Life-Cycle Cost Analysis and Optimization of Health Clinic PV System for a Rural Area in Oman

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***Abstract*—Solar energy resources are the highest in rural desert areas in Oman so that Photovoltaic (PV) system could represent a suitable choice for electricity generation as stand-alone power system. In this research a 9 kW solar PV system have been designed to supply health clinic in Oman. The average daily load demand is 24.307 kWh/day and details loads are listed. The energy that is generated by the PV system has been estimated using real weather data for Sohar-Oman. Basic principles of designing a quality PV system have been used to design the system. HOMER software is used to analysis and estimate the life cycle of the PV system. The cost of PV system energy is calculated with different sizes for PV, battery and converter. The results indicate that the solar energy utilization is an attractive option with initial cost, net present cost of the system, and energy cost are 96,470 $, 3046 $/year and 0.418 $/kWh, respectively, in comparison with diesel generator operating cost 0.558 $/kWh. We conclude that using the PV system for these types of applications in Oman is justified on technical and economic grounds.**

***Index Terms*— Photovoltaic Cell Sizing and Optimization, Solar Energy System, Electricity Cost, Rural Electrification**

I. INTRODUCTION

THE PV solar power represents one of the most promising renewable energy in the world [1]-[2]. Oman has one of the highest solar densities globally. The high solar energy density is available in all parts of the country. This is because of its location in the Middle East, on the eastern edge of the Arabian Peninsula. The latitude and longitude of Sohar-Oman, the second large city, is 24 20 N, 56 40 E. The climate is generally very hot, with temperatures reaching 54 °C (129.2 °F) in the hot season, from May to September. In addition, the climate of Oman remains dry and particularly hot, but also is humid in the coastal region, 1,700 km long, throughout most of the year [3]-[7]. The coastal areas in the southern part of Oman have the lowest solar density and areas of highest solar density are the desert areas [8]-[10].

This paper reports the evaluation of solar energy cost per kWh using different sizes of PV and battery at Sohar-Oman. Environmental Monitoring Station (EMS) has been used for acquiring data of the ambient conditions to measure: hourly (global horizontal irradiance) global irradiance, relative humidity, ambient temperature, direction wind and speed. EMS recorded data for 2012 have been used to assess solar energy potential in Oman as shown in Figure 1. The EMS found that the average global horizontal solar resource (July 2012) is 6.19 kWh/m^2/day and the average daily number of sunshine hours in Oman is about 12 hours.

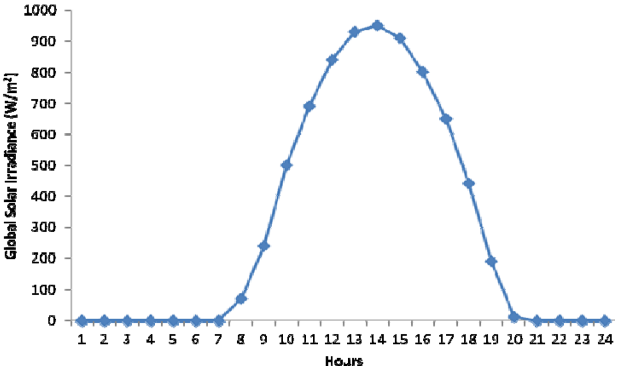

Fig. 1 Global solar irradiance in Sohar-Oman on July 2012

II. FEASABILITY OF PV SYSTEM IN OMAN

The proposed system designed used to power the health clinic was done according to the solar international design manual [11]. The feasibility of the PV system analyzed using HOMER software developed by the National Renewable Energy Laboratory (NREL). HOMER is a computer model that simplifies the task of evaluating design options for distributed-generation, remote, and stand-alone applications. HOMER's optimization and sensitivity analysis algorithms allow one to evaluate the technical and economic feasibility of a large number of technology options. HOMER contains a number of energy component models and evaluates suitable technology options based on cost and availability of resources. HOMER models a power system's physical behavior and its life-cycle cost. HOMER

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allows the modeler to compare many different design options based on their economic and technical merits [12]-[15].

