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A Review of Optimum Sizing Techniques for Off-Grid Hybrid PV-Wind Renewable Energy Systems

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Abstract **– Hybrid renewable energy power systems have proven their ability to address limitations of single renewable energy system in terms of power stability, efficiency and reliability while running at minimum cost. In the present decade, lots of research and practical experiences have been done. This paper will present an overview of the different hybrid solar (PV)- wind renewable energy systems for power generations. Different criteria of selecting the right sizing of different component of hybrid renewable energy power plant at the most preferable economical, logistical environmental considerations will be discussed. In some cases when the weather data are not available, this paper will discuss some optimization approaches which are used to compare the performance and energy production cost of different system configurations using simulation techniques. Based on the fact that, potential of the wind and solar energy is not equal in Oman, this paper will discuss the optimum sizing process of two proposed hybrid solar-wind plants in Oman.**

Key Words: **Hybrid Energy, wind, solar, sizing and optimization.**

I. INTRODUCTION

Hybrid Renewable Energy Systems are defined as an electric energy system which is made up of one renewable and one conventional energy source or more than one renewable with or without conventional energy sources, that works in off-grid (stand alone) or grid connected mode [1]. The main feature of hybrid renewable energy systems is to combine two or more renewable power generation and so they can address efficiency, reliability, emissions and economical limitations of single renewable energy source [2].

Hybrid Renewable Energy Systems are becoming popular for stand-alone power generation in isolated sites due to the advances in renewable energy technologies and power electronic converters [3]. Based on the availability of the natural local resources, there are some advantages of the hybrid system. Higher environmental protection, especially CO_2 and other emissions reduction is expected due to the lower consumption of fuel. The cost of wind energy, and also solar energy can be competitive with nuclear and the diversity and security of natural resources who are abundant, free and inexhaustible [4]. Most of these appliances can be easily installed and they are rapidly deployed. Financially, the costs are predictable and not influenced by fuel price fluctuations [5-8]. However, because of the solar-wind unpredictable nature and dependence on weather and climatic changes, a common drawback to solar and wind power generations is that both would have to be oversized to make their stand- alone systems completely reliable for the times when neither system is producing enough electric power [9].

Many areas are concerned with the applications of the hybrid renewable energy generation. Researches [1, 10] have focused on the performance analysis of demonstration systems and the development of efficient power converters, such as bi-directional inverters and the Maximum power point trackers [11-12]. Other researches focused on the storages devices and the battery management units [6].

In the last decade, various hybrid energy systems have been installed in many countries, resulting in the development of systems that can compete with conventional, fuel based remote area power supplies [13]. However, there are several combinations of hybrid energy system which mainly depend on the natural available resources, the wind or the solar energy practically represents one source of the hybrid renewable energy systems.

With the advance development of the hybrid solar-wind systems for electrical power generation, the target to achieve efficient and reliable performance became complicated task. So the need to select and configure the right sizing of all components is important in order to obtain the initial minimum capital investment while maintaining system reliability [14-15]. This paper will overview three common used sizing methods for hybrid solar-wind systems. Beside that, the paper will discuss some optimization approaches of the solar-wind hybrid renewable energy systems. These approaches are used to compare the performance and energy production cost of different system configurations using simulation techniques.

This work will focus on the off-grid solar (PV)-wind hybrid energy systems as both solar and wind has the highest potential in Oman compared to the others [16-17]. Two research cases will be discussed as a practical implementation of the right sizing and optimization of the Masirah Island and Al-Halaniyat Island proposed hybrid renewable energy plants.

II. Hybrid Solar- Wind Energy

In fact, the use of small isolated hybrid energy systems is expected to grow tremendously in the near future [18], both in industrialized and developing countries. Solar and wind are naturally complementary in terms of both resources being well suited to hybrid systems [19]. Hybrid electric systems combine solar-wind systems to make the most of the area's seasonal wind and solar resources; with wind relatively more available in winter months and at night time, and solar relatively more available in summer months and during winter's sunlit days [13].

