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Optimised Model for Community-Based Hybrid Energy System

ABSTRACT

Hybrid energy system is an excellent solution for electrification of remote rural areas where the grid extension is difficult and not economical. Such system incorporates a combination of one or several renewable energy sources such as solar photovoltaic, wind energy, micro-hydro and may be conventional generators for backup. This paper discusses different system components of hybrid energy system and develops a general model to find an optimal combination of energy components for a typical rural community minimizing the life cycle cost.

The developed model will help in sizing hybrid energy system hardware and in selecting the operating options. Micro-hydro-wind systems are found to be the optimal combination for the electrification of the rural villages in Western Ghats (Kerala) India, based on the case study. The optimal operation shows a unit cost of Rs. 6.5/kW h with the selected hybrid energy system with 100% renewable energy contribution eliminating the need for conventional diesel generator.© 2006 Elsevier Ltd. All rights reserved.

Keywords: *Hybrid Energy System; Micro-Hydro; Solar PV; Wind*

1. Introduction

India has an enormous renewable energy potential of about 100,000 MW, which is mostly untapped [1]. It is estimated that 40% of villages in the country are not electrified through grid electricity mainly due to capacity shortage and difficult terrain and environmental considerations. It becomes necessary to take up electrification of remote villages through non-conventional energy sources such as solar, micro-hydro and wind systems. Standa- lone units are already in operation at many plantations/colonies though the availability of solar, hydro or wind energy is not continuous. Isolated operation of these power units may not be effective in terms of cost, efficiency and reliability. A viable alternative solution is by combining these different renewable energy sources to form a hybrid energy system [2]. A system using a combination of these different sources has the advantage of balance and stability that offers the strengths of each type of sources that complement one another. The main objective is to provide 24 h grid quality power in remote communities. Hybrid energy systems are pollution free, takes low cost and less gestation period, user and social friendly. Such systems are important sources of energy for shops, schools, and clinics in village communities especially in remote areas. Hybrid systems can provide electricity at a comparatively economic price in many remote areas.

In order to obtain electricity from a hybrid system reliably and at an economical price, its design must be optimal in terms of operation and component selection. Many attempts have been tried to explore a relatively simple method for designing hybrid energy systems. An algorithm based on energy concept to optimally size solar photovoltaic (PV) array in a PV/wind hybrid system was reported [3]. Different system developments in hybrid energy system for Thailand were published [4]. A simple numerical algorithm was used for unit sizing and cost analysis of a stand-alone wind, solar PV hybrid system [5]. A linear programming technique was developed for optimal design of a hybrid wind/ solar PV power system for either autonomous or grid-linked applications [6]. Different aspects of PV, wind diesel and battery-based hybrid system including optimal sizing and operation has been detailed [7,8]. A probabilistic performance of stand alone Solar PV, wind energy system with several wind turbines of same or different sizes, with PV models and storage batteries has been presented [9]. A hydro-based system was discussed in synchronized operation with wind energy [10]. Pre-feasibility study on hybrid energy based on wind and fuel cell system was published [11].

This paper attempts to develop a general model to find an optimal hybrid system among different renewable energy combinations for a rural community, minimizing the total life cycle cost while guaranteeing reliable system operation. Solar PV, wind, micro-hydro with diesel and battery backup are considered in the model. A case study is conducted in a typical remote village of Western Ghats in Kerala, India. The objective is to find the suitable component sizes and optimal operation strategy for an integrated energy system. The results will lead to the design and planning of an optimal hybrid energy system ensuring reliable and economical power supply to the village community.

2. Methodology

The hybrid energy system integrates various renewable combinations of micro-hydro, PV, wind energy units, etc. applicable depending on availability. In general, there can be 2^n-1 combinations, where 'n' is the type of renewable energy resources. A parallel hybrid configuration of these components is used in this approach with battery storage and diesel generators as backup sources. The criterion of selecting the best hybrid energy system combination for a proposed site is based on the trade-off between reliability, cost and minimum use of diesel generator sets. For different renewable combinations, the output of the optimal sizing and operation is a set of component sizes for a given application together with recommendations for system operation. The component sizes are restricted to that available in the markets. From the cost comparisons of different combinations, the most economical system is selected which ensures power supply continuity. Basic power modules of hybrid energy system considered for the rural community in Kerala are micro-hydro, wind and solar PV with diesel or battery backup. Micro-hydro units considered here are very small in size below 100 kW.

