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Optimal Hybridization of Renewable Energy Systems to Improve Energy Efficiency

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Energy is the prime mover of the economic growth and developmental process. To enhance the energy security of India, use of renewable energy is the utmost important. Electrical energy is the richest form of energy which is having an important role in Industrial growth. Depleting fossil fuel resources which form about more than 60 % of Indian energy generation cannot prime the growth process that is sustainable. They need to be gradually replaced by renewable sources of energy, which are perennial in nature. The increasing gap between power supply and demand is alarming the power industry to work hard in reducing the gap. In order to achieve the sustainable energy growth with the increased population and energy demand and to provide more energy to the rural populations, the non-conventional and renewable energy sources need to be installed and used [1]. The energy resource like solar radiation & wind data are measured, the energy availability, reliability of energy systems and economics of the systems are carried out by using a HOMER and MATLAB Simulink software. This paper discusses about the improving of energy efficiency by hybridization of different forms of renewable energy sources with respect to energy availability, reliability, cost, ease of operation and maintenance, etc, with detailed discussion.

Keywords: *Hybrid Energy Systems, Renewable Energy Sources, Life Cycle Costing, Optimal Hybridization, Energy Efficiency*

1.0 INTRODUCTION

Hybridization of renewable energy is an important way of increasing utilization, energetic and exergetic efficiencies of energy conversion and utilization systems. Energy systems are integrated through sources or tasks, spatially or time-wise to increase their overall energy utilization factor, enhance the security of energy supply and reduce capital and running costs of equipment [2].

Hybridization involves renewable energy sources like, solar photovoltaic, wind and micro-hydel and conventional energy systems (like DG sets or central grid) for supply of consumer loads. Such energy hybridization encounters complexities arising from the diverse nature of the renewable energy sources, low energy densities, intermittent availability and stochastic elements. Recent developments in processing, control and management of power are enabling stable operation of renewable-diesel support integrated systems.

Energy supply from solar, wind and micro-hydel sources can all be represented in terms of stochastic and deterministic components. Solar energy follows a parabolic profile during the daytime and no supply during the night. Winds are more stochastic and highly seasonal. Micro-hydel

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sources are deterministic over a daily time frame but there is considerable stochastic component in the annual energy availability

2.0 HYBRIDIZATION OF RENEWABLE ENERGY SYSTEMS

A typical integrated energy system consists of solar, wind and hydro energy sources along with Diesel Generator. Figure 1 gives the schematic of the integrated energy system. The power produced by the Solar PV will be DC and is to be inverted to AC for supplying the power to the load through AC autonomous grid. The batteries are used to store the energy that can be charged by DC bus.

