DESIGN AND EVALUATION OF PHOTOVOLTAIC SYSTEMS: AN OVERVIEW AND CASE STUDY

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Abstract. In this paper, photovoltaic system design intuitive, numerical and analytical techniques are revised and discussed. The intuitive and numerical methods are used to design and evaluate PV system for supplying houses in rural area in Oman. In the numerical techniques, two softwares are used. The average daily load demand of the test system is 4.7 kWh/day using real weather data for Sohar-Oman. HOMER and REPS.OM software's are used to design and evaluate the PV system. The results indicate that REPS.OM gives more accurate results in comparison with intuitive technique and HOMER results. Also, the results show that the solar energy utilization is an attractive option with net present cost of the system, and cost of energy are, 7,105 USD and 0.20 USD/kWh, respectively, in comparison with diesel generator operating cost which is 0.558 USD/kWh. It is concluded that numerical techniques give more accurate design than intuitive technique. Using the PV system instead of diesel generators in rural areas in Oman is justified on economic grounds.

Keyword. Solar Photovoltaic, Renewable Energy, intuitive technique, numerical technique, analytical technique, PV System Design.

INTRODUCTION

The main three concerns of humankind today are: food, water and energy. Understanding of world energy consumption may lead to systemic ways and patterns that could help in solving the current energy issues [1]. There are two types of energy resources in the world: renewable and nonrenewable [2].

Nonrenewable energy resources are limited. One day they will run out, so human must reduce their consumption and reduce their dependency on such resources. To achieve this goal, it is important to look for new alternatives. Renewable energy resources are considered as the best option and the solution for the shortage of the nonrenewable energy resources [3]. Examples of renewable energy resources are solar, geothermal, hydro, and wind. One advantage of using renewable energy resources is that it produces almost zero pollution during its operation [4].
The sun is a giant ball of gas that sends out huge amount of energy every day. Only less than 50% of solar radiation reaches the surface of the earth, where 20% is absorbed by atmospheric gases and 30% is reflected back to the space [5].
As energy demand around the world increases, some projections indicate that the global energy demand will almost triple by 2050. Using photovoltaic (PV) cells is one way to meet the global energy need, converting sunlight directly into electricity with no moving parts and no harmful pollution during this operation. Although more conventional sources of energy, such as fossil fuels, are still satisfying the majority of the world's energy demand, PV systems are used in a great variety of applications. These applications may be grouped into three categories: utility interactive systems, stand-alone systems, and solar tracking systems [4]-[6].
Oman has an area of 309,500 km^2 and a coastline that totals 2092 km^2. It is located in the Middle East, on the eastern edge of the Arabian Peninsula. The latitude and longitude of Oman is (21 00N, 57 00E). The climate is generally hot, with temperatures reaching 48 ◦C in the hot season, from May to

