ECONOMIC FEASIBILITY OF DECENTRALIZED HYBRID PHOTOVOLTAIC-DIESEL TECHNOLOGY IN SAUDI ARABIA
A Way Forward for Sustainable Coastal Development

by

Syed M. SHAAHID

Center for Engineering Research, Research Institute,
King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Original scientific paper
DOI: 10.2298/TSCI150722281S

In view of growing concerns of global warming and depleting oil/gas reserves, many nations are considering use of hybrid photovoltaic-diesel technology as an option for power generation The Kingdom of Saudi Arabia has higher level of solar radiation and is a prospective candidate for deployment of solar photovoltaic systems. Literature indicates that commercial/residential buildings in the Kingdom consume about 10-45% of the total electric energy generated. The aim of this study is to analyze solar radiation data in city of Yanbu to assess the techno-economic feasibility of utilizing hybrid photovoltaic-diesel-battery power systems to meet the load of a typical residential building. The monthly average daily solar global radiation ranges from 3.61 to 7.90 kWh/m^2. National Renewable Energy Laboratory's HOMER software has been used in the study. The simulation results indicate that for a hybrid system, composed of 4 kWp photovoltaic system together with 10 kW diesel system, and a battery storage of 3 hours of autonomy (average load), the photovoltaic penetration is 21%. The cost of generating energy from that hybrid system has been found to be 0.180 \$/kWh. With use of this hybrid system, about 2 tons per year of carbon emissions can be avoided entering into the local atmosphere. Also, for a given hybrid configuration, the operational time of diesel generators has been found to decrease with increase in photovoltaic capacity. The investigation examines impact of photovoltaic penetration on: carbon emissions, diesel fuel consumption, net present cost, cost of energy, etc.

Key words: *hybrid photovoltaic-diesel systems, residential loads, diesel generators, carbon emissions, solar irradiance*

Introduction

The world is highly concerned about extensive use of fossil fuel (oil/gas) for power generation due to unprecedented growth of industrialization and world population. This has led to climate change and global warming issues (CO_2 emissions) which are subject matters of debate by researchers. The CO_2 emissions are hazardous to our planet. To mitigate that issues, researchers and policy makers are deliberating on exploitation of the renewable energies (solar, photovoltaic-PV, and wind) as the alternative to the conventional fossil fuels. The Kingdom of Saudi Arabia's (KSA) total installed electricity generation capacity has increased significantly (from 1,141 MW in 1975, to 46,000 MW in 2010, and also the peak demand is expected to be 59,000 MW in 2020) during the last two decades. The annual demand growth is

* Author's e-mail: mshaahid@kfupm.edu.sa

8 percent. About 70 percent of the power generated goes into air-conditioning [1-4]. This increase can be attributed to rapid growth in residential, commercial, and industrial sectors. Literature reveals that commercial/residential buildings in KSA consume 10-45% of the total electric energy consumed [1]. Increased rate of electric energy consumption is one of the biggest problems being encountered by the electric companies in the KSA. In order to cope with the increasing electricity consumption trends, it is necessary to explore every feasible option for generating more energy [4]. Various alternatives for generating more energy include (but not limited to): use of full PV power systems to meet load, use of hybrid systems (such as wind-diesel, PV-diesel, wind-PV-diesel), use of stirling-engine driven generators, *etc.* In KSA perspective, one of the potential option to overcome energy issue is by exploitation of solar energy [5]. Since KSA is blessed with high solar radiation levels, an appreciable portion of its energy needs may be harnessed from solar energy (indispensable/sustainable/nature-friendly). Solar radiation intensities of geographically different provinces of KSA are presented in tab. 1. However, the present work (as a case study) concentrates on Yanbu (western province). More importantly, the future prospects of renewable/solar PV based power systems are expected to be promising.

Table 1. **Monthly average daily global solar radiation in W/hm^2 of different provinces (major cities) of the KSA**

Province [City]	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual avg.
Eastern [Hofuf]	4171	4862	5691	6108	6875	7323	7064	6707	6133	5144	4347	3592	5671
Western [Yanbu]	3980	4640	5740	6325	6660	7900	7200	6700	5700	4730	4140	3610	5610
North [Qurayat]	3464	4736	5486	6421	7095	7418	7514	6936	6077	4741	3804	3027	5562
South [Abha]	4372	5275	6083	6025	6527	6459	5746	5985	6197	6433	5923	4853	5824
Central [Riyadh]	3526	4578	5073	5480	5641	6140	6125	5881	5707	5286	4503	3639	5132

Note: Data represents average of the period 1971-1980. *Source: Saudi Arabian Solar Radiation Atlas, Riyadh, KSA, 1983*

