Feasibility Study and Economic Analysis of a Hybrid PV/diesel Energy System for Remote Rural Healthcare Center

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Abstract— This paper investigated the optimal design and economic viability of renewable-based hybrid power supply system for application in the basic health center (BHC) at an off-grid rural area in Nigeria. The BHC has average energy consumption per day of 14.6kWh and a peak load demand of 2.73kW. HOMER Pro evaluation software has been engaged for the simulation and techno-economic analysis. At 2.25 SAR/L diesel fuel price and 5.51 kWh/m^2/day solar annual average radiation, PV/diesel/battery hybrid power system was adjudged the most preferred configuration technically and economically for powering basic health center in the selected area. The outcome of the optimal simulation reveals that the cost of energy (COE) ranges between 1.51 SAR/kWh and 1.62 SAR/kWh for varying global solar radiation. As regard to the fuel consumption and CO_2 emission, the conventional diesel system consumes 3431.6 L/yr. more than the optimal architecture to emit 9,041 kg/yr. CO_2. Hence, the optimal best configuration performs better than the diesel-based architecture.

Index Terms— HOMER pro; renewable based hybrid energy system; basic health center; Nigeria; Optimal design.

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1 INTRODUCTION

Ensuring a continuous and reliable electricity supply represents a perpetual challenge for the sustainable development of any country. . Unavailability of electricity in many rural areas has widened the economic gap, fostered poverty and made it increasingly difficult to upgrade their standard of living. An attempt to connect the rural areas to the national grid is like a pipe dream, as the government is focusing more on expanding the power infrastructure to further convey the energy generated to the priority customers Nigeria is endowed with conventional and renewable energy resources in abundance. Harnessing these renewable sources in areas where there is the comparative advantage of impressive global annual solar radiation is key to achieving the electrification goals of the nation. Being a signatory to the UNDP Sustainable development goals, goal number 7 is to ensure access to affordable, reliable, sustainable and modern energy for all (SE4ALL) [1]. An improved power condition will boost economic activities, powering water pumps, enhance health operations at the clinics, support small & medium scale enterprises and ease security challenges. A hybrid power system is a combination of renewable energy sources (Solar, wind, biomass, etc.) and diesel generators with/without deep-cycle rechargeable batteries. Numerous researches have been conducted on the hybrid systems with interest in its reliability, cost-effectiveness, performance, ecological impact and many more. Aziz [2] investigated the techno-economic of different hybrid energy systems for power supply at a desert safari camp in UAE using HOMER. He concluded that HPS comprising of PV, wind, and battery is the optimum system with higher efficiency. Bhandari et al. [3] demonstrated the implementation of HPS consisting of wind, solar and hydropower for powering off-grid remote villages at Makawanpur District, Nepal using two RE source integration techniques. They stated that HPS is the best option for power supply in remote areas in terms of cost, environmental sustainability, and lifestyle improvement. Ramli et al. [4] evaluated the possibility of using a hybrid solar/wind energy system for electricity supply in Yanbu, Saudi Arabia. The authors concluded that the studied area has huge potential for these resources and wind turbine contribution of energy is less as compared to that of the PV module of similar size. Kaldellis et al. [5] modeled an autonomous standalone PV system using pay-back energy method. They analyzed two separate areas of high and medium solar potential with different PV-battery autonomous energy system. The authors stated that the battery contribution is more than 27% of the system energy requirement in all cases investigated.

This research is conducted to evaluate performance of the proposed system for Ja'agi village, in Niger state, Nigeria. The community is remote, unconnected to the utility grid, with difficult terrain and the extension of the utility grid to their homes is grossly impractical. An appropriate stand-alone power system is obviously the most viable option to adopt. Ja'agi village has a good potential of solar energy which is indicated by a high level of insolation. However, a PV system is incapable of satisfying load on a 24-hours basis [6]. Stand-alone diesel-fueled power generators, on the other hand, are way very expensive to operate and maintain. Their average operation costs increase marginally at low load levels, especially less than 40% rated capacity [7]. In this study, NREL's HOMER Pro software [8] is used to carry out an assessment of a variety of combinations that could be simulated for the Ja'agi community, with the aim of identifying the most befitting model, their sensitivities to varying climatic conditions, load dynamics and fuel prices.

2 Detail of input Variables

2.1 Basic Healthcare Load Analysis

The basic healthcare center selected for this study is located at Ja'agi village. The basic health center consists of a female ward, male ward, labor room, an emergency room, a family planning room, consulting room, an antenatal hall and a record room where medical records are kept. There are approximately 15 beds,11 ceiling fans, 18 compact fluorescent lamps,1 vaccine and blood bank refrigerator, 1 Television etc. In general, this clinic required electricity for powering major and important loads such as lighting, few laboratory pieces of equipment and refrigerator (for vaccine and blood bank) because of the limited use of diesel generator coupled with inaccessibility to the national grid. A typical load profile representing the chosen community during daily working hours is shown in Fig. 1. The daily average energy consumption is 14.6kWh/day (or 5.329MWh/year) with a peak load demand of approximately 2.73kW. In actual sense, the community load shape and size is expected to vary time to time. Hence, a day-to-day and a time-step variability of 15% and 10% were selected.

