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Procedia Manufacturing 7 (2017) 622 – 629

Procedia MANUFACTURING

International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2017, 23-25 January 2017, Kruger National Park

Optimum Design of a Stand-alone Hybrid Power System with Demand-Side Management

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Abstract

Hybridising renewable energy sources improves the reliability of renewable energy systems for stand-alone applications. However, the high system cost is one of the setbacks that contribute to the slow growth of renewable energy development. The system cost can be reduced by optimal system design. This paper presents hybrid system design strategies that minimize the system capital cost. The design concept considers integration of demand-side management (DSM) strategy in the system design process. In this strategy, the residential load is divided into three categories and prioritized two of them. This reduces the peak load, in effect reduces the system design capacity. A traditional design method was used to design a hybrid system to meet a specific daily load profile of a typical 3-bedroom residential facility in Tema, Ghana. The system capacity, system capital cost, net present cost, capacity shortage and excess generation of the system were considered as hypothesis. The algorithm of the proposed design strategy was used to design an optimal system for the same daily load profile. Upon comparison of the two systems, the following observations were made; the system capacity reduced from 8.4 kW to 4.3 kW, the initial cost and the net present cost of the optimal system reduced by 48% and 41.5% respectively, system capacity shortage was slightly improved from 9.5% to 8.8%. The costs of energy (COE) improved from 0.793 kWh to 0.742 kWh, 6.4% reduction. The results indicate that, the proposed design method reduces the system capacity by almost half which significantly reduced the system initial cost by 41.5 percent.

Keywords: Design method, Demand-side Management, Hybrid system;

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doi:10.1016/j.promfg.2016.12.093

1. Introduction

The deployment of renewable energy resources such as photovoltaic (PV) and wind energy system has rapidly grown in electric power systems due to the environment-friendly nature of these resources on one hand and the increasing cost of conventional energy sources on the other. The clean energy resources are considered to be the solution to the current energy crises in sub-Saharan region. Apart from the unavailability of natural grid network in the remote communities in the region, the residents in the urban communities show great interest in renewable energy due to power shortage and the escalating cost of energy in the region. Due to the intermittent generation nature of the renewable energy resources, it is not a reliable source of energy when used in stand-alone application. To improve the reliability, there are other alternative energy sources which are readily dispatchable. The slow growth of renewable energy system development is as a result of the current high system cost. The factors that contribute to the high system cost has been grouped into three categories; energy resource availability, cost of system components and design methodology system cost is a dependant of system capacity, whereas system capacity also depends on the load, energy source availability and the design method.

The paper presents a strategic method of designing an optimum hybrid power system using load management strategy. The peak load of a particular load profile is considered to be a stand-alone hybrid power system. Amongst the factors that influence the system design capacity is the design peak load. Managing the load to reduce the peak load will eventually reduce the system capacity. The paper first presents demand-side management strategy of typical 3 – bedroom residential facility in Tema, Ghana. It further presents two system designs, one with demand-side management strategy and the other without DSM strategy.

Nomenclature

P_{Load}	Daily consumption in KW
P_{t1}	Load at time t1 in KW
P_{t2}	Load at time t2 in KW
t_1	First hour of the day
t_2	Second hour of the day
T_{12}	Time difference between t1 and t2 in hour

2. State-of–the–Art – a Brief Overview

Several studies relating the use of Hybrid Power System as an alternative solution for the conventional energy are presented in many literatures. Yang, et.al. [1], proposed methodology for sizing an optimum hybrid solar-wind system with battery bank. Genetic algorithm was used to estimate the optimum system configuration that could achieve the clients required loss of power supply probability with minimum annualized cost of systems.

Saeid et. al. [2] proposed the use of imperialist competitive algorithm in designing a stand-alone hybrid solar-wind-diesel power generation. The objective of the study was to minimize the net study present cost of hybrid system for life-time of project by considering reliable supply of load and loss of power probability index. The study compared the use of imperialist competitive algorithm, to the particle swarm optimization and ant colony optimization. The investigation revealed that the imperialist competitive algorithm is considered to be faster and more accurate than others and has more certain design in comparison to PSO and ACO algorithms. Since the study considers load management strategy to reduce peak demand of a specific load profile, it is essential to review research reports on demand-side management. DSM application improves grid flexibility and supports intermittent renewable energy utilization. It is widely used in micro grid networks. Little research work is done on integrating demand-side management in stand-alone hybrid power systems for residential facilities.

