at Arar will not produce any electricity for about 30 % of the year.

The yearly diurnal variation of wind data indicates that the wind speed is lowest during daytime while it is highest during nighttime. This clearly indicates that there is a good possibility for utilizing hybrid systems (wind plus solar) to increase the energy generated during the daytime.

Table 2 Monthly average wind speeds in(m/sec.) at different heights at Arar for 1997

Height	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Yearly
20 m	4.480	4.520	6.072	5.294	4.940	5.422	6.218	5.844	4.852	4.761	3.982	4.863	**5.10**
30 m	5.100	5.110	6.625	5.874	5.444	5.941	6.758	6.318	5.326	5.259	4.406	5.440	**5.63**
40 m	5.370	5.320	6.911	6.058	5.524	6.153	7.042	6.587	5.686	5.624	4.662	5.739	**5.89**

Table 3 Percentage wind speed frequency distribution at Arar for 1997 at 40 m

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Yearly
Ws< 3.5	28.09	36.76	14.52	21.39	32.26	18.61	11.29	15.32	24.58	25.81	39.72	34.35	**25.1**
3.5<ws<5	20.56	18.90	14.11	24.17	16.13	16.53	13.31	16.53	20.28	23.52	22.08	19.81	**18.8**
5<ws<7	30.24	21.58	29.84	25.69	24.87	34.31	24.46	27.28	28.33	27.55	23.33	25.9	**26.99**
7<ws<10	20.43	17.26	30.78	20.56	22.98	26.53	45.83	34.54	25.56	18.01	13.61	16.34	**24.48**
ws>10	0.672	5.506	10.75	8.194	3.763	4.028	5.108	6.317	1.250	5.108	1.25	3.601	**4.635**

4. WIND MACHINE CHARACTERISTICS

Information about wind turbines available in the market from different companies was collected. NORDEX provided complete information about a wide range of wind turbines [Nordex, 2000]. Therefore the wind turbines manufactured by NORDEX were selected for the present study. Specifications of Nordex wind turbines are provided in Table 4. The power curves of wind machines model N27/150, and N29/250 are shown in Fig.1

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Table 4 Specifications of Wind Turbines available from Nordex Company

Model	N27/150	N29/250	N43/600	N54/1000	N60/1300
Nominal power (kW)	150/30	250/45	600/125	1000/200	1300/250
Cut-in wind speed (m/s)	3-4	3-4	3-4	3-4	3.5
Nominal wind speed (m/s)	16	15.5	13	14	15
Cut-out wind speed (m/s)	25	26	43	25	25
Rotor diameter (m)	27	29.7	47	54	60
Steel tower, hub height (m)	30,40,50	30,40,50	40,50,60	50,60,70	50,60,70
Cost ($)	160,274	173,732	385,392	675,354	874,779