These hybrid systems provide a more consistent year-round output than either wind-only or solar-only systems and can be designed to achieve desired attributes at the lowest possible cost [20]. Most hybrid systems have backup power through batteries and/or and diesel engine generator.

Moreover, Fig 1 compares PV system capital costs of three common PV types. The cost of electricity of the three PV types has dropped 15- to 20 times; and grid-connected PV systems currently sell for about $5-$10 per peak Watt (20 to 50¢/kWh), including support structures, power conditioning, and land. In contrast, the system efficiency of the three types has increased for about 10-13% [21].

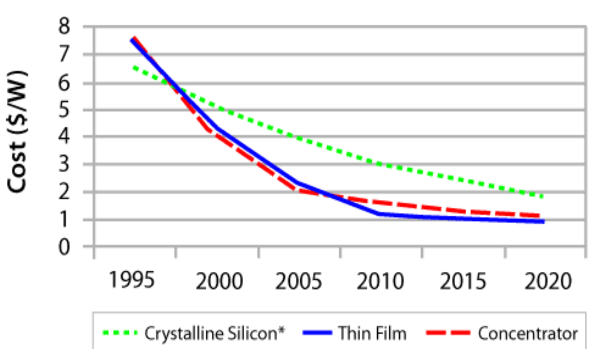

Fig 1 PV system capital cost

The wind capital cost of class 4 and 6 wind turbines is shown in Fig 2. The cost of both systems has dropped by 180$ per KW in the last two decades.

Fig 2 Wind capital cost

However both Fig 1 and Fig 2 show promised figures for the real investments of the PV and wind renewable energies, the optimum design of hybrid system becomes complicated through uncertain renewable energy supplies uncertain load demand, non-linear characteristics of the resources with the increased complexity, the need for practical sizing and optimum configuration becomes an issue [22].

Researcher and industries faces some challenges in the developments of the hybrid solar-wind energy systems. The following may be considered, poor efficiency of the solar PV sources as the efficiency cannot reach more than 17.5 % , high manufacturing cost which leads to longer payback time [16-17].

Beside all of the technical considerations there are other factors which must be included such as the financial investment, social aspects, local infrastructure and the whole system durability. Furthermore, references [1, 10] has presented some steps which must be taken into account before installing PV-wind hybrid systems. They include selecting the most suitable location for installation, acquiring data on the local natural potential of available wind energy and solar energy and the annual energy consumption must be determined. Then the right sizing of the whole system can be set as it will discuss in the following section.

III. Sizing Methods of Solar -Wind Hybrid Systems

Before setting up or installation of a new hybrid renewable energy system, it is essential to do the right sizing of the individual components to obtain the initial capital investment[18]. Unit sizing is basically a method of determining the right practical sizing of the hybrid system components by minimizing the system cost [14] while maintaining system reliability. The right sizing is to determine the wind generator capacity (number and size of wind turbines), the number of PV panels and number and capacity of battery needed for the stand-alone system. Note that it is important to maintain optimum resource management in a hybrid generation system in order to avoid wrong sizing. Over sizing the system components will increase the system cost whereas under sizing can lead to failure of power supply [14]. References have presented three methods of sizing.

A. The Yearly Monthly Average Sizing Method

The PV panels and wind generators size are measured from the average annual monthly values of energies statement. This calculates is basing on the average annual monthly data of sunning and the wind.

B. The Most Unfavorable Month Method

The PV and wind generators are being calculated in the most unfavorable month. Generally the month most unfavorable in wind is favorable in irradiation. Here the system must be dimensioned in two most unfavorable months (unfavorable irradiation month and unfavorable wind month). When the system functioned in this month it's automatically functioned in the author month.