Ben Christopher [3], proposed control strategies for balancing the dynamic demand in a grid connected hybrid system. His study aimed to enhance the greatest use of solar and wind power by maintaining uninterrupted power to the customers, guided by system operating cycle. In this strategy, sound energy storage unit was used to control the power mismatch. The reliable power supply in the whole system is opted through exact technical control using energy conservation and valley filling methods.

Kennedy J. et. al. [4], proposed a new demand-side management strategy in which loads and distributed generators are able to detect the conditions where the load of the Island cannot be sufficiently supplied. In this strategy a load shedding algorithm systematically removes loads from the system until an island can be maintained within satisfactory operating limits utilizing the load DG.

3. Methodology

3.1. Traditional Design Method

3.1.1 Residential Load

The bottom-up approach is used to determine the daily residential load. In this method, daily load is anticipated and summed to yield an average daily demand. This is achieved by multiplying the power ratings of all the appliances by the number of hours it is expected to operate on an average day to obtain watt-hour value.
The load data was obtained from a pre-payment electrical energy meter of a typical 3-bedroom residential house. The average daily consumption was recorded for thirty days (March 10 – April 9). The average daily consumption of March 18 recorded 20.76 kWh which represents the highest daily average consumption of the thirty days period. The average daily consumption is 20.76 kWh even though the consumption varies throughout the year due to the different climatic seasons in Ghana. The daily consumption profile varies according to working nature of the residents. The highest daily consumption is considered to be the design load. A 24-hour consumption profile of the highest consumed day (March, 18) is presented in Table1 with the corresponding load curve is shown in Figure 1. The hourly consumption is a time series data and total daily consumption is estimated by calculating the area under the consumption profile curve by equation 1.

$$\textit{Daily consumption} = P_{Load} = \int_{t_1}^{t_{24}} f(x)dt \tag{1}$$

Where

$$f(x) = \tfrac{1}{2}(P_{t_1} + P_{t_2})T_{12} \tag{2}$$

From equation 1, total daily AC consumption is the area under this load profile curve which is 20.76 kWh and the equivalent DC consumption is 24.44 kWh, considering convention efficiency of 85% (inverter efficiency).

Table 1 Daily Load (March 18)

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Load (kW)	0.63	0.68	0.64	0.57	0.72	0.66	0.67	1.11	0.94	0.99	1.26	0.46	0.60	0.54	0.63	0.72	0.49	0.24	1.36	1.33	1.81	2.36	1.80	0.49

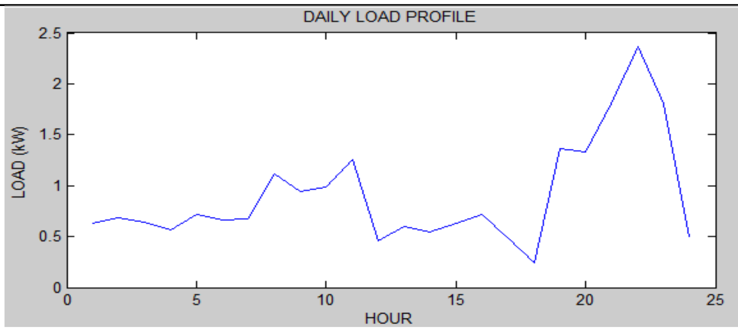


Fig. 1 Daily load profile of the highest consumed day (March, 18)

3.1.2 *Daily available solar energy*

Monthly average solar radiation data of Tema was obtained from the Energy Commission's database. The data is available for all renewable energy developers in Ghana. Homer software was used to obtain the Hourly mean solar radiation. In Ghana, yearly average sunlight hours varies from 6 to 10 hours/day and maximum area is over 9 hours/day. The data obtained from NREL through Homer software showed that in Tema, solar radiation is over 5.0 kWh/m^2/day varies from 07:00 am to 17:00 pm. The sun hour is 8 hours/day.
The monthly average radiation of Tema, a city in sub-Saharan region with geographical location: Latitude 5^o – 6′ North and Longitude 0^o – 1′ West is shown in Table 1. The average solar radiation is 5.03 kWh/m^2/day. However, the worst monthly average solar radiation (4.56 kWh /m^2/day) in June is considered to ensure that, the designed system can operate year-round. Table 2 shows the daily solar radiation (June 14), Tema. The daily total solar energy is estimated by calculating the area under the solar radiation curve using equation 1. Therefore total solar radiation in June 14 is 7.66 kWh/m2/d.