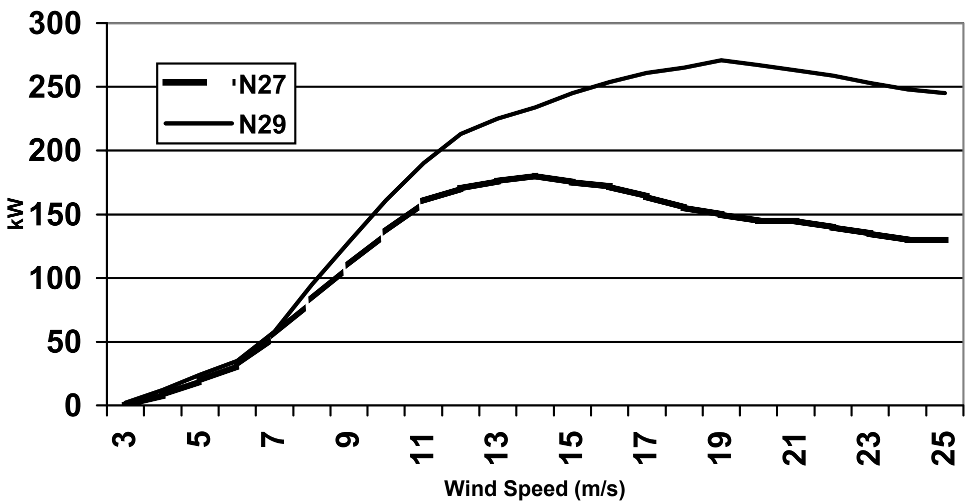

Figure 1. Power curve of N27/150 kW and N29/250 turbines from Nordex

To study the wind machines performance, stand alone wind energy systems with an electrical storage was adopted as a start. In order to calculate the energy generated from wind turbines using hourly wind speed measured at the selected site, a computer program was developed. It starts with calculating the hourly wind energy generated from the specified number and rated power of wind machines. The generated hourly energy is then compared to the hourly demand. If the demand is more than the generated energy the difference is obtained from the storage system. When the generated wind energy is more than the load, the excess energy is utilized to charge the storage system until the storage capacity is reached. After the storage capacity is supplied, the excess generated energy is dumped to a dummy load.

The tabulated power curve data were curve fitted to obtain a mathematical model to calculate the energy generated under the typical hourly wind speed data collected. The monthly average daily values of generated energy from wind farms, each of 6 MW capacity, made up of 40*150, 24*250, 10*600, and 6*1000 kW wind turbines were calculated using the wind data for Arar. The results are shown in Table 5[KACST, 2000].

The results depicted in Table 5 indicate that the wind farm made of 40 wind turbines each of rated power of 150 kW produces more energy, every month of the study period, than those produced by wind farms of the same overall rated power made of wind turbines of larger rated power. Therefore the wind turbines of rated capacity of 150 kW will be utilized in the remaining part of this study. It was also found that a wind farm of a 6 MW rated power will not satisfy the load during any month of the study period and consequently it cannot be utilized with any storage system. A wind farm of 12 MW rated power was then considered.

Table 5. Monthly average daily values of generated wind energy in (kWh) utilizing the wind speed data of the year 1997

Month	Wind Machines Rated Power (kW)				Demand (kWh)
	150	250	600	1000	
January	30,422	20,502	17,738	14,317	52,166
February	33,809	22,578	20,826	16,463	46,536
March	58,106	38,291	35,759	27,524	35,796
April	42,283	27,835	25,959	19,607	33.408
May	35,216	23,556	21,065	16,687	50,178
June	42,462	28,374	25,045	19,936	68,065
July	59,910	39,746	35,999	28,379	70,294
August	52,089	34,646	31,305	24,840	82,796
September	35,658	23,922	20,940	16,800	66,408
October	34,996	23,340	21,284	16,677	36,708
November	22,114	15,023	13,027	10,547	30,493
December	28,884	19,438	13,027	13,798	42,630

The time frequency distribution of the state of charge of the storage system for a wind farm of 12 MW rated power with storage capacities of 1,000, 1,200, 1,500 and 1,700 MWh is provided in Table 6. These storage capacities were selected based on trial and error basis. For example, the storage charge level will be equal or less than 10 % of the full charge capacity of the storage systems of 1,000, 1,200, 1,500, and 1,700 during 9.4, 7.3, 1.3, and 0.0 % of the time, respectively. The data presented above, assuming the storage system can be discharged to 10 % of its capacity, indicate that a storage capacity of 1,700 MWh will be required with the wind farm of a rated power of 12 MW to satisfy the specified demand. This required storage capacity is about 66 % of the energy required to meet the load during the month of July, which is 2,566,676 kWh. In order to decrease the storage capacity to be utilized, two wind farms with capacities of 15 and 18 MW have been studied. Assuming the storage system can be discharged to 10 % of its capacity, the results indicate that a storage capacity of 700 MWh will be required with the wind farm of a rated power of 15 MW and a storage capacity of 350 MWh will be required with the wind farm of a rated power of 18 MW to satisfy the specified load.

Table 6 Percentage time frequency distribution of the storage state of charge for a wind farm of 12 MW rated power.