September. In addition, the climate of Oman remains dry (no rainfall) and hot, but also is humid in the coastal region throughout most of the year [7].
The total population of Oman in 2010 is 3,174,000 including 1,156,000 expatriate [1]. The total number of housing in Oman is in the order of 540,770, includes individual houses and apartments in building. In 2010, the following sectors share in the Gross Domestic Product GDP reached (in millions of Omai Rial OR): 7317.2 oil and gas, 258.6 agriculture and fishing, 3325.3 industrial activities, and 7519.0 service activities (0.386 OR ≈ 1 US$). Oman has one of the highest solar densities in the world [6]. According to the Authority for Electricity Regulation in Oman, "Oman and solar energy has the potential to provide sufficient electricity to meet all of Oman's domestic electricity requirements and provide some electricity for export" [8]. The solar PV technology is suitable for use in northern parts of Oman for producing electricity. Also, it is found that there is significant wind energy potential in coastal areas in the southern part of Oman and in north of Salalah on the mountains.
Some PV systems design and evaluation work done for Oman can be found in [9-13]. In [9] solar energy averages were predicted for 17 sites in Oman namely Buraimi, Khasab, Majis , Mina Qaboos, Rumais ,Seeb , Saiq , Rusail , Fahud , Sur , Yalooni , Masirah, Thumrait, Marmul, Salalah, Qairoon Hairiti, Mina Raysut. The authors concluded that the average solar energy for these sites is 5.597 kWh/m^2/day. After that the authors used some intuitive method to size the PV system's components. The authors concluded that the cost of energy produced by a PV system located in Oman is about 0.21 USD/kWh. However, in this research the author used simple method to design the system. Also, they did not state the availability of the designed system. In [10] the choice of applying a standalone PV/wind/ Diesel generator for rural area in Oman is assessed using HOMER. The result of this study shows that the proposed systems can displace diesel generation significantly and the economical benefits of the resulting hybrid systems depended on load and renewable energy resources. This means that the potential of the wind and solar energy are not equal in Oman and thus, an optimization of the renewable energy sources share in such a system must be done. Such an optimization provides design recommendations in order to achieve the desired feasibility and reliability levels. Other utilization of HOMER for investigating renewable energy system in Oman can be found in [11]. In this study the optimum size of renewable systems is determined by HOMER in order to be able to fulfill the electrical energy requirements of remote sites located in Hajer Bani and Hameed in the North of Oman, Masirah Island and the Mothorah area in the South of Oman. As a result, the cost of energy produced by the proposed systems was found to be 0.206, 0.361 and 0.327 USD/kWh for Masirah Island, Mothorah and HB Hameed, respectively.
In reference [12] the authors used data from 25 sites in Oman in order to investigate the feasibility of PV systems in these sites. The authors concluded that the average solar energy for these sites is in the range of (4-6) kWh/m^2.day with average value equals to 5 kWh/m^2.day. After that the authors considered a 5 MWp PV plant applied to each site and discuss its feasibility by calculating the cost of energy using RETscreen. The authors reported that the cost of energy produced by such system is (0.21- 0.304) USD/kWh. In addition to that the authors used the capacity factor to do technical evaluation of the system and it was found to be in the range of (0.14- 0.2). From the reviewed work, we can found that most of the authors used HOMER or RETscreen softwares in their study despite the fact that these softwares only deals with monthly averages data as input which may affect the accuracy of the results. Thus, authors of in [13] proposed a method for optimal sizing of a standalone PV system for remote areas in Sohar. PV array tilt angle and the size of the PV system are designed optimally for better performance and to lower energy cost. Numerical methods for optimization of the PV module tilt angle, PV array size and storage battery capacity are implemented using MATLAB and hourly meteorological data and load demand. The results show that for Sohar zone, the tilt angle of a PV array must be adjusted twice a year. The PV array must be slanted at 49◦ in the period of 21/09–21/03 (n = 255–81), while it must be horizontal (tilt angle is zero) in the period of 21/03–21/09 (n = 81–255). This adjustment practice gains the energy collected by a PV array by 20.6%. As for the PV system size, the results show that the sizing ratio of the PV array for Oman is 1.33 while the sizing ratio for battery is 1.6. Moreover, the cost of the energy generated by the proposed system is 0.196 USD/kWh.
In this paper, HOMER and REPS.OM softwares are used to discuss and compare different design techniques of PV/Battery systems using the weather data of Sohar-Oman. Intuitive and numerical methods are used and compared.

STANDALONE PV SYSTEM SIZE OPTIMIZATION

Currently, in desert area the electric provisioning of electrical sector is done by the solar photovoltaic (PV) or hybrid systems of production of electricity whose diesel and natural gas generators plays a significant role like auxiliary source. These hybrid systems involve combination of different hybrid systems such as wind/battery, PV/battery, wind/ PV/battery and wind/PV/diesel/battery systems.
However, a PV/battery system must be designed to meet the desired load demand at a defined level of security. Several optimization methods for PV/Battery system can be found in the literature. Based on the reviewed work, it is found that there are three major systems sizing procedures, namely, intuitive, numerical (simulation based) and analytical methods in addition to some individual methods as shown in Fig 1.

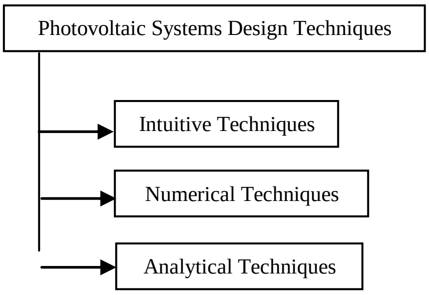

Figure 1 PV system design techniques

A. Intuitive Technique

The intuitive technique is defined as a simplified calculation of the size of the system carried out without establishing any relationship between the different subsystems or taking into account the random nature of solar radiation [13].
Firstly in designing the PV power system, an estimation of the energy demand of the load should be done by multiplying the power of each appliance by the average number of hours of use. Then a 20% might be added to allow for losses caused by wiring [53], DC to AC conversion, dirty modules, etc. Loads whatever AC or DC loads should be described in a work sheet by load current, load voltage, daily duty cycle, weekly duty cycle, power conversion efficiency, nominal systems voltage and Amp-hour load. The designer should consider energy conserving substitutes for items that are used often. Identify large and/or variable loads and determine if they can be eliminated or changed to operate from another power source. LED lamps should be used in place of incandescent lamps. They provide better light levels with much lower power demand. The operating voltage selected for a standalone PV system depends on the voltage requirements of the loads and the total current. If the system voltage is set equal to the voltage of the largest load then these loads may be connected directly to the system output. However, it is recommended that the current in any source circuit be kept below 20 with a 100 amperes limit for any section of the system. Keeping the current below these recommended levels will allow use of standard and commonly available electrical hardware and wires. When loads require AC power, the DC system voltage should be selected after studying available inverter characteristics.
The optimum selection of the inverter is represented by choosing an inverter meets the load and keeps the DC current below 100A. Selection of an inverter is important and affects both the cost and performance of the system. Generally, the efficiency and power handling capability are better for units operating at higher DC voltages. A 48 V unit are usually more efficient than a 12 V unit. The designer should obtain information on specific inverters, their availability, cost and capabilities, from several manufacturers before making the decision on system voltage. Another fact to consider is the basic building block in the array and storage subsystems gets larger as the voltage increases. For example, a 48 volt system has four PV modules connected in series to form the basic building block. However, the advantage of the higher operating voltage is the lower current required to produce the same power. High current means large wire size and expensive and hard to get fuses, switches and connectors. Again, a prior knowledge of the cost and availability of components and switchgear is critical to good