3. Optimal Hybrid Energy System

While planning, designing and constructing a hybrid energy system, the problem becomes complex through uncertain renewable supplies, load demand, non-linear characteristics of components and the fact that the sizing and operation strategies of hybrid systems are interdependent. This calls for an optimized hybrid energy system with the objective of minimizing the life cycle cost while guaranteeing reliable system operation. As the component sizes and operation are interdependent, different set of component configurations are analyzed in each hybrid combination to get an optimal hybrid system.

3.1 Unit Sizing

Numerical iterative algorithm is used for unit sizing of hybrid energy system, minimizes the capital cost for 2^n–1 combinations of renewable sources. Timely availability of energy resources, load demand-supply balance, minimum–maximum operating limits of the units are the basic constraints. Since the energy density of the micro-hydro and wind, far exceeds that of a single solar PV module, the number of wind turbines and micro-hydro are fixed as one each and number of PV modules is incremented until the system is balanced. The optimal operating strategy and annual life cycle costs of this configuration is determined. These steps are repeated with the number of wind turbines with incremental steps. In the same manner, the entire procedure is repeated for all the seven combinations. The combination with lowest cost, minimal use of diesel generators and service reliability is selected as the optimal one. The battery bank is sized with a capacity equal to the difference between positive and negative peaks of the energy curve.

The unit sizing for a PV-wind-micro-hydro hybrid combination is to minimize the total capital cost C_c given by

$$C_c = \sum_{h=1}^{N_h} C_h + \sum_{w=1}^{N_w} C_w + \sum_{s=1}^{N_s} C_s + \sum_{g=1}^{N_g} C_g + \sum_{b=1}^{N_b} C_b \,, \quad (1)$$

where N_h; N_w; N_s; N_g; N_b are the total no. of micro-hydro, wind, solar PV, diesel generator and battery units, respectively, and C_h; C_w; C_s; C_g; C_b are the corresponding capital costs.

As detailed models of hydro, wind and PV systems have already been published, only the final expressions for the electrical power output of these components are given below. The electrical power generated by the micro-hydro unit is given by

$$P_h = \eta_{\text{hyd}} \cdot \rho_{\text{water}} \cdot g \cdot H_{\text{net}} \cdot Q \,, \quad (2)$$

where η_{hyd} the hydro efficiency as obtained from the quadratic fit to the manufacturers' data, ρ_{water} the density of water, g the acceleration due to gravity, h_{net} the effective head, Q the flow rate.

The wind power output,

$$P_w = \eta_t \cdot \eta_{\text{g}} \cdot 0.5 \cdot \rho_{\text{a}} \cdot C_P \cdot A \cdot \text{V}_r^3 \,, \quad (3)$$

where V_r the wind velocity, ρ_{air} the factor to account for air density, C_p the power coefficient of wind turbine depends on design, A the wind turbine rotor swept area, η_t, η_g the wind turbine and generator efficiency, respectively, as obtained from the quadratic fits to the manufacturers' data.

The hourly output power of solar PV array,

$$P_{\text{pv}} = \eta_{\text{pv}} \cdot N_{\text{pvp}} \cdot V_{\text{pv}} . I_{\text{pv}} \,, \quad (4)$$

where η_{pv} the conversion efficiency of a PV module, V_{pv} the module operating voltage, I_{pv} the module operating current, N_{pvp}, N_{pvs} , the number of parallel and series solar cells, respectively.

The use of diesel generator is common in many hybrid combinations to ensure supply continuity and battery model accounts for energy storage.

From experimental tests it has been found that for a diesel generator, a linear function fits for light load working conditions, while in proximity of rated power, it asks for quadratic expression. For an interval, the rate of fuel F, consumed by the diesel generator delivering the power P, is expressed in general as

$$F = aP^2 + bP + c\,, \tag{5}$$

where a, b, c the coefficients of diesel generator as obtained from the manufacturers' data.