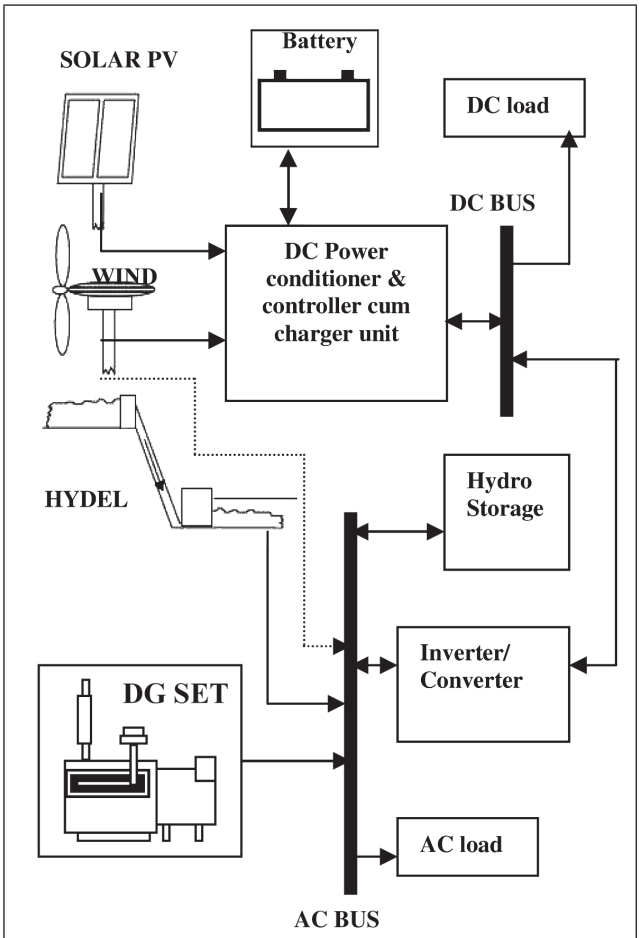

FIG. 1 SCHEMATIC OF THE INTEGRATED ENERGY SYSTEMS

The power produced by wind will be either DC or AC. To produce DC power, compound wound, shunt or permanent magnet DC generators are to be used. The operation is simple but the maintenance is more cumbersome because the use of slip-rings and brushes but now a days brusheless DC alternators are also being used. In case to produce AC power, Induction generators (IG), and Doubly fed induction generator (DFIG) are to be used, but to start the generator the presence of autonomous grid is essential because these generators work as motor during starting and draw reactive power from the grid. But the use of DFIG the burden of reactive power on grid can be reduced during motoring action. In case of synchronous generator, the machine size and converter-inverter system is essential. The mini/ micro hydro generators produce AC power.

2.1 The solar component

The solar energy is the most simplest form of renewable energy and is determined by the solar radiation received at a particular site in kWh/m^2. Solar radiation consists of direct and diffuse components. Energy captured from direct solar radiation depends on the tilt angle of the collector, and is attenuated by atmospheric effects such as cloud and pollution. Diffuse irradiance on the other hand is due to reflection and scattering and is dependent on the surroundings and atmospheric effects, and the energy captured is not dependent on the tilt angle of the collector [3]. Although the maximum direct irradiance can be calculated, the actual direct irradiance plus the amount of diffuse irradiance, or the global irradiance, is difficult to compute accurately and is usually estimated from historical records. Maximum annual energy collection can be achieved by setting the collector tilt angle to the angle of latitude of the site.

2.2 Wind component

The power generation by wind generators will directly proportional to cube of the wind velocity. 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. The power generation by wind turbine generators is binded by the cut-in speed i.e., the speed at which the generator starts generation and cut-out speed i.e.,the speed at which the generator stops. Generally in modern wind generators pitch control is used to generate nearly constant power by changing the pitch angle of the blade upto the cut-out speed. The maximum power generation by wind generator is restricted to 59.3 % (Betz coefficient) and the realistic power output will be in the range of 30 – 35 % [4]. Consideration also has to be given to wind turbulence. It is well known that turbulence increases with rough terrain and obstructions above ground, and the higher the wind speed, the more the wind turbulence will be. For the installation of wind turbines, a height of 10 m above ground is considered to be the minimum. However, a building of 10 m high may not be an appropriate site upon which to install a wind turbine, as the building itself causes turbulence. A common practice is to install wind machine on tower, rising 5 m above any obstructions within the range of 150 m [5].

2.3 Hydro component

The power generated by mini/micro hydel plant (falling water) is the rate at which it delivers energy, and this depends on the flow rate and water head [6]. Micro hydel schemes involved hydel power generation is in the range from 10 kW to 1 MW [7]. Micro hydel units use turbines to suit the head-discharge characteristics, have rapid start-up and backing down characteristics and are the least problematic of the energy sources.

2.4 The Energy Storage component

Since the renewable energy systems are highly unpredictable and stochastic in nature, to utilize these energy systems to the great extent and avoid the unmet load, energy storage system is essential. Sometimes, all the renewable energy systems (i.e., wind and solar) are available simultaneously but there is no load demand, the excess energy had to be either stored or use the dump load. The energy storages can be many types, battery bank and hydro storage systems are the two popularly used energy storage systems. The battery storage is energy efficient, with round trip efficiencies nearly 90 %, but the cost of energy storage is very expensive. Pumped hydro storage is more amenable to long term storage, has high efficiencies, and can be cost effective in some situations, but siting can be a problem. The third option for energy storage is hydrogen storage. In this the electricity is converted into hydrogen gas through electrolysis of water. Again the hydrogen gas is converted back to electricity through fuel cell or heat engine. The cost of energy storage through hydrogen system is one seventh of the cost for energy storage in batteries [8]. But this concept is yet to be popularized in large scale.

