INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
P. Arun ,Vol.5, No.3, 2015

Optimum Design of Biomass Gasifier Integrated Hybrid Energy Systems

Arun P*‡

* Department of Mechanical Engineering, National institute of Technology Calicut, NIT Campus (PO), Kozhikode, Kerala, India 673601.

(arun.p@nitc.ac.in)

‡ Corresponding Author; Arun P, Department of Mechanical Engineering, National institute of Technology Calicut, NIT Campus (PO), Kozhikode, Kerala, India 673601, Tel: +914952286424,

Fax: +91495228750, arun.p@nitc.ac.in

Received: 25.05.2015 Accepted:11.07.2015

Abstract- Hybrid energy systems combine multiple energy conversion devices and are suitable options for isolated power generation. Such systems have no interaction with the grid. They serve the power needs of remote locations where the extension of the grid is infeasible. The design of such systems has several options. The units may include diesel generator sets, renewable energy based systems like solar photovoltaic panels, wind turbines or a combination of these systems with energy storage. In the present study, optimum design of biomass gasifier integrated hybrid systems is addressed. A multi-objective optimization approach minimizing cost of energy and unmet load fraction is illustrated. An exhaustive enumerative approach based on epsilon-constraint method is adopted for generating the Pareto front corresponding to the design problem. The software tool HOMER is used for the detailed simulation of the system configurations. The design approach is illustrated based on a case study corresponding to a remote location of Kerala in southern India. The proposed approach provides a useful tool for the design and planning of hybrid energy systems.

Keywords Hybrid systems, Multi-objective optimization, gasifier, epsilon-constraint method, Pareto front.

1. Introduction

Hybrid energy systems combine multiple energy conversion devices and energy storage units for meeting a specific energy end use like remote electrification. They are particularly useful in the electrification of locations where grid extension is infeasible. In India, hybrid systems utilizing solar and biomass resource needs significant attention. India being a tropical country receives abundant sunshine and has variety of biomass resources having potential to be converted into secondary fuels like producer gas and biodiesel [1]. Optimum design and performance assessment of hybrid systems involving conventional and renewable sources is a vital step in their appropriate utilisation. System design involves the determination of ratings of the generation units and storage units in order to meet the specified demand, ensuring desired reliability requirements. Mathematical modeling based simulation is often a preferred approach for the system design and optimization [2-4]. Considering the limitations of diesel as a non-renewable and expensive fuel, active steps are being taken to operate generators using renewable fuels. Gasification of biomass and utilization of producer gas in engine systems is increasingly being considered as a suitable option especially in the rural sector of developing countries [5]. Optimization studies have been undertaken for biomass gasifier based hybrid energy systems in the past, specific to rural applications in developing economies [6,7]. The optimization studies of biomass gasifier integrated hybrid systems have in general, considered single objective optimization on economic basis. It is observed that there is scope for the studies on multi-objective optimization of biomass gasifier integrated hybrid systems.

The present work illustrates the optimum design of a biomass gasifier integrated hybrid energy system considering cost and capacity of the system to meet the load. The multi-objective optimization approach seeks to determine system configurations that ensure minimum cost of energy and capable of meeting the load without deficiency in the power to be supplied. The study further aims to investigate the effect of operation of the system in the dual fuel mode with producer gas co-firing. A simulation based optimization method adopting epsilon-constraint approach is proposed in this work. The methodology is illustrated for a rural location in southern India. The Pareto front has been obtained and the details of the system configurations are illustrated for the case study.

2. System configuration and design

The schematic representation of the hybrid system is given in Figure 1. The system comprises of a gasifier-integrated diesel generator connected to the AC bus. A co-fired generator operates on a mixture of diesel and producer gas. The photovoltaic units are connected to the DC bus. The system operates in the parallel mode and hence the demand can be met by the shared generation from both the sources collectively in combination with the energy storage. The sizing of the hybrid system principally seeks to obtain the ratings of the generation units (photovoltaic arrays and the gasifier integrated diesel generator), and the capacity of the battery bank.

