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An Optimal Operating Strategy of an Integrated Energy System for a Typical Rural Village in Bangladesh

[1]Shamim Kaiser, M., [2]M. Arifur Rahman, [2]M. Mostafizur Rahman,
[1]A.K.M. Fazlul Haque, [2]M. Abu Taher and [1]S.K. Aditya
[1]Department of Electronics and Telecommunication Engineering,
[2]Department of Computer Science and Engineering, Daffodil International University,
102 Shukrabad, Mirpur Road, Dhaka-1207, Bangladesh

Abstract: Hybrid energy system is an excellent solution for power generation in rural areas where the grid is infeasible. Such a system incorporates a combination of one or several energy sources such as solar PV, wind energy units, diesel generators etc. This study discusses various system components for remote area power supplies and then proceeds to an optimal operating strategy of an integrated system for a typical rural village at Kutubdia in Bangladesh. In order to determine the hourly operating states of a hybrid system more accurately, practical mathematical models characterizing PV module, wind generators are used. Battery and diesel generator are used as back up power sources. Quasi Newton algorithm is applied for optimizing the operation of wind and PV integrated energy systems. The result of the case study shows that the cost of electricity is 23 Tk/kWh for a PV/wind hybrid system.

Key words: Hybrid energy system, renewable energy, wind, solar PV and micro hydro

INTRODUCTION

Traditionally electricity for rural areas has derived from diesel driven alternators characterized by high reliability, high running cost, low efficiency and high maintenance. Most of the disadvantages can be traced back to the need of prolonged operation of the diesel at low load factors. This is unavoidable given that the capacity of the diesel must accommodate the peak system load. More efficient systems can be devised by renewable energy sources such as wind, solar PV, micro hydro where appropriate. Stand-alone units are already in operation at colonies. But the availability of solar or wind energy is not continuous. Isolated operation of these power stations may not be effective in terms of cost, efficiency and technology. An excellent solution is by combining these different energy sources to form a Hybrid Energy System[1].

A system using a combination of these different sources has the advantage of balance and stability. A typical decentralized hybrid energy system integrates PV modules, wind generator, battery bank and diesel generator sets. The main objective is to provide 24 h grid quality AC 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, clinics for village communities. In addition they can provide essential supply for national parks, farms and tourist facilities, which are far away from main grids. By incorporating appropriate power conditioning and control algorithms[2], the hybrid systems may be expected to provide a near optimal load on the system, extract maximum power, reduce peak capabilities and increase the overall capacity of the system. While planning, designing and constructing a hybrid energy system, the problem becomes complicated through uncertain renewable supplies, load demand and non-linear characteristics of components. This calls for an optimized hybrid energy system with the objective of minimizing the life cycle cost while guaranteeing reliable system operation[3].

A hybrid system utilizes renewable energy from PV/wind sources. Storage batteries and diesel generators are also incorporated as back up source of power. In practice, the storage batteries are used to store excess power from the renewable sources if the load demand is low. When the load demand exceeds the capacity of renewable generators, the batteries are used to supplement the supply. If the demand is still not met by the above combination, the diesel generators are operated

Corresponding Author: Shamim Kaiser, M., Department of Electronics and Telecommunication Engineering, Daffodil International University, 102 Shukrabad, Mirpur Road, Dhaka-1207, Bangladesh

to supply the deficit. This results in reduction of fuel consumption and ensures reliable power supply to the community. In this study, it is aimed to investigate conventional and renewable options of an integrated energy system for the typical rural community. The results of this study will lead to the planning and optimal operation of the hybrid energy system.

MATERIALS AND METHODS

Optimal dispatch strategy of hybrid energy system deals with the finding of an optimal schedule for the PV, wind, diesel and battery charge/discharge strategies, while meeting the load demands. Quasi Newton algorithm is used to solve the problem of scheduling of hybrid energy systems. Given the data of load, solar radiation, wind velocity for a typical day, the task is to determine the unit commitment and dispatch of diesel generators for the scheduling period and the battery charge/discharge policy within the same period, with an objective to minimize the operating cost while meeting the system constraints. The renewable energy source constraints are such that they should be used as much as possible. For battery storage, they must be operated between 20%-90% of the capacity for better life expectancy. The diesel generator constraints include the operation of the set within minimum and allowable rating. Diesel generator must be operated above 45% of the rated capacity, as the efficiency of the generator is low at low loads. The total power generated must meet the load to minimize loss of load probability is the general constraint.