Global radiation on a horizontal surface usually used to determine the energy input to PV system. The average global horizontal annual solar resource in Oman is 5.936-6.879 kWh/m^2/day, which is promising [16]. These numbers are not the energy amount that can be produced by a PV system. The output of PV is rated by manufacturers under Standard Test Conditions (STC), temperature = 25 ^{o}C; solar irradiance (intensity) = 1000 W/m^2, and solar spectrum as filtered by passing through 1.5 thickness of atmosphere. These conditions are easily recreated in a factory but the situation is different for outdoor. There are many factors affecting the produce energy from PV include the type of PV technology, the solar declination, hour angle or azimuth and the solar elevation or zenith angle, temperature, dust, humidity, air mass, the level of sunlight and in general weather conditions. On the electrical side of the charger controller used to protect the batteries and reduce the fluctuation, inverter needs to convert DC current into AC, switches, conductors (wires), fuses and disconnects as shown in Figure 2 [17]-[23].

Usually a roof of buildings is the best location for a PV system. Ground-mounted PV systems are typically cheaper than roof-mounted PV systems and usually it is used for large scale solar systems. But a roof is a convenient location because it is out of the way and is usually un-shaded. For that the roof of health clinic building in Sohar has been selected to install the PV system. The proposed PV system in this paper has the following components: PV modules, inverters, battery charge controller, batteries, various wiring, mounting hardware, and combiner boxes, and sensors and monitoring equipment. Table I shows the specification of the modeled PV system.

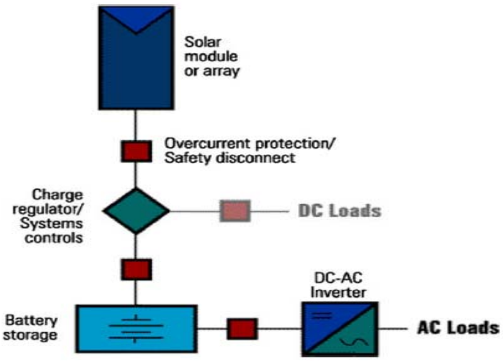

Fig. 2 Stand-alone photovoltaic system.

The clinic building comprises the following rooms: waiting room, administration room, doctor room, nurses' room, three treatment rooms, pharmacy, and two restrooms. The medical equipment, lighting, and other devices used in this clinic are the following: freezer (85 W), refrigerator (85 W), vaporizer (45 W), oxygen concentrator (280 W), water pump (110 W), electric sterilizer (1400 W), 20 LED lamps (10 W each), color TV set (100 W), seven ceiling fans (50 W each), and three evaporative coolers (450 W each). The schematic diagram in HOMER model for the built PV system is presented in Figure 3. Table II shows a proposed estimate of the average daily watt-hours (Wh) used by the health clinic. It is representing the average daily electricity that is use by the clinic also; we tried to define the amount of energy that the PV system must generate daily. The hourly load demand for the health clinic in a rural area at Sohar is shown in table II. The economic assumptions of the system are given in Table III. Figure 4 illustrates the load profile. A small base load of 0.05 kW assumed to supply the outside lighting of the clinic from 5 PM until 7 AM. The load analysis calculation is listed in table IV.

TABLE I
MODLLED PV SYSTEM SPECIFICATION

PV array	
PV module rated power	200 Wp
Maximum voltage	36.5 V
Maximum current	5.21 A
Open circuit voltage	45.0 V
Short circuit current	5.6 A
Efficiency	14.9%
Temperature coefficient of Vo.c	-0.36 %/k
Temperature coefficient of Is.c	0.036 %/k
Inverter	
Rated power	1 kW
AC voltage	220-240
Efficiency	94.1%

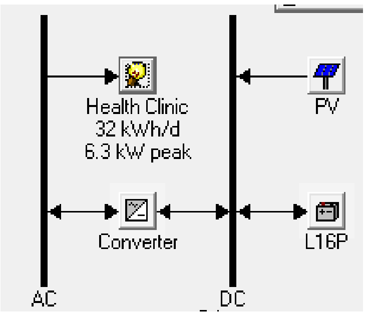

Fig. 3 HOMER schematic diagram for the PV system

TABLE III
ECONOMIC ASSUMPTION OF PV SYSTEM

component	Capital ($/kW)	Lifetime (Years)	Replacement ($)	O&M ($)	Fuel ($)
PV	18,000	25	0	3,154	0
Inverter	3,000	15	2,006	0	0
Battery	16,000	5	19,413	39,417	0