In the present work, multi-objective optimization of the hybrid system involving gasifier integrated diesel generator is illustrated. The system design considers the essential requirement of meeting the expected electrical demand of the location ensuring the compliance of the other relevant techno-economic constraints. In the proposed approach, two objectives are considered for the optimization: minimization of cost of energy (COE) and the unmet load fraction (UL). A simulation based optimization approach has been adopted. An exhaustive evaluation of different possible and feasible system configurations is essential for identifying the desired system configurations meeting the specified objectives. The detailed system simulation is carried out using the software tool HOMER [8]. HOMER simulates system configurations comprising of different specified components by performing energy balance calculations for hourly time steps over a year. All infeasible configurations are consequently ruled out. The hybrid system under consideration includes gasifier integrated diesel generator, photovoltaic arrays and battery bank. The power output from the PV module is dependent on the available solar resource of the location. The reduction in power output from the module is accounted by the incorporation of suitable value of derating factor [8]. This will take into account factors like dust accumulation on panels, wiring losses, shading, aging etc.

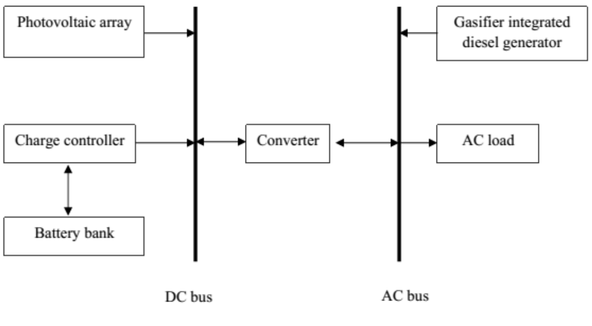

Fig. 1. Schematic of the gasifier integrated hybrid energy system

The preliminary search space for the photovoltaic system including the battery bank is identified based on guidelines of Sandia National Laboratory available in the literature [9]. For the simulation of the gasifier integrated diesel generator, it is essential to estimate the mass flow rates of the producer gas and diesel corresponding to generator power output levels. HOMER models the operation of the biomass gasifier integrated diesel generator system based on the following assumptions: (1) producer gas substitution ratio (ratio with which the producer gas replaces diesel in the co-fired operation) is a constant (2) the operation of the system will attempt to maximize the use of producer gas and minimize diesel consumption (3) the fossil fraction cannot go below a specified minimum value (4) the generator can produce rated power provided and the fossil fraction would be maintained accordingly. HOMER uses the Kinetic Battery Model to determine the amount of energy that can be absorbed by or withdrawn from the battery bank for the hourly time step. Details of the mathematical modelling frame work for the individual components are available in the literature [8] and hence are not detailed here. A cycle charging strategy is adopted for the generator dispatch. Whenever the generator needs to operate to serve the primary load, it operates at full output power. The excess generation is utilised for charging of the battery bank.

3. System optimization

A multi-objective optimization approach has been adopted in the system design. The objective functions to be minimized include the cost of energy (COE) and the unmet load fraction (UL). The cost of energy accounts for the capital cost and operational cost of the system. The cost of energy COE is evaluated as:

$$COE = \frac{C_{ann}}{E} \tag{1}$$

where C_{ann} is the total annualized cost of the system ($/year) and E is the total load served by the system (kWh/year). The unmet load fraction is the ratio of the load not met by the system to the expected total load to be met by the system. Epsilon-constraint method has been adopted for the generation of the Pareto front corresponding to the design problem. In this approach, one objective is selected for optimization and the remaining objectives are treated as constraints subjected to specified target levels. By considering various values of the target levels, the non-inferior solutions of the problem are determined [10]. In the present work, a simulation based optimization is adopted. The hybrid system simulation is carried out using the software HOMER. The decision variable involved in the system design problem is:

$$P = [P_{DG}, P_{PV}, B, C] \tag{2}$$

where P_{DG} is the generator rating, P_{PV} is the photovoltaic array rating, B is the battery capacity and C is the converter rating. Cost of energy is the objective function to be minimized and unmet load fraction is the other objective, also to be minimized, but treated as the bounded constraint. The optimization problem seeks to obtain the system configuration to attain minimum COE, subject to UL ≤ α_{UL}. The values of α_{UL} need to be appropriately input by the decision maker on the basis of the UL to be tolerated depending on the criticality of the loads to be met by the hybrid system. HOMER is able to simulate the various system configurations based on the range of values specified for the different components, namely the ratings of generator, photovoltaic module rating and the battery capacity, evaluating COE and UL for each run, maintaining the system energy balance. Thus, the optimization problem is:

Minimize [COE, UL]

Subject to:

$$UL \leq \alpha_{UL} \quad (3)$$

The following additional constraints also need to be met: (i) energy flow at any time step must be less than the energy capacity of the component

$$E_j(t) \leq P_j \Delta t \quad (4)$$

where Δt is the time interval (taken as one hour for the present analysis)

(ii) power level of the components must lie between the specified limits:

$$P_{min,j} \leq P_j(t) \leq P_{max,j} \quad (5)$$

(iii) state of charge of the battery must lie between the specified limits:

$$SOC_{min,j} \leq SOC_j(t) \leq SOC_{max,j} \quad (6)$$

(iv) non-negativity constraint of the energy level at each time step to be ensured:

$$E_j(t) \geq 0 \quad (7)$$

Hence, based on the numerical search aided by HOMER, system configurations with minimum COE and UL which forms the Pareto front are identified from the overall set of feasible system configurations.

3.1. Case study

The solar resource data and electrical demand data for a rural community in Kerala, India have been considered [11]. The typical hourly variation in the load on any given day is given in Figure 2. It is assumed that this load pattern prevails for the entire year. The surface solar energy data set provided by NASA is taken as the input data for the solar resource [8]. The solar radiation data input to the system is the monthly average daily radiation data available for the location (Figure 3). Hourly values of solar radiation for the entire year are synthesized by HOMER software. It is assumed that woody biomass of calorific value 18.5 MJ/kg is used as the feed stock in the gasifier. The gasification ratio is taken as 2.89 and the LHV of the producer gas is assumed to be 4.8 MJ/kg.

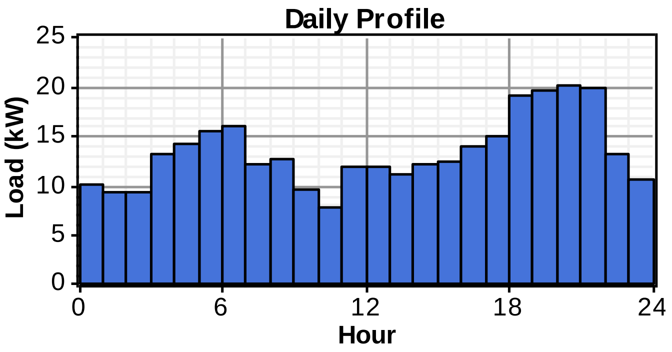

Fig. 2. Load profile of the location

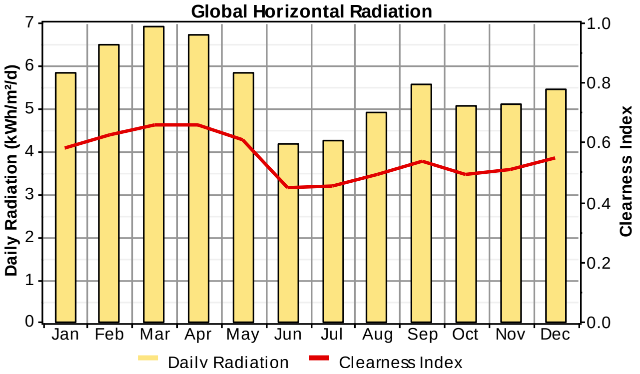

Fig. 3. Solar resource profile of the location

The cost details of the various equipment and fuel are sourced from data available in literature and based on prevailing market conditions [7,11]. Cost details of the major components are given in Table 1. The prevailing market price of diesel in India has been considered assuming an exchange rate of 1 USD being equal to 60 INR.