The state of charge of battery can be calculated from the following equations:

Battery discharging,

$$P_b(t) = P_b(t-1)\cdot(1-\sigma) - (P_h(t)/\eta_i - P_l(t))\,, \tag{6}$$

Battery charging,

$$P_b(t) = P_b(t-1)\cdot(1-\sigma) + (P_h(t) - P_l(t)/\eta_i)\cdot\eta_b\,, \tag{7}$$

Where $P_b(t-1)$, $P_b(t)$ the battery energy at the beginning and the end of interval t, respectively, $P_l(t)$ the load demand at the time t, $P_h(t)$ the total energy generated by PV array, micro-hydro unit and wind generators at the time t, σ the self-discharge factor and η_b, η_i the battery charging and inverter efficiency, respectively, as obtained from the manufacturers' data.

As per the recommended practice to ensure sufficient lifetime, batteries are cycled between a minimum and maximum levels of rated capacity. Renewable sources like biomass and fuel cells are not modeled, as they are not commonly used for electricity production in Kerala.

Total hybrid power generated at any time t,

$$P(t) = \sum_{h=1}^{N_h} P_h + \sum_{w=1}^{N_w} P_w + \sum_{s=1}^{N_s} P_s\,, \tag{8}$$

3.2 Optimal Operation

Optimal dispatch strategy of hybrid energy system is to find the most economical schedule for different combinations of renewable generators with diesel and battery backup, satisfying load balance, resource availability and equipment constraints. The dispatch strategy is such that the battery charges, if the renewable energy is in excess after meeting the demand and discharges, if load exceeds the renewable energy. Diesel generator is used as part of the system to respond to the emergency cases where renewable generation and stored energy are not sufficient to meet the load.

The hourly operation strategy of the different hybrid configurations is determined with the use of non-linear constrained optimization energy are not sufficient to meet the load. The renewable energy source constraints are such that they should be used as much as possible.

The optimal operation strategy for a solar PV/wind/micro-hydro combination so as to minimize the annual operating cost C_o computed based on the operating cost for the interval t in a day as shown below.

$$C_{\mathrm{ot}} = \sum_{1}^{365}\{\sum_{t=1}^{24}(C_{\mathrm{oh}}(t) + C_{\mathrm{ow}}(t) + C_{\mathrm{os}}(t) + C_{\mathrm{og}}(t) + C_{\mathrm{ob}}(t))\} \tag{9}$$

subjected to the constraints as expressed in Equations. (2–7). $C_{\mathrm{oh}}(t)$; $C_{\mathrm{ow}}(t)$; $C_{\mathrm{os}}(t)$; $C_{\mathrm{og}}(t)$, $C_{\mathrm{ob}}(t)$ are the operational costs of micro-hydro, wind turbine, solar PV, diesel generator and battery units for the hourly interval t (t=1–24), respectively. Operational costs are calculated on the basis of component characteristics, size and efficiency.

Total annualized life cycle cost of the system incorporating components of both capital and operating cost,

$$C_{\mathrm{an}} = (C_{\mathrm{c}}.CRF + C_{\mathrm{ot}}). \tag{10}$$

Unit cost of electricity by hybrid energy system,

$$C_{\mathrm{oe}} = \frac{C_{\mathrm{an}}}{E_l}\,, \tag{11}$$

where E_l the load served in kW h/year and CRF the capital recovery factor for the system with expected discount rate.

The optimization model developed above can be solved by non-linear constrained optimization techniques. The solution yields optimal combination with unit sizing of energy components minimising the total life cycle cost. The flowchart for finding an optimal hybrid energy system is shown in Figure 1.