C. Loss of Power Supply Probability (LPSP) Method

The LPSP is the probability that an insufficient power supply results when the hybrid system is not able to satisfy the load demand [23-24]. This method consists in determining the optimal number of the batteries and the photovoltaic modules according to the optimization principle knowing: the reliability, which is based on the concept of the probability of loss of energy [25-26], and on the cost of the system. This method presents the advantage that the introducing of the wind generator permits to minimize the cost of the photovoltaic stand-alone system, by the minimizing the size of the photovoltaic generator and the storage number of battery [27]. Two methods can be used for the application of the LPSP in designing a grid-off hybrid solar–wind system. The first one is based on chronological simulations. The second approach uses probabilistic techniques to incorporate the fluctuating nature of the resource and the load, thus eliminating the need for time-series data.

IV. Optimization Methods of Solar -Wind Hybrid Systems

Optimization approaches of the solar-wind hybrid renewable energy systems are used to set up the optimum configuration of renewable energy configuration. Simulation techniques are used to compare the performance and energy production cost of different system configurations. Several software tools [28] are available for designing of hybrid systems, such as homer, hybrid2, hoga and hybrids [29]. Depends on the availability of the metrological data, two approaches are followed to achieve the right optimum sizing. The conventional techniques are based on the energy balance and reliability of supply and they make use of the metrological weather data. If the weather data are not available, the system must be optimized using different methods as will be discussed in this section.

A. Graphic Construction Technique

This technique can configure the optimum combination of PV array and battery for a stand-alone hybrid solar–wind system based on using long-term data of solar radiation and wind speed recorded for every hour of the day for very long years [2]. For given load and a desired LPSP, the optimum sizing of the hybrid PV-wind can be achieved by assuming that the total cost of the system is linearly related to both the number of PV modules and the number of batteries. The minimum cost will be at the point of tangency of the curve that represents the relationship between the number of PV modules and the number of batteries.

B. *Probabilistic approach*

The effect of variation of the solar radiation and wind speed are the main factors in the system design of this method. Reference [29] has proposed a sizing method treating storage energy variation as a random walk. The probability density for daily increment or decrement of storage level was approximated by a two-event or three- event probability distribution. This method was extended to account for the effect of correlation between day to day radiation values.

Other applications presented the probabilistic approach based on the convolution technique. The fluctuating nature of the resources and the load is incorporated, thus eliminating the need for time-series data for the assessment [30].

C. Iterative Technique

Reference [31] proposed a Hybrid Solar–wind System Optimization (HSWSO) model, which utilizes the iterative optimization technique following the LPSP model and Levelised Cost of Energy model for power reliability and system cost respectively. Three sizing parameters are considered, i.e. the capacity of PV system, rated power of wind system, and capacity of the battery bank. For the desired LPSP value, the optimum configuration can be identified finally by iteratively searching all the possible sets of configurations to achieve the lowest Levelised Cost of Energy.

Similarly, in [32] an iterative optimization method was presented by to select the wind turbine size and PV module number using an iterative procedure to make the difference between the generated and demanded power (DP) as close to zero as possible over a period of time. From this iterative procedure, several possible combinations of solar–wind generation capacities were obtained. The total annual cost for each configuration is then calculated and the combination with the lowest cost is selected to represent the optimum mixture.

D. *Artificial intelligence methods*

There are different artificial intelligence methods which are widely used to optimize a hybrid system in order to maximize its economic benefits [32], such as Genetic Algorithms, Artificial Neural Networks and Fuzzy Logic. Genetic Algorithms are also widely used in the design of large power distribution systems because of their ability to handle complex problems with linear or non-linear cost functions. [33] Proposed one optimum sizing method based on Genetic Algorithms by using the Typical Meteorological year data, while desired LPSP with minimum Annualized Cost of System is maintained. Two optimization variables that are not commonly seen, PV array slope angle and turbine installation height have been considered. Such algorithms are applicable for the conventional optimization methods such as dynamic programming and gradient techniques [33]. Ref [18] has compared between all optimization techniques and listed all advantages and disadvantages.