The wind component: The power output from wind turbines will vary with the wind speed. The energy that a wind turbine will produce depends on its wind speed power curve and the wind speed frequency distribution at the installation site[4]. The performance of a wind generator is very dependent on the site selected. Wind turbines generate power by converting the momentum in the wind into mechanical power and converting the mechanical power into ac power via standard ac generation techniques. Electrical power generated by wind turbine is given by:

$$Pw = \eta_t \cdot \eta_g \cdot 0.5 \cdot \rho \cdot Cp \cdot A \cdot Vr^3 \quad (1)$$

Where Vr = wind speed at projected height Hrin m/s,
ρ = factor to account for air density (1.225 g/m^2 at sea level),
Cp = power coefficient (0.35 for a good design),
A = wind turbine rotor swept area in m^2,
η_t = turbine efficiency,
η_g = generator efficiency.

The wind output Pw is a function of wind velocity ☼ such that:

$$Pw = Pt \quad \text{if } Vci \le Vr \le Vco \quad (2)$$

$$Pw = 0 \quad \text{if } 0 < Vr < Vci \text{ or } Vr > Vco \quad (3)$$

where Vci = cut-in speed in m/s,
Vt = rated power velocity in m/s,
Vco= cut-off speed in m/s,
Pt= rated power of wind generator in kW.

The wind speed Vrcan be found by using the formula:

$$Vr = Vm\left(\frac{Hr}{Hm}\right)^{\gamma} \quad (4)$$

Where Vm = measured wind speed at height ☼ in m/s,
Hr = rotor height in mts.,
y = ground surface friction coefficient (1/7).

The solar component: Solar Cells are normally grouped in to modules, with ☼number of parallel solar modules and ☼number of solar modules in series. The PV panel output is a function of the solar radiation and panel temperature. Assuming that Maximum Power Point Tracker (MPPT) is used and the PV module is always working at the maximum power point. The formulas for calculating the optimum operating point current and voltage under arbitrary conditions have the following forms[5]:

$$Ipv = Isc \cdot \left\{1 - C_1 \cdot \left[\exp\left(\frac{Vpv - \Delta V}{C2 \cdot Voc}\right) - 1\right]\right\} + \Delta I \quad (5)$$

Where

$$C_1 = (1 - Ipm/Isc) \cdot \exp\left[-Vpm/\left(C_2 \cdot Voc\right)\right] \quad (6)$$

$$C_2 = \frac{Vpm/Voc - 1}{\ln(1 - Ipm/Isc)} \quad (7)$$

$$Vpv = Vpm \cdot \left[1 + 0.0539 \cdot \lg\left(\frac{Ett}{Est}\right)\right] + \beta \cdot \Delta T \quad (8)$$

$$\Delta V = Vpv - Vpm \quad (9)$$

$$\Delta I = \alpha \cdot \left(\frac{Ett}{Est}\right) \cdot \Delta T + \left(\frac{Ett}{Est} - 1\right) \cdot Isc \quad (10)$$

$$\Delta T = Tcell - Tst.\ Tcell = Ta + 0.02.\ Ett \quad (11)$$

The hourly output power of PV array is:

$$Ppva = \eta_{pv} \cdot Npvp \cdot Npvs \cdot Vpv \cdot Ipv \cdot Fc \cdot Fo \quad (12)$$

Where η_{pv} = conversion efficiency of a PV module,
Fc= connection loss factor,
Fo= accumulative dust loss factor,
Ppva = output power of PV array (W),
Vpv = module optimum operating point voltage at arbitrary conditions (V),
Vpm = module optimum operating point current at arbitrary conditions (A),
Vpm = module maximum power voltage (V),
Ipm = module maximum power current (A),
Voc = module open circuit voltage (V),
Isc = module short circuit current (A),
Ett = total irradiance incident on tilted plane and horizontal surface (W/m2),
Est = standard light intensity (1000 W/m2),
Ta = ambient temperature at arbitrary conditions (°C),
Tst = standard temperature (25°C),
α = module current temperature coefficient (A/°C),
β = module voltage temperature coefficient (V/°C).