Table 2 Monthly solar radiation

Month	Clearness Index	Daily Radiation (kWh/m^2/d)
January	0.509	4.83
February	0.514	5.14
March	0.507	5.28
April	0.505	5.26
May	0.484	4.88
June	0.464	4.56
July	0.462	4.58
August	0.486	4.96
September	0.498	5.15
October	0.545	5.48
November	0.579	5.54
December	0.511	4.75
Average	0.505	5.03

Table 3 Monthly average wind speed

Month	Wind Speed (m/s)
January	4.5
February	5.5
March	5.6
April	5.2
May	4.8
June	4.8
July	4.9
August	4.9
September	5.7
October	5.8
November	5.1
December	4.8
Average	5.1

3.1.3 Daily Available Wind Energy

Monthly average wind speed was obtained from the Energy Commission. The data were obtained by a six-year satellite-borne measurement provided by the U.S. National Renewable Energy Laboratory (NREL). The data collected included average wind speed, average wind direction and standard deviation. The monthly average wind speed measurement at 12 metres above ground level varies in the range of 4.8 to 5.6m/s. Amongst the six coastal sites east of Tema, Lolonya recorded the highest wind speed of 5-6 m/s and the predominant direction of the wind was 240^0 with corresponding mean wind speed of 5 – 6 m/s and frequency of 47%. Table 3 shows the monthly average wind speeds of Tema at 12 metres instrument height and the extrapolated height of 50 metres. The worst month (January) wind speed of 4.5 m/s was used to determine the available useful energy to ensure that the designed system can operate year-round.

3.1.4. System Component Sizing

Fig. 2 shows the traditional method of sizing the system components. The system design capacity in kilowatts is determined by the ratio of daily AC load and the renewable energy window in a day. The rated AC power is converted into rated DC power by considering the inverter efficiency. The system rated power is adjusted by 30% according to IEEE-1013 due to the anticipated system loses and uncertainty. The PV array and wind turbine sizes are determined by computation using the available solar and wind energy resources and adjusted rated power. Fig. 2 shows the detailed steps.

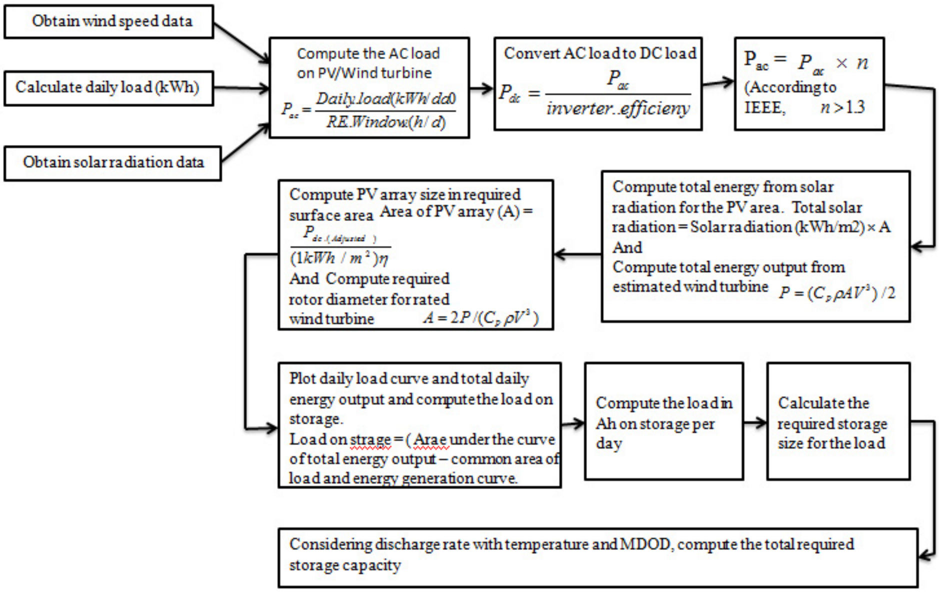


Fig. 2 Traditional method of designing hybrid power system

3.1.5 System Model and Simulation

This stand-alone hybrid system configuration model consists of 6.6 kW PV, 1 SW Skystream 3.7 Wind turbine, 5 kW Inverter and 12 Hoppecke 8 OPzS 800 batteries. The system was designed and optimized with HOMER software tool. The simulation result indicates that, even though the renewable energy generators generated much more electricity than the total load demand, it is still unable to meet load demand for the 24-hour period. In some hours of the day, the electricity generation is less than the load at that moment while in some time of the day the electricity generation is greater than the load. All the generation shortage are estimated as total unmet load or capacity shortage. The total electrical energy generated from the hybrid power system was 12,453 kWh/yr where 9,096 kWh/yr from PV represents 73% and 3,353 kWh/yr from wind turbine represents 27%. The total net present cost (NPC) is $ 22,343 and levelized cost of energy (COE) is $ 0.793/kWh.