4. Case Study

The evaluation is based on a typical farming village of Western Ghats in Kerala, India. It is around 110 km away from the nearest local town. The mode of transportation is limited to jeeps (that too to certain areas only) and distance to the existing grid line is around 15 km. It is expensive and complex to extend the grid due to hilly terrain and nature of landscape. The village has 120 families with a population of over 600. A 6.25 kVA community-based diesel generator (DG) unit supplies power to about 35% of the population. DG set operates six hours a day during peak hours. During emergencies and festival seasons, the DG operation is extended to remaining hours of the day. Individuals for their typical household applications own other small units of diesel generators of ratings 1 kVA and less. About 40% of the population is deprived of electricity. The principal demand of electricity is for lighting and radio. In this study, the electrical appliances in the village include 11 and 20 W compact fluorescent lamps, 60 W fan and 35 W radio set. From the detailed study, data collection and survey conducted in the site with the assistance of a non-governmental organization [12], it is estimated that

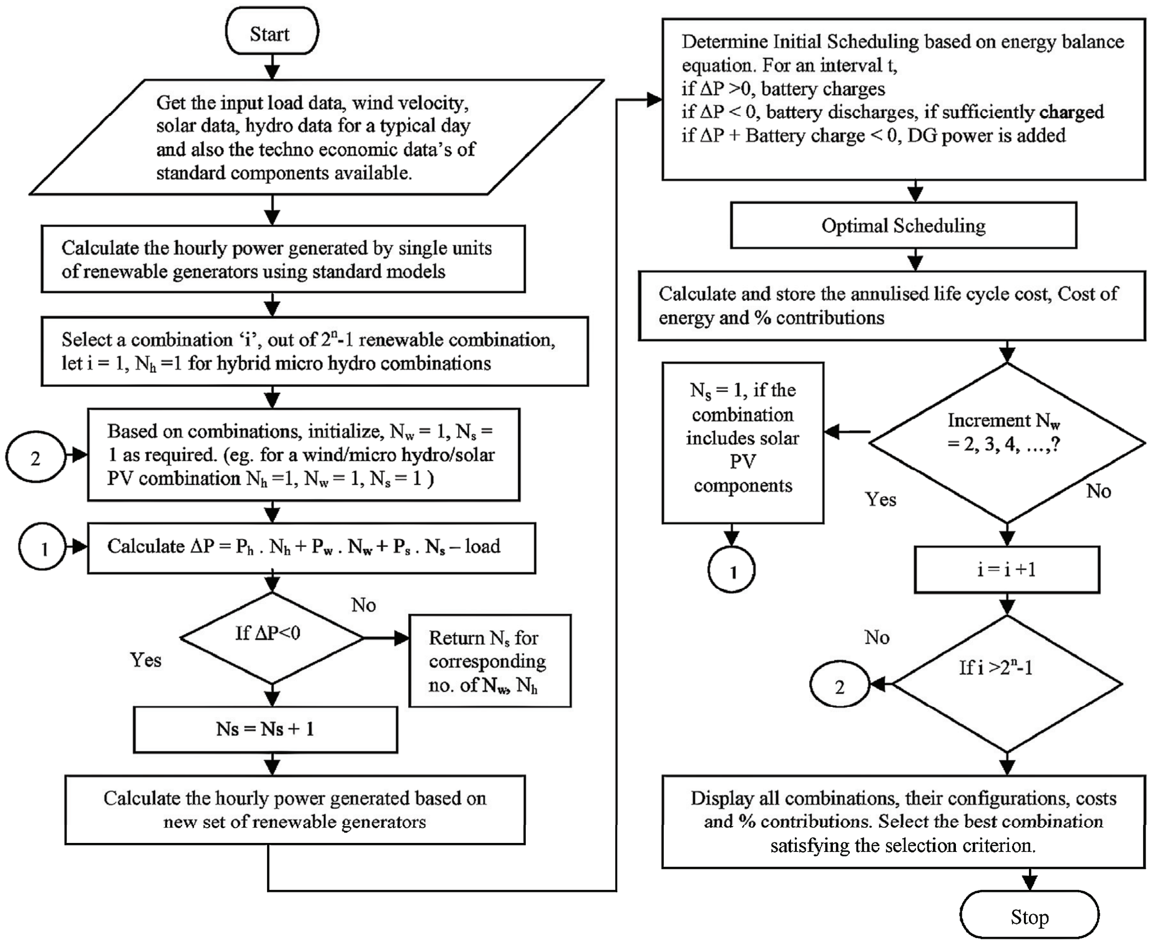

Figure 1. Flowchart to find optimal hybrid system

there exists potential of renewable sources like several water streams flowing down hills, wind and solar energy. The load profile of the population was estimated considering 10% demand growth rate.

