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HYBRID (SOLAR AND WIND) ENERGY SYSTEMS FOR RURAL ELECTRIFICATION

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ABSTRACT

Hybrid power system can be used to reduce energy storage requirements. The influence of the Deficiency of Power Supply Probability (DPSP), Relative Excess Power Generated (REPG), Energy to Load Ratio (ELR), fraction of PV and wind energy, and coverage of PV and wind energy against the system size and performance were analyzed. The technical feasibility of PV-wind hybrid system in given range of load demand was evaluated. The methodology of Life Cycle Cost (LCC) for economic evaluation of stand-alone photovoltaic system, stand-alone wind system and PV-wind hybrid system have been developed and simulated using the model. The comparative cost analysis of grid line extension energy source with PV-wind hybrid system was studied in detail. The optimum combination of solar PV-wind hybrid system lies between 0.70 and 0.75 of solar energy to load ratio and the corresponding LCC is minimum.

The PV-wind hybrid system returns the lowest unit cost values to maintain the same level of DPSP as compared to standalone solar and wind systems. For all load demands the levelised energy cost for PV-wind hybrid system is always lower than that of standalone solar PV or wind system. The PV-wind hybrid option is techno-economically viable for rural electrification.

Keywords: model, solar, wind, hybrid, energy, rural electrification.

1. INTRODUCTION

Energy is vital for the progress of a nation and it has to be conserved in a most efficient manner. Not only the technologies should be developed to produce energy in a most environment-friendly manner from all varieties of fuels but also enough importance should be given to conserve the energy resources in the most efficient way. Energy is the ultimate factor responsible for both industrial and agricultural development. The use of renewable energy technology to meet the energy demands has been steadily increasing for the past few years, however, the important drawbacks associated with renewable energy systems are their inability to guarantee reliability and their lean nature. Import of petroleum products constitutes a major drain on our foreign exchange reserve. Renewable energy sources are considered to be the better option to meet these challenges.

More than 200 million people, live in rural areas without access to grid-connected power [4]. In India, over 80,000 villages remain to be un-electrified and particularly in the state of Tamil Nadu, about 400 villages (with 63% tribes) are difficult to supply electricity due to inherent problems of location and economy. The costs to install and service the distribution lines are considerably high for remote areas. Also there will be a substantial increase in transmission line losses in addition to poor power supply reliability. Like several other developing countries, India is characterized by severe energy deficit. In most of the remote and non-electrified sites, extension of utility grid lines experiences a number of problems such as high capital investment, high lead time, low load factor, poor voltage regulation and frequent power supply interruptions. There is a growing interest in harnessing renewable energy sources since they are naturally available, pollution free and inexhaustible. It is this segment that needs special attention and hence concentrated efforts are continually provided in implementing standalone PV, wind, bio-diesel generator and integrated systems at sites that have a large potential of either solar, wind or both. Traditionally, electrical energy for remote villages has been derived from diesel generators characterized by high reliability, high running costs, moderate efficiency and high maintenance. Hence, a convenient, cost-effective and reliable power supply is an essential factor in the development of any rural area. It is a critical factor in the development of the agro industry and commercial operations, which are projected to be the core of that area's economy.

At present, standalone solar photovoltaic and wind systems have been promoted around the globe on a comparatively larger scale [7]. These independent systems cannot provide continuous source of energy, as they are seasonal. For example, standalone solar photovoltaic energy system cannot provide reliable power during non-sunny days. The standalone wind system cannot satisfy constant load demands due to significant fluctuations in the magnitude of wind speeds from hour to hour throughout the year. Therefore, energy storage systems will be required for each of these systems in order to satisfy the power demands. Usually storage system is expensive and the size has to be reduced to a minimum possible for the renewable energy system to be cost effective. Hybrid power systems can be used to reduce energy storage requirements.

2. OPTIMIZATION OF HYBRID SYSTEMS

Different types of hybrid systems and modeling [3] procedures, performance studies of hybrid systems,

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operating strategies, economic analysis and case studies are discussed in details. The technical terms of interest are:

Deficiency of power supply probability

The Deficiency of Power Supply Probability (DPSP) is defined as the sum of the deficit in power generated by hybrid system with respect to the total annual load.

Relative excess power generated

The Relative Excess Power Generated (REPG) for the hybrid system is defined as a ratio of the total annual excess power generated by the hybrid system in a year to that of the total annual load.

Energy to load ratio

Energy to Load Ratio (ELR) is used for designing the system and analyzing performance of the hybrid system. It is the ratio of energy produced by the renewable components to energy demand.

Life cycle cost

Life Cycle Cost (LCC) of a hybrid system consists of initial capital investment, the present value of operation and maintenance cost and the battery replacement cost. Life cycle cost analysis is a tool used to compare the ultimate delivered costs of technologies with different cost structures.

Levelised energy costs

The Levelised Energy Costs (LEC) is defined as the ratio of the product of LCC with capacity rate factor (CRF) to the energy generated per year.

Life cycle unit cost

Life Cycle Unit Cost (LUC) is defined as the ratio of life cycle unit cost to the total power generated for a given period of time.

3. DESIGN AND OPTIMIZATION METHODOLOGY

In a PV-wind hybrid system with battery autonomy, the optimization[5] of the size of the individual systems can be made in a variety of ways, depending upon the choice of parameters of interest. Unlike the LPSP [2] and graphical construction methods[8] the algorithm developed in the present work, employs an iterative technique to determine the optimum size of solar panels, wind machines and capacity of batteries of a hybrid system based on Levelised Energy Cost (LEC), Life Cycle Unit Cost (LUC), Life Cycle Cost (LCC), Deficiency of Power Supply Probability (DPSP) and Relative Excess Power Generation (REPG). The structure of the model developed consists of a database that serves as a backhand tool during the computation and in the front end, calculations on size of the wind, solar and battery systems are carried out following an iterative scheme based on the respective average daily data on energy generated. Initially, the size of wind machines required to meet the average daily demand is calculated on a daily basis throughout a year from which the maximum and minimum size of the wind machines required is determined. Then, a loop is operated between the maximum size of the wind machine type chosen and the calculated minimum size of the wind machine. For each size of the wind machine, the size of solar panel is determined for the difference in load (E_L-E_w) on a daily average basis, from which the maximum and minimum size of the PV panel required are found. Then an inner loop for each size of the wind machine is operated between the minimum and maximum size of the chosen solar type. Next, the size of the battery system is calculated for the deficit in energy generated by both the wind and PV system on a daily basis throughout the year. Thus for each size of the wind and solar PV system combination, the maximum and minimum size of the battery are calculated. Innermost loop for every assigned size of the wind and PV system is then operated between the minimum and maximum size of the chosen battery model. The inner most loop is executed completely first, the second loop next and finally the outer loop. The quantities of interest are then evaluated from the results obtained for the set of combinations of wind/PV/battery system. The optimal size of wind/PV/battery system of a specific type can then be obtained from the final output with respect to DPSP, based on LCC or LUC or LEC and REPG.

It can be understood that the optimization of hybrid systems are carried out in order to minimize the deficiency as well as the excess power generated thereby reducing the cost of the system. However matching the load requirements for a most probable period throughout the year is difficult in most of the cases. Therefore in the present analysis, battery banks are designed/optimized taking into account the deficiency in power generated throughout the year, during the combined operation of wind and PV system.

4. ECONOMIC ANALYSIS

It is pertinent that economic justification should be made while attempting to optimize the size of integrated power generation systems favouring an affordable unit price of power produced. The economic analysis[7] of the hybrid system has been made and the cost aspects have also been taken into account for optimization of the size of the systems. Using the model developed various costs namely, LEC, LUC and LCC have been computed considering the life period and replacement costs of the individual systems. Life cycle cost analysis is a tool used to compare the ultimate delivered cost of technologies with different cost structures the pay back analysis method for PV wind hybrid system depends on the various parameters such as investment, replacement cost, annual operation and maintenance cost, income etc. Table-1 shows the cost values of the economic parameters and components for the base case.

5. RESULTS AND DISCUSSIONS

5.1. Comparison of model

The model output data is compared with the real time output data, which is obtained for a hybrid plant installed at Chunnambar, Pondicherry. Chunnambar Island is located about 3km from the nearest motorable road (Pondicherry-Cuddalore road). The latitude is 11.46^o N and longitude 70.46^o E. The location is on the beach and receives good sunshine that is complemented by local wind. Mean annual wind speeds are relatively low in Chunnambar Island and the annual average wind speed is about 4.55 m/s at 25m height. Solar radiant flux is abundant at the location. The mean daily insolation is in the range of 4.8-6.9 kWh/m^2. The daily energy requirement at the site is 12.11 kWh/day and the annual energy consumption is 4320 kWh. The plant is installed with wind machine 3.3 kW and capacity of solar panel 1.8 $kW_{p.}$

From Table-2 it is observed that the output from the model for a 3.3 kW wind energy system is 3569 kWh whereas the real output from the site was only 3347 kWh per year. The variation is estimated to be 6.22%. Similarly for a 1.8 kW_p solar photovoltaic generation system, the predicted power generation was found to be 3094 kWh against the real value, 2872 kWh. The estimated variation is 7.18%. The percentage variation of total energy generation between the model output and the real value is found to be 6.66%.

5.2. Case study

For a given location, the choice of various combinations of the sizes of wind machines, solar PV array and battery is made from the results obtained from the computations. The optimal selection of a suitable combination of solar, wind and battery capacities for a specific type can be made based on the calculated values of the quantities such as DPSP, REPG, LCC, LEC and LUC. For a given DPSP, an optimal combination of the system is obtained based on the minimum LCC or LEC or minimum REPG.

A case study is attempted at a place called Poompuhar (11^o 8'N, 79^{o}51'E), located in Tamil Nadu, India. The choice of the site has been made based on the fact that the wind and solar power throughout the year is adequate for setting up a hybrid power generation. The mean daily insolation was found to be 5.63 kWh/m^2 and the annual average wind speed was about 4.8m/sec at 25 m height. The daily energy requirement at the site is 450 kWh/day. The model developed is used for design, analysis and optimizing a hybrid system for this location considering various parameters of the location.

In the developed model of PV-wind hybrid system the specific data related to the location Poompuhar (11^o 8'N, 79^{o}51'E) are given as inputs by considering the parameter DPSP of 0.20, the wind velocity 4.8m/sec at 25m height, solar insolation 5.63 kWh/m^2, environment temperature of 32°C for a load of 450 kWh/day. Wind system parameters like cut-in-speed of 3m/sec, cut-off-speed of 25m/sec, rated speed of 12m/s, rotor diameter of 25m, hub height of 40m, PV parameters like peak module power of 52 W_p. It computes the output parameters like PV capacity, array configuration, number of modules, tilt angle, battery capacity, wind machine capacity, Life cycle cost and pay back period. The computed output parameters are PV capacity of 57 kW_p and 110 modules; 3 days of autonomy tubular stationary batteries, tilt angle 15° and 50 kW wind system. This generates an annual output of 1189159kWh from solar PV system and 43998kWh from wind system with a life cycle cost of Rs.445 lakhs with a pay back period of 11.8 years. The variation of deficiency of power supply probability with respect to solar PV system capacity is shown in Figure-1. It is seen that 50 kW wind machine with 18 kW_p solar PV capacity has 0.5 DPSP. By increasing the solar PV system capacity to 78 kW_p the DPSP is reduced to 0.01 and hence the reliability is increased to 99%. Similarly, a two 50 kW wind machine with 18 kW_p solar PV system capacity has 0.35 DPSP whereas two 50 kW wind system with 60 kW_p PV system capacity has 0.01 DPSP. From the Figure-1, it was found that 50 kW wind system with 78 kW_p PV system capacity may satisfy the load requirement for most of the time during the year. Increasing the solar PV system capacity of above 82 kW_p with 50 kW wind system does not improve the reliability of the system.

Figure-2 indicates the variation of levelised energy cost with respect to solar PV system capacity for variable wind system capacity. It is observed from the Figure-2 that for a 50 kW wind machine with 3 days of battery autonomy that the levelised energy cost decreases with increase in solar PV capacity. For the system with a 50 kW wind machine and 43 kW_p PV module, the levelised energy cost is as high as Rs.80.00 per kWh whereas by installing two 50 kW wind machines with 43 kW_p PV system capacity, the levelised energy cost is Rs.72.00 per kWh. Increasing the capacity of wind machine can decrease the levelised energy cost. It is also examined from the above Figure 2 that at larger solar PV capacity, the variation of levelised energy cost is small. At lower capacity of solar PV the levelised energy cost is high.

Figure-3 shows the variation of DPSP with respect to life cycle cost for standalone photovoltaic, wind and hybrid system. The life cycle cost decreases with increase in DPSP for standalone and hybrid systems. For a considered DPSP of 0.2, the life cycle cost of hybrid system is Rs.550 lakhs and for a solar system it is Rs.675 lakhs whereas for wind system it is Rs.750 lakhs. For the same system life cycle cost, the hybrid system ensures the lowest DPSP values and proves most optimal in terms of performance cost relationship. It is also observed from the Figure 3 that achieving a further small decrease in DPSP in the lower levels there is a sharp increase in the life cycle cost for the hybrid and standalone photovoltaic systems.

Figure-4 shows the variation of system capacity with respect to energy to load ratio of solar or wind for a given DPSP of 0.1 at Poompuhar. The energy to load ratio of solar PV increases from 0 to 1 indicated left to right in the Figure-4, whereas for wind it decreases from 1 to 0 indicated from right to left in the Figure-4. For example, 0.46 solar or wind refers to 46% solar PV and 54% wind energy generated with respect to load. It is seen from the Figure-4 that the energy to load ratio of solar PV or wind increases with increase in capacity of solar PV system or decrease in wind system capacity. The capacity of the wind and solar system required can be found from the Figure-4 for a given energy to load ratio. This combination obtained may or may not result in the optimum hybrid system. It is observed from the Figure-4 that when the energy to load ratio of solar PV or wind is at 0.72, the system capacity of solar PV and wind system is 50 kW each. It was concluded from the Figure-4 for a given annual average daily load demand for 450 kWh for the location under consideration the optimum combination of solar PV wind hybrid system can be obtained at solar energy to load ratio of 0.72 at 0.1 DPSP. This is a unique value for this selected location.

The life cycle cost of the hybrid system with respect to energy to load ratio of solar or wind for a given DPSP is shown in Figure-5. It implies that the life cycle cost of the hybrid system depends largely on the energy to load ratio. The LCC decreases gradually with increase in energy to load ratio of solar or wind upto a certain value and then it increases sharply. This is mainly due to the large storage capacity of battery required when the hybrid system has major contribution from the solar system. It is noted from the Figure-5 that a minimum cost of energy to load ratio of solar occurs at a value of 0.72 for 450 kWh/day. The Figure-5 also represents the minimum cost of each combination of the considered solar PV wind hybrid system and indicates a minimum life cycle cost of Rs.688 lakhs at 0.72 of energy to load ratio. The comparative cost of grid line extension energy source with PV wind hybrid system is a vital parameter to decide the viability of installing a PV wind hybrid system. The break-even point for a grid extension varies with the load demand. Figure-6 indicates the variation of life cycle cost of PV wind hybrid system and grid extension systems with respect to energy demand for variable PV life cycle cost. It is evident from the study that, to meet out the daily energy demand of 75 kWh a fixed life cycle cost of Rs.150 lakhs is required for a grid line extension of 50 km for 11 kV line.This LCC does not vary even when the load demand is less than 75 kWh/day for the same grid line extension. But in the autonomous PV-wind hybrid system LCC is Rs.150 lakhs for a daily energy demand of 75 kWh, and for a load less than 75 kWh the LCC proportionately reduces. Similarly, a fixed LCC of Rs.250 lakhs is required to meet out the load demand of 150 kWh per day or less than that for a grid line extension of 100 km. As in the earlier case here again for PV-wind hybrid system life cycle cost required for a load demand of 150 kWh per day is Rs.250 lakhs and for load less than 150 kWh, the LCC proportionately reduces. The drop in the slope refers to the reduction of cost from Rs.160.00 to Rs.100.00 of PV module per peak watt as indicated in the Figure-6. The amount of drop in the slope meets out an additional energy demand, which makes the PV wind system economically viable.

It is obvious from the Figure-6 that when the cost of PV module decreases then the viability range of load demand for PV wind hybrid system increases from 75 kWh to 125 kWh per day for grid extension distance of 50km. In comparison with the grid extension, it is concluded that the PV wind hybrid has more economical viability when the grid extension distance is longer than 50 km and load demand is lower than 75 kWh/day.

6. CONCLUSIONS

In the present scenario standalone solar photovoltaic and wind systems have been promoted around the globe on a comparatively larger scale. These independent systems cannot provide continuous source of energy, as they are seasonal. The solar and wind energies are complement in nature. By integrating and optimizing the solar photovoltaic and wind systems, the reliability of the systems can be improved and the unit cost of power can be minimized.

A PV wind hybrid systems is designed for rural electrification for the required load at specified Deficiency of Power Supply Probability (DPSP). A new methodology has been developed to determine the size of the PV wind hybrid system using site parameters, types of wind systems, types of solar photovoltaic system, number of days of autonomy of battery and life period of the system.

A primary model was developed to optimize PV-wind hybrid system for any specific location, by considering the parameters DPSP and REPG. The developed model processes the input parameters pertaining to the wind velocity, solar insolation, environment temperature, load distribution, wind and PV system parameters like cut-in-speed, cut-off-speed, rated speed, rotor diameter, hub height, peak module power, capacity of the PV panel and wind systems. It computes the output parameters like PV capacity, array configuration, number of modules, tilt angle, inverter capacity, battery capacity, charge controller capacity and wind machine capacity. The optimal size of the hybrid system is determined based on the calculated values of REPG for a specified DPSP. Thus the model suggests the optimum combination of the capacity of wind, PV and battery units of a chosen type that can generate power with a minimum REPG by implementation of iterative technique.

A secondary model developed for optimizing techno economic aspects like LCC, LEC or LUC considering the parameters like life period of solar system, wind system, battery discount rate, escalation rate, cost of the module, wind machine, battery, inverter BOS components and CO_2 mitigation cost for solar photovoltaic wind hybrid system.

In the developed model of PV-wind hybrid system the specific data related to the location Ottapidaram (8°54'N, 78°1'E) are given as inputs by considering the parameter DPSP of 0.15, the wind velocity 5.1m/sec, solar insolation 5.89 kWh/m^2, environment temperature of 32°C for a load of 72 kWh/day. Wind system parameters like cut-in-speed of 3m/sec, cut-off-speed of 20m/sec, rated speed of 12m/s, rotor diameter of 20m, hub height of 30m, PV parameters like peak module power of 52W. The computed output parameters are PV capacity of 0.5 kW_p with 3 days of battery autonomy and wind machine capacity 10 kW for a REPG of 0.07. Thus the model suggests the optimum combination of the capacity of wind 10 kW and PV capacity of 0.5 kW_p with 3 days of battery autonomy can satisfy the load requirement for a given DPSP of 0.15 with a minimum REPG of 0.07 for a minimum LUC of Rs.26.93.

The comparative cost of grid line extension energy source with PV wind hybrid system is a vital parameter to decide the viability of installing a PV wind hybrid system. It is evident from the study that, to meet out the daily energy demand of 75 kWh a fixed life cycle cost of Rs.150 lakhs is required for a grid line extension of 50 km. This LCC does not vary even when the load demand is less than 75 kWh/day for the same grid line extension. But in the autonomous PV-wind hybrid system LCC is Rs.150 lakhs for a daily energy demand of 75 kWh, and for a load less than 75 kWh, the LCC proportionately reduces. In comparison with the grid extension, it is concluded that for a load less than 75 kWh per day and when the grid line is 50 km away from the load point then the PV wind hybrid is economical. Also that when the grid extension distance is longer than 50 km and load demand is lower than 75 kWh/day the autonomous PV wind hybrid system is economically viable.

The model output data is compared with the real time output data, which is obtained for a hybrid plant installed at Chunnambar, Pondicherry (11.46^o N, 79.46^{o}E). The estimated value of energy generated by the model of solar system and wind system deviates by 6.22% and 7.18% respectively with the real time values. In the case of PV-wind hybrid system the deviation is found to be 6.66%. From the studies for a given energy to load ratio the capacity of the solar wind hybrid system is found for a given load demand. The study reveals that at vicinity of 0.74 solar or wind energy to load ratio the PV-wind hybrid system capacity converges to be optimum and also the life cycle cost is minimum. In the case of Ottapidaram the optimum combination is achieved with 7.8 kW_p solar PV capacity and 8 kW of wind system for a annual average daily load demand of 72 kWh at DPSP of 0.02 and solar or wind energy to load ratio of 0.74. Also it is noted that this point corresponds to minimum life cycle cost of Rs.130 lakhs.

After implementing the model in the case studies, a thorough analysis is made and the results are obtained which highlights the following important conclusions:

i) An optimum hybrid system ensures minimum REPG for a given DPSP for a specific location. The optimum combination of solar PV wind hybrid system lies between 0.70 and 0.75 of solar or wind energy to load ratio and the corresponding LCC is minimum;
ii) Life cycle unit cost of power generation from hybrid system is less compared with standalone solar and wind systems. It lies between Rs.20.00 and Rs.30.00 per kWh;
iii) Load demand is less than 75 kWh per day and when the grid line of 11 kVA is 50 km away from the load point, then the PV wind hybrid is economical for the PV module cost of Rs.200 per Wp;
iv) When the module efficiency is increased from 10 to 20% then LUC is reduced by 25% for given module cost of Rs.200 per Wp;
v) If insolation is increased by 65% the LEC decreases by 27%; and
vi) Variation in LUC is meager after a life period of 20 years.

The PV wind hybrid option is techno-economically viable for rural electrifications when the PV module cost is below Rs.100 per W_p and the efficiency of PV module is higher than 20%. The scope of implementing these systems in suburbs will be possible in near future.

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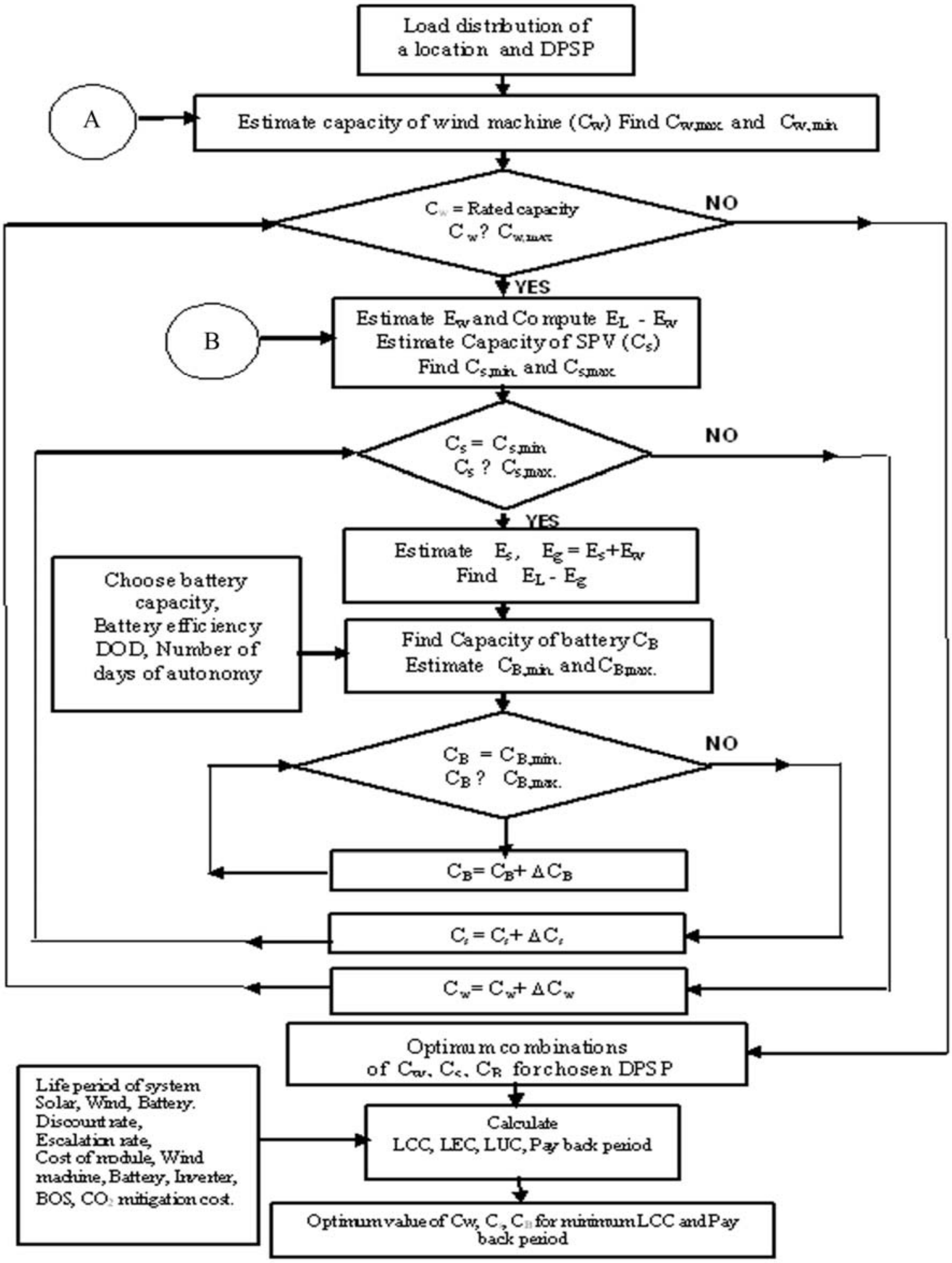

Figure 1 Flow chart for optimization methodology to PV-wind hybrid system

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Table-1. Cost values of the economic parameters and components for the base case.

S. No.	Parameters	Cost
1.	Silicon type PV module cost	Rs.150-200 /Wp
2.	Lead acid battery cost	Rs.4000 /kWh
3.	Cost of battery charge controller	Rs.350 /kWh
4.	Wind system cost	Rs.45,000 /kW
5.	Economic evaluation period	20-30 years
6.	Lead acid battery average life	4-5 years
7.	Life period of wind machine	10 years
8.	Life period of SPV system	25 years
9.	Battery DOD	0.5-0.8
10.	Silicon type module efficiency	8-14%
11.	General inflation rate	7.5%
12.	Discount rate	10-20%
13.	Escalation rate	7.5%
14.	CO_2 emission in PV system	68,600g /MWh
15.	CO_2 emission in Wind system	18,060g /MWh
16.	Externality of CO_2	Rs. 0.81 /kg

Table-2. Comparison of model and real time energy outputs for site Chunnambar, Pondicherry.

Energy generation systems	Model output in kWh per annum	Real output from site in kWh per annum	Percentage variation
Wind energy generation system (3.3 kW)	3569	3347	6.22
SPV generation system (1.8 kWp)	3094	2872	7.18
Total energy generation	6663	6219	6.66

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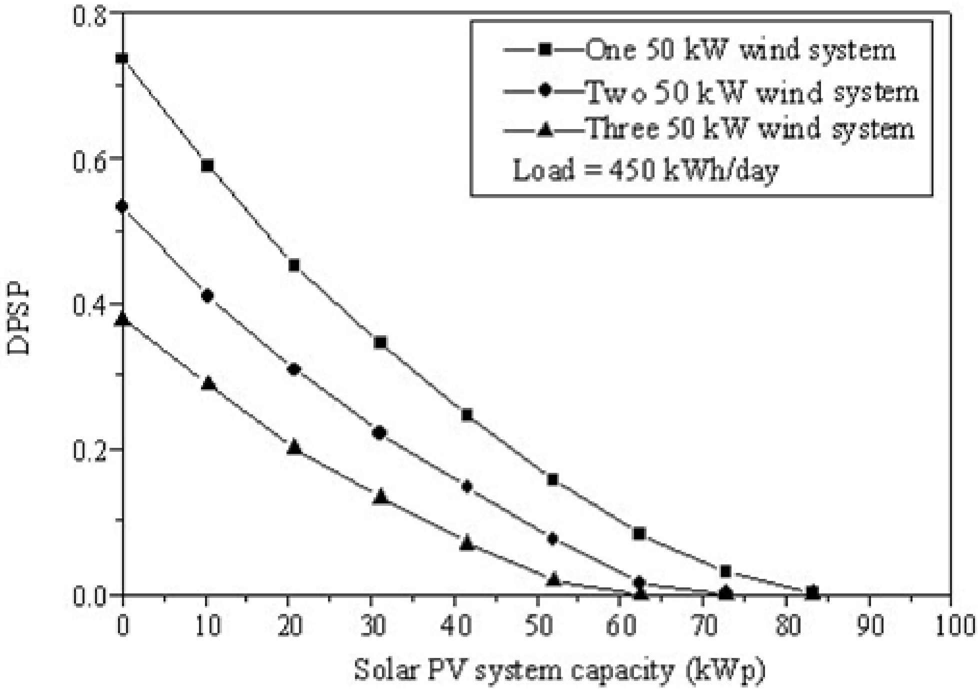

Figure-2. Variation of deficiency of power supply probability with respect to solar PV system capacity at Poompuhar.

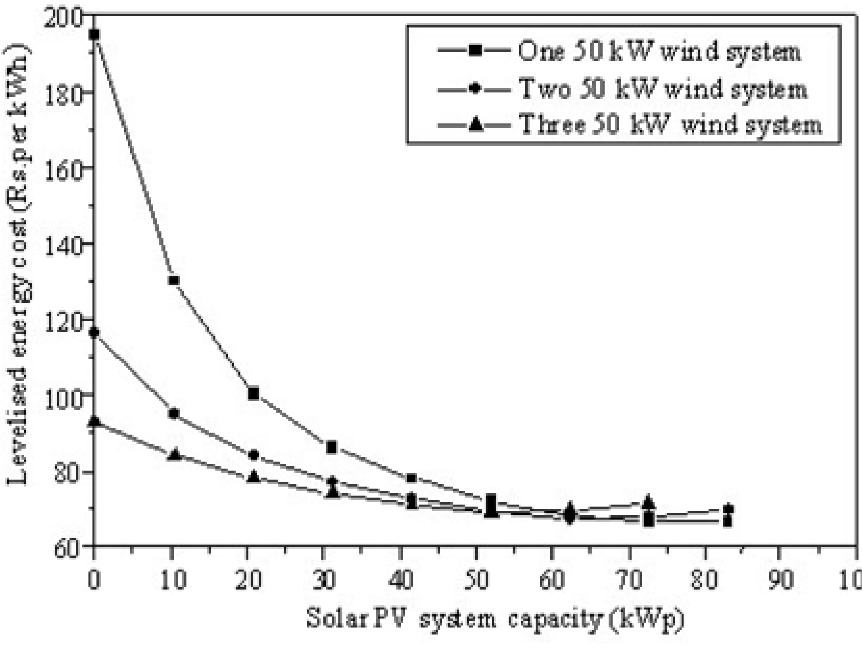

Figure-3. Variation of levelised energy cost with respect to solar PV system capacity with variable wind system capacity for 3 days of battery autonomy at Poompuhar.

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