V. DISCUSSION OF SOLAR- WIND ENERGIES IN OMAN

Study [17] has discussed and addressed all renewable energy resources in Oman, solar and wind energy present the highest potential for applicability in the country. The following sections overview these energies and their potential applications.

A. Solar Energy

In Oman, solar energy is the main renewable energy resource which is currently utilized in Oman for some local small applications. Oman is one of the highest solar energy densities in the world, the received solar radiation ranging from 5,500-6,000 Wh/m2 a day in July to 2,500-3,000 Wh/m2 a day in January[17].

A solar energy evaluation study [34] covered several years in order to estimate the long term average solar energy resources. The average global isolation data which is the sum of direct and diffuse radiation from 1987 to 1992 for six locations in Oman is depicted in Fig 3.

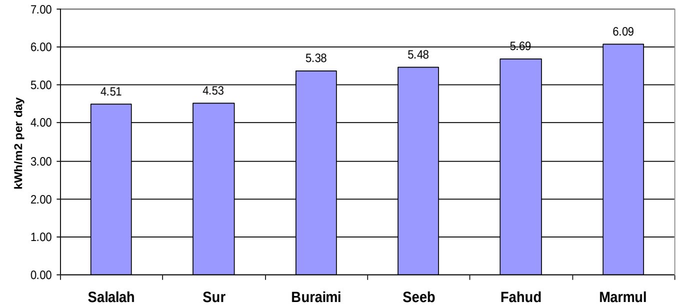

Fig 3 Global average radiation for 1987-1992 for the stations included in this study.

As shown in Fig 3, the solar isolation varies from 4.5 to 6.1 kWh/m2 per day which corresponding to 1640– 2200 kWh per year per square meter. Salalah and Sur have a significant lower insolation compared with other stations; this is due to the summer rain period in Salalah and the frequent period with fog in Sur. Relatively high solar energy density is available in all region of Oman. The total solar energy resources in Oman are enormous and can cover all energy demands as well as could provide export [17].

The consumption of energy is higher during the summer time due to the need for air conditioning. During the winter time the surplus production can be exported to Europe where the need for energy is highest [17]. For real solar PV energy investment in Oman, the following points must be considered [8]:

- The solar PV technology is suitable for use in northern parts of Oman.
- The solar PV technology is also suitable for electricity generation in off-grid power plants in rural desert areas where the solar energy can reduce diesel fuel use. The efficiency of PV cells is influenced by high air temperature and dust contamination.
- It was found that highly suitable land for PV applications in Oman can provide more than 600 times the current electric energy demand if Thinfilm PV technology is used [8].

A research paper [35] has investigated the economical prospect of the solar PV in Oman for a 25 location assuming a 5MW plant as shown in Fig 4.

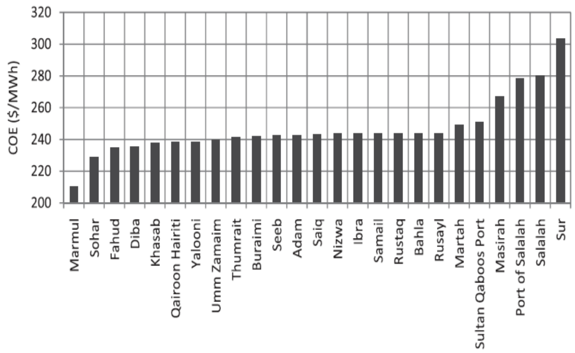

Fig 4 The COE for 25 locations in Oman

The research results revealed the following:

- The renewable energy produced each year from 5MW PV power plant vary between 9000 MWh at Marmul to 6200 MWh at Sur while the mean value is 7700 MWh of all the 25 locations.
- The capacity factor of PV plant varies between 20% and 14% and the cost of electricity varies between 210 and 304 US$/MWh for the best location to the least attractive location.
- The study has also found that the PV energy at the best location is competitive with diesel generation without including the externality costs of diesel.
- An average of about 6000 tons and 5000 tons of GHG emissions can be avoided for each implementation of PV station that is currently using diesel and natural gas, respectively.