4.1 Proposed Scheme

Even though the potential of renewable sources are high, the application of renewable generators as stand alone units will not be sufficient to provide a continuous power supply due to seasonal and non-linear variation of renewable resources. To ensure a balance and stable power output, different renewable generators might be installed and integrated to form a hybrid energy system. An optimal combination of a decentralized hybrid energy system will eliminate the resource fluctuations, increase overall energy output and reduce energy storage. The existing-diesel generators may be used during emergencies or contingencies to add to the security of the system. Annualized life cycle cost of the proposed hybrid energy system is computed based on capital and operating costs of different energy components. The capital cost of micro-hydro, wind, solar PV and DG units are Rs. 90/W, Rs. 125/W, Rs. 200/W, and Rs. 15/W and the operating costs of micro-hydro, wind and solar PV units are Rs. 0.15/kW h, Rs. 0.1/kW h and Rs. 0.05/kW h, respectively [13]. The operating cost of DG units includes fuel cost (Rs. 24/l) and operation and maintenance cost of Rs. 0.2/kW h. The project lifetime is taken as 20 years with 15% discount rate.

From the hourly load profile of the village, after considering the demand growth rate, the daily energy demand is taken as 317 kW h. The average hourly load profile for the typical day is shown in the Figure 2. The design flow for the micro-hydro scheme is 35 l/s. The lowest recorded flow measured is 60 l/s during dry period with the measured head 60 m. The average daily solar radiation based on annual measurement is 6.53 kW/m^2/day with variations shown in Figure 2. The average hourly variations of ambient temperature (°C) and wind speed based on the measured data are also plotted in Figure 2. The wind blows in northwesterly direction for most of the year. The average wind velocity is estimated as 9.1 m/s.

Locally available standard micro-hydro, wind and solar PV units suitable to the resource measurements are

Table 1. Iteration results (partial) of hybrid energy component sizes and cost

No.	Micro hydro (15 kW)	Wind unit (5 kw)	SPC (120 kW)	DG set (kW)	Batt. No. (360 Ah, 6 V)	Coe (Rs./ kW h)	Renewable (%)	DG (%)
1	1	1	26	0	32	7.09	100	0
2	1	1	0	10	24	6.3	98.4	1.6
3	1	2	0	0	28	6.5	100	0
4	1	0	50	10	32	9.33	89.44	10.56
5	0	1	332	15	72	26.49	75.57	24.43
6	0	2	268	10	68	22.05	82.01	17.99
7	0	3	191	10	56	17.9	88.25	11.75
8	0	4	113	5	48	13.47	94.22	5.78
9	0	5	26	0	40	9.9	100	0
10	1	0	0	10	12	7.05	79.82	20.18
11	0	1	0	20	8	28.9	18.12	81.88
12	0	2	0	15	8	19.9	37.77	62.23
13	0	3	0	15	8	13.42	57.45	42.55
14	0	4	0	15	16	10.15	77.26	22.74
15	0	5	0	10	32	8.68	97.27	2.73
16	0	6	0	0	40	9.85	100	0
17	0	0	359	15	76	31.4	76.8	23.2

Table 2. Cost comparisons between different energy supply schemes

Description	Daily hours of operation	Population electrified (%)	Cost of electricity (Rs./kW h)
Proposed micro-hydro-wind hybrid system	24	100	6.5
Grid supply extended	24	100	7.11
Diesel generator units	6	40	10.12