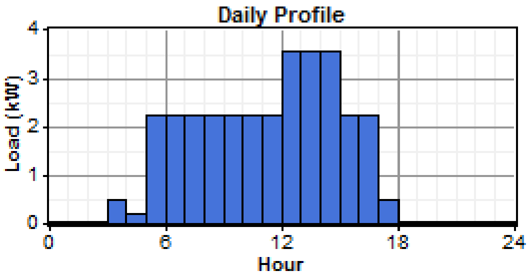

Fig. 4 Hourly load profile.

Solar radiation data for Sohar region were measured on July 2012 and used in this study. Figure 5 shows the solar resource profile over a 1-year period. HOMER introduces

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clearness index from the latitude information of the site (Sohar-Oman). The system uses several PV modules connected in series-parallel combinations to produce enough energy to meet the demand. Also, the system contain beside PV arrays, inverters, battery charge controller, batteries, various wiring, mounting hardware, combiner boxes and monitoring equipment.

TABLE IV
SCALED DATA FOR SIMULATION.

Data source	Synthetic
Daily noise	15%
Hourly noise	20%
Scaled annual average	32.4 kWh/day
Scaled peak load	6.3 kW
Load factor	0.214

A. *PV Array*

There are different types of PV cells which make solar modules: crystalline silicon, multi-crystalline (multi-c), mono-crystalline (mono-c), amorphous silicon (a-Si), etc. PV technology is well-proven for producing electricity [21]-[22]. PV systems can be either grid connected (with electricity fed directly into the grid system) or PV systems used in off-grid applications in small power systems in combination with diesel power gen-sets. Solar PV technology is especially suitable for electricity generation in off-grid power plants in rural desert areas and the use of solar energy in such hybrid systems can reduce diesel fuel use [23]. The suggested PV modules to be used in the system simulation are 36 V, 200 W (at 1000 W/m^2, and 25 ^{o}C). These modules are connected to produce array with 36 V. Estimated capital cost of PV is 2.0$/W. The lifetime is assumed to be 25 years. 90% derating factor was applied to the electric production from each PV panel. The panels were modeled as fixed and tilted south at an angle equal to the latitude of the site. Capacities of different PV panels (0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 kW) were considered in the analysis.

B. *Batteries*

As the system considered working 36 hours, battery and controller were also formed as a main part of the system. Throughout battery life time HOMER assumes that the properties remain constant and not effected by external factors such as temperature. The chosen battery has a 6 V, 225 Ah capacities. The battery price estimated to be 160$. Its life time is considered to be 845 kWh of throughput per battery. Different number of batteries considered in this analysis (0, 50, 75, 100, 125, 150, 175 and 200).

C. *Inverter*

An inverter is a circuit converts DC power to AC. Its efficiency is assumed to be 94.1 % for all sizes considered. The estimated price of an inverter is 1$/W, and its lifetime is up to 15 years. Inverters of various sizes (1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 kW) were considered in the analysis.

III. SYSTEM ANALYSIS

HOMER simulates the system to determine whether it is feasible or not. Also, it estimates the life cost of installing and operating the system over its lifetime. After running the model, 800 feasible solutions are found and out of these 64 best solutions ranked according to the system minimum net present cost (NPC) are shown in table V. The table shows that that the greatest optimal result is achieved when the system is composed of 9 kW PV module, 100 batteries, and 6 kW inverter. In the optimum solution, the total NPC is 96,470 $ with operating cost of 3046 $/year and the cost of energy equals to 0.418 $/kWh. The most expensive system is when we use 10 kW PV module, 200 batteries and 10 kW inverter, with an initial cost, NPC, and electricity cost of 57,000 $, 172,330 $, and 0.746 $, respectively.

The cost of energy in the modeled system as shown in table VII is a little bit higher but acceptable in comparison with the cost of reference [14] 0.21- 0.304 $/kWh, and reference [15] 0.361-0.327 $/kWh. The current energy cost of diesel engine system 0.5581 $/kWh [16]-[17] is higher than the proposed system, which make it a good option for supplying the health clinic in the rural area of Oman. This is due to poor efficiency of diesel engine and short life time.