3.0 OPTIMAL HYBRIDIZATION

The optimization of integrated energy system can be based on different criteria:

i) Availability of energy throughout the year

ii) Reliability of the system

iii) Site specific

iv) Operation and Maintenance of the system

v) Ease of control and protection

vi) Cost of the system

3.1 Energy Availability

While deciding the energy systems, the energy availability of the energy throughout the year must be considered because some energy systems are seasonal and stochastic. The wind velocity varies widely. Therefore, the energy availability varies drastically throughout the year. It is essential to integrate the energy availability with respect to time [9], [10].

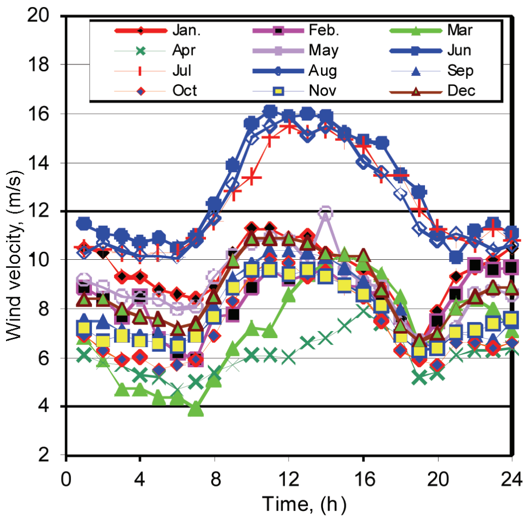

FIG. 2 VARIATION OF WIND VELOCITY.

Figure 2 gives the variation of hourly average wind velocity for each month throughout the year for a typical site. The wind energy starts increasing from 0700 hours and is peak during 1200 to 1400 hours. During the evening and night hours from 1800 to 0700 hours, the wind energy availability is very less. Figure 3 gives the variation of hourly average, minimum and maximum measured wind velocity throughout the year for a typical site.

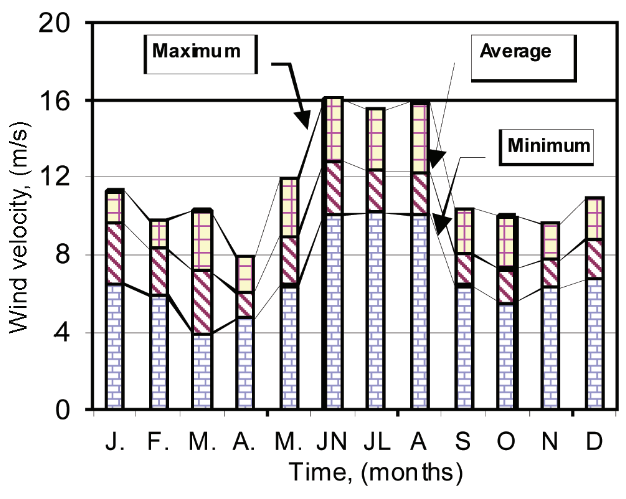

FIG. 3 VARIATION OF AVERAGE, MAXIMUM & MINIMUM WIND VELOCITY

The hourly average wind velocity for a month of a typical site can be computed as:

$$V = A_0 + A_1 * h + A_2 * h^2 + A_3 * h^3 + A_4 * h^4 + A_5 * h^5 + A_6 * h^6 \qquad m/s \qquad ....(1)$$

Where V is the average Wind velocity in m/s, A_0, A_1, ….A_6 are constants given in Table 1 for different months.

The wind potential is more during the months of June, July and August. Figure 4 gives the variation of wind frequency distribution measured at a height of 19 m above the ground level at a typical site, demonstrating that a high frequency over 1000 hours per year occurs for the wind velocity range between 4 m/s to 11 m/s.

The principal feature of solar radiation is the strong seasonal dependence with a minimum in winter and maximum in summer [11]. Figure 5 gives the variation of average, minimum and maximum solar insolation through out the year for a typical site.