Charge Level	Storage Capacity (MWh)			
	1,000	1,200	1,500	1,700
0 – 10 %	9.4	7.3	1.3	0.0
10 – 20 %	4.4	4.8	5.9	0.8
20 - 30 %	1.7	2.5	3.1	6.9
30 – 40 %	1.0	1.6	3.8	3.5
40 – 50 %	3.1	1.0	3.2	3.7
50 – 60 %	2.9	4.5	2.6	2.8
60 – 70 %	3.6	5.2	6.5	6.3
70 – 80 %	8.2	6.2	6.8	6.3
80 – 90 %	11.0	12.0	13.3	14.8
90 – 100 %	54.7	54.9	53.5	54.9

5. WIND/DIESEL SYSTEM

The performance of hybrid wind/diesel energy conversion systems was investigated. Small storage capacity of 1 MWh (just enough to supply the peak demand for about 12 minutes) was utilized with all considered systems. In this case, the wind energy was utilized to meet the demand. If the hourly-generated wind energy was not enough, energy was obtained from the storage system. If both the wind energy and the storage were not enough to meet the demand, the diesel system was operated and the diesel-generated energy was calculated together with the number of hours during which the diesel was in operation. The required diesel power and the diesel power frequency distribution were also calculated. When the generated wind energy was more than the demand, the excess energy was utilized to charge the storage system.

In order to investigate the interaction between the wind farm and the diesel generator, four different wind farm sizes 3, 6, 9, 12 MW were considered. Table 7 shows the monthly average daily values of energy generated from the wind farms while Table 8 shows the monthly average daily values of energy generated from the diesel for the year 1997. The number of hours of diesel-generated power is provided in Table 9 and the number of hours of diesel operation each month is given in Table 10 for the year1997.

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Table 7 Monthly average daily values of wind generated energy (kWh) for wind farm rated power of 3, 6, 9, and 12, MW for the year 1997

Month	Wind Farm Rated Power (MW)				Demand
	3	6	9	12	(kWh)
January	15,211	30,422	45,633	60,845	52,166
February	16,904	33,809	50,713	67,618	46,536
March	29,053	58,106	87,160	116,213	35,796
April	21,141	42,283	63,425	84,567	33.408
May	17,608	35,216	52,824	70,432	50,178
June	21,231	42,462	63,694	84,925	68,065
July	29,955	59,910	89,866	119,821	70,294
August	26,044	52,089	78,133	104,177	82,796
September	17,829	35,658	53,488	71,317	66,408
October	17,498	34,996	52,494	69,992	36,708
November	11,057	22,114	33,171	44,228	30,493
December	14,442	28,884	43,326	57,768	42,630

Table 8 Monthly average daily values of diesel generated energy (kWh) for wind farm rated power of 3, 6, 9, and 12 MW for the year 1997

Month	Wind Farm Rated Power (MW)				Demand
	3	6	9	12	(kWh)
January	37,553	29,443	25,716	23,623	52,166
February	32,083	27,271	24,914	23,458	46,536
March	14,954	10,338	8,441	7,401	35,796
April	18,345	14,425	12,692	11,599	33.408
May	35,002	28,013	25,307	23,678	50,178
June	47,402	34,432	27,805	24,515	68,065
July	41,193	26,384	21,444	18,761	70,294
August	56,854	40,095	33,152	29,575	82,796
September	48,923	37,429	32,163	29,157	66,408
October	22,444	17,020	14,874	13,713	36,708
November	21,268	17,658	16,212	15,358	30,493
December	30,028	25,117	22,976	21,622	42,630

Table 9 Number of hours of diesel power requirement with wind farm rated power of 3, 6, 9, and 12 MW for the year 1997

Diesel Power Requirement (MW)	Wind Farm Rated Power (MW)			
	3	6	9	12
0 – 0.5	501	360	251	203
0.5 – 1.0	1088	754	580	468
1.0 – 1.5	1859	1381	1198	1090
1.5 – 2.0	1560	1178	1011	918
2.0 – 2.5	1066	797	665	608
2.5 – 3.0	689	495	447	439
3.0 – 3.5	347	307	280	248
3.5 – 4.0	200	159	144	129
4.0 – 4.5	32	24	20	19
4.5 – 5.0	0	0	0	0

Table 10 Number of hours of diesel operation per month for wind farm rated power of 3, 6, 9, and 12 MW for the year 1997

Diesel Power Requirement (MW)	Wind Farm Rated Power (MW)			
	3	6	9	12
January	681	531	450	409
February	557	467	419	393
March	429	280	222	190
April	488	363	323	291
May	641	484	435	399
June	678	519	396	329
July	662	379	290	241
August	726	507	392	328
September	679	535	442	397
October	610	445	376	348
November	602	482	434	411
December	589	463	417	386