Diesel generator component: 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 consumption function burnt by a generator at power level kW, is expressed as:

$$F(t) = f(Pg(t)) \quad (13)$$

$$F = aP^2 + bP + c \quad (14)$$

Diesel generator must be operated above 45% ☼of the rated capacity, as the efficiency of the generator is low at light load. The operating range of the generator is also limited to the following constraints,

$$Pg\ min \le Pg\ (t) \le Pg\ max \quad (15)$$

Taking into account the routine maintenance and major overhaul costs, the total operating cost ☼of ☼diesel generators in the interval ☼can be derived as:

$$Cog(t) = \sum_{g=1}^{G} (Cf \cdot F(t) + Cmg \cdot Pg(t)) \quad (16)$$

Where a, b, c = coefficients of diesel generator,
Cf = the fuel cost in rupees,
Cmg = the maintenance cost in Tk./kWh,
Pg min = minimum rated limit of generator to be operated,
pg max = maximum rated limit of generator to be operated.

Battery/inverter component: A Battery being a voltage source is rated according to its Watt-hour or ampere-hour capacity[6].

$$Wh = Ah.\ Rated\ Voltage.\ Depth of\ Discharge \quad (17)$$

The state of charge or stored charge of battery can be calculated from the following equations.
Battery discharging,

$$Pb(t) = Pb(t-1)\cdot(1-\sigma) - \left(Psw(t)/\eta_{inv} - Pl(t)\right) \quad (18)$$

Battery charging,

$$Pb(t) = Pb(t-1)\cdot(1-\sigma) + \left(Psw(t) - Pl(t)/\eta_{inv}\right)\cdot\eta_{batt} \quad (19)$$

Although it is theoretically possible to fully discharge the battery, it is not recommended in practice. Hence, it should be ensured that a minimum amount of charges 20% Pb is retained. To ensure sufficient lifetime, they are not cycled through more than 90% ☼of their rated capacity
This can be expressed as the constraints,

$$Pb\ min \le Pb\ (t) \le Pb\ max \quad (20)$$

Where
Pb (t-1), Pb (t) = battery energy at the beginning and the end of interval t respectively,
Pl (t)= load demand at the time t (kW),
Psw (t)= total energy generated by PV array and wind generators at the time t (kW),
σ = the hourly self-discharge rate (0.001),
Pb min = minimum charge quantity of battery bank (Wh),
Pb max = maximum charge quantity of battery bank (Wh),
η_{batt} = battery charging efficiency,
η_{inv} = inverter efficiency.

Mathematical formulation for optimal operation: The optimal operation strategy for the hybrid energy system so as to minimize the operating cost[7] for the interval t is

$$Com = \sum_{t=1}^{24}\left(Cow(t) + Cos(t) + Cog(t) + Cob(t)\right) \quad (21)$$

Total Hybrid Power Generated,

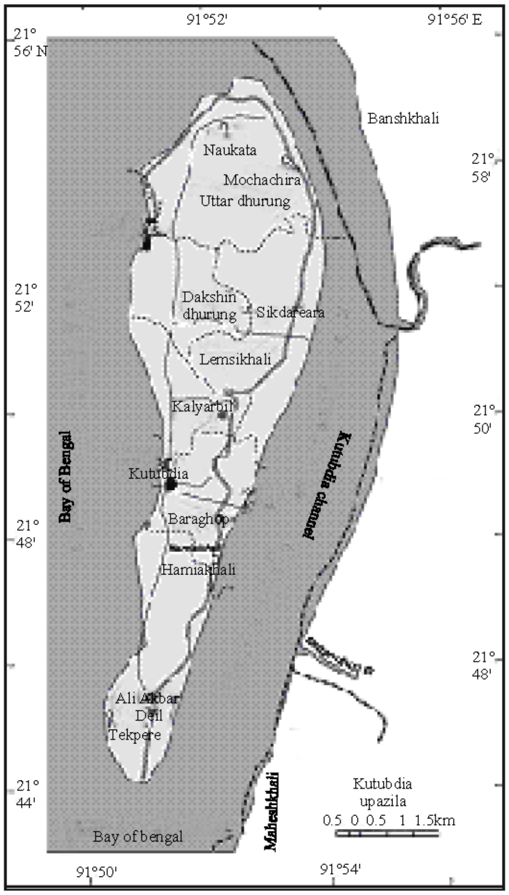

Fig. 1: Map of kutubdia upazila

$$Ph(t) = \sum_{w=1}^{W} Pw + \sum_{s=1}^{S} Ps + \sum_{g=1}^{G} Pg \pm \sum_{b=1}^{B} Pb \qquad (22)$$

satisfying load balance equation neglecting system losses,

$$Ph(t) - Pl(t) = 0 \qquad (23)$$

Where Cog (t), Cow (t), Cos (t), Cob (t), = total operational cost of diesel generators, wind turbines, PV units and batteries for the hourly interval t (t = 1 to 24), respectively in Tk.,

G, W, S, B = total no. of diesel generators, wind units, solar modules and batteries, respectively.