Theoretically, it is possible to power Oman by utilizing about 280 km^2 of desert from solar collectors, corresponding to 0.1% of the area of the country [35].

B. Wind Energy

Wind power has become a major source of energy today, it is free, clean, and inexhaustible source of energy. In 2007, wind power capacity increased by a record-breaking 20,000MW, bringing the world total to 94,100MW, which is sufficient to satisfy the residential electricity needs of 150 million people. Existing wind power capacity grew by 29% in 2008 to reach 121GW, more than double the 48GW that existed in 2004 [36].

The assessment of the wind energy resources in Oman is based on the hourly wind speed data measured at twenty one stations in 2005 under the responsibility of Directorate General of Civil Aviation & Meteorology (DGCAM) [34]. The wind data is measured at 10 m and estimated at 80 m above ground level to represent a hub height of a modern large wind turbine (capacity 2-3 MW). Five stations with the highest wind speeds were identified and the annual mean wind speed is shown in Fig 6.

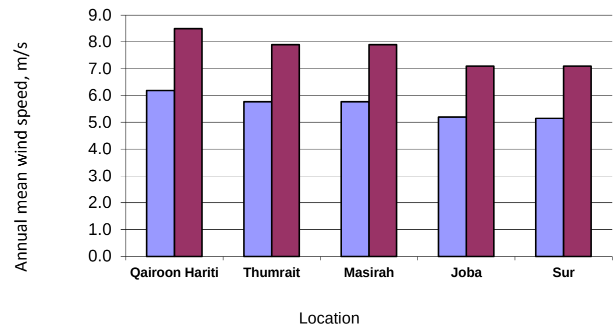

Fig 5 Annual mean wind speed at 10m and at 80 m above ground level at five meteorological stations

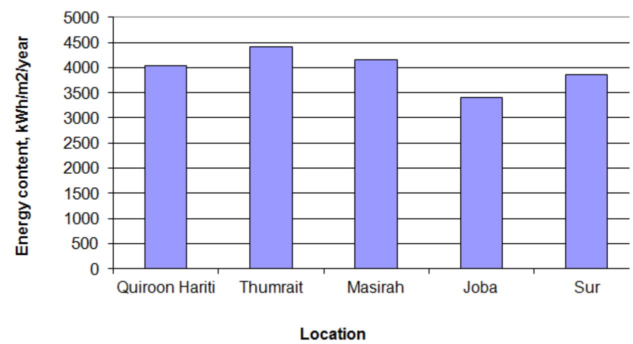

Fig 6 Energy content in the wind at 80 m above ground level at five meteorological stations

Further assessment was done to estimate the annual energy content at each of the five stations. The energy is specified as kWh per year through a vertical area of one m2, kWh/year/m^2. The maximum expected energy is at Thumrat for an almost 4.5 kWh/m^2/year. The assessment results are shown in Fig 6.

The main findings of the study are:

- The high wind speeds are found along the coast from Masirah to Salalah. The highest wind speeds are in the Dhofar Mountain Chain north of Salalah. The low wind speed areas are in the north and western part of Oman.
- The highest wind energy speeds are observed during the summer period. The summer period is also the period with the highest electricity demand in Oman.
- The study reveals that at the present gas price of 1.5 US$/MMBtu wind energy is not economical. The wind energy at Quiroon Hariti, the highest wind potential in Oman, becomes marginally economical at a gas price of 6 US$/MMBtu [34].

- This clearly shows that wind application for large wind farms is not presently economical. However, the wind energy remains a suitable option for hybrid applications.

VI. HYBRID SOLAR- WIND ENERGY SYSTEMS IN OMAN

Study [13] has investigated different combinations of hybrid systems of diesel generator, wind turbine, PV array, battery, and power converter for Masirah Island in Oman. The wind and the solar assessment for Masirah Island are presented in Fig 7 & Fig 8 respectively.