Solar energy is one of the sustainable/potential/in-exhaustible, site-dependent, benign/nature-friendly (does not produce emissions that contribute to greenhouse effect) source of renewable energy options. This renewable energy source has been pursued by a number of countries with monthly average daily solar radiation level in the range of 3-6 kWh/Sq.m, in an effort to reduce their dependence on fossil-based non-renewable fuels [6-13]. Solar collectors can be classified as either solar thermal energy converters or solar electric energy converters. Devices that directly convert solar into electric energy are generally called PV [11]. The concept of PV is well-understood and currently thousands of PV based power systems are being deployed worldwide, for providing power to small, remote, grid-independent/de-centralized applications [6]. Additionally, use of renewable/solar energy reduces combustion of fossil fuels and the consequent CO_2 emission which is the principal cause of global warming. Global warming is expected to change terrain and climate of many countries unless measures are taken [14-17]. More importantly, in the light of December 1997's Kyoto's protocol on climate change (due to carbon emissions), about 160 nations have reached a first ever agreement (to turn to renewable/wind/PV power) to limit/cut carbon emissions. Although, solar energy is enormous, but PV driven power system is still an expensive option (PV system capital cost is about 4000$/kW, capital cost of conventional power systems is about 1000$/kW) [18]. The high initial investment cost of PV systems poses to be the main barrier/pressing-factor/road-block that hampers promotion of this technology in large-scale. Nonetheless, PV finds application in remote areas (where it is un-economical to extend/stretch the utility grid) which lack access to electric grid [18, 19]. The PV systems have the advantage of minimum/un-attended maintenance and easy expansion (up-sizing) to meet growing energy needs. The PV modularity/expandability (modules are available off-the-shelf) is one of its major strength and it allows the users to tailor PV system capacity to the desired load. The PV systems produce electricity during the times when we demand it most, on hot sunny days coinciding with our peak electricity consuming periods. The demerits are: PV is capital-cost-intensive and its sunshine-dependent output does not match the load on 24 hours basis. However, technological break-throughs (yielding cost reduction of PV, improved efficiency, *etc.*) may change the situation [10, 18].

Despite abundant availability of solar energy, a PV system alone can not satisfy load on a 24 hour basis [18]. Stand-alone diesel power generation sets (relatively inexpensive to purchase), are generally expensive to operate and maintain especially at partial loads [20]. Often, the variations of solar energy generation do not match the time distribution of the load. Therefore, power generation systems dictate provision of battery storage facility to narrow-down/ /smoothen/dampen the time-distribution-mismatch between the load and solar energy generation and to facilitate for maintenance/outages of the systems [10, 21]. The PV generated electricity stored in batteries can be retrieved during nights. Use of diesel system with PV-battery reduces battery storage requirement. Research conducted world-wide indicates that hybrid PV/diesel/battery system (represents an economically acceptable compromise between the high capital cost of PV autonomous system and high O&M + fuel cost of fossil fuel generators) is a reliable source of electricity [19]. Hybrid systems add a new dimension to the time-correlation of intermittent PV sources. The PV and diesel have complementary characteristics: capital cost of PV is high as compared to diesel, operating cost of PV is low (relative to diesel), maintenance requirements of PV are less as compared to diesel, diesel energy is available all the time where as availability of PV is highly dependent on solar radiation [19]. The prospects of hybrid systems have gained momentum and a number of PV-diesel-battery installations (with capacity factors in the range of 20-35%) exist around the world [19, 22, 23]. The cumulative installed capacity of all solar systems around the world was about 3,120 MWp in 2003. The global installed capacity of solar power is expected to reach 207 GWp by 2020 (the cost of solar modules is likely to go down to US$1 per watt delivered). Also, the projections indicate that by 2020 solar systems can provide energy to over a billion people globally and provide 2.3 million full-time jobs [24].

The research on feasibility of renewable energy systems at city of Dhahran, KSA, has been the subject matter of several earlier studies [25-29]. In the present work, the economic analysis of utilization of hybrid PV-diesel-battery power systems to meet the load of a typical residential building (with annual electrical energy demand of 35,120 kWh) in Yanbu (latitudes 24° 07' N, 38° 03' E, West coast) western province of KSA has been studied by analyzing long-term (1971-1980) solar radiation data. In general, long-term data indicates that the monthly average daily solar radiation/insolation of KSA varies from 3.61-7.90 kWh/m^2. The solar radiation intensity has been used to assess the potential of using solar PV technology for residential loads. National Renewable Energy Laboratory's (NREL) or HOMER Energy's HOMER software has been employed to perform the techno-economic analysis. The HOMER is a sophisticated tool or computer-model that facilitates design of stand-alone electric power systems [30]. The hybrid systems considered in the analysis comprise of different combinations of PV modules/arrays supplemented by battery storage and diesel power generation sets. Also, for that hybrid configuration, the study examines the impact of PV penetration on: carbon emissions (tons per year), diesel fuel consumption (L per year), net present cost (NPC, US$), COE (US$/kWh), *etc.*

Background information and load data

The KSA is basically an arid/desert land with long hot summers, and short cold winters. The topographic features of the KSA are characterized by mountains in the west bordering the Red Sea that act as wind deflectors, large desert areas in the interior where high temperatures create low pressure cells, and the Arabian Gulf and Red sea which are Sea areas in the east and west, respectively. To the west of KSA, the Gulf of Aqaba and the Red Sea form a coastal border of almost 1,800 kilometers. The KSA is located within the latitudes 16^o N and 32^o N. The month of March marks the beginning of spring and the transition from winter to summer climate. Climatic conditions dictate the availability and magnitude of solar energy at a site. Solar PV systems are characterized by availability of solar insolation/regime/resource. The long-term solar radiation data of used in the present study covers the period 1971-1980 [31].