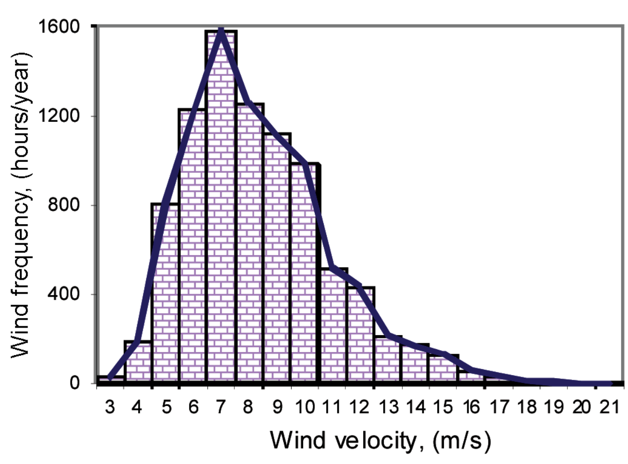

FIG. 4 WIND FREQUENCY DISTRIBUTION

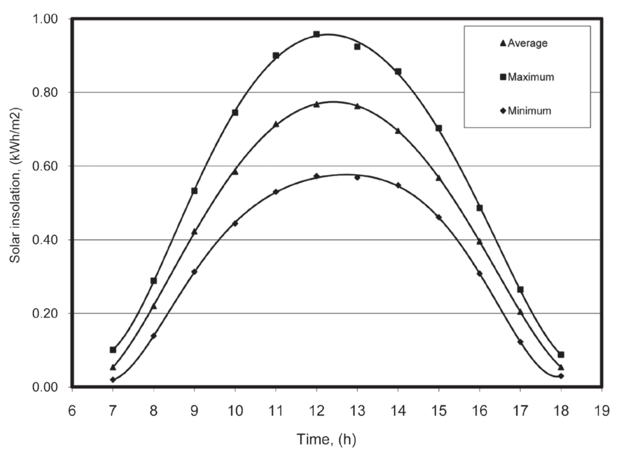

FIG. 5 VARIATION OF AVERAGE, MAXIMUM & MINIMUM SOLAR INSOLATION

The tilt of the solar panel also plays an important role in energy generation. The module installation angle in relation to the sun affects the module energy output. The module produces more power when the sun light source is directly perpendicular to the surface of the module. A typical optimum tilt angle for average module power production over the year in a fixed system will be latitude of the particular site. The monthly best tilt angle of the PV array is given by:

$$S = \phi - \delta \quad degree \qquad ....(2)$$

Where Φ is the latitude of the site in degree, δ is the sun's declination angle, degree ranges between +/- 23.45°.

TABLE 1

COEFFICIENTS OF WIND VELOCITY

Month	A_0	A_1	A_2	A_3	A_4	A_5	A_6
Jan.	9.0682	2.4731	-1.341	0.248	-0.0201	0.0007	-1E-05
Feb.	6.4574	3.6248	-1.717	0.296	-0.0229	0.0008	-1E-05
March	5.4564	2.0768	-1.251	0.229	-0.0176	0.0006	-8E-06
April	5.6026	0.7634	-0.413	0.068	-0.0096	0.0001	-1E-06
May	7.6949	2.3253	-1.174	0.217	-0.0175	0.0006	-8E-06
June	10.939	1.2056	-0.797	0.163	-0.0133	0.0005	-6E-06
July	9.1873	2.0187	-0.959	0.175	-0.0135	0.0005	-6E-06
Aug.	8.6277	2.8288	-1.316	0.240	-0.0190	0.0007	-9E-06
Sept.	6.6764	1.5534	-0.856	0.166	-0.0135	0.0005	-6E-06
Oct.	6.0472	1.5732	-1.006	0.204	-0.0171	0.0006	-9E-06
Nov.	6.4321	1.2520	-0.721	0.144	-0.0120	0.0004	-6E-06
Dec.	6.6377	2.8760	-1.404	0.256	-0.0205	0.0007	-1E-05
Avg.	**7.4063**	**2.0476**	**-1.079**	**0.201**	**-0.0160**	**0.0006**	**-8E-06**
Max.	**10.912**	**1.2583**	**-0.826**	**0.170**	**-0.0139**	**0.0005**	**-6E-06**
Min.	**6.3082**	**0.0785**	**-0.337**	**0.072**	**-0.0056**	**0.0002**	**-2E-06**

The optimum fixed tilt angle for the selected site is 12.97° (latitude of the site) this will reduce the average energy output by about 3 % for the whole year compared to the tracking system. As the tilt increases upto the latitude of the site the output increases and beyond the latitude the out decreases [12]. The solar tracking system gives the maximum power output but needs more control and cost [13]. The total solar radiation in a month is presented in Figure 6. The solar intensity is more during the month of March to May. The solar energy is available from 0700 hours to 1800 hours and will not be there during evening and night hours from 1800 – 0700 hours.