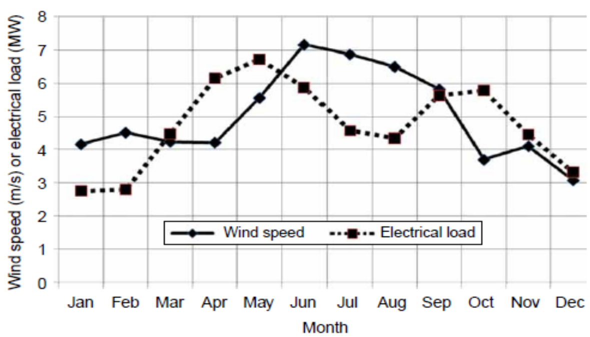

Fig 7 Masirah monthly average wind speed in m/s and monthly load in MW (2008)

Fig 5 & Fig 7 show that the average yearly wind speed is 4.99 m/s and the measured wind speed happens to be quite high when the electrical load requirement is also high. Moreover, wind speeds are generally higher during the months of April to September compared to other months. The average monthly solar radiation between 2004- 2008 is shown Fig 8.

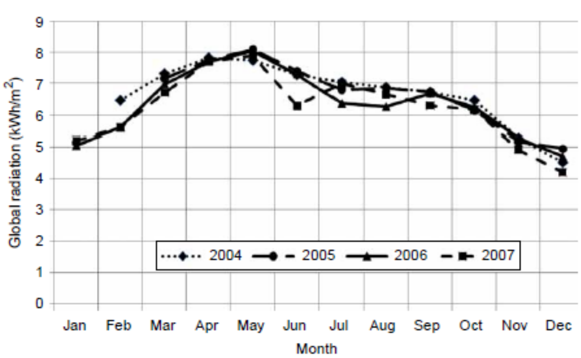

Fig 8 Masirah monthly average solar radiation between 2004- 2008

TABLE 1

TECHNICAL DETAILS OF THE LOAD AND DIFFERENT SOURCES AT MASIRAH ISLAND

Item	Details	Remark
Site information (Masirah Island)	Area of about 649 km^2 population estimated to 12,000	Scattered in 12 villages
Average wind speed	4.99 m/s	1997-2008 At 10-m height
Solar average daily radiation	6.4 kWh/m^2	from 2004 till 2007
Annual electrical energy demand	43,624,270 kWh	Year 2011 minimum load 550kW maximum load 9530 kW

Using the above metrological weather background and the technical details given Table 1, the optimum sizing of the system components was selected based on the monthly average sizing approach. The optimum sizing results are illustrated on table 2.

TABLE 2

OPTIMUM SIZING CONFIGURATION FOR THE PROPOSED MASIRAH ISLAND HYBRID PLANT

Proposed Diesel generator details	10 units Capacity between 200kW to 3300kW	The actual diesel price for Masirah Island is 0.468 US$/L
Number of the PV panels	1.6 MW PV, Cost = 3000 US$/kW O & M cost=10US$/year/kW	
Proposed Wind turbine	Rated power=250kW @ Height= 31m Rated wind speed =13m/s	
Batteries	Type 6CS25P, Nominal voltage 6V, Nominal capacity 1156 Ah Nominal energy capacity of Each battery (VAh/1000) 6.94 kWh	
Converter	Cost=900US$/kW Efficiency=90%	
Level of RE penetration	25%	

Furthermore, a comparison of cost of energy of different hybrid solar –wind- battery- diesel systems was developed as shown in table 3.