4. System optimization

To reduce the solving time, the search space is carefully selected by following the SANDIA guide lines for the initial selection of photovoltaic-battery configurations (as mentioned earlier). The Pareto front obtained corresponding to the cost of energy and unmet load fraction is illustrated in Figure 4.

Table 1. Cost details used in the optimization

Component	Cost ($=USD)
Gasifier integrated diesel generator	1060 $/kW
Diesel fuel	0.976$/litre
Operation and maintenance costs	0.5 per hour
Photovoltaic module	3000 $/kW$_p$
Battery	608$/battery
Converter	360 $/kW

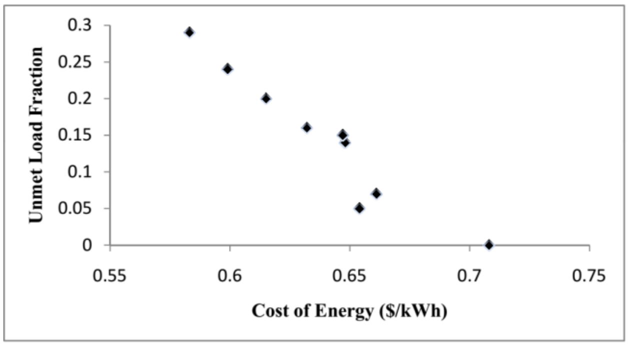

Fig. 4. Pareto front based on cost of energy and unmet load fraction

Table 2. System configurations in the Pareto front

PV rating (kW_p)	Diesel generator rating (kW)	Battery capacity (Number)	Cost of Energy ($/kWh)	Unmet Load Fraction
32	19	105	0.708	0
34	14	60	0.654	0.05
25	13	45	0.661	0.07
24	11	45	0.648	0.14
27	11	21	0.647	0.15
35	11	-	0.632	0.16
32	10	-	0.615	0.2
30	9	-	0.599	0.24
30	8	-	0.583	0.29

This solution set enables the decision maker to configure the system by simultaneously considering the unmet load fraction and the cost of energy. The details of the system configurations are provided in Table 2. The system configurations in the Pareto front, up to which the unmet load fraction is 15%, include co-fired generator, photovoltaic units and battery bank. As expected, the cost of energy decreases by 18% as the unmet load fraction is permitted to increase up to 30% (as compared to the system configuration without any loss of load). All the system configurations in the Pareto front require the dispatchable diesel generator, though the required generator rating decreases significantly as the expected unmet load fraction is allowed to be higher. The battery requirement also comes down with increase in unmet load fraction.

4.1. Sensitivity analysis

Sensitivity analysis is useful to study the influence of the parameters affecting the optimum system configuration. An increase in diesel fuel cost of 20% and 30% has been considered. Based on the market trends, photovoltaic module costs are expected to decrease and hence 25% and 50% decrease in their capital costs have been considered for the analysis. Representative results for the Pareto fronts obtained for diesel fuel cost of 1.17$/l and module cost of 2250 $/kW and for that of 1.27$/l and 1500 $/kW are shown in Figure 5. It is observed that optimum systems are more influenced by the cost reduction in the module costs as compared to the fuel cost escalation. In the present study, an increase of up to 30% of diesel fuel cost and decrease of up to 50% of PV module cost have been considered for the sensitivity analysis. These values are taken up for illustration of hypothetical scenarios considering the general market trend of increasing fuel price and decreasing PV module price. The study can be more realistic if the actual trends of fuel cost and PV module costs are analyzed over a period of time and the corresponding data are used for the analysis. For the optimum system without unmet load fraction, 8.78% reduction in diesel fuel consumption has been observed as compared to the 'diesel-generator only' based system configuration due to the gasifier integration. Further, 29.6 % reduction in CO_2, 35.2% reduction in CO, 35.2% reduction in SO_2 and 35.11% decrease in NO emissions are also noted for the gasifier integrated system as compared to the diesel generator-only configuration. The presence of the co-fired generator results in significant reduction in the diesel consumption and emissions.