system design. The required PV modules and battery capacity can be calculated using some of formulas as below [1],

$$P_{PV} = \frac{E_L}{\eta_S \eta_{inv} PSH} S_f \tag{1}$$

where E_L is daily energy consumption,
PSH is the peak sun hours,
η_S and η_{inv} are the efficiencies of the system components
and S_f is the safety factor that represents the compensation of resistive losses and PV cell temperature losses.

On the other hand, the battery capacity can be calculated by,

$$C_{Wh} = \frac{E_L \times D_{Autonomus}}{V_B DOD \eta_B} \tag{2}$$

Where V_B and η_B are the voltage and efficiency of the battery block, respectively, while *DOD* is the permissible depth of discharge rate of a cell.

B. Numerical Technique

A system simulation is used in the case of numerical technique. For each time period considered, usually a day or an hour, the energy balance of the system and the battery load state is calculated. These methods offer the advantage of being more accurate, and the concept of energy reliability can be applied in a quantitative manner. Two simulation softwares has been used in this study, HOMER and REPS.OM.

HOMER models both renewable-energy and conventional technologies. 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 [14].

REPS.OM is MATLAB based user friendly software tool used for optimal sizing of PV systems in Oman [1]. The software has the capabilities of optimizing the PV module/array tilt angle, optimizing the inverter size and calculating the optimal capacities of PV array, battery, and diesel generator in hybrid PV systems.

The HOMER software program is considered a widely optimization software tool used by many researchers for optimizing all types of PV systems and performing emission and economic analyses for the designed system. However, the disadvantage of the HOMER software is that it is not able to predict the performance of the designed PV system. Table I shows comparison between the two softwares.

Table 1 Comparison of Commercial PV Software Tools

Software	Types	of	PV	Systems	Simulation Capability
	PV	PV/wind	PV/diesel	GC	
HOMER	√	√	√	√	√
REPS.OM	√	x	√	√	√

C. Analytical Technique

In the analytical technique, equations that describe the size of the PV/Battery system as a function of the reliability are developed. The main advantage of the this method is that the calculation of the system size is very simple while the disadvantage of this method is represented by the difficulty of finding the coefficients of these equation in addition to the fact that these equation are location specific. It is worth mentioning that in this study only intuitive and numerical methods are discussed.

RESULTS AND DISCUSSION

In this study, a standalone PV system is designed as shown in Fig. 2. Table II shows the specifications of the modeled PV system. In this study, the proposed estimate of the average daily watt-hours (Wh) used by the household in Oman are energy conservative load in comparison with the load type used nowadays in Oman.

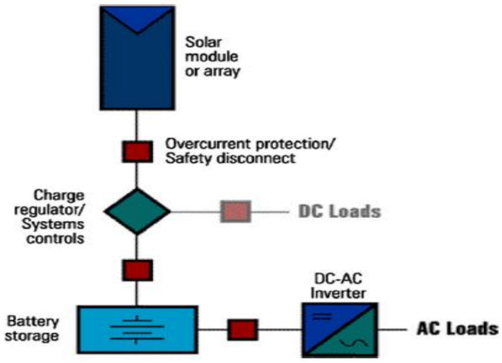

Figure 2 Standalone photovoltaic system

Table 2 Modeled PV System Specifications

PV array	
PV module rated power	140 Wp
Maximum voltage	17.7
Maximum current	7.91
Open circuit voltage	22.1
Short circuit current	8.68
Efficiency	13.9%
Temperature coefficient of Vo.c	-0.36 %/k
Temperature coefficient of Is.c	0.06 %/k
Inverter	
Rated power	1 kW
AC voltage	220-240
Efficiency	94.1%

The hourly load demand for house needs in a rural area at Sohar is shown in Fig. 3. The equipment, lighting and other devices used in this house are the following: fluorescent lights (15 W), refrigerator (50 W), television (100 W), satellite TV system (40 W), computer (45 W), radio telephone receive and transmit (2 W), phone answering machine (6 W), washing machine (100 W), monitoring equipment (100 W), battery charger (4 W) and air conditioning (1000 W). The average daily load demand is 4.7 kWh/day, with a peak power equals to 520 W. The economic assumptions of the system are given in Table III.