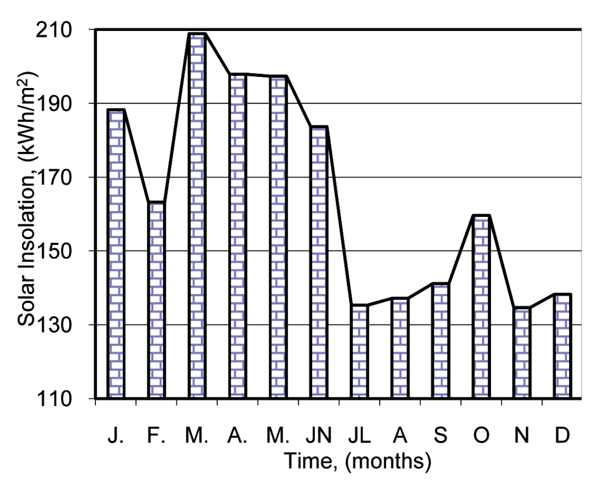

FIG. 6 MONTHLY TOTAL SOLAR INSOLATION

The daily average solar insolation falling at a typical site can be computed as:

$$P = B_0 + B_1 * h + B_2 * h^2 + B_3 * h^3 + B_4 * h^4 + B_5 * h^5 + B_6 * h^6 \qquad W/m^2 \qquad ....(3)$$

Where P is the average solar insolation falling in W/m^2, B_0, B_1, ….B_6 are constants given in Table 2 for different months.

Figure 7 gives the share of energy potential available throughout the year. The share of wind energy is more during June, July and August months whereas the share of solar energy is more during March, April and May months

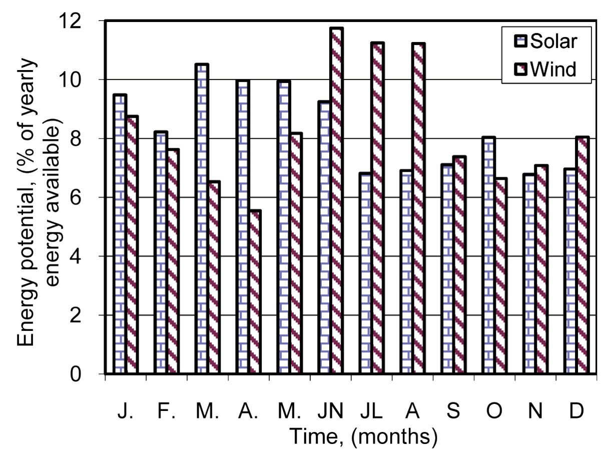

FIG. 7 MONTHLY SOLAR & WIND ENERGY AVAILABILITY

TABLE 2

COEFFICIENTS OF SOLAR INSOLATION

Month	B_0	B_1	B_2	B_3	B_4	B_5	B_6
Jan.	21.918	-11.089	2.189	-0.2191	0.012	-0.0004	5E-06
Feb.	23.916	-12.660	2.654	-0.2867	0.173	-0.0006	8E-06
March	36.662	-19.257	4.017	-0.4304	0.025	-0.0008	1E-05
April	38.105	-20.555	4.422	-0.4908	0.030	-0.001	1E-05
May	19.739	-10.452	2.174	-0.2309	0.014	-0.0004	6E-06
June	22.145	-11.532	2.361	-0.2458	0.014	-0.0004	5E-06
July	31.264	-17.54	3.946	-0.4589	0.029	-0.001	1E-05
Aug.	-13.38	16.858	-1.473	0.1674	-0.010	0.0003	-4E-06
Sept.	29.705	-15.725	3.326	-0.3634	0.022	-0.0007	9E-06
Oct.	9.7745	-5.0679	1.014	-0.1038	0.006	-0.0002	3E-06
Nov.	23.245	-11.455	2.225	-0.2208	0.012	-0.0004	4E-06
Dec.	4.6776	-1.9922	0.268	-0.0102	-0.0003	3E-05	-5E-07
Avg.	**20.647**	**-10.872**	**2.2607**	**-2.2417**	**0.0143**	**-0.0005**	**6E-06**
Max.	**41.27**	**-21.438**	**4.4469**	**-0.4756**	**0.0282**	**-0.0009**	**1E-05**
Min.	**60.727**	**-32.871**	**7.1883**	**-0.817**	**0.0513**	**-0.0017**	**2E-05**

3.2 Reliability of the system

Reliability is defined as the probability that a system will perform properly for a specified period of time t under a given set of operating conditions.