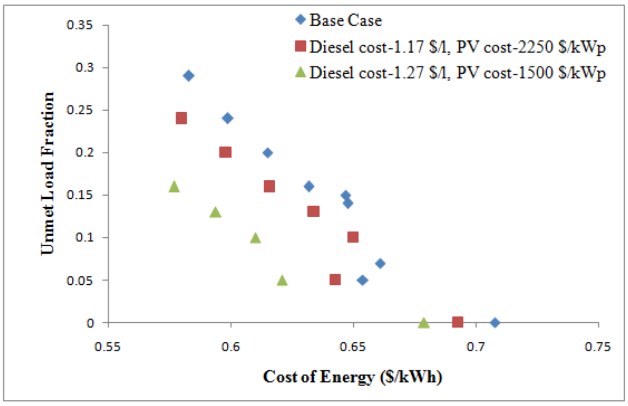

Fig. 5. Pareto fronts for representative variations in fuel cost and module cost

5. Conclusions

Multi-objective optimization of biomass gasifier integrated hybrid energy systems has been illustrated in this paper. The design process seeks to identify system configurations which are economically feasible meeting the load requirements within acceptable reliability levels. Hence, Pareto fronts corresponding to cost of energy and unmet load fraction are generated to aid in the decision making related to the hybrid system design. Epsilon-constraint method has been adopted for the system optimization which is especially suitable when two objectives are considered for the optimization. The integration biomass gasifier in the system makes the system more sustainable as indicated by the significant reduction in the diesel fuel consumption and emissions. For the illustrative case study, it has been observed that the cost of energy decreases by 18% as the unmet load fraction is permitted to take up values up to 30%. The proposed approach is simple and computationally efficient. A sensitivity analysis is carried out to study the influence of the fuel cost escalation and the effect of module cost on the optimum system configuration. The multi-objective optimization approach gives useful insights into the trade-offs required for the planning and design of hybrid energy systems.

Acknowledgements

The author gratefully acknowledges the funding provided by National Institute of Technology Calicut for the project ‘Multi-objective Optimization of Hybrid Energy Systems’ under the Faculty Research Grant scheme.

References

[1] MNRE, Ministry of New and Renewable Energy, India. http://mnre.gov.in, accessed October 2014.

[2] L. B. Jose, and R. Dufo-Lopez, “Simulation and optimization of stand-alone hybrid renewable energy systems”, Renewable and Sustainable Energy Reviews, vol. 13, pp. 2111–2118, 2009.

[3] R. Banos, F. Manzano-Agugliaro, F. G. Montoya, C. Gil, A. Alcayde, and J. Gomez, “Optimization methods applied to renewable and sustainable energy: A review”, Renewable and Sustainable Energy Reviews, vol. 15, pp. 1753–17766, 2011.

[4] O. Erdinc, and M. Uzunoglu, “Optimum design of hybrid renewable energy systems: Overview of different Approaches”, Renewable and Sustainable Energy Reviews, vol. 16, pp. 412–425, 2012.

[5] O. Jimenez, A. Curbelo, and Y. Suarez, “Biomass based gasifier for providing electricity and thermal energy to off-grid locations in Cuba. Conceptual design”, Energy for Sustainable Development, vol. 16, pp. 98-102, 2012.

[6] P. Balamurugan, S. Ashok, and T. L. Jose, “An optimal hybrid wind-biomass gasifier system for rural areas”, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 33 (9), pp. 823-832, 2011.

[7] S. Bhattacharjee, and A. Dey, “Techno-economic performance evaluation of grid integrated PV-biomass hybrid power generation for rice mill”, Sustainable Energy Technologies and Assessments, vol 7, pp. 6-16, 2014.

[8] HOMER. http://homerenergy.com, accessed April 2015.

[9] Sandia National Laboratory, Stand-alone PV system-A Handbook of Recommended Design practices, 1995.

[10] M. Sharafi, and T. Y. ELMekkawy, “Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach”, Renewable Energy, vol. 68, pp. 67-79, 2014.

[11] P. Arun, R. Banerjee, and S. Bandyopadhyay, “Optimum design of diesel generator integrated photovoltaic-battery system”, Energy and Fuels, vol. 24(12), pp. 6565-6575, 2010.