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Design of hybrid power plants for Indian conditions

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This paper presents the basic considerations for design of solar photovoltaic-wind-battery-grid connect hybrid power plants(HPPs). For ensuring the successful operation of hybrid power plants at low diesel input and low battery storage requirement, high level of reliability of power supply and reliability of component are essential. This paper provides factors involved in ensuring that high level of reliability of components and power availability is fulfilled in the hybrid plants. For both SPV and wind, the annual energy generation is divided into three regimes: summer, winter and rainy seasons and all these three have to fulfil the load requirement. It is seen that for 30% solar and 70 % wind generation curve is the smoothened with less variation.With improved day ahead predictability of both wind and solar the reliability can be improved considerably.

Keywords: *solar photovoltaic, wind power, hybrid power plant, renewable power, high reliability, load smoothening*

1.0 INTRODUCTION

Hybrid power packs are designed for firm, steady and mobile power. Traditionally, these consist of diesel/gas generation (DGs) with battery energy storage (BES) for back up and grid connection wherever feasible for increasing the life of the BES and minimizing DG operation. Some of the other combinations of hybrid power packs are:

- Solar photovoltaic (SPV) – battery-grid SPV-DG
- Wind electric generators (WEG)- DG
- SPV-wind-DG

These are small rated plants below 10 kW capacity and designed to provide steady electric power in islanded mode for grid tied systems and distributed micro grid mode for stand alone systems.

There is a large market segmentin India for hybrid power packs. The market is almost 8 lakh systems for communication and signaling sectors, 2 lakh systems for Department of posts and 10 lakh systems for micro rural power systems.

Larger plants with a much wider scope of operation are termed as Hybrid power plants (HPP). A present day HPP is a mix of two or more electrical power generating sources which includes a significant component of renewable energy in the power system and addresses limitations in terms of fuel flexibility, efficiency, reliability, emissions or economics.

HPPs are nearing 50 years in existence. Earliest HPPs (1970s) consisted of SPV or WEG paralleled to DGs to reduce the dependence on fossil resources. During that period the SPV and WEG being highly cost intensive were

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introduced in small capacities to augment DGs. BES (round trip efficiency: 80 %) were intended only for startups, stabilization and transient operations. The minimum capital cost of HPP was obviously 100 % DG. Capital cost on the basis of life cycle costing (LCC) indicated an optimum configuration with high WEG, low SPV, high DG and low battery.

The HPPs of the 1990s were designed to provide a steady power using high WEG, medium SPV and low DG (to minimize fuel dependence) ad high BES (one day storage) [2,3].

BES. The design goals are to minimize fossil sources (DG) and keep BES minimum only for system stabilization under transient/stabilization/startup conditions. Meanwhile SPV is becoming cheaper by the year and available with different options like crystalline, thin film, etc., to choose from. Grid tie is another new aspect of present day HPPs.

HPPs have some limitations on micro rooftop levels (3-5 kW) because of the unhindered location of WEGs. However, if there is a supplementary area for location of WEGs then they can be designed for rooftop configurations.

National Aeronautical Laboratory (NAL), has come out with a 500 kW SPV-WEG hybrid energy farm [1].

2.0 DESIGN OF HYBRID POWER PLANTS

Figure 1 gives a view of a general hybrid system. Presently, SPV and WEG are considered as infirm power, implying that their generation is not schedulable (day ahead schedule as in the case of DG and conventional thermal and hydro generation). For converting SPV and WEG into steady generation the battery requirements are too high and cost intensive (capital and operating cost). The strategy for power balance can be achieved at the DC bus or at the AC bus. In the AC bus the frequency represents the dynamic equilibrium ,whereas in the DC bus it is the bus voltage. Mere paralleling of two sources cannot be considered as a HPP. The HPP must act as one power source and not as two sources in parallel to the grid.

Energy balance is maintained at the DC level through the charging and discharging of the battery banks, but the dynamics of SPV and wind charging are much faster than the battery charge/discharge operations which can lead to overvoltage in the system.

Considerationsfor matchingof HPPs are :

- Reliability of power generation
- Minimizing fossil resource consumption (Restricted DG operation to 0-6 h/day).
- Daily pattern of power and energy generation
- Seasonal patterns of power and energy generation
- Capital cost of components
- Plant load factor (capacity factor) of individual components
- Power quality
- System integrability
- Grid connectivity- off grid (stand alone), grid tied or micro grid tied (weak grid).
- Ratio of day average power to peak power generation (kW_{av}/kW_p).

Some of the factors which determine the success of a HPP are:

- Site specific design
- Power system design (sizing, controls and communication)
- Equipment design, reliability: Earlier equipment design failure rates were as high as 65 %.
- Degradation of performance of SPV plants @ 1%/year is also a factor which affects the reliability [4].
- Equipment O & M reliability: System failure rates as high as 50 % are seen due to O & M issues (in both unmanned and manned systems).

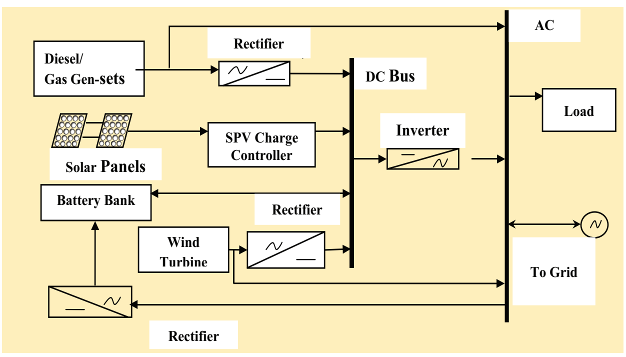

FIG. 1 VIEW OF A HYBRID POWER PLANT

Design goals set forth for present day HPPs are:

- Very high penetration of renewable components and minimum use of fossil resources.
- Minimization of BES component to negligible value.
- Power quality stabilization in all types of systems- off grid, grid tied and rural micro grids with weak grid tie.

Figure 2 shows the basic concept of an HPP wherein SPV and WEG ideally complement each other to give a steady power output to minimize energy storage of fossil fuel(DG)

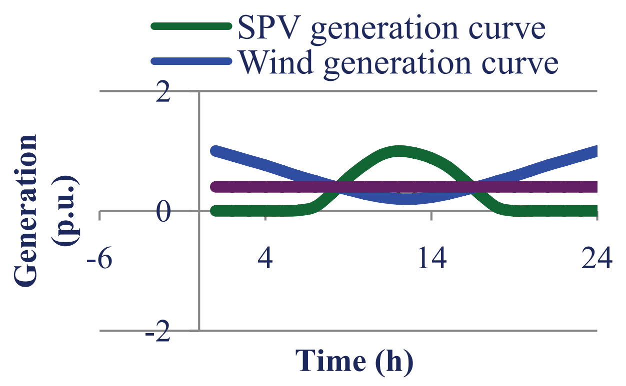

FIG. 2 BASIC CONCEPT OF EVENING OUT GENERATION BY SOLAR PV-WIND HYBRID

3.0 RESULTS

3.1 Component characteristics

3.1.1 Component characteristics-SP

The array to load ratio (A/L ratio) is the ratio of the peak capacity to the daily energy requirement (load).

$$\frac{A}{L} ratio = \frac{(kWp)_{gen}}{(kWh/day)_{load}} = \left(\frac{kWp}{kWh/day}\right) \quad ....(1)$$

Figure 3 gives the generation pattern along with an average load handled by the plant up to the technical maximum value. As the average load increases the probability of meeting the full load (on a continuous basis) decreases. For example, for a 1000 kW SPV plant, the probability of meeting a load of 100 kW is almost 100 % . As the average load increases the probability of meeting the load decreases.

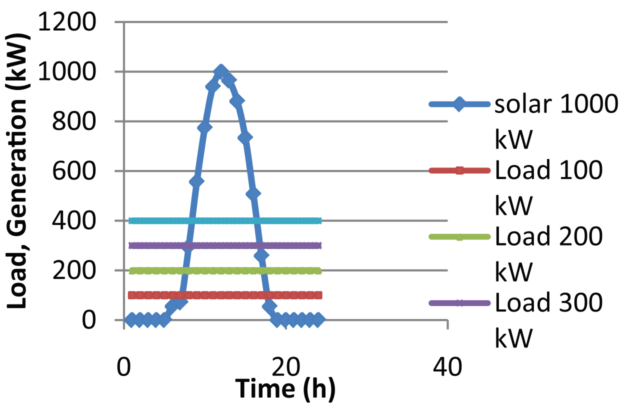

FIG. 3 GENERATION PATTERN AND AVERAGE LOAD HANDLED BY THE PLANT

Figure 4 gives the average load versus the A/L Ratio. It is seen from energy balance considerations for an average array to load ratio of 0.18 (5.56 kWh (per day) / kWp) the sustainability level of average load is 28-33 % of the peak load.

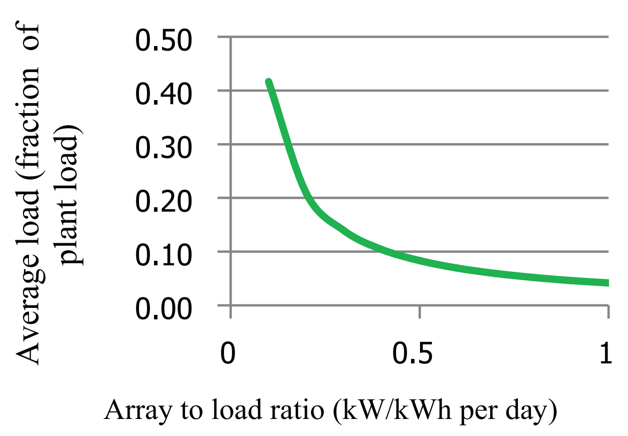

FIG. 4 AVERAGE LOAD VS. A/L RATIO

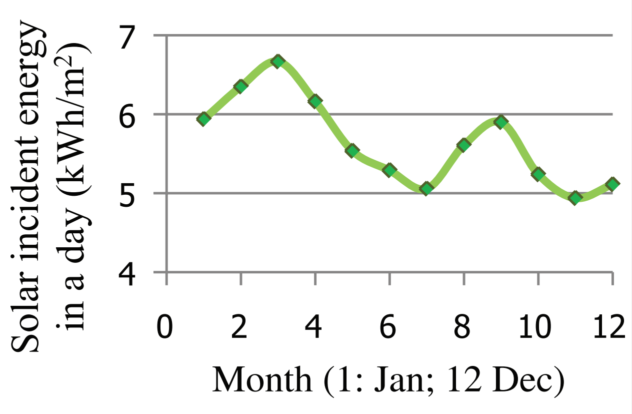

FIG. 5 ARIATION OF SOLAR INCIDENT ENERGY GENERATION IN A DAY OVER THE MONTHS

The index of SPV generation is given by,

$$SEP_{gen} = \frac{(kWh/m^2/day)_{rad}}{(kWp/m^2)_{rad}} \, x \left(\frac{\eta_{Module}}{\eta_{Module}}\right) x \, (\eta_{Non-module\ system}) \quad ....(2)$$

It can be seen from the Equation (2) since the module efficiencies can be taken as nearly load invariant (as a first order approximation), the SEP is a simple transformation of the energy generated in a day multiplied by the non-modular system efficiency.

Figure 5 gives the variation of solar incident energy generation in a day over the months.For the purpose of analysis, annual, monthly data can be divided into three seasons-summer,rainy and winter.The date in these three classes is more orderly and homogenous with less variation.

Figure 6 gives the specific energy production (SEP) per day for different plants in India.

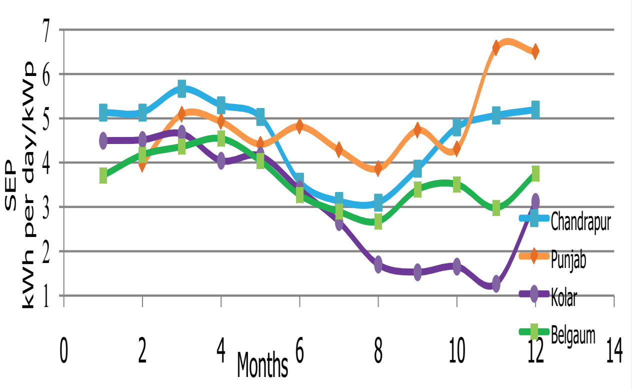

FIG. 6 SPECIFIC ENERGY PRODUCTION PER DAY FOR DIFFERENT TYPES OF PLANTS

3.1.2 Component characteristics-WEG

Classification of wind sites (IEC 61499-1) is given in Table 1.

TABLE 1

CLASSIFICATION OF WIND SITES

Sl. No.	WEG classification	Wind speed at hub height (m/s)
1	Class 1	10
2	Class 2	8.5
3	Class 3	7.5
4	Class 4	6.0

Wind energy production is characterized by,

$$\text{Wind power rating}$$

$$= \frac{\text{Wind power output } (kW)}{\text{Primary electrical load } (kW)} \quad ....(3)$$

$$SEP_{gen} = \left(\frac{kWh/day}{kWp}\right)_{gen} \quad ....(4)$$

Figure 7 gives the limits of SEP in a day for crystalline silicon and amorphous silicon thin film plants.

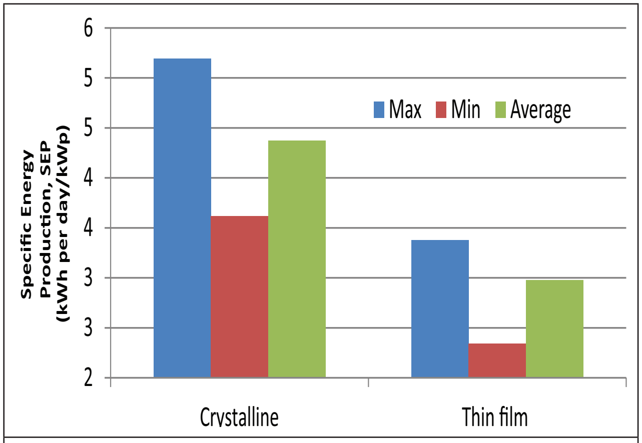

FIG. 7 LIMITS OF SPECIFIC ENERGY PRODUCTION IN A DAY

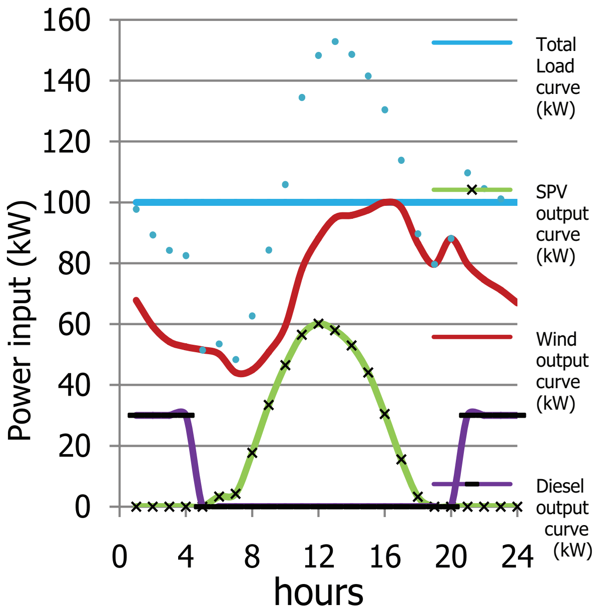

FIG. 8 COMPONENT GENERATION CURVES WITH CONSTANT LOAD CURVE

3.2 System characteristics

Figure 8 gives the HPP generation curve vis-à-vis the equivalent constant load curve.

To match a load of 100 kW the following generation components are considered:

- WEG: 100 kW_p
- DG: 30 kW_p
- Balance SPV: 60.1 kW_p

While DG and BES are not time dependent the WEG and SPV show daily time variation and seasonal time variation. For the purpose of design in Indian conditions three seasons (4 months each) are considered:

There is reasonable similarity in the energy patterns in these classes during the three seasons.

- Summer
- Rainy season
- Winter

3.2.1 HPP daily curves

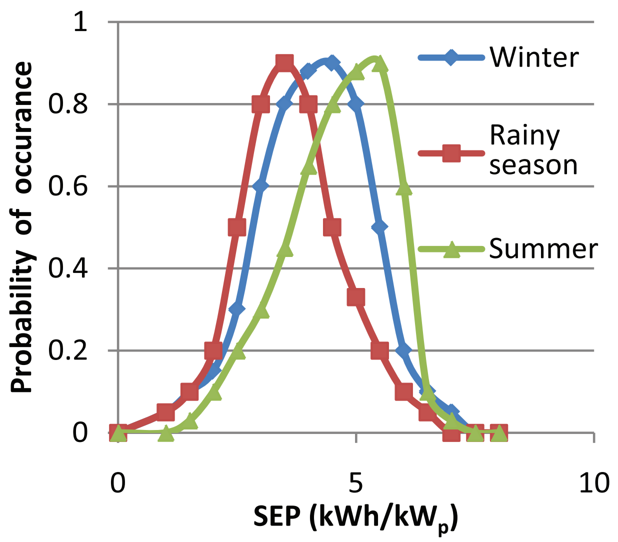

FIG. 9 SPECIFIC ENERGY PRODUCTION FOR THREE SEASONS

3.2.2 HPP monthly curves

Figure 10 gives the annual performance(generation) curve for individual components (SPV & WEG) and Figure 11 gives the monthly performance (generation curve for the HPP (renewable component only). Figure 12-14 gives the performance of HPP with various combinations of SPV and wind during rainy,winter and summer seasons and Figure 15 gives the performance for 30% solar and 70 wind HPP for all seasons.

TABLE 2

COST DATA OF COMPONENTS

Sl. No.	Power plant component	Capital cost (Rs. (Cr)/ MW)	Energy cost (Rs./ kWh)
1	Solar photovoltaic generation	7.0 - 8.5	7.0 - 10.0
2	Wind Electric Generation *(Wind Zone IV)	6.5 - 7.0	3.2 - 3.9*
3	Diesel Generation Plants	2.0 - 3.0	12 - 18
4	Gas Generation Plants	2.0 - 3.0	2.5 - 3.5
5	Battery Energy Systems *(Rs. (Cr)/MWh)	14.0- 30.0 0.6 - 1.5*	14.0 - 16.0
6	Inverter	0.6 - 0.8	0.15 - 0.20

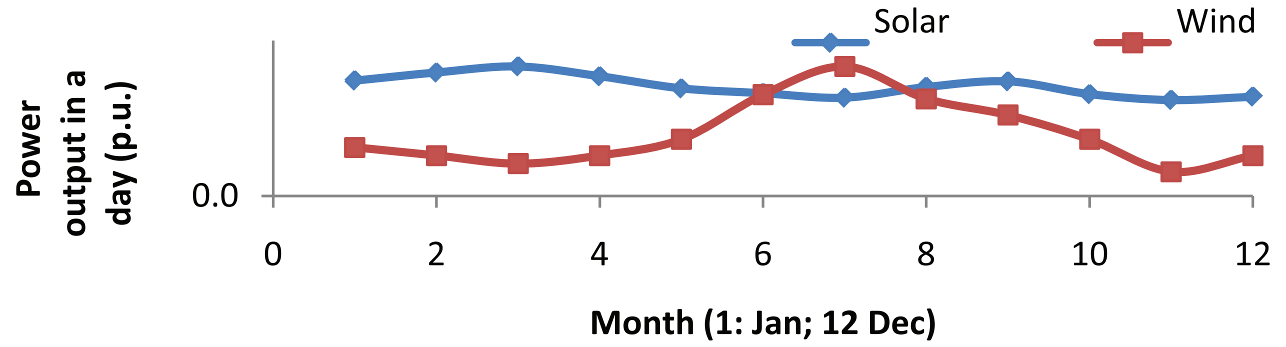

FIG. 10 ANNUAL PERFORMANCE (GENERATION) CURVE FOR INDIVIDUAL COMPONENTS

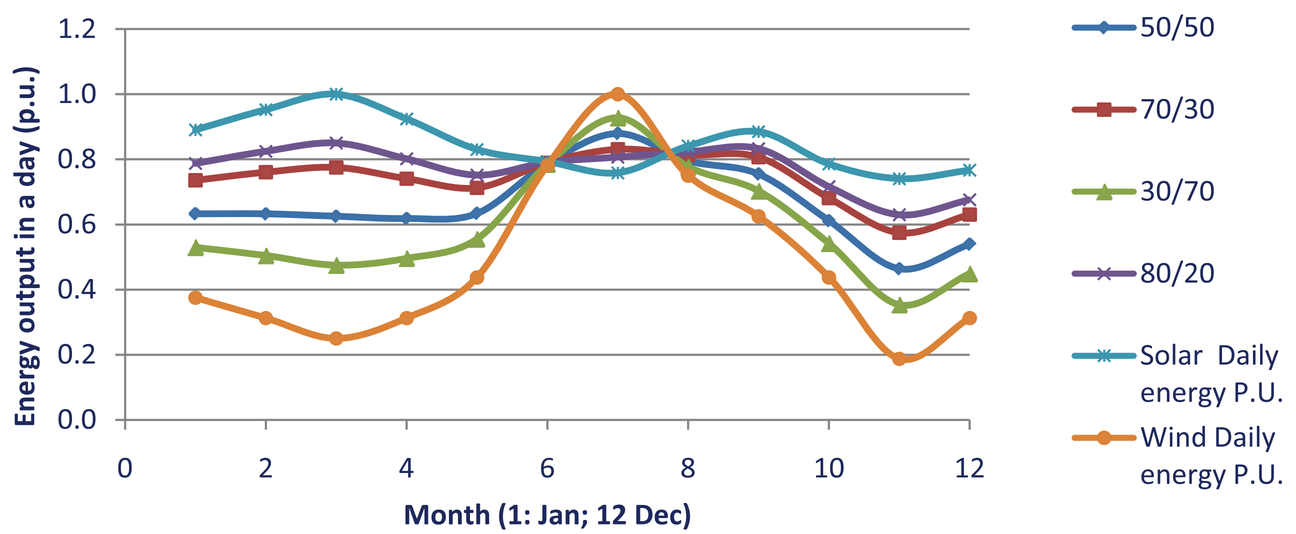

FIG. 11 MONTHWISE SPV WIND HYBRID PERFORMANCE

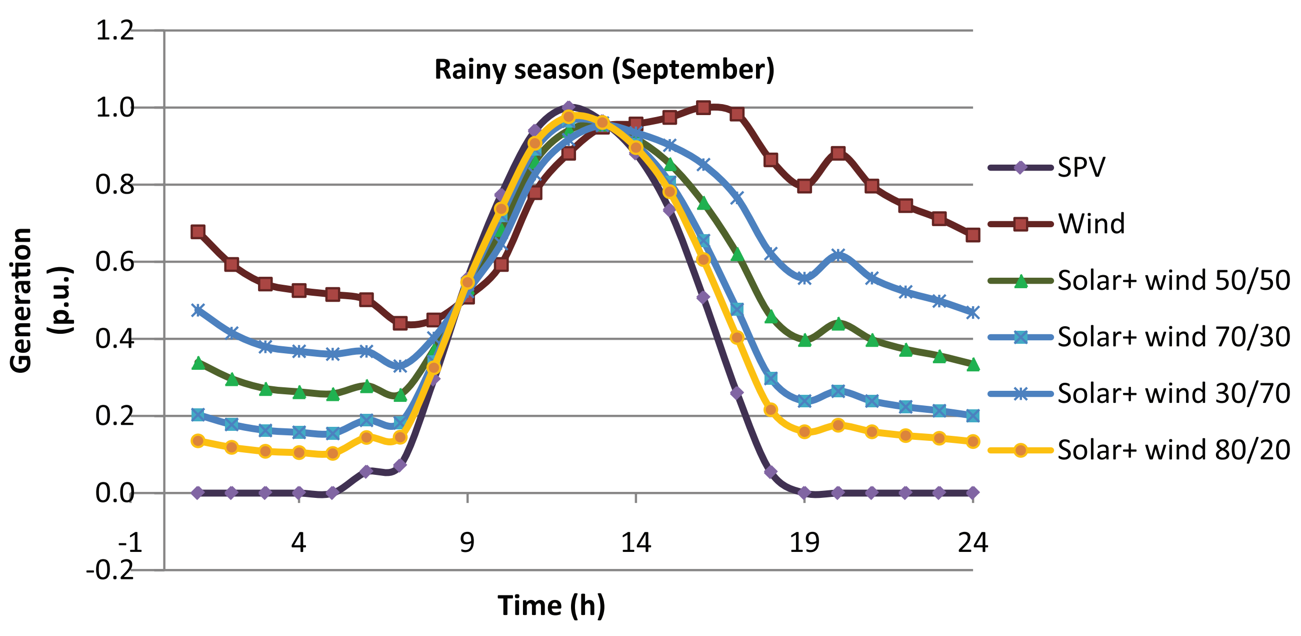

FIG. 12 PERFORMANCE OF HPP DURING RAINY SEASON

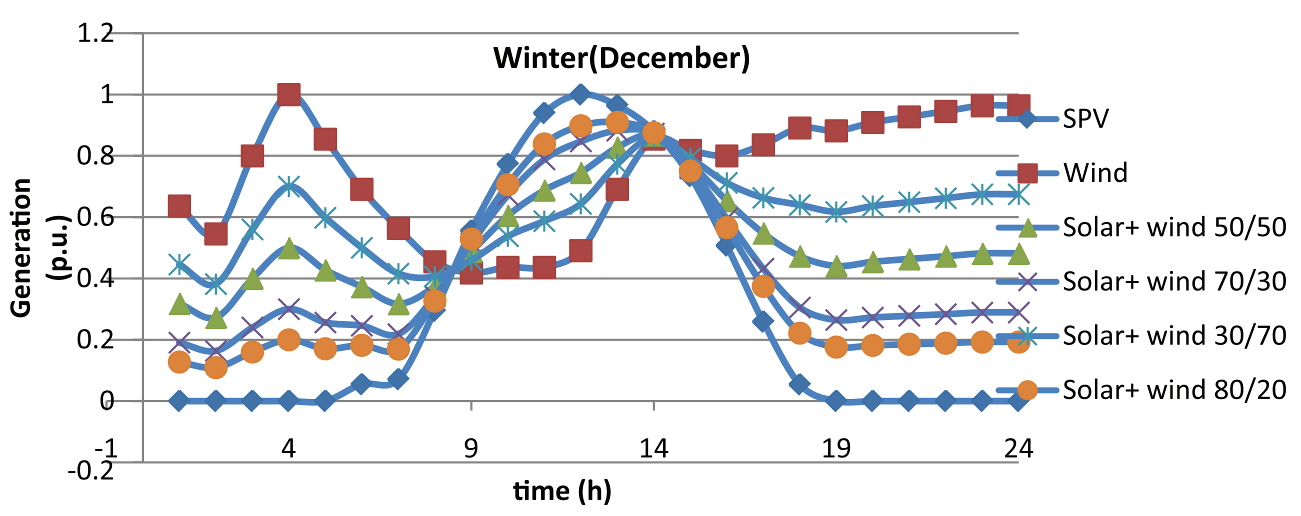

FIG. 13 PERFORMANCE OF HPP DURING WINTER SEASON

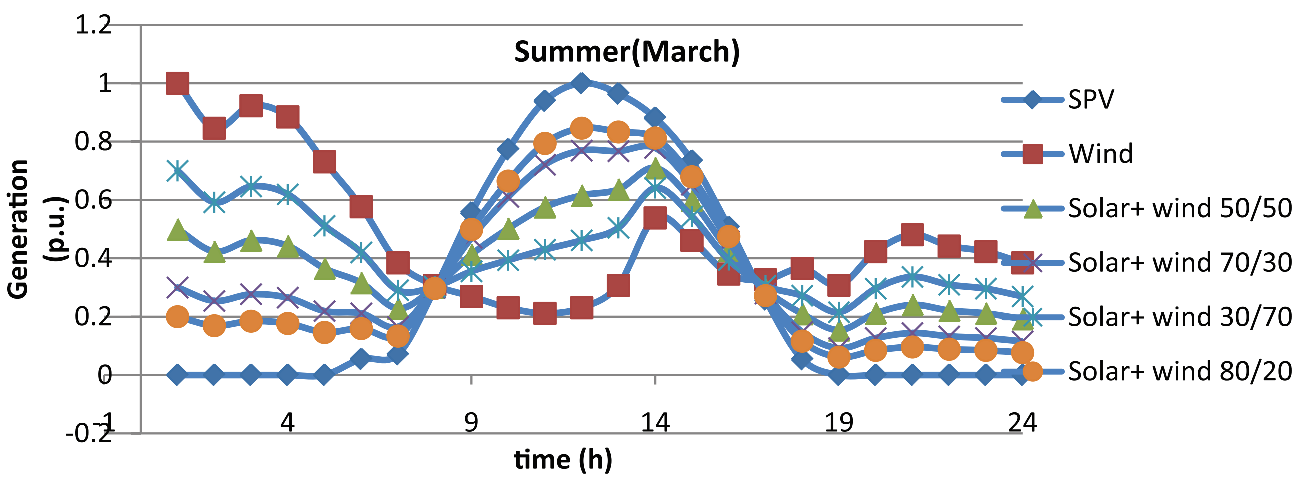

FIG. 14 PERFORMANCE OF HPP DURING SUMMER SEASON

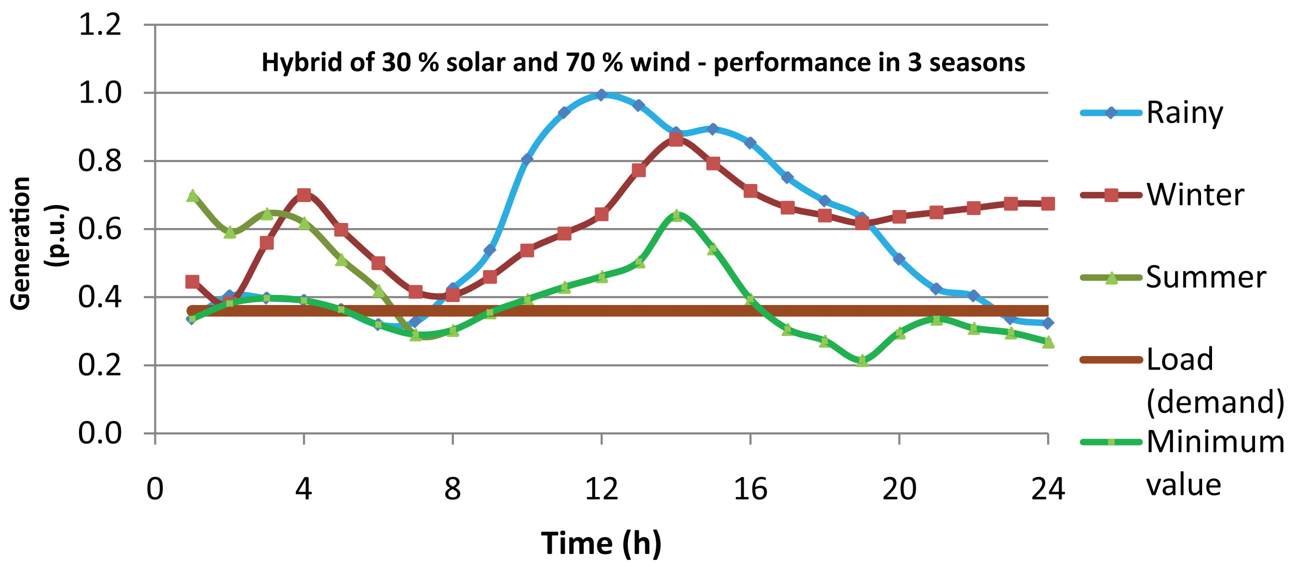

FIG. 15 PERFORMANCE FOR 30 % SOLAR AND 70 % WIND HPP FOR ALL SEASONS.

TABLE 3

RELIABILITY LEVEL OF COMPONENTS

Sl. No.	Parameter Units		SPV	WEG	DG	BES
01	Reliability of Power	%	80 - 90	80 - 90	90 - 95	96 - 98
02	Reliability of Equipment	%	80 - 90	40 - 50	80 - 85	94 - 96
03	Capacity Factor *(Max)	%	18 - 21	18 - 35	70 - 80	30
04	Maximum capacity factor	%	28	55	95	99

3.3 HPP cost and capacitycharacteristics

$$PLF(\sim CF) = \left(\frac{Energy\ generated}{Unit\ capacity\ x\ Time\ slot}\right) = \left(\frac{kWh/year}{kWp\ x\ 8760}\right) \qquad ....(5)$$

Table 2 gives cost data of the components and Table 3 gives the reliability level of components. Table 4 gives the curve fits of the relative sizing of HPP components as follows:

$$Y=A_0+A_1X \qquad ....(6)$$

The curve fits are based on actual field installed capacitiesof pure and hybrid plants. Fit No. 1-3 give the capacity of SPV, wind and DG individual plants (in pure mode – not as HPP) for consumer loads (upto 80 kW). Fit 4 gives the energy generated per day for different inverter capacities (up to 150 kW). Fit. 5 gives the sizing of batteries (kWh) for storages upto 1200 kWh/ day in HPPs. Fits 6-1 and 6-2 gives the breakup of SPV- wind HPPs and Fits 6-1 and 6-3 give the breakup of SPV-DG generation in a HPP. Table 4.

TABLE 4

RELATIVE SIZING OF HPP COMPONENTS

Sl.No.	Particulars	Units	A_0	A_1
	X : Load (0-80 kW)	kW		
1	Y : SPV Installed Capacity in pure mode (not HPP)	kWp	10.904	0.6429
2	Y : WEG Installed Capacity in pure mode (not HPP)	kW	19.549	3.6263
3	Y : DG Installed Capacity in pure mode (not HPP)	kVA	50.652	1.396
	X : Inverter Capacity (0-150 kW)	kW	0.715	33.073
4	Y : SPV Capacity in pure mode (not HPP)	kWp	8.1351	0.2948
	X : Energy handled per day (0-1200 kWh/ day)	kWh/day	22.024	13.15
5	Y : Battery Capacity for HPPs	kWh	321.1	0.1809
	X : Total Load Capacity (0-600 kW)	kW		
6-1	Y : SPV Capacity for SPV-wind or SPV-DG HPP	%	33.241	-0.042
6-2	Y : WEG Capacity for SPV-wind HPP	%	60.81	-0.0195
6-3	Y : DG Capacity for SPV-DG HPP	%	59.822	0.0294

3.4 Design considerations

The main considerations for the design of HPPs are:

- High penetration of renewable components
- Minimization of DG and BES to nearly nil
- High reliability of power availability

TABLE 5

PREDICTION ACCURACY OF SPV

Sl. No.	Period of forecast (ahead) (h)	Accuracy level (%)
1	1	96 - 97
2	4	86 - 95
3	24	81 - 93

High level of control software components are essential for energy balance, prediction of energy generation and optimization of the performance to meet the design goals. While zeroth order calculations are adequate for feasibility, first order calculations are required in design and 2nd order calculations are required in performance prediction for load balance.

The day ahead prediction and intra day prediction of SPV and wind is essential for scheduling of renewable resources in 144 time slots/day (10 min. each). Solar incident radiation (accuracy: 3 %, time constant 10 s) forecasts can be used to predict the power generation from a plant.

Other SPV prediction methods are:

- Satellite based (cloud movement and detection)
- Numerical weather prediction (NWP)
- WRF (weather research and forecast) model

The prediction accuracy of SPV is given in Table 5. The basis for accuracy assessment is:

- RSME (root mean square error)
- MEA (Mean absolute error)
- MBE (mean bias error)

TABLE 6

ACCURACY LEVEL OF WIND FORECASTS

Sl. No.	Seasons in an year	Period of prediction (ahead) (h)	Day ahead accuracy (%)	Intra-day accuracy (%)
01	Summer	24	94 - 95	95 - 96
02	Winter	24	92 - 95	93 – 96
03	Rainy	24	85 – 90	90 – 92

Wind power is assessed through:

- Physics based models
- Statistical based models
- Plant output based models

Table 6 gives the accuracy levels for forecasts for wind. Normally for day ahead forecasts for scheduling, 4 forecasts of 6 h/day are undertaken. Wind speed error is independent of wind speed magnitude.Besides extreme gust data and overload data for site is required to improve the reliability of equipment and lower life. Load modeling is also required to balance the generation to the load.

4.0 CONCLUSIONS

The main conclusions of the study are:

- For ensuring high reliability of power supply over the designated life of 25 years of 2 lakh operating hours,the year is divided into three seasons of rainy season, summer and winter and the energy cum power patterns are designed to meet the requirements in these three seasons.
- The mix of solar photovoltaic/wind is site specific and can vary from 70/30 to 30/70. Earlier high cost of SPV was a consideration. Now this has been evened out.
- Average load under all restrictive conditions of 40 % of the system capacity can be ensured which means that the equipment must be over sized to fulfill the power and energy and power requirement under all circumstances.

- Battery energy storage and diesel sets can be minimized to only operational safety requirements such as transient operations, start ups, low load support or stabilization.
- Day ahead prediction is an essential software component for optimization of performance of HPPs to meet the design requirements.

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