When the conventional energy systems are idle or under repair, no fuel is consumed and production resumes when failures are cleared. Since the fuel for renewable energy systems is free, every time the system is non-operational, the opportunity for energy production is lost and the loss of revenue. Therefore, the effects of downtimes on system performance are utmost importance in evaluating the life-cycle cost [14].

The commonly used approach in reliability modelling is to model the time between failures as a random variable. The time between failures can be modelled as a Weibull distributed random variable [15], with probability density function f(t) and cumulative distribution function F(t) computed as :

$$f(t) = \frac{\beta}{\eta^{\beta}} t^{\beta-1} e^{-\left[\frac{t}{\eta}\right]^{\beta}} \qquad ....(4)$$

$$F(t) = 1 - e^{-\left[\frac{t}{\eta}\right]^{\beta}} \qquad ....(5)$$

The scale parameter η is directly proportional to the mean time between failures (MTBF) index, while the shape parameter β the nature of the failures.

The behaviour of the renewable energy system can be characterized by using the reliability "bathtub" curve which consists of three failure modes, i.e., the initial reduced failure rate (infant-mortality) is followed by a relatively long nearly constant failure rate (useful life), then the probability of failures sharply increases toward the end of the life of energy system (wear-out period). The shape parameter will be for infant mortality $\beta<1$, for useful life $\beta=1$, for wear-out period $\beta>1$.

The infant-mortality failures will dominate in the beginning of the energy system, and their influence will decrease over time. After some time, only constant failures will occur and this time can be used to obtain Weibull parameters of failure during constant failure rates. The failure rates are more for Wind energy systems compared to Solar PV energy system and mirco-hydel systems.

The reliability of the energy systems can also be characterized by computing the following system reliability indices:

The system reliability indices can be computed as

i) Average Energy System Interruption Index (AESII) :

This index is the ratio of the total number of interruptions of energy system during the year to the total energy generated by the energy system. It is computed as follows:

$$AESII = \frac{\text{Total No. of interruptions per year}}{\text{Energy Generated in a year}} \quad ..Nos/kWh \qquad ....(6)$$

This index shows that how many times and how frequently, the particular energy system is under shut-down (forced and planned) or interrupted in a year. This index is very important for wind energy system because if the wind generator is of induction generator type, for every start, it will run as motor for a while and draw the reactive power from the autonomous grid.

Table 4 gives the system reliability indices for wind energy solar PV energy systems for some typical sites. The AESII is higher for wind energy systems compared to solar PV systems.

ii) Average Energy System Interruption Duration Index (AESIDI) :

This index is the ratio of the total interruption duration of the energy system during the year to the total energy generated during the year. It is computed as follows:

$$AESIDI = \frac{\text{Sum of total No. of interruptions (in hours) per year}}{\text{Energy Generated in a year}} \qquad ....(7)$$

This index shows that how much time the particular system is out of service (planned and forced) in an year. This index shows the healthiness of the energy system.

iii) Average Availability Index (AAI) :

This is the ratio of energy system available to cater the power supply in hours/year to the total theoretical number of hours in a year for example solar PV will be available between 0700 – 1800 hours in a day (i.e., 4015 hours/year). It is computed as follows:

$$AAI = \frac{\text{Total No. of hours of energy system available per year}}{\text{Total Theoretical No. of hours}} \qquad ....(8)$$

This index represents the fraction of availability of energy system to cater the load in an year.

iv) Average Load Factor Index (ALFI) :

This index is the ratio of total energy generated by the energy system during the year to the total estimated energy generation in a year. It can be computed as follows:

$$ALFI = \frac{\text{Total Energy generated per year}}{\text{Total estimated energy per year}} \qquad ....(9)$$

All these indices show that the performance of the individual system. Table 3 gives the reliability indices for wind and solar energy systems. The machine interruptions are more in wind energy systems compared to other systems. Therefore, the availability index of wind energy systems will be lower than that of solar PV energy system. The solar PV is more reliable than other energy systems [16], [17].