6. SOLAR ENERGY CONVERSION

One of the most critical steps in designing Stand Alone Photovoltaic (SAPV) systems is the sizing of the PV array and storage capacity to supply a particular load at a given site. Determining the array area and storage capacity requirements by the use of monthly output computations is well covered [Groupos and Papageorgiou, 1987]. The array area required for each month is determined by

$$A = \frac{DL}{\eta(I - M.S)} \tag{1}$$

Where

DL is the daily demand for a specific month (Wh/day)

η $= \eta_a x \eta_b$ is the system efficiency, which is a product of the array conversion efficiency, η_a and the battery efficiency η_b. The array conversion efficiency is related to the cell temperature, which is related to clearance factor and several other weather parameters (wind speed and ambient temperature).

I is the average insolation during a specific month (kWh/m^2 per day)

S is the standard deviation in the daily insolation for a specific month (kWh/m^2 per day)

M is the fractional monthly average insolation difference. It is a balancing parameter in sizing of the solar array and battery and is given by:

$$M = \frac{(I - I_D)}{S}$$

Where I_D is the insolation, which is required to exactly meet the load demand.

The process of sizing a SAPV system is a repetitive one. Groupos and Papageorgiou proposed a better methodology for optimal sizing [8]. In the methodology proposed, the total life cycle cost for a SAPV power system for a given loss of load probability (LOLP) is mathematically expressed as a differentiable function of the balancing parameter *M*. This gives an expression, which can be minimized and provides the optimal solution of the total life-cycle cost as a function of the balancing parameter *M*.

The weather and insolation data for AL-Jouf for the year 1998 obtained from KACST was considered and used to determine the potential of PV power at Al-Oweiqela. Lead-acid batteries are the most common in PV systems because their initial cost is low and because they are readily available. Shallow cycle batteries cannot tolerate being deeply discharged. These batteries are not a good choice for a PV system. Deep cycle batteries are designed to be repeatedly discharged by as much as 80 percent of their capacity so they are a good choice for power systems. Even though they are designed to withstand deep cycling, these batteries will have a longer life if the cycles are shallower. The Sealed deep-cycle lead-acid batteries are maintenance free and recommended for remote unattended power systems.

The size of the battery bank depends on the storage capacity required, the maximum discharge rate, the maximum charge rate, and the minimum temperature at which the batteries will be used. Temperature has a significant effect on lead-acid batteries. At 40°F they will have 75% of rated capacity, and at 0°F their capacity drops to 50%.

The insolation data for AL-Jouf for the year 1998 obtained from KACST was used to determine the potential of PV power at Al-Oweiqela. Several schemes of storage were investigated. A computer program using the optimization algorithm was developed and used to determine the array area (m^2) and the battery capacity (kWh) required for each month[Groupos and Papageorgiou, 1987]. The array size, energy generated, and the required battery size to meet the load were calculated. The results of these calculations are shown in Table 11. Also, using the array size for the month of January (the largest area) and a system efficiency of 8 percent, the monthly average daily values of generated solar energy are shown in Table 12. The results presented in this section will be utilized to calculate the cost of producing 1 KWh of electrical energy using photovoltaic panels and hence to select the most cost effective renewable energy system that will meet the load demand at the selected site.

Table 11 Monthly results; Array and battery sizes

Months	Array Size (m^2)	Battery Size (kWh)
January	199,000	262,000
February	174,000	387,000
March	91,700	158,000
April	62,200	39,000
May	90,100	73,300
June	105,000	63,600
July	117,000	64,000
August	157,000	76,200
September	138,000	75,800
October	89,100	47,600
November	104,000	91,500
December	166,000	119,000

Table 12 Monthly average daily values of generated solar energy (KWh) for 199,000 photovoltaic Array Size (m^2).