Cann = Cacap + Caom

$$Coe = \frac{Cann}{Cd \cdot 365}$$

Where Cann = total annualized cost of the system in Tk/yr,
Cacap = total annualized capital cost of the system in Tk/yr,
Caom = annual operation and maintenance cost of the systems in Tk/yr,
Coe = unit cost of electricity in Tk/kWh,
Cd = demand in kW.

Case studyl: Kutubdia Island (21°54.71' North Latitude 91°52.43' East Longitude) is 9.82 square-km as shown in Fig. 1. It has a population of 20249; male 53.04%, female 46.96%. There are 14690 household in rural areas and 3970 in town. One village is considered for analysis[8].

Existing Scheme: Consider, There exist stand alone units of solar PV modules of approximately 40 Nos. x 120 Wp (120 kWp) with 17 Nos. battery support, 3 Nos. of 225 kW wind power units each (675kW) and 380kVA DG set which supply power to various utilities like farming and household applications. These units are mostly operated during night h to meet the lighting requirements, but wind and DG units are used during daytime for farming and other typical applications. The ratings, specifications and costs of system components are shown in Table 1. The National Grid is located 10 km. away from the load centre of the village under study.

Proposed scheme: As the operation of these units is independent and due to the non-linear variation of the load demand and renewable resources, they are not reliable to meet the total power requirements of the village as stand alone units. It is also expensive to depend mostly on diesel generators, which are normally considered as peak load generators. To ensure a balance and stable power output these units may be integrated to form a hybrid energy system for the proposed village. A decentralized hybrid energy system with PV/Wind/Diesel/Battery configuration is considered for optimal power sharing with battery as primary back-up source and DG set as the secondary back up. 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. A diesel generator is used as part of the system to respond to the emergency cases where PV/Wind generation and stored energy are not sufficient to meet the load. To optimize the operating strategy, the battery and power conditioning unit sizing is resized to incorporate the new hybrid configuration. The battery units are sized as per standard calculations with two days of autonomy. The batteries have to be replaced every 4 years. The project lifetime is assumed to be 20 years and 15% is considered as annual interest rate.

Table 1: Configurations of various system components

Wind Generator data		Solar PV Module rating		Battery Specifications	
Generator type-Asynchronous 3-Φ		Maximum power (P_{MAX})	120 W	Type of battery	Lead acid battery
Wind Generator capacity	225KW	Voltage at P_{MAX} (V_{PV})	33.7V	Battery rating	360Ah, 6V
Cut in wind speed	2.7 m/s	Current at P_{MAX} (I_{PV})	3.56A	Cost of single battery	30000
				Cost of power conditioning unit (Tk./kVA)	150000
Cut out wind speed	20m/s	Short-circuit current (I_{SC})	3.87A	Diesel Generator ratings	
Rated wind speed	10m/s	Open-circuit voltage (V_{OC})	42.1V	Specifications	380kVA, 415V, 0.8 p.f., 50Hz, 1500rpm
Diameter of rotor	27m	Temperature coefficient of I_{SC} (â)	0.0008A/°C	a = -0.000088	b = 0.19 c = 13
Height of tower	33m	Temperature coefficient of V_{OC} (â)	-160mV/°C	Fuel Cost (Tk./litre)	35
Capital Cost (Tk/W)	200	Capital Cost (Tk./W)	300	Capital Cost (Tk./W)	20
Balance of system cost (% of capital)	25%	Balance of system cost (% of capital)50%		Balance of system cost (% of capital)	20%
O&M Cost (Tk/Kwh)	0.2	O & M Cost (Tk/Kwh)	0.4	O & M Cost (Tk/Kwh)	0.25