3.3 Site specific

Many renewable energy systems are site specific. For example, wind potential is not available at all the places. The mini & micro hydel potential is available in very remote areas like hilly areas. The solar energy availability is also varies for different locations [18].

3.4 Operation and Maintenance of the energy systems

The operation and maintenance plays a major role in selecting the energy systems. Because the O&M cost for wind energy system forms 10 %

TABLE 3

RELIABILITY INDICES FOR TYPICAL WIND AND SPV SYSTEMS

Sl. No.	Reliability indices	Wind (5 kW – 1 MW units)	Solar PV (20 W – 10 kW units)
01	Average Energy System Interruption Index, (Nos./kWh)	0.0158 – 0.0564	0.00084 - 0.0127
02	Average Energy System Interruption Duration Index, (h/kWh)	0.0891 – 0.0102	0.00091- 0.0871
03	Average Availability Index	0.57 – 0.85	0.36 – 0.55

of the total installed cost (considering the life of equipment as 15 years) whereas for solar energy system it is only 1 % of the installed cost [19]. Since the wind energy systems have the moving parts, requires more maintenance than that of solar energy system. The solar PV panels required frequent cleaning against dust accumulation on the surface of the panel. The dust accumulations for a period of 18 months (without cleaning the surface of the panel) reduce the power output by 1 % [20].

3.5 Controls and protection

While selecting the energy system, the controls and protection system must be considered. The solar PV requires more care about the grounding of solar PV cell. The wind energy system will require more control and protection strategies compared to solar energy system because the wind energy system will have:

- yaw control for rotating the blades towards the wind direction,
- pitch control for adjusting the blade angle according to the wind velocity,
- in case of grid connected induction generator system, during low wind velocity the generator will work as induction motor and draws very high reactive power from the grid.
- protection against very high wind velocities.

3.6 Cost of the system

The optimal integration of energy system mainly depends on the cost factor of the energy systems. While evaluating the cost of the renewable energy systems, the life-cycle cost or the levelized cost of energy for each energy system must be considered instead of capital cost or running cost. The levelized cost of energy includes (a) annualized capital cost (Rs./year), (b) Annualized replacement cost (Rs./year), (c) annual maintenance cost (Rs./year) and (d) annual fuel cost (Rs./year)

i) ***Annualized capital cost:*** The annualized capital cost is calculated by:

$$ACC = CC * CRF\left(i, L_{proj}\right) \text{Rs./year} \qquad \text{....(10)}$$

where CC is initial capital cost in Rs., CRF is capital recovery factor & is given by

$$CRF\left(i, L_{proj}\right) = \frac{i(1+i)^{L_{proj}}}{(1+i)^{L_{proj}} - 1} \qquad \text{....(11)}$$

where i is interest rate in % & L_{proj} is life of the project in years

ii) ***Annualized replacement cost :*** The annualized replacement cost is calculated by:

$$ARC = CRC * \left[f_{rep} * SFF\left(i, L_{comp}\right) - \left(\frac{L_{rem}}{L_{comp}}\right) * SFF\left(i, L_{proj}\right) \right] \qquad \text{....(12)}$$

where CRC is capital recovery cost at the end of life of component in Rs., f_{rep} is replacement factor and is given by

$$f_{rep} = \frac{CRF\left(i, L_{proj}\right)}{CRF\left(i, L_{rep}\right)} \quad for \quad L_{rep} \succ 0 \qquad \text{....(13)}$$
$$= 0 \qquad for \quad L_{rep} = 0$$

where L_{rep} is replacement cost duration and is given by

$$L_{rep} = L_{comp} * INT\left(\frac{L_{proj}}{L_{comp}}\right) \quad ....(14)$$

where L_{comp} is life time of the individual components in years, Lrem is remaining life of component in years & SFF is sinking fund factor and is given by:

$$SFF(i, L_{proj}) = \frac{i}{(1+i)^{L_{proj}} - 1} \quad ....(15)$$

iii) Annual maintenance cost : Annual maintenance cost consists of operation and maintenance cost, man power cost & other running costs and is calculated by

$$AMC = MMC * 12 \quad \text{Rs.}/year \quad ....(16)$$

where MMC is monthly maintenance cost in Rs./month

iv) Annual fuel cost : Annual fuel cost is calculated by considering the total quantity of fuel used and cost per litre of fuel (i.e., diesel in this case)