3.2. Proposed Design Method

3.2.1 Demand-Side Management Strategy

Demand-side management scheme is popular in the smart grid network operation, to shed the load when the demand is greater than the supply. The current research on demand-side management focuses on the application of the scheme on domestic electrical wiring network to control the residential load when the energy supply is less than the residential energy demand. Many load shedding strategies for controlling residential load are introduced in many research reports [5, 6, 7, 8]. In this study we developed a design methodology which integrates DSM scheme in stand-alone hybrid power system design. There is an assumption that, a smart distribution board can perform the connect/disconnect operations of the priority lines automatically. The load shedding algorithm is shown in Fig. 3. The smart distribution board has three priority lines called PL1, PL2 and PL3. When the power consumption at a specific time is less or equal to the power generation, then first priority is considered in which all the three lines are

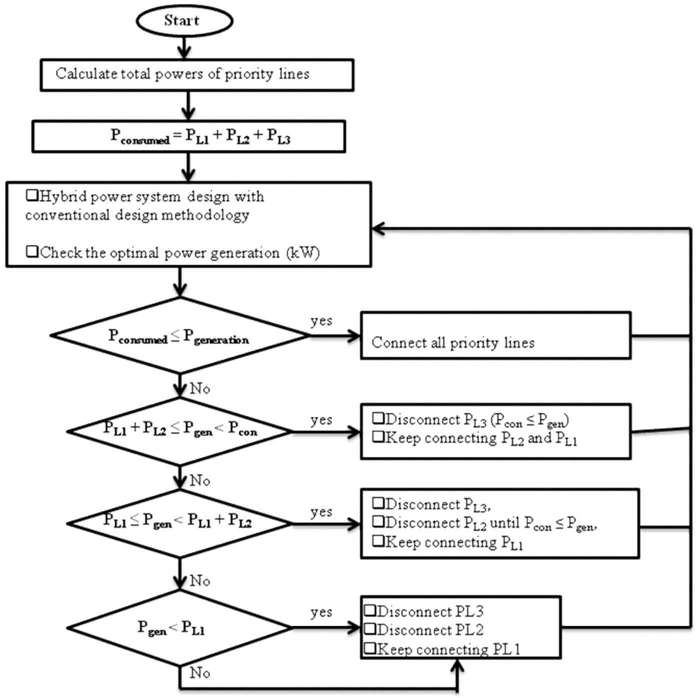


Fig. 3 Demand-Side Management algorithm

Table 4 Daily load on priolity lines

Appliances	Priority Lines		
	Line 1 (kWh)	Line 2 (kWh)	Line 3 (kWh)
Light	1520		
Kettle	250		
Pressing-Iron	675		
Blender	125		
Refrigerator		10,800	
Fan		560	
Television			375
CD Player			560
Air-conditioning			5,000
Washing machine			900
Microwave	300		
Total	**2,870**	**11,360**	**6,835**

activated. When power consumption is greater than the power generation but less than total consumption of line 1 and 2, then disconnect line 3 until generation is greater than consumption, keeping lines 1 and 2 activated. Implementation of load shedding continues until power generation is less than the consumption in line 1, then all the three lines are disconnected. Table 4 shows the results of the proposed Demand-Side Management scheme. Total load on priority line (11,360 kWh) is considered as the design load of the proposed hybrid system.

3.2.2 Proposed System Model and Simulation

The new stand-alone hybrid system consists of 2.5 kWh PV, 1 SW Skystream 3.7 Wind turbine, 3 kW Inverter and 6 Hoppecke 8 OPzS 800 batteries. The system was designed with the DSM integrated design approach and modelled with HOMER software tool. Load on priority lines 1 and 2 (14,230 kWh) is considered as system design load.