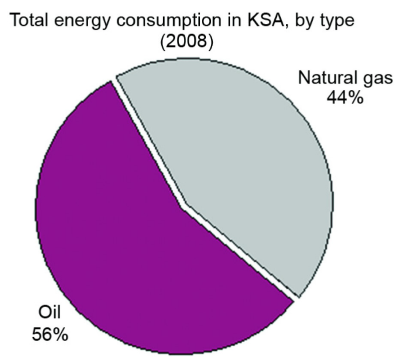

Figure 1. **Conventional power generation sources in Saudi Arabia (Source: International energy statistics, 2008)**

Yanbu is a major Red Sea port and 30 years old industrial city that plays a major role in the economy of KSA. The population is 250,000. It is an important petroleum shipping terminal and is home to several petrochemical plants. The power generation plant in Yanbu has a capacity of 1,030 megawatts. The KSA has approximately one-fifth of the world's oil reserves, and is the largest oil producer and exporter of total petroleum liquids in the world. Natural gas and oil had 44% and 56% share in conventional power generation in 2008. Figure 1 shows the contribution of different energy sources in the total conventional power generation in the country [32].

An important consideration of any power generating system is load. Load has substantial impact on system design. The present work focuses attention on residential loads. As a case study and as a representation of residential buildings, the annual average energy consumption of a typical two bedroom house (floor area = 169.8 m^2) has been considered as yearly load (35,120 kWh) in the present study [33]. The daily average load profile is shown in fig. 2. The load seems to peak during June to September. The peak requirements of the load dictate the system size. The load could also be a representation of many remotely located residential buildings which lack access to the utility grid (even today, there are many communities living or dwelling in small pockets in remote locations of KSA). The KSA area is large, with large number of settlements (far from electric grids) scattered all over the KSA. The supply of electricity to these remote

Figure 2. Daily average load for a complete year in kW

villages through diesel generators alone or by connecting into the nearest grid could be an expensive option. The retrofitting of PV systems along with the diesel systems may result in reduced fuel transport/storage/consumption, lower diesel emissions, fewer diesel spills, and longer engine life.

In the present study, the selection and sizing of components of hybrid power system has been done using NREL's (HOMER Energy's) HOMER software. The HOMER is a hybrid system design software that facilitates design of electric power systems for stand-alone applications. Input information to be provided to HOMER includes: electrical load data, renewable resources data (solar radiation data), component technical details/costs, constraints, controls, type of dispatch strategy, *etc.* The HOMER designs an optimal power system to serve the desired loads. The HOMER is an simplified optimization model/code, which performs hundreds or thousands of hourly simulations over and over (to ensure best possible matching between supply and demand) in order to design the optimum system. It uses life cycle cost to rank order these systems. It offers a powerful user interface and accurate sizing with detailed analysis of the system. The software also performs automatic sensitivity analysis to account for the sensitivity of the hybrid system design to key parameters, such as the resource availability or component costs [30].

Solar radiation data and characteristics of hybrid PV-diesel system

The long-term (1971-1980) monthly average hourly values/profiles of solar radiation for Yanbu are plotted in fig. 3. In general, the monthly average daily values of solar global radiation/insolation (of the locations considered in the study) range from 3.61-7.90 kWh/m^2 [31]. The yearly average daily values of solar radiation of different locations/provinces are shown in tab. 1. It can be depicted from fig. 3 that solar radiation is generally higher during the summer months (May to August) as compared to other months (this is due to topography). This implies that solar systems would produce appreciably more energy during summer time. This seasonal pattern/trend of solar radiation matches with the higher load requirements during summer period in KSA. This is a favorable characteristic because electricity demand is high during the summer months in KSA Relatively less load can be met/covered during non-summer months because of blocking of Sun's rays by clouds.