Months	Energy Generated(KWh)	Demand (kWh)
January	57,487	52,166
February	61,626	46,536
March	88,356	35,796
April	113,780	33,408
May	121,819	50,178
June	133,330	68,065
July	127,789	70,294
August	111,472	82,796
September	101,474	66,408
October	86,668	36,708
November	63,059	30,493
December	54,558	42,630

7. WIND/SOLAR ENERGY CONVERSION SYSTEMS

In this section the performance of hybrid wind/solar energy conversion systems are discussed. Such systems are expected to reduce the storage requirements for the stand-alone wind energy conversion system. The storage requirement for each system was investigated. In this case, the wind and solar energy was utilized to meet the load. If the wind and solar energy was not enough, energy was obtained from the storage system. When the generated energy from wind and solar were more than the load, the excess energy was utilized to charge the storage system.

Photovoltaic areas of 200,000, 100,000, and 50,000 were considered with the wind farms of 6, 12, and 15 MW rated power. The results indicate that a wind farm of 12 MW rated power with Photovoltaic system of area of 50,000, 100,000, 200,000 m^2 will require storage capacity of 225, 150, and 45 MWh respectively. It is also important to mention that for the wind farm of 12 MW with Photovoltaic system of an area of 100,000 m^2, the difference between the storage capacities of 150 and 100 MWh is very small. The storage charge capacity will reach the range 0-10% of the storage capacity for only 0.1 % of the time (11 hours out of 8784 hours). Therefore if the village can stay without electricity for 11 hours, a storage system of a capacity of 100 MWh is suitable.

The expected energy generated from the investigated wind farms utilizing the wind data for 1997 are shown in Table 13 for a solar area of 50,000 square meters. The expected solar energy to be generated from the Photovoltaic area of 100,000 and m^2 is simply twice that of the 50,000 square meters area.

Table 13 Monthly average daily values of wind and solar generated energy (kWh) for a Photovoltaic area of 50,000 m^2 for the year 1997

Month	Wind Farm Rated Power (MW)			Demand	Solar Energy
	6	12	15	(KWh)	(KWh)
January	30,422	60,845	76,056	52,166	14,442
February	33,809	67,618	84,523	46,536	15,470
March	58,106	116,213	145,267	35,796	22,196
April	42,283	84,567	105,709	33,408	28,584
May	35,216	70,432	88,040	50,178	30,602
June	42,462	84,925	106,156	68,065	33,500
July	59,910	119,821	149,777	70,294	32,104
August	52,089	104,177	130,222	82,796	28,005
September	35,658	71,317	89,146	66,408	25,494
October	34,996	69,992	87,490	36,708	21,774
November	22,114	44,228	55,285	30,493	15,843
December	28,884	57,768	72,210	42,630	13,706

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8. WIND/SOLAR/DIESEL ENERGY CONVERSION SYSTEMS

The performance of hybrid wind/solar/diesel energy conversion systems consisting of wind farms of 3,6,9,and 12 MW rated power together with Photovoltaic areas of 50,000, 100,000, and 200,000 m^2 were investigated. Small storage capacity of 1 MWh was utilized with all considered systems. This storage capacity is just enough to supply the demand for about 12 minutes. The monthly average daily values of the diesel-generated energy for the considered wind farm rated powers with 50,000 m^2 of Photovoltaic area are provided in Table 14 for the year 1997.

9. ECONOMIC ANALYSIS

This section presents the results of the economic analysis of the various supply systems being considered in this project. These are diesel, wind, solar, wind-diesel and wind-diesel-solar systems. A study for the connection to the nearest grid is also included. The objective is to determine and compare the cost of producing one-kilowatt hour of electrical energy from each system that is under investigation. There are many components to be considered in an economic analysis of a plant. These are such as capital investments, depreciation expenses, fuel expenses, the cost of the storage system wherever applicable and operation and maintenance (O&M) costs. In this study, various energy systems will be evaluated to determine the most cost effective system. This is done by calculating the cost of producing 1 kWh of electrical energy by each stand-alone or hybrid system. The cost of production is then determined for each year by dividing by the electrical energy produced. The cost of production is expressed in present worth (PW) terms using standard methods. Table 15 shows the capital cost of the units as adopted in the study.