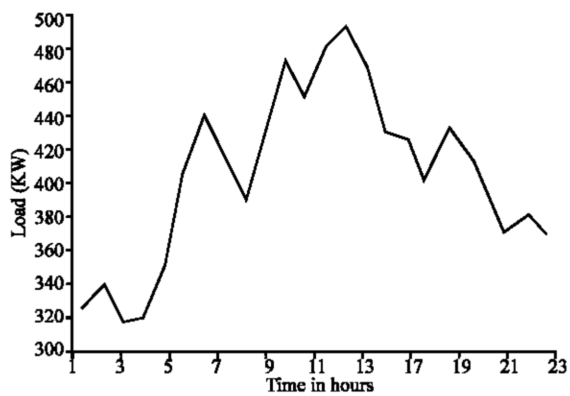

Fig. 2: Hourly load profile for a typical day

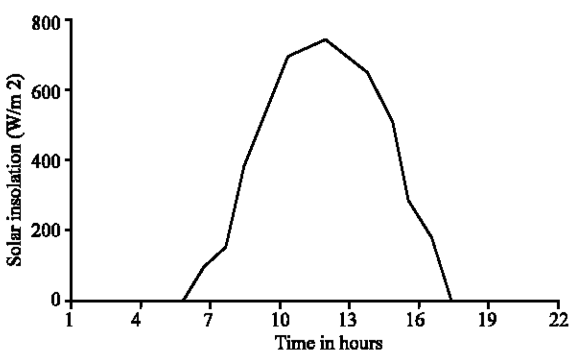

Fig. 3: Hourly variations of solar radiations for a typical day

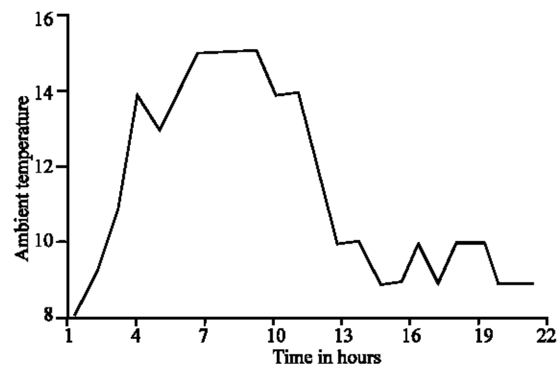

Fig. 4 : Hourly variations of ambient

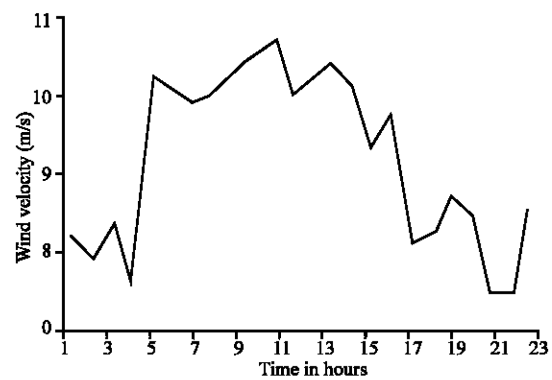

Fig. 5: Hourly wind velocity (m/s) for temperature (°C) for a typical day a typical day

From the hourly load profile of a typical day in the village, the peak demand is found to be 480 kW. The average hourly load profile for a typical day is shown in the Fig. 2. The solar radiations for a typical day in the village considered are zero during nighttime and peak values are reflected during daytime between 10a.m. to 5p.m as shown in Fig. 3. The solar radiation is estimated as 4.1 kW/m^2/day. The average hourly variations of ambient temperature (°C) for a typical day are plotted in Fig. 4. The hourly variations of wind speed data are shown in Fig. 5. The wind blows in northwesterly direction for most of the year. The average wind velocity is estimated as 4.15 m/s. The maximum and minimum wind velocities are observed as 2.75 m/s and 6.17 m/s, respectively.