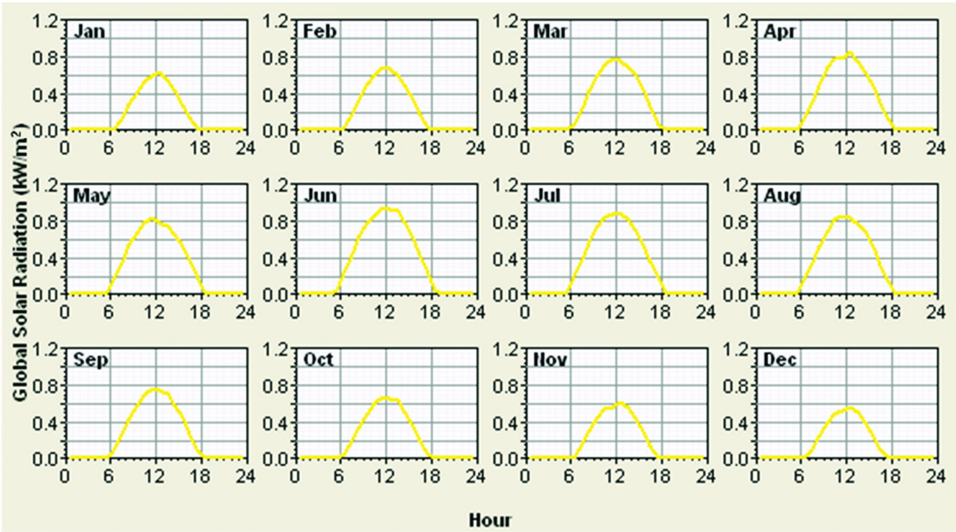

Figure 3. **Monthly average hourly solar radiation at Yanbu**

The long term average data (of Yanbu) shown in tab. 1 has been used for simulations (in HOMER). The energy calculations are made by matching the solar radiation data with the characteristics of PV modules [34]. The characteristics of some of the commercial PV modules are furnished in tab. 2. The PV modules which are composed of several solar cells are integrated/clustered in series-parallel arrangement (cells are wired in series to provide greater voltage and in parallel to provide greater current) to form solar arrays. Despite advancements in the state-of-the-art, today's best PV systems can achieve an overall efficiency of about 15-20% [11]. These lower efficiency values may not make this alternative attractive at the moment. However, technological breakthroughs may change the scenario [10, 18].

Table 2. **Characteristics of some commercial PV modules**

Module size* $L \times W \times D$	Rated power Rp [W]	Current [A]	Voltage [V]	Module Reference, η
1113 × 502 × 50 mm	60	3.5	17.1	0.107
1108 × 660 × 50 mm	83	4.85	17.1	0.113
18.5 × 25.7 × 2.1 inch	35	2.33	15.0	0.15
25.2 × 25.7 × 2.1 inch	50	3.00	16.7	0.15
34.1 × 25.7 × 2.2 inch	70	4.14	16.9	0.15
56.1 × 25.7 × 2.2 inch	120	7.10	16.9	0.15
50.8 × 39.0 × 1.4 inch	167	7.2	23.2	0.15

* L – length; W – width; D – depth. Modules are high efficiency solar electric modules and Kyocerasolar modules. Power specifications are at standard test conditions of: 1000 W/m^2 solar irradiance, 25 °C cell temperature.

The schematic of hybrid PV-diesel-battery system is shown in fig. 4. The dispatch strategy is load following type and interaction between different components is: in normal operation, PV feeds the load demand. The excess energy (the energy above the average hourly demand; if any) from the PV is stored in the battery until full capacity of the battery is reached. The main purpose of introducing battery storage is to import/export energy depending upon the situation. In the event, that the output from PV exceeds the load and the battery's state of charge (SOC) is maximum, then the excess energy is fed to some dump load or goes un-used (due to lack of demand). A diesel system is brought-online at times when PV fails to satisfy the load and when the battery storage is depleted (*i. e.* when the battery's SOC is minimum).

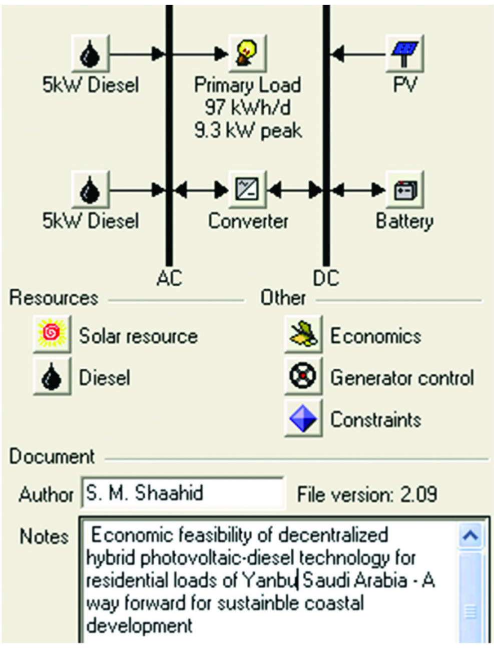

Figure 4. **Schematic of hybrid PV-diesel-battery power system**

Results and discussions

The hybrid systems simulated consist of different combinations of PV panels/modules supplemented with battery bank and diesel generators. The study explores a suitable mix of inter-dependent dominant/key parameters/variables such as: PV array power (kWp), battery storage, and diesel capacity to match the predefined load (with 0% capacity shortage, zero load rejection). As a rule of thumb, diesel generators are sized to meet the peak demand of the power. The peak demand of the present case-study is 9.3 kW as depicted in fig. 4. In this regard, two diesel generator sets with a combined power of 10 kW (to cover peak load and to cover spinning/operating reserve of about 10% to overcome rapid changes in load) have been considered for carrying out the techno-economic analysis of the hybrid systems. Two diesel power generation sets (D1, D2) each of 5 kW capacity have been considered. Multiple power generation sets are used to reduce excess. The operating/spinning reserve is surplus electrical generation capacity (over/above the load) that is instantly available to serve/cover additional loads. It provides a safety margin that helps ensure reliable electricity supply even if the load were to suddenly increase or the renewable power output were to suddenly decrease.