TABLE 3
A COMPARISON OF COST OF ENERGY FOR DIFFERENT SYSTEMS

	Battery unit	PV–diesel hybrid system	Wind–diesel hybrid system	PV–Wind-diesel hybrid system
COE	**Yes**	**0.186 US$/kWh** with 28 minutes battery system	**0.189 US$/kWh** with 28 minutes battery system.	**0.182 US$/kWh** with the presence of 28 minutes battery unit
	No	**0.189 US$/kWh** without batteries and the annual diesel consumption will increase by 1%	**0.187 US$/kWh** with no battery system used	**0.185 US$/kWh** if the battery unit is removed from the hybrid system

It is shown here that using PV–wind–diesel hybrid system with a battery unit will produce the lowest COE (0.182 US$/kWh) compared to other hybrids. It can be noticed that the combination and the ratio of the types of energy depending greatly on the resources locally available in each geographical area ref.

The second study is presented in for Al Hallaniyat Island in Oman [37]. The technical and economic viability of utilizing different configurations of hybrid system (Wind, PV, diesel) was investigated using the weather data from 2004-2008. Al Hallaniyat's annual electrical energy demand for the year 2008 was 1,303,290 kWh with a minimum load of 50kW and a maximum load of 320kW . The average wind speed at 10m height was 5.19 m/s and the yearly average daily value of solar radiation was 6.8 kWh/m^2 [37].

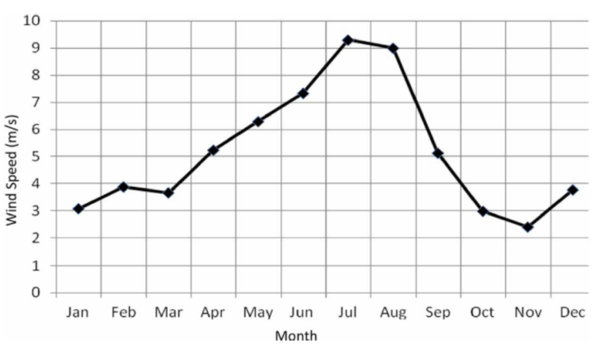

Fig 9 Monthly average wind speed at Al Hallaniyat Island

The wind assessment at Al Hallaniyat Island shows that wind speeds are generally higher during the months of May to August when compared with other months. The wind duration analysis indicated that the wind speeds are less than 4 m/s for about 40% of the time during the year, as shown in

Fig 9.

The monthly average solar radiation for the 2004–2007 is plotted in Fig 10. The insolation level is high during the high electrical load season (March–May) when compared with other months. The yearly average daily value of solar radiation is 6.8 kWh/m^2.

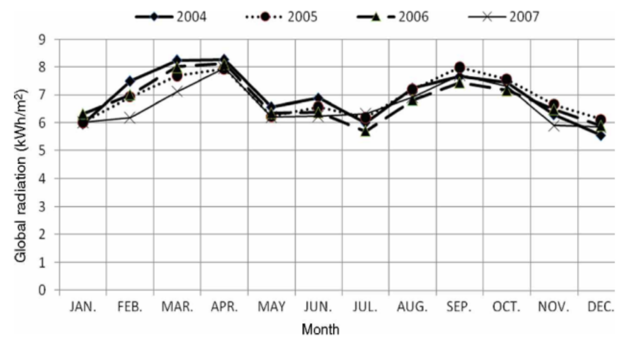

Fig 10 Monthly average daily global radiation at a site near Al Hallaniyat Island

The technical details of the site and the load are summarized in table 4. Since both wind and PV are promising systems in this location, a hybrid system was considered in the analysis consisting of the following combinations: wind–PV–diesel with batteries and wind–PV–diesel without batteries. Fig 11 shows the proposed hybrid system which can be implemented Al Hallaniyat Island. Using the above metrological weather background and the technical details given Table 1, the optimum sizing of the system components was selected based on the monthly average sizing approach. The optimum sizing results are illustrated on table 5.