$$AFC = \frac{Q * R}{100000} \quad \text{Rs.}/year \quad ....(17)$$

where Q is total quantity of fuel used during one year, litres/year & R is price of fuel in Rs./litre

v) Total annualized cost is given by:

$$TAC = ACC + ARC + AMC + AFC \quad \text{Rs.}/year \quad ....(18)$$

vi) Levelized cost of energy is calculated by

$$COE = \frac{TAC * 100000}{E_{RES} + E_{DG} + E_{BATT}} \text{Rs.}/kWh \quad ....(19)$$

where E_{RES} is energy supplied by renewable energy system to load, kWh/year, E_{DG} is energy supplied by DG set to load, kWh/year & E_{BATT} is energy supplied by Battery to load, kWh/year

The installed capital cost includes all planning, equipment purchase, construction and installation. Table 4 gives the capital cost of renewable energy systems. The capital cost for solar PV system is more compared to other systems.

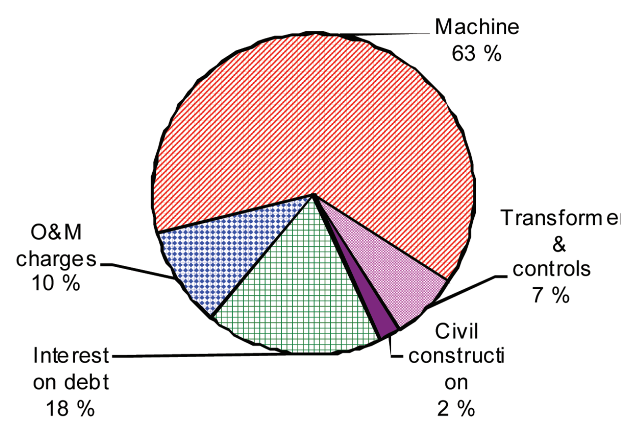

FIG. 8 COST COMPONENTS OF WIND ENERGY SYSTEM.

Figure 8 shows the cost components of a typical wind energy system. The installation cost accounts for 72 % of the total cost and the O & M cost is about 10 % [21].

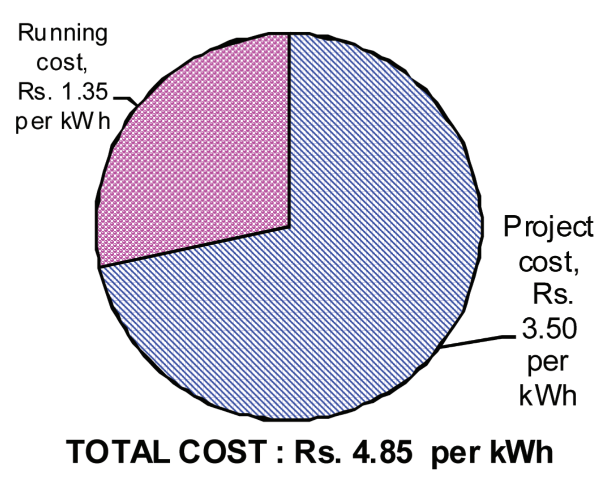

FIG. 9 LEVELIZED COST FOR WIND ENERGY GENERATION.

Figure 9 presents the levelized cost for wind energy system of a typical site. The project cost is Rs. 4.85 per kWh whereas the running expenses are Rs. 1.35 per kWh for wind generator of 225 kW machines.

4.0 CONCLUSIONS

The integration of individual system with conventional power i.e., DG set or storage battery works out to be costly. The availability and reliability indices are not encouraging. Therefore, integration of two or more energy systems with conventional power gives better economical aspects and also more availability & reliability indices. Different combinations of energy systems give different techno-economic feasibility, reliability & availability aspects.

TABLE 4

CAPITAL AND RUNNING COST OF RENEWABLE ENERGY SYSTEMS

Sl. No.	**Energy systems**	**Capital cost, (Rs. In lakhs/kW)**	**O&M (running) cost, (Rs./kWh)**
01	Wind Generators 5 kW to 1 MW (single units)	1.50 – 4.80	1.12 – 1.86
02	Solar Photo voltaic with inverter 20 W to 10 kW (single units)	2.85 – 5.50	0.20 – 1.15
03	Micro-hydel	0.48 – 0.60	0.20 – 1.50
04	Bio-gas	1.10 – 2.10	1.40 – 1.80

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