Several simulations (assuming diesel fuel price of 0.1 $/L) have been made by considering different PV capacities. The PV capacity has been allowed to vary from 0 to 24 kWp. The battery storage/bank size (in kWh) considered is to three load-hours/autonomy (equivalent to three hours of average load, *i. e.* equivalent to three Surette batteries with details listed in tab. 3). The study assumptions made for making simulations on HOMER are presented in tab. 3. An earlier study indicates that maximum benefits of battery storage can be realized for a battery capacity of 3 hours of autonomy [8]. In this context, battery storage in the present study has been considered as 3 hours of average load. The results of simulations (for diesel price of 0.1 US$/L) for different PV penetrations for Yanbu (for a given battery storage of 3 hours; equivalent to 3 hours of average load) are presented in tab. 4. The details furnished in tab. 4 include: PV penetration [%], NPC (US$), diesel fuel consumption (L per year), carbons

Table 3. Technical data and study assumptions of PV, diesel units, and batteries

Description	Data
PV	
Capital cost	6,900 US$/kW
Life time	25 years
Diesel generator units	
Rated power of diesel unit 1 [D1]	5 kW
Minimum allowed power (min. load ratio)	30% of rated power
No. of load fuel consumption	0.42 L per hour
Full load fuel consumption	1.65 L per hour
Rated power of diesel unit 2 [D2]	5 kW
Minimum allowed power (min. load ratio)	30% of rated power
No. of load fuel consumption	0.42 L per hour
Full load fuel consumption	1.65 L per hour
Batteries	
Type of batteries	Surette 6CS25P
Nominal voltage	6 V
Nominal capacity	1,156 Ah
State of charge	40%
Nominal energy capacity of each battery (VAh/1000)	6.94 kWh
Dispatch/Operating strategy	Multiple diesel load following
Spinning reserve	
Additional online diesel capacity (to shield against increases in the load or decreases in PV power output)	10% of the load

emissions that can be avoided (tons per year), cost of energy (COE) generation, $US/kWh) of 1 kWh of energy, *etc.*

As a starting point (and as a reference), simulations have been performed for PV-diesel systems with zero PV. The COE from diesel system (10 kW diesel system, no-storage, 0% annual capacity shortage) with 0% PV fraction has been found to be is 0.129 US$/kWh as shown in tab. 4. However, for this scenario, the diesel fuel consumption (13,902 L per year) and carbon emissions (10.03 tons per year) are on the higher side as compared to the situations with presence of PV and battery storage. It can be noticed from the results (tab. 4) that in general the PV penetration (renewable energy fraction) has varied from 0 to 68%. In an isolated system, renewable energy contribution of 68% is considered to be high. Such a system might be very difficult to control while maintaining a stable voltage and frequency. The level of renewable energy fraction in hybrid systems (deployed around the world) is generally in the range of 11-35% [19]. A trade-off/balance need to be established between different feasible options.

The simulation results indicate (tab. 4) that for a hybrid system composed of 4 kWp PV system together with 10 kW diesel system and a battery storage of 3 hours of autonomy (equivalent to three hours of average load), the PV penetration is 21%, (with 0% capacity shortage). The cost of generating energy (COE, US$/kWh) from the hybrid system has been found to be 0.180 $/kWh (assuming diesel fuel price of 0.1 $/L). Also, for a hybrid system composed of 8 kWp PV system together with 10 kW diesel system and a battery storage of 3 hours of autonomy (equivalent to 3 hours of average load), the PV penetration is 38%, (with 0% capacity shortage). The cost of generating energy (COE, US$/kWh) from the hybrid system has been found to be 0.215 $/kWh. Literature indicates that COE from PV systems is about 0.20 US$/kWh [35-38].