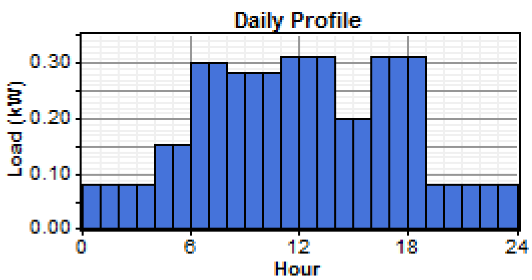

Figure 3 Hourly load profile.

An intuitive and numerical (HOMER and REPS.OM) method has been used to design and evaluate the system. The results are as follows:

Table 3 Economic Assumption of PV System

component	Capital ($)	Lifetime (Years)	Replacement ($)	O&M ($)	Fuel ($)
PV	6,290	25	0	0	0
Inverter	1,000	15	800	0	0
Battery	400	5	400	60	0

A. Intuitive Technique

The designed system is composed of 1.7 kW PV module (3.7$/W), 6 batteries (66$/Ah), and 1.5 kW inverter (1.5$/W). In the optimum solution, which adopt the same technique in reference [15], the total NPC is 8,012 USD with operating cost of 197 USD/year and the cost of energy equals to 0.31 USD/kWh.

B. Numerical Technique-HOMER

The optimal result is achieved when the system is composed of 1.54 kW PV module, 5 batteries, and 1 kW inverter. In the optimum solution, the total NPC is 7,364 USD with operating cost of 169 USD/year and the cost of energy equals to 0.22 USD/kWh. The most expensive system is when we use 3 kW PV array, 3 batteries and 1.5 kW inverter, with an initial cost, NPC, and electricity cost of 7,680 USD, 9,556 USD, and 0.426 USD, respectively.

C. Numerical Technique-REPS.OM

The optimal result is achieved when the system is composed of 1.4 kW PV module, 5 batteries, and 0.9 kW inverter. In the optimum solution, the total NPC is 7,105 USD with cost of energy equals to 0.20 USD/kWh.

The cost of energy in the modeled system as shown in table IV is acceptable in comparison with the cost of institutive, and numerical (HOMER and REPS.OM) techniques 0.31, 0.22 and 0.20 USD/kWh respectively, and reference [16] 0.21- 0.304 USD/kWh, and reference [17] 0.361-0.327 USD/kWh. The current energy cost of diesel engine system 0.5581 USD/kWh [18]-[19] is higher than the proposed system, which makes the PV/battery system a good option for houses in rural area of Oman. This result is attributable to the high cost of diesel.

Table 4 System Cost of Energy Comparison

Reference	CoE ($/kWh)
Proposed research (Intuitive)	0.310
Proposed research (HOMER)	0.22
Proposed research (REPS.OM)	0.20
([16] Al-Badi et al., 2011)	0.21- 0.304
([17] Al-Badi et al., 2012)	0.361-0.327
([18] Annual report, 2010)	0.5581
([19] Annual report, 2011)	0.5581

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 V shows the emissions banned according to the analysis of using a PV system instead of a diesel generator for this small project.

Table 5 Amount of Emission Prevented by Using a PV System Installed of Diesel Generator

Type of emission	Emission (kg/year)
Carbon dioxide (CO_2)	2,177
Carbon monoxide (CO)	5.37
Nitrogen oxide (NOx)	0.595
Unburned hydrocarbon (HC)	0.405
Sulfur dioxide	4.37
Suspended particles	47.9

CONCLUSION

In these paper intuitive and numerical techniques used for PV system design has been discussed. The designed system has assessed based on cost of energy per kWh produced using different sizes of PV, batteries and inverters. It is found that numerical technique gives more accurate results. Using HOMER and REPS.OM softwares, the most economic system for houses in rural area in Oman has been determined. The test system has a daily load of 4.7 kWh/day. The results show that the optimum cost of PV system energy (0.20 USD/kWh) is more economical in comparison with the cost of diesel engine energy (0.5581 USD/kWh). The intuitive technique is overestimating the NPC and electricity cost in comparison with HOMER and REPS.OM Also, using intuitive technique in calculating the cost of energy (0.31USD/kWh)still shows that the PV system cost of energy is more economical than the diesel generator option. Investigations show that PV system could represent a good option to be used to supply houses in rural area of Oman. Moreover, the results demonstrate that using PV system instead of diesel generator will reduce emissions by 2,177 kg/year of CO_2, 5.37 kg/year of CO, 0.595 kg/year of NOx, 0.405 kg/year of HC, 4.37 kg/year of SO2, and 47.9 kg/year of suspended particles.

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