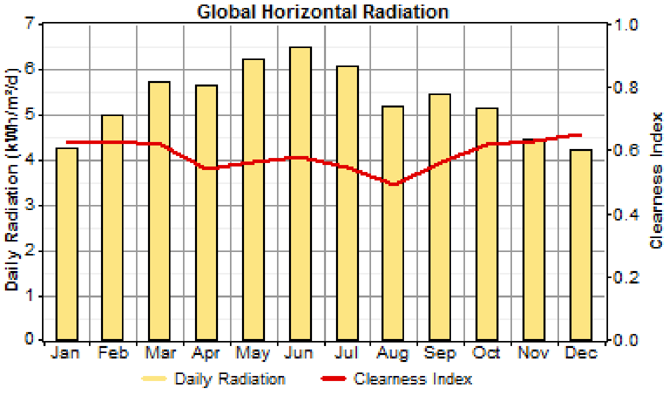
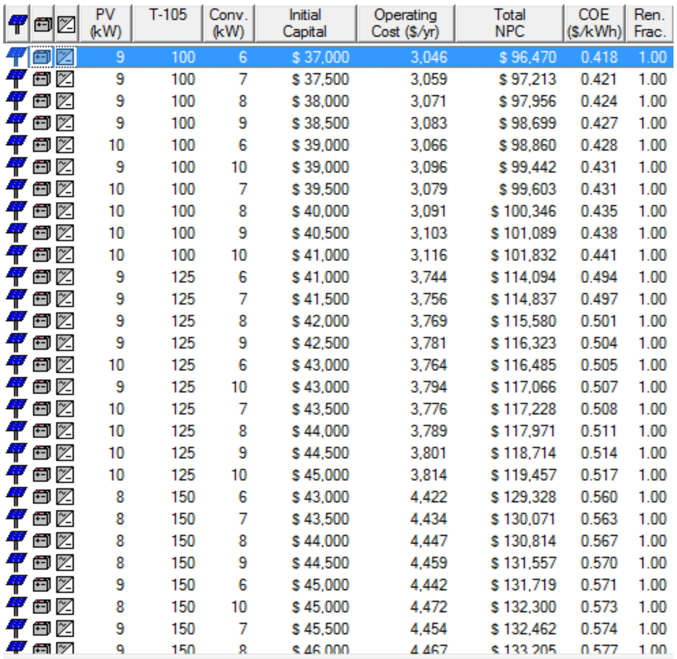


Fig. 5 Solar radiation profile.

TABLE V
OPTIMUM SOLUTION FOR PROPOSED PV SYSTEM



PV (kW)	T-105	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
9	100	6	$ 37,000	3,046	$ 96,470	0.418	1.00
9	100	7	$ 37,500	3,059	$ 97,213	0.421	1.00
9	100	8	$ 38,000	3,071	$ 97,956	0.424	1.00
9	100	9	$ 38,500	3,083	$ 98,699	0.427	1.00
10	100	6	$ 39,000	3,066	$ 98,860	0.428	1.00
9	100	10	$ 39,000	3,096	$ 99,442	0.431	1.00
10	100	7	$ 39,500	3,079	$ 99,603	0.431	1.00
10	100	8	$ 40,000	3,091	$ 100,346	0.435	1.00
10	100	9	$ 40,500	3,103	$ 101,089	0.438	1.00
10	100	10	$ 41,000	3,116	$ 101,832	0.441	1.00
9	125	6	$ 41,000	3,744	$ 114,094	0.494	1.00
9	125	7	$ 41,500	3,756	$ 114,837	0.497	1.00
9	125	8	$ 42,000	3,769	$ 115,580	0.501	1.00
9	125	9	$ 42,500	3,781	$ 116,323	0.504	1.00
10	125	6	$ 43,000	3,764	$ 116,485	0.505	1.00
9	125	10	$ 43,000	3,794	$ 117,066	0.507	1.00
10	125	7	$ 43,500	3,776	$ 117,228	0.508	1.00
10	125	8	$ 44,000	3,789	$ 117,971	0.511	1.00
10	125	9	$ 44,500	3,801	$ 118,714	0.514	1.00
10	125	10	$ 45,000	3,814	$ 119,457	0.517	1.00
8	150	6	$ 43,000	4,422	$ 129,328	0.560	1.00
8	150	7	$ 43,500	4,434	$ 130,071	0.563	1.00
8	150	8	$ 44,000	4,447	$ 130,814	0.567	1.00
8	150	9	$ 44,500	4,459	$ 131,557	0.570	1.00
9	150	6	$ 45,000	4,442	$ 131,719	0.571	1.00
8	150	10	$ 45,000	4,472	$ 132,300	0.573	1.00
9	150	7	$ 45,500	4,454	$ 132,462	0.574	1.00
9	150	8	$ 46,000	4,467	$ 133,205	0.577	1.00