TABLE 4

TECHNICAL DETAILS OF THE LOAD AND DIFFERENT SOURCES AT AL HALANIYAT ISLAND

Item	Details	Remark
Site information (Al Hallaniyat Island)	Area of about 56 km^2 population estimated to 150	Among five the Khuriya Muriya Islands
Average wind speed	5.19 m/s	at 10m height
Average daily value of solar radiation	6.8 kWh/m^2	from 2004 till 2007
Annual electrical energy demand	1,303,290 kWh	Year 2008 minimum load of 50kW and a maximum load of 320kW

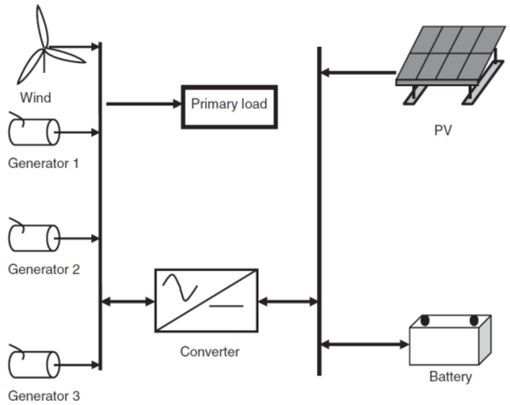

Fig 11 Proposed hybrid solar-wind- diesel system for AL Halaniyat

TABLE 5
OPTIMUM SIZING CONFIGURATION FOR THE PROPOSED AL HALANIYAT ISLAND HYBRID PLANT

Proposed Diesel generator details	10 units Capacity 1080.8 kW	Diesel Price : US$0.508 l^{-1}
Number of the PV panels	70 kW with 30 min storage capacity	A standard cost of \$3000kW−1 Lifetime 25 years O&M cost US$10 per kW per year
Proposed Wind turbine	Rated power=60kW@ 11.3 m/s Height= 10m Rated speed =11.3m/s	capital cost US$60,000 Replacement cost US$40,000 Lifetime 30 years
Batteries	Type US305HC, Nominal voltage 6V, Nominal capacity 305 Ah Nominal energy capacity of Each battery (VAh/1000) 1.83 kWh	
Converter	Cost=900US$/kW Efficiency=90%	
Level of RE penetration	From 10 -25%	

This study has investigated the technical and economic viability of utilizing different configurations of a hybrid system. The main finding is that potential site for deployment of a PV and wind power station, especially with the diesel fuel price \$0.508l^{-1}. The simulation results showed that for a hybrid system composed of 70kW PV, 60 kW wind, 324.8kW diesel generators together with a battery storage, with renewable energy penetration of 25%, the total COE was found to be \$0.222 kWh^{-1}. Moreover, removing the 30 min battery unit from the hybrid system will increase the COE to \$0.225 kWh^{-1}.

VII. CONCLUSION

This paper addresses the concepts of off-grid hybrid renewable energy sources for electrical power generation. Hybrid renewable energy system allows high improvement in the system efficiency, power reliability and reduce the system requirements for storages devices. Most of the advantages of the hybrid PV-Wind hybrid systems were given and the difficulties which faces these industries were also discussed. The paper has also presented different methods of sizing off-grid hybrid solar PV-wind renewable energy sources. Right sizing of a new hybrid renewable energy system can significantly help to determine the initial capital investment while maintaining system reliability at minimum cost. The optimization techniques of the hybrid solar-wind renewable energy systems were also discussed. The optimization approaches compare the performance and energy production cost of different system configurations and that will help to set up the optimum configuration of renewable energy configuration using simulation techniques.

Two proposals for optimum sizing of off-grid hybrid solar-wind power system are discussed. The first was for Masirah Island 12 MW hybrid PV-wind solar plant and the other one was for Al Halaniyat Island.

Optimum sizing analysis showed using PV–wind–diesel hybrid system with a battery unit will produce the lowest COE (0.182 US$/kWh) compared to other hybrids for Masirah Island. For AL Halaniyat Island, the analysis showed that for a hybrid system composed of 70kW PV, 60 kW wind, 324.8kW diesel generators together with a battery storage, with renewable energy penetration of 25%, the total COE was found to be 0.222 US$/kWh.

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