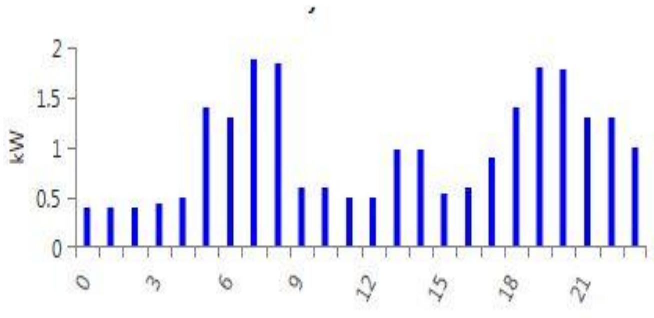

Fig. 1. Daily load sketch of the chosen community.

2.2 Solar Radiation

The solar resource data used for this research was obtained from the NASA Langley research center website by specifying the latitude and longitude of the area [9]. Fig 2 displays the changes in average solar radiation per month and the corresponding clearness index. The monthly daily radiation varies from 4.43kWh/m2/day to 6.26kWh/m2/day hence, the energy output per month of the conversion systems (i.e. for solar energy) would equally vary from month-to-month. The annual average solar radiation and clearness index were found to be 5.51kWh/m^2/day and 0.56 respectively. This shows that there is huge potential for solar energy application in this area even though these resources are being underutilized at the moment.

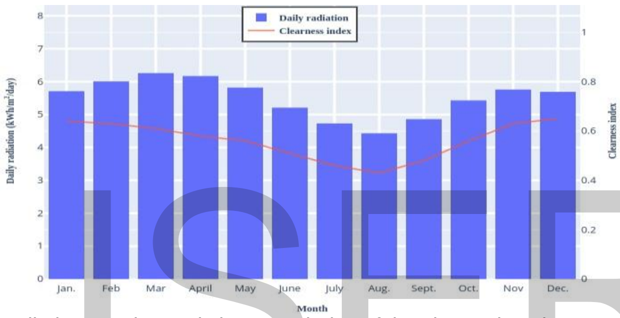

Fig. 2. Monthly average graph of solar radiation per day and clearness index of the chosen location

3 Methodology

3.1 System detail and components specification

The proposed hybrid power system is made up of four major components which comprise of PV arrays, batteries, diesel generator, and a power converter. The converter is expected to operate in two directions, i.e. as an inverter or as a rectifier while the battery main target is to supply energy to the load in the event of any shortage in capacity from the PV energy system The simulation diagram of the energy system in HOMER Pro during the simulation process is shown in Fig. 3. Detailed information on model specification and description for the individual component alongside the input values required for simulation are presented in Table 1. The current diesel fuel price in Nigeria is 2.25 SAR per liter [6] and the cost of the various components are obtained from different distributors on-line [7][8]. HOMER pro gross system cost in US dollar, this was later converted to Saudi riyal using the present exchange rate; US $1 equals 3.75SAR.

3.2 Dispatch strategy

Two approaches (i.e load following and cycle charging) were strategically implemented in the dispatch process for proper investigation of the hybrid system cost of energy, diesel generator lifespan as well the extra energy generated. In the load-following (LF) approach, the dc voltage from the PV solar system charges the storage device while the generator (Generic small-sized) is solely responsible for producing enough power to meet the appliances/equipment need. Cycle-charging (CC) scheme enables generic generator to supply enough energy than the load can accommodate, with the excess energy is utilized by the battery for charging purpose.

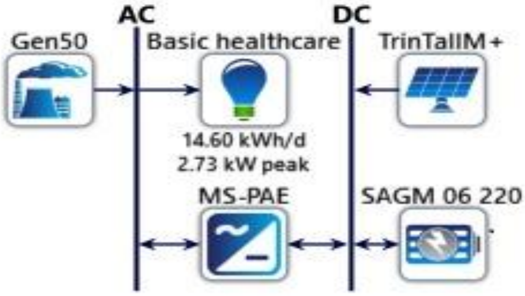

Fig. 3. The schematic diagram of the hybrid PV-diesel-battery energy supply system as arranged in HOMER pro modeling software.