Emission of greenhouse gases from the fuel of equivalent conventional system is significant. By adapting PV technology, the emission of all these harmful gases can be substantially reduced. Table VI shows the emissions banned according to the analysis of using a PV system instead of a diesel generator for this small project.

TABLE VI
MOUNT OF EMISSION PREVENTED BY USING A PV SYSTEM INSTEAD OF DIESEL GENERATOR.

Type of emission	Emission (kg/year)
Carbon dioxide (CO2)	36,277
Carbon monoxide (CO)	89.5
Nitrogen oxide (NOx)	9.92
Unburned hydrocarbon (HC)	6.75
Sulfur dioxide	72.8
Suspended particles	799

TABLE VII
SYSTEMS COST OF ENERGY COMPARISON.

Reference	CoE ($/kWh)
Proposed research	0.418
([17] Al-Badi et al., 2012)	0.21- 0.304
([18] Al-Badi et al., 2012)	0.361-0.327
([19] Annual report, 2010)	0.5581
([20] Annual report, 2011)	0.5581

IV. CONCLUSIONS

In this paper model design to assess solar power cost per kWh of energy produced using different sizes of PV, batteries and inverters. Using HOMER software the most economic system used to supply health clinic in rural area in Oman has been determined. The system has a daily load of 42.307 kWh/day, 9 kW PV modules, 100 batteries, (6 V and 225 Ah), and 6 kW inverter. The results have shown that the optimum cost of PV system energy 0.418 $/kWh is attractive option in comparison with the cost of diesel engine energy 0.5581 $/kWh. The most expensive system is when we use 200 batteries and 10 kW inverter, with an initial cost, NPC, and electricity cost of 57,000 $, 172,330 $, and 0.746 $/kWh, respectively. Also, this option still feasible more than the diesel generator option. Investigations have shown that PV system could represent a good option to be used to supply health clinic in rural area of Oman. Moreover, the analysis shows that using PV system instead of diesel generator will prevent green house gases emission 36,277 kg/year of CO_2, 89.5 kg/year of CO, 9.92 kg/year of NOx, 6.75 kg/year of HC, 72.8 kg/year of SO_2, and 799 kg/year of suspended particles.

AKNWOLEDGMENT

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TABLE II
LOAD PROFILE FOR TYPICAL HEALTH CLINIC

Electrical load	Qty	Volt	Amps ≈	Run watts	Hours / day	Days/ weeks	/7 days	= Ave. WH / Day
Freezer	1	230	0.37	85	14	7	7	1190
Refrigerator	1	230	0.37	85	14	7	7	1190
Vaporizer	1	230	0.19	45	3	6	7	115.7
Oxygen conc.	1	230	1.21	280	2	6	7	480
Elec. Steril	1	230	6.08	1400	3	6	7	3600
Water pump	1	230	0.48	110	7	6	7	660
TV set	1	230	0.43	100	12	6	7	1028.5
Ceiling fan	7	230	0.22	50	12	6	7	514.3
Evap. cooler	3	230	1.95	450	12	6	7	13,885.7
Lamps	15	230	0.04	10	12	6	7	1542.8
Lamps (out)	5	230	0.04	10	12	7	7	100

AC total connected load (Watts)	4,005
AC average daily load (Watts)	24,307