RESULTS AND DISCUSSION

The hourly output of solar PV module and wind turbine is shown in Fig. 5 and 6 displays the diesel

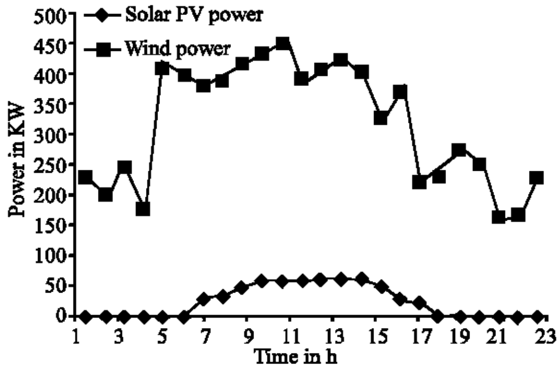

Fig. 6: Power output from solar PV modules and wind turbines

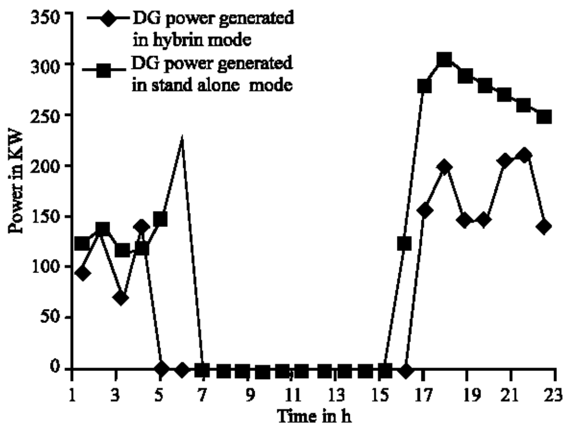

Fig. 7: Comparison of Diesel power generated in hybrid and stand alone modes of operation

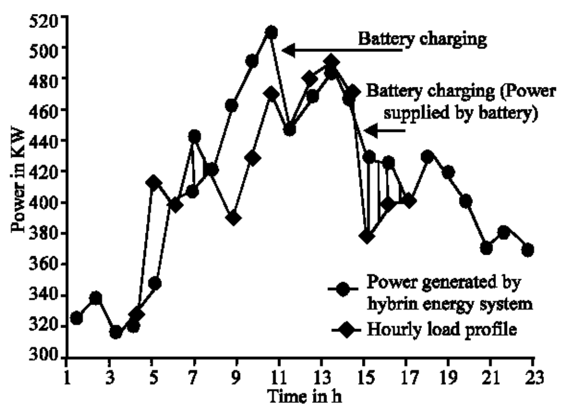

Fig. 8: Battery charge/ discharge schedule

scheduling for both isolated and hybrid mode of operation. It is observed that for a hybrid system, there is a reduction of 1288 kWh/day of diesel power production when compared to stand alone system. Thus for a hybrid system, there is daily reduction of approximately 400 litres of diesel fuel consumption. Diesel back up is only required during night peak h where the demand is not met by renewable energy sources. During day h when generation is more than that of demand, the surplus power is stored in the battery and delivered during shortage, if sufficient charge is present as shown in Fig. 7. Thus the community load is met for the whole day and the expensive diesel generator operation is optimized.

The wind energy system contributes to 76% of the total supplied energy, 17% by diesel generator and 7% by solar PV. The battery throughput is 348kWh/day. The unit cost of electricity for the above hybrid system is 23 Tk/kWh. The cost of energy (Tk/kWh) for a hybrid energy system will vary from site to site, since it largely depends on a number of factors that are site-related. These factors include the average solar radiation, the average wind speed as well as load pattern. The average conventional energy cost is 8 Tk/kWh. However, with more favorable solar and wind speed conditions, we can anticipate the cost/ kWh reduction. Hybrid energy cost may reduce to 50%, if efforts are made to reduce the cost of renewable energy sources and battery backup are successful. In future, the cost of renewable sources is expected to reduce further with R&D, Government subsidies and incentives. Keeping the long term health and cost benefits associated with pollution reduction and reduction of foreign exchange consumption, renewable energy is better option.

CONCLUSION

An optimal dispatch strategy for a PV/wind hybrid energy system is developed. System is also supported with battery and conventional diesel generator back up. Diesel generator is used to meet critical loads whenever generation is not sufficient in the analysis. The system is simulated using meteorological and load data collected from the site considered for case study. The optimum and reliable operation of PV/wind systems is realized by satisfying the load demand, non-linear seasonal variations and equipment constraints. From the case study results, it is inferred that the unit cost of hybrid energy system is Tk.23/-. The diesel generator fuel consumption is reduced by 43% in a PV/wind hybrid energy system. The total renewable energy fraction of electricity is 83% while diesel generator contributes to the remaining 17%.

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