TABLE 1

TECHNICAL SPECIFICATION AND ECONOMIC VALUE OF VARIOUS COMPONENTS

PV Module	
Model	TrinTall M+
Capital cost	3638.47SAR/kW
Replacement cost	3274.2SR/kW
Sizes consideration	HOMER optimizer
Rating	0.345kW
Lifetime	25 years
De-rating factor	90%
Ground reflection	20%
Storage battery	
Model	Trojan SAGM 06 220
Rated capacity	6V 1.45kWh. 241Ah
Capital cost	1304.97SR per battery
Replacement cost	1304.97SR per battery
Maintenance cost	26.26SAR/year
String size	8
Energy produced per string	11.57kWh
Min state of	20%

charge	
Roundtrip efficiency	85%
Generator	
Model	Generic Gen50
Rating	3.3kW 22.6A
Capital cost	750.2SAR/kW
Replacement cost	750.2SAR/kW
Maintenance cost	1.88SR/op. hr.
Lifetime	15,000hr
Slope	0.2730L/hr./kW output
Intercept coefficient	0.0571L/hr./kW rated
Converter	
Model	Magnum MS4448PAE
Rated power	4.4kW
Capital cost	1514.04SAR/kW
Replacement cost	1514.04SR/kW
Maintenance cost	37.51SR/year
Maximum power	8.5kW
Lifetime	10 years
Efficiency	94%

4 Results and discussion

Generally, HOMER pro software executes a timely simulation for all feasible and infeasible system configuration based on the values presented at the initial stage. The feasible system architecture was later categorized using the following operational parameters (i.e. electrical energy production on a yearly basis, load served per year, amount of renewable energy penetration etc.). Solar energy, diesel generator as well as the storage element were adequately investigated in-line with the energy requirement of the health center. The results of the best configuration as analyzed by HOMER pro is presented below.

4.1 Optimization results

The solar resources data and the energy required on a daily basis by the clinic load were implemented for the evaluation of the optimum configuration. The potential of solar resources as well as the availability of fuel for running the generic generator was analyzed to ascertain the possibility of hybrid system. The top two configurations from the optimization results based on the sensitivity variable of 5.51kWh/m^2/day and 2.25 SAR per liter of diesel fuel were assessed, after which comparison with the diesel-only system was done. However, the optimum result as ranked by HOMER Pro for the basic healthcare center (BHC) located at the ja'agi village is shown in Table 2.

The optimal architecture as noticed from this table is a hybrid system with 3.2kW generic small generator, 6.26kW PV module, 3 strings (i.e. 24 batteries) Trojan SAGM 06 220 battery and a 2.79kW MS-PAE converter. The total NPC and COE for this configuration are 123,056 SAR and 1.31 SAR per kWh respectively. This system was strategically dispatched using the load following controller. Furthermore, the second best optimal configuration which has no footprint of any pollutant emission consists of 6.08kW PV, 16 units SAGM battery, 2.09kW Magnum converter with a cycle charging dispatch approach.

The diesel standalone system comprising of only one source of energy (i.e 3.2kW generic small genset) is considered unsuitable for supplying electricity used for powering the clinic load due to its high COE (i.e 11.4SAR per kWh) coupled with a total NPC of approximately 1,068,500SAR. The total NPC of this system is relatively high, this is as a result of the high cost of operation, hence the inclusion of batteries and solar resources is recommended for the present energy sources (diesel generator system) at the healthcare center to ease the over dependant on fuel, thereby reducing pollutant emission.

TABLE 2

PERFORMANCE VARIABLES OF VARIOUS SYSTEM ARCHITECTURE

Parameter	Configuration		
	PV/diesel /battery Hybrid energy system	*PV/battery Hybrid energy system*	*Diesel-only System*
PV module	6.26	6.08	-
Generator capacity (kW)	3.20	-	3.20
Battery capacity	24	16	-
Converter capacity (kW)	2.79	2.09	-
Dispatch strategy	LF	CC	CC
Total capital cost (SAR)	63,465	48,911	5,138
Total NPC (SAR)	123,056	104,704	1,068,566
Total O&M cost (SAR/year)	1,454	895.2	51,480
Total fuel cost (SAR/year)	50.4	-	7,770
Cost of energy (SAR/kWh)	1.31	1.15	11.40
PV production (kWh/year)	9,691	9,410	-
Diesel production(kWh/year)	47.2	-	6,914
AC load serve (kWh/year)	5,329	5,177	5,329
Renewable fraction (%)	99.5	100	-
Capacity shortage (kW/yr.)	0	188	0
Unmet load (kWh/year)	0	152	0
Excess electricity	3,585	3,434	1,585

Parameter	Configuration		
	PV/diesel /battery Hybrid energy system	*PV/battery Hybrid energy system*	*Diesel-only System*
(kWh/yr.)			
Fuel consumption (L/yr.)	22.4	0	3,454

4.2 Sensitivity evaluation

The availability of solar resources on a yearly basis is not uniform, this is due to its intermittent nature. Also, the cost of diesel fuel per liter changes based on government intervention through the subsidy programme and the global market. In this present study, the price of diesel per liter and the global annual average solar radiation of the area considered were varied by ±15% in order to analyze their effect on the cost of electricity (COE). Sensitivity results for variation in solar radiation with constant diesel price and variation in diesel fuel price with fixed solar radiation were displayed in Figures 4 and 5. It can be noticed that increasing the value of solar radiation significantly reduces the COE as well as the total NPC. On the other hand, the COE and the total NPC changes slightly when the fuel price was varied

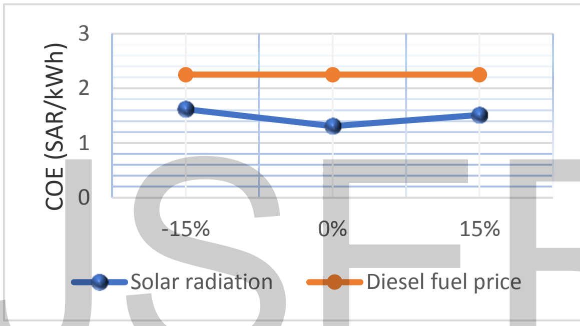

Fig. 4. Optimal design type graph for varying solar radiation (a) 4.68 kWh/m^2/day (b) 6.34 kWh/m^2/day at fixed diesel price

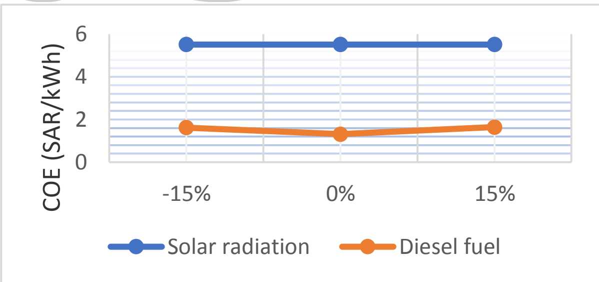

Fig. 5. Optimal design type plot for varying diesel price (a) 1.91SAR per liter (b) 2.59SAR per liter at fixed solar radiation.

4.3 Emission analysis

The pollutant emission for various combinations, including the current diesel standalone system at the selected area was investigated. The various components of this emission include; unburned hydrocarbon (UHC), carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM), nitrogen oxide (NO_x) and sulfur dioxide (SO_2). Fig 6 depicts the emission component's value for the optimal design and diesel-only configuration in kilogram per year. The PV/battery configuration produces no pollutant emission, this is because the diesel generator is not included in the combination. The optimal configuration produces 58.6 kg/yr of CO_2 and 0.366 kg/yr of CO in this sites while the diesel-only system produces a high value of CO_2 (i.e 9,041 kg/yr) with a relatively low CO of 56.4 kg/yr. Also, the addition of renewable energy source (solar in this case) to the existing conventional diesel system can prevent the emission by 99.35% (from all the pollutant emission) and make the system more economical in the supply of energy.

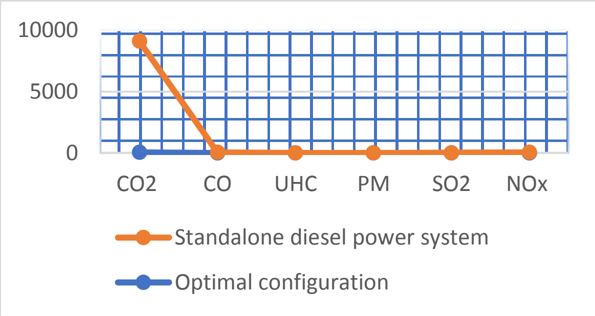

Fig. 6 Graph of emission component's in optimal best system and conventional diesel system.

5 Conclusion

In this paper, the optimal configuration of PV/diesel/battery, PV/battery and a standalone diesel power system for application in a remote health center located in ja'agi village of Nigeria, is evaluated. Based on the amount of CO_2 emitted, NPC, COE as well as the fuel consumed per year, PV/battery/diesel hybrid system is found to be the best optimal system for energy supply to the proposed clinic, even though the PV/battery hybrid system is most favorable because it has no pollutant emission. The conventional standalone diesel system operates for 8,571 hours per year to release a total of 9,041kg/yr CO_2 and provide the highest NPC (1,068,566 SAR) among all studied combinations. This result shows that the system is not economically feasible and also the high rate of pollutant emission (CO_2) would further contribute to global warming. Hence, integrating PV solar technology into the energy mix of decentralized hybrid power supply system will go a long way to improve the life of rural dwellers through effective and efficient healthcare delivery.

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