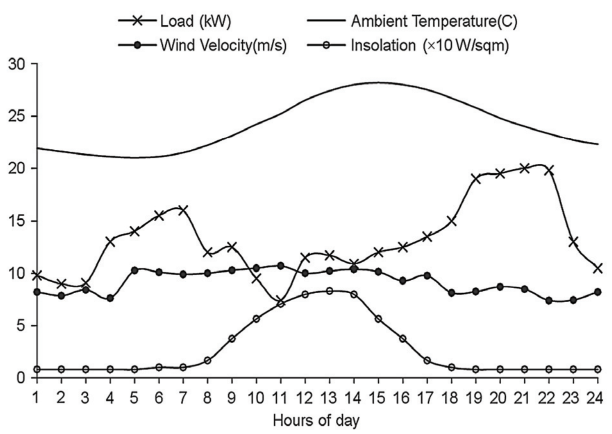

Figure 2. Hourly load and renewable energy data for the village

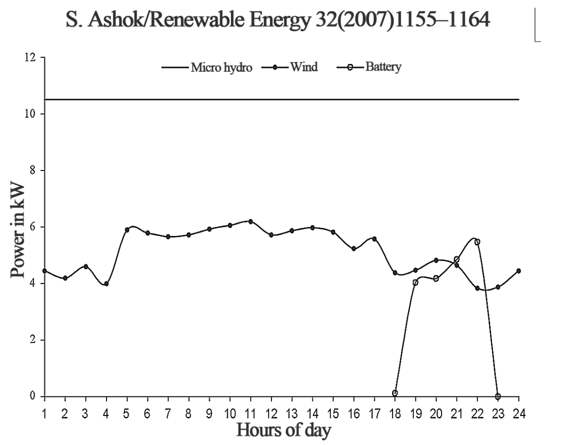

Figure 3. Hourly power output under optimal hybrid energy system

selected for unit sizing for the benefit of service and maintenance. 15 kW, 3 Phase Kaplan-Induction-type micro-hydro turbo units, 5 kW 3 Phase AEP 5000 asyn chronous wind units, 120 W BP Solar 33 V, 3.56 A PV units, 5 kW 3 Phase DG sets and 360 AH, 6 V battery units are used for calculation. Their characteristics are obtained from manufacture's data [13].

The optimization model developed is applied for the village with the above data to determine the optimal number of different renewable energy units and also to find the optimal schedule. Quasi-Newton algorithm is used to solve the optimization problem [14].

4.2 Results

With the three renewable sources considered, the analysis will be to determine the optimal one out of seven combinations for the village. Iterative results of certain components are shown in Table 1. The optimization does not choose PV system, naturally due to high capital cost. Even though the second configuration with single wind unit is cheaper, it requires diesel generator backup to meet the demand during the peak hours. The third configuration with two wind turbines eliminates the need for the diesel generator but with a small battery backup. So this configuration contributing to 100% renewable energy and reduced emission is recommended. Here, the surplus energy stored in the battery unit meets the peak load instead of DG. The hourly output under optimal operation of the hybrid system is shown in Figure 3.

The micro-hydro contributes 78% and wind 22% of the total supplied energy system. The battery throughput is 85 kW h/day. The unit cost of electricity for the above hybrid system is Rs. 6.5/kW h.

The proposed hybrid system can supply the entire village population with 24 h quality power eliminating the need for peak load diesel generators. The existing diesel power units can supply only half of the population on an average six hours operation in a day. A 25 kVA diesel generator is required to supply the whole population with unit costs of Rs. 11.63/-. The cost comparisons of different schemes are given in Table 2. Cost of grid charge is arrived using annualised grid extension charge of Rs. 50,000/km and grid energy cost of Rs. 4/kW h. With the installation of the proposed micro-hydro/wind hybrid energy system in the village, the entire population will have reliable electricity for their basic needs.

5. Conclusions

A general optimization model for finding an optimal combination of community-based hybrid energy systems is developed for Indian conditions. This compatible model is applicable to renewable power generation in any rural village. A decision support system designed and developed using this model to help a designer in sizing the hybrid power system hardware and in selecting the operating options on the basis of overall system performance and economics when site specific conditions and load profiles are known.

From the case study, a micro-hydro/wind hybrid energy system is found to be the optimal combination for the rural community. This hybrid system with battery backup will provide 24-hour electric supply to every household in the village at the unit cost of Rs. 6.5/ kW h. The total renewable energy fraction of electricity is 100%, which eliminates the need for conventional diesel generator.

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