Table 4. Characteristics of PV-diesel-battery power systems for a given residential load for different PV penetrations (solar PV sizes) at Yanbu (based on diesel fuel price of 0.1 US$/L and battery storage of 3 hours of average load)

PV-diesel system details	PV penetration [%]	NPC [$]	Diesel fuel consumption [L per year]	Carbon emissions [tons per year]	COE [$/kWh]
0 kWp PV + 10 kW diesel	0	71,397	13,902	10.03	0.129
4 kWp PV + 10 kW diesel	21	99,540	11,411	8.26	0.180
8 kWp PV + 10 kW diesel	38	119,163	9862	7.1	0.215
12 kWp PV + 10 kW diesel	50	143,867	9219	6.65	0.260
16 kWp PV + 10 kW diesel	58	169,949	8886	6.41	0.307
20 kWp PV + 10 kW diesel	64	196,543	8667	6.25	0.355
24 kWp PV + 10 kW diesel	68	223,458	8518	6.15	0.403

The study has examined the impact of PV penetration on: carbon emissions, diesel fuel consumption, NPC (US$), COE, (US$/kWh) as shown in tab. 4. It has been observed that increase in PV penetration results in increase in COE and NPC. On the other hand, increasein PV penetration results in decrease in diesel fuel consumption and carbon emissions. These are welcome features because several countries world-wide are putting significant efforts to reduce diesel fuel consumption and hence to cut-down on carbon emissions. This is a way forward for sustainable green (carbon-free) future. It can be noticed from tab. 4 that the NPC with presence of PV system is high. This highlights that initial cost of PV system in hybrid system is predominant. However, annual operation and maintenance cost of PV system, is 0% of the total O&M + fuel cost.

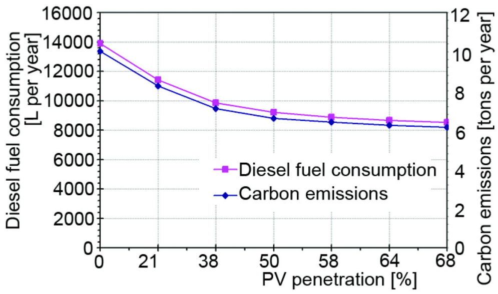

Figure 5. Impact of PV penetration on diesel consumption and carbon emissions at Yanbu for hybrid system

The percentage fuel savings by using hybrid system (4 kW PV + 10 kW diesel system + 3 hours of battery) as compared to the diesel only situation is about 18% as shown in tab. 4. Moreover, percentage fuel savings increases by increasing the PV capacity. This indicates that introduction of PV panels decreases load on the diesel generators. The diesel fuel savings may only be quantifiable by justifying the additional capital expenditure invested in PV. It has also been observed (tab. 4) that the percentage decrease in carbon emissions with 21% PV fraction is about 18% as compared to diesel-only (zero % PV energy) case. The effect of PV penetration on diesel fuel consumption, carbon emissions, COE, excess energy generation, *etc.*, has been demonstrated explicitly in figs. 5 and 6. For a given hybrid configuration, the study

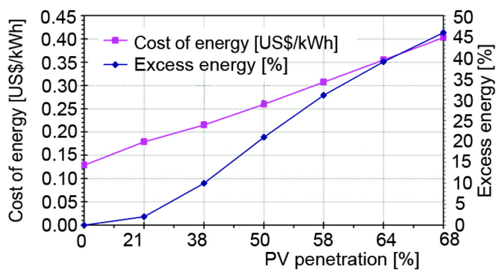

Figure 6. Impact of PV penetration on COE and excess energy generated at Yanbu for hybrid system

exhibits that increase in PV capacity results in decrease in the diesel-fuel-consumption/carbon-emissions and increase in COE/NPC/excess-energy. It should be mentioned over here, that more often, the excess energy produced goes un-used due to lack of demand (sometimes it is fed to dump loads). For a given PV capacity, the lower the excess energy the better is the economy of the PV-diesel-battery systems.

The present study shows potential of Yanbu for utilizing of solar energy (hybrid PV-diesel power systems). Also, considerable attention is focused by different countries (such as France, Malaysia, Greece, Iran, Banglasesh, Thailand, *etc.*) world-wide on utilization of hybrid PV-diesel power systems [39-45].

Conclusions and recommendations

In the wake of appreciable monthly average daily solar global radiation intensity (3.61 to 7.90 kWh/m^2), the study indicates that Yanbu in particular and KSA in general is a prospective candidate for deployment of PV power systems for residential applications in crisis. The simulation results indicate that for a hybrid system comprising of 4 kW PV system together with 10 kW diesel system and a battery storage of 3 hours of autonomy (equivalent to three hours of average load), the PV fraction/penetration is 21%. The cost of generating energy from the hybrid PV-diesel-battery system has been found to be 0.180 US$/kWh (assuming diesel fuel price of 0.1$/L). The study exhibits that for a given hybrid PV-diesel configuration, the number of operational hours of diesel generators decreases with increase in PV capacity. It has been found that for a given PV-diesel hybrid system, the decrease in diesel run time is further enhanced by inclusion of battery storage. The percentage fuel savings by using hybrid PV-diesel-battery system (4 kW PV, 10 kW diesel system, 3 hours storage) is 18% as compared to diesel-only situation. The percentage decrease in carbon emissions by using hybrid system (4 kW PV, 10 kW diesel system, 3 hours of battery, with 21% PV fraction) is 18% as compared to the diesel only scenario. More importantly, with use of the hybrid system, about 2 tons per year of carbon emissions can be avoided entering into the local atmosphere.