Table 14 Monthly average daily values of diesel generated energy (kWh) for wind farm rated power of 3, 6, 9, and 12 MW with PV of 50,000 m^2 and storage capacity of 1 MWh for the year 1997

Month	Wind Farm Rated Power (MW)				Demand (kWh)
	3	6	9	12	
January	27,902	21,982	19,185	17,360	52,166
February	22,842	19,093	17,317	16,286	46,536
March	9,085	5,922	4,730	4,037	35,796
April	8,533	6,268	5,212	4,638	33.408
May	17,861	13,783	12,214	11,235	50,178
June	22,049	14,066	10,864	9,435	68,065
July	19,064	10,087	7,850	6,674	70,294
August	31,598	18,872	14,639	12,723	82,796
September	28,666	20,111	16,635	14,679	66,408
October	12,346	8,390	6,938	6,141	36,708
November	13,409	10,890	9,811	9,174	30,493
December	21,380	17,806	16,106	15,039	42,630
Yearly	19,540	13,887	11,735	10,560	

Table 15 Unit Capital Cost Data

Unit type	Size(kW)	Cost	Lifetime (years)
Diesel	1000	\$1520/kW	20
Wind	150	\$1180/kW	20
Solar Array	-	\$ 800 /m^2	20

A number of financial parameters were also adopted for the purpose of the economic study. The discount rate is six percent while the present worth factor is five percent. The study also adopted the straight line depreciation method throughout plant lifetime.

Table 16 shows a comparison of the cost of production for the various hybrid systems for the year 2000. The installed diesel system is 4 MW for all hybrid systems. For an area of 50,000 square meters, the cost varied from SR1.39 per kWh to SR1.59 per kWh when the size of the wind farm increased from 3 MW to 12 MW. The increase is not substantial considering that the number of wind turbines has increased from 20 to 80 units. However, when the solar area is increased, for the same wind farm, substantial changes in the production cost are observed. In the case of 3MW wind farm, the production cost has increased from SR1.39 kWh for a 50,000 square meters to SR4.4 kWh for the 200,000 square meters. This shows that the driving factor in the hybrid system is the cost of the solar arrays and their associated costs.

Table 16 Production Cost in SR/kWh for different Wind Farms and Solar Arrays in the year 2000

	Area in m^2		
Wind Farm (MW)	50,000	100,000	200,000
3	**1.39**	2.39	4.4
6	1.45	2.45	4.46
9	1.52	2.52	4.53
12	1.59	2.59	4.6

Table 17 provides a comparison between the various supply systems that were investigated. The table indicates that the hybrid system of wind-diesel provides the lowest energy cost for the village under consideration. The cost is SR 0.34 per kWh. The hybrid system is made of 1.5 MW wind farm and 5MW of diesel units. A storage capacity of 1 MWh is also needed.

Table 17 Comparison of Production Cost for Various Systems

System	Details	Storage (MWh)	Size or m^2	Energy Cost (SR/kWh)
Wind Alone	180*150 kW units	280	24	2.16
Diesel Alone	6*1MW units	NA	6	0.386
Wind –Diesel	10*150 kW wind units+ 5*1 MW diesel units	1	1.5 +5	0.34
Solar Alone	400,000 modules	387	50,000 m^2	6.30
Wind-solar	40*150 kW units + 400,000 modules	210	15 +50,00 m^2	2.665
Wind-diesel-solar	20*150 kW units+ 4*1MW diesel+400,00 modules	1	3+4 +50,000 m^2	1.39
Grid alone	2 * 132 kV lines over 150 km	NA		0.68

10. CONCLUSIONS

Several systems for supplying the electric energy to a remote settlement were investigated. Stand-alone diesel, solar, and wind energy systems were considered. In addition, hybrid energy conversion systems composed of wind/solar, wind/diesel, and wind/solar/diesel were studied. The process used for sizing these systems and the determination of the required energy storage systems is highlighted in the paper. The results indicate that the most cost-effective hybrid system among the studied ones is the wind/diesel system. The cost of producing 1KWh of electrical energy using a 1.5 MW wind farm, 5 MW diesel units plus 1 MWh storage capacity is estimated to be 34 Halala for the year 2000. The results indicate also that standalone wind and PV systems are not economical because of the large storage capacity required to meet the load demand. It also shows that hybrid systems reduce the storage capacity requirements significantly and hence result in an economically viable option compared to other studied options.

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