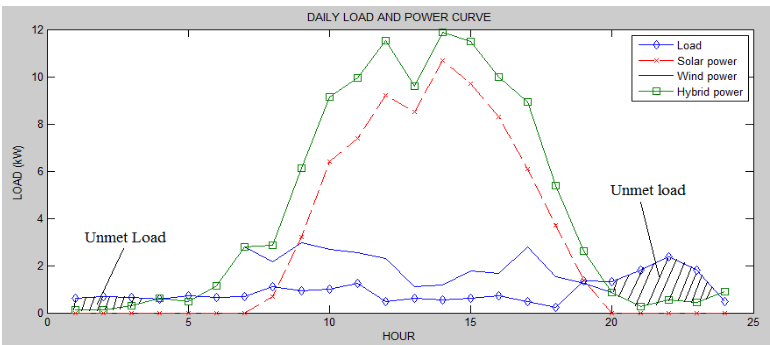


Fig. 4 Daily load and available power from renewable energy sources

A comparison of the new daily load and the energy generation from various renewable energy sources is shown in Fig. 4. Daily generation shortage is indicated by the shaded area of the load and power curve. The capacity of the battery bank is based on the daily unmet load and other factors. The total electrical energy generated from the hybrid power system was 8,378 kWh/yr where 3,445 kWh/yr from PV represents 41% and 4,933 kWh/yr from wind turbine represents 59%. The economic performance of the optimum hybrid power system are; total NPC $ 14,212 and the levelized COE $ 0.742/kWh. The capacity shortage and excess electric load are 455 kWh/yr and 341 kWh/yr represent 8.8% and 6.6% of total energy production respectively

4. Results and Discussion

The simulation results of the two hybrid systems, the system designed without consideration of DSM strategy and the system designed with DSM strategy, are shown in table 4. The comparative analysis shows the implementation of the proposed system design methodology reduces the system capacity significantly (48%). Since system initial cost is a dependant variable of system capacity, about 48% reduction of system capacity yields a significant reduction of system initial cost. (41.5%). Comparing the economic performance of the two systems, the system with the proposed design method stands a better position in terms of net present cost (NPC) and costs of energy (COE). The proposed method reduced the total NPC and COE to 63.6% and 93.6% respectively. Capacity shortage and excess electricity are very critical variables so far as the system efficiency is concerned.

These two variables have been the problem with stand-alone renewable energy system. An optimum system has these two variables carefully controlled. Due to the variation and intermittence of the renewable energy sources throughout the period of one year, the electricity generated by RE systems does not meet the demand all the time. An attempt to minimise the shortage capacity potentially increase the excess electricity, in effect, increases the system initial cost as the system capacity is increased. The proposed method reduced the capacity shortage by 0.7%. However, the method also increased the excess electricity by 1.9%

The main drawback of this system is the energy supply quality especially demand and supply match. This disadvantage is not peculiar to most of the renewable energy systems. To address this drawback, energy management systems are incorporated into most renewable energy systems even though that provides discomfort to the consumers at critical load period. At the period where total demand exceeds the energy generation, the load shedding scheme is implemented in order to ensure demand and supply match.

Table 4 Simulation Results

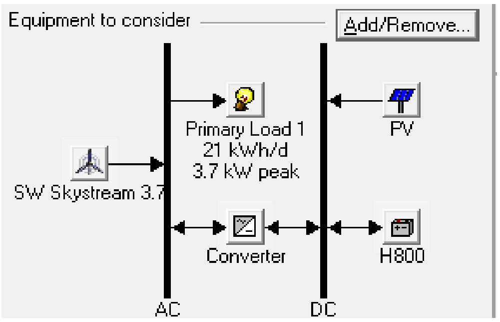
System Configuration	System Capacity	System initial costs	Total NPC	COE	Capacity Shortage		Excess Electricity	
	(kW)	($)	($)	($/kWh)	(kWh/yr)	(%)	(kWh/yr)	(%)
Ssytem without DSM	8.4	14,949	22,343	0.793	723	9.5	4,243	34.1
System with DSM	4.3	8,760	14,212	0.742	455	8.8	3,043	36
Difference	**4.1**	**6,189**	**8,131**	**0.051**	**268**	**0.7**	**1,225**	**1.9**
	48%	**41.5%**	**36.4%**	**6.4%**	**37.1%**		**28.9%**	

5. Conclusion

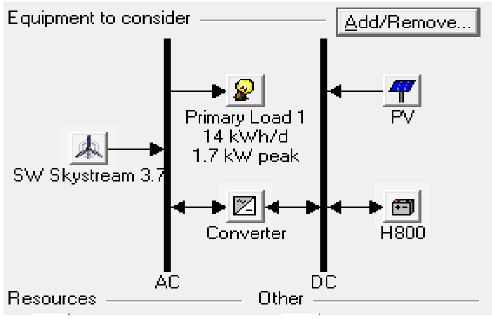
The higher system initial cost slows down the growth of renewable energy development. This paper has proposed a design methodology which considers an integration of demand-side management strategy in the system design process. The study modeled two hybrid power systems, one with conventional design method and the other with the proposed design approach with DSM. The comparative analysis showed that the design method with DSM reduced the system capacity by 48% which in turn reduced the system initial cost by 41.5%. The consideration and implementation of DSM integrated system design method would improve the affordability of the renewable energy systems.

Appendix A.

(a) System configuration without DSM



(b) System configuration with DSM



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