Investments in mobilization of hybrid PV-diesel system technology may stimulate/gear-up the local economy (in a long-run) by exploitation of available local resources. The present work shows that a fraction of KSA energy demand may be harnessed from PV systems. The findings of this investigation can be employed as a frame-of-reference in designing of hybrid PV-diesel-battery systems for other locations having similar climatic and load conditions.

Acknowledgment

The author acknowledges the support of the Research Institute of the King Fahd University of Petroleum and Minerals. The author is also very thankful to NREL and HOMER Energy for making available freely HOMER software for design of hybrid electric power systems. The author extends special thanks to Dr. Tom Lambert and Dr. Peter Lilienthal for their time and effort in reviewing HOMER files and for their cooperation.

References

[1] ***, Ministry of Industry & Electricity, Electrical Growth and Development in the Kingdom of Saudi Arabia, Report No. 1, Electrical Affairs Agency, Riyadh, Kingdom of Saudi Arabia, 1997
[2] Omar, B., Future Potential for Energy Services in Saudi Arabia, *Proceedings,* 1st Symposium on Energy Conservation & Management in Buildings, Dhahran, Saudi Arabia, 2002, pp. 175-183
[3] ***, Saudi Consolidated Electric Company, Annual Report No. 1, Eastern Province/Saudi Arabia 1999/2000

[4] Abdulrahman, S. H., Charging Experiments on a Cool Thermal Store Filled with Balls Containing Water, *Proceedings,* 1st Symposium on Energy Conservation & Management in Buildings, Dhahran, Saudi Arabia, 2002, pp. 103-112
[5] Joyashree, R., Soma, G., Cost of Oil-Based Decentralized Power Generation in India: Scope for SPV Technology, *Solar Energy, 57* (1996), 3, pp. 231-237
[6] Post, H. N., Thomas, M. G., Photovoltaic Systems for Current and Future Applications, *Solar Energy, 41* (1988), 5, pp. 465-473
[7] Mahmoud, M., Experience Results and Techno-Economic Feasibility of Using Photovoltaic Generators in Stead of Diesel Motors for Water Pumping from Rural Desert Wells in Jordan, *IEE Proceedings, 137* (1990), 6, pp. 391-394
[8] Shaahid, S. M., Elhadidy, M. A., Technical and Economical Assessment of Grid-Independent Hybrid Photovoltaic-Diesel-Battery Power Systems for Commercial Loads in Desert Environments, *International Journal of Renewable and Sustainable Energy Reviews, 11* (2007), 8, pp. 1794-1810
[9] Richard, N. C., Development of Sizing Nomograms for Stand-Alone Photovoltaic/Storage Systems, *Solar Energy, 43* (1989), 2, pp. 71-76
[10] Traca, A., *et al.*, Source Reliability in a Combined Wind-Solar-Hydro System, *IEEE Transactions on Power Apparatus and Systems, PAS-102* (1983), 6, pp. 1515-1520
[11] Frank, W., Terrence, G., Fundamental Characteristics and Economic Operation of Photovoltaic Solar Collectors, in: Solar Energy Technology (Ed. W. M. Worex, A. A. Pesaran), SED, Anameem, Cal., USA., Vol. 13, pp. 75-79, 1992
[12] Douglas, B., The Essence Way Renewable Energy System, *Solar Today, 5* (1997), 6, pp. 16-19
[13] Oparaku, O. U., Assessment of the Cost-Effectiveness of Photovoltaic Systems for Telecommunications in Nigeria, *International Journal of Solar Energy, 22* (2002), 3-4, pp. 123-129
[14] Jeffery, K., Global Warming and Energy Efficiency, *SunWorld, 14* (1990), 2, pp. 44-52
[15] Ali, S., Global Progress in Renewable Energy 2001, *Book of Abstracts,* 7th Arab International Solar Energy Conference, Sharjah, U. A. E., 2001
[16] Coiante, D., Barra, L., Renewable Energy Capacility to Save Carbon Emissions, *Solar Energy, 57* (1996), 6, pp. 485-491
[17] Roger, H. B., The Environmental, Health, and Safety Implications of Solar Energy in Central Station Power Production, *Energy, 18 (*1993), 6, pp. 681-685
[18] Hansen, U., Technological Options for Power Generation, *The Energy Journal, 19* (1998), 2, pp. 63-87
[19] Bergey, M., Village Electrification: Hybrid Systems, *Wind Energy Applications and Training Symposium*, Amarillo, Tex., USA, 1993
[20] Nayar, C. V., *et al.,* Novel Wind/Diesel/Battery Hybrid Energy System, *Solar Energy, 51* (1993), 1, pp. 65-78
[21] Chowdhury, B. H., Saifur, R., Analysis of Interrelationships between Photovoltaic Power and Battery Storage for Electric Utility Load Management, *IEEE Transactions on Power Systems, 3* (1988), 3, pp. 900-907
[22] Luiz, C. G. V., Silvio, C. A. A., Economic Analysis of Diesel/Photovoltaic Hybrid System for Decentralized Power Generation in Norther Brazil, *Energy, 23* (1998), 4, pp. 317-323
[23] ***, On Briefing/Case-Studies of Several Projects, Report No. 1, Northern Power Systems, May 1994
[24] ***, Greenpeace Briefing, http://www.greenpeace.org, http://martinot.info, http://www.solarbuzz.com
[25] Elhadidy, M. A., Shaahid, S. M., Decentralized/Stand-Alone Hybrid Wind-Diesel Power Systems to Meet Residential Loads of Hot Coastal Regions, *International Journal of Energy Conversion and Management, 46* (2005), 15, pp. 2501-2513
[26] Elhadidy, M. A., Shaahid, S. M., Feasibility of Hybrid (Wind+Solar) Power Systems for Dhahran, Saudi Arabia*, Proceedings*, World Renewable Energy Congress, Florence, Italy, 1998
[27] Shaahid, S. M., *et al.,* Potential of Autonomous/off-Grid Hybrid Wind-Diesel Power System for Electrification of a Remote Settlement in Saudi Arabia, *International Journal of Wind Energy, 28* (2004), 5, pp. 621-628
[28] Shaahid, S. M., Elhadidy, M. A., Optimal Sizing of Battery Storage for Hybrid (Photovoltaic+Diesel) Power Systems, *International Journal of Sustainable Energy, 24* (2005), 3, pp. 155-166
[29] Shaahid, S. M., *et al.,* Techno-Economic Potential of Retrofitting Diesel Power Systems with Hybrid Wind-Photovoltaic-Diesel Systems for off-Grid Electrification of Remote Villages of Saudi Arabia, *International Journal of Green Energy, 7* (2010), 6, pp. 632-646
[30] ***, National Ren. Laboratoraty, http://www.nrel.gov/international/tools/HOMER/homer.html

[31] ***, The Saudi Arabian National Center for Science & Technology, Saudi Arabian Atlas, Riyadh, Saudi Arabia, 1983
[32] ***, Energy Sources of Saudi Arabia, http://www.eia.gov/cabs/Saudi_Arabia/Full.html
[33] ***, Analysis of Electric Energy Consumption in Residential Buildings, Internal Report No. P/N#12031, Research Institute, KFUPM, Dhahran, Saudi Arabia, 1992
[34] Essam, El., R., *et al*., Load/Weather/Insolation Database for Estimating Photovoltaic Array and System Performance in Egypt, *Solar Energy, 41* (1988), 6, pp. 531-542
[35] ***, Cost Energy from Photovoltaic Power Systems, http://www.phillysolar.org/docs/pvfactsheetv2.pdf#search='Photovoltaic%20Pricing
[36] ***, Cost of Energy from PV Systems, http://www.energy.state.or.us/renew/costs.htm
[37] ***, Cost of Energy from Photovoltaic Power Systems, http://www.p2pays.org/ref/12/11346.pdf#search='Cost%20of%20PhotovoltaicGenerated%20Electricity
[38] ***, Cost of Energy from Photovoltaic Power Systems, http://www.nrel.gov/docs/fy04osti/35297.pdf#search='A%20consumer's%20guide%20%20Get%20your%20power%20from%20the%20sun
[39] Yamegueu, D., *et al.,* Experimental Study of Electricity Generation by Solar PV/Diesel Hybrid Systems without Battery Storage for off-Grid Areas, *Renewable Energy, 36* (2011), 6, pp. 1780-1787
[40] Lau, K. Y., *et al.*, Performance Analysis of Hybrid Photovoltaic/Diesel Energy System under Malaysian Conditions, *Energy, 35* (2010), 8, pp. 3245-3255
[41] Kaldellis, K. J., Ioanna, N., Energy Balance Analysis of Combined Photovoltaic-Diesel Power Telecommunication Stations, *Electrical Power and Energy Systems Journal*, *33* (2011), 10, pp. 1739-1749
[42] Kaldellis, K., *et al*., Optimum PV-Diesel Hybrid Systems for Remote Consumers of the Greek Territory, *Applied Energy Journal*, *97* (2012), Sept., pp. 61-67
[43] Abolfazl, G., *et al*., Techno-Economic Analysis of Stand-Alone Hybrid Photovoltaic-Diesel-Battery Systems for Rural Electrification in Eastern Part of Iran – A Step Towards Sustainable Rural Development, *International Journal of Renewable and Sustainable Energy Reviews, 28* (2013), Dec., pp. 456-462
[44] Alam, H. M., Manfred, D., Hybrid Systems for Decentralized Power Generation in Banglasesh, *Energy for Sustainable Development Journal, 14* (2010), 1, pp. 48-55
[45] Phuangpornpitak, N., Kumar, S., User Acceptance of Diesel/PV Hybrid System in an Island Community, *Renewable Energy*, *36* (2011), 1, pp. 125-131

Paper submitted: July 22, 2015
Paper revised: October 29, 2016
Paper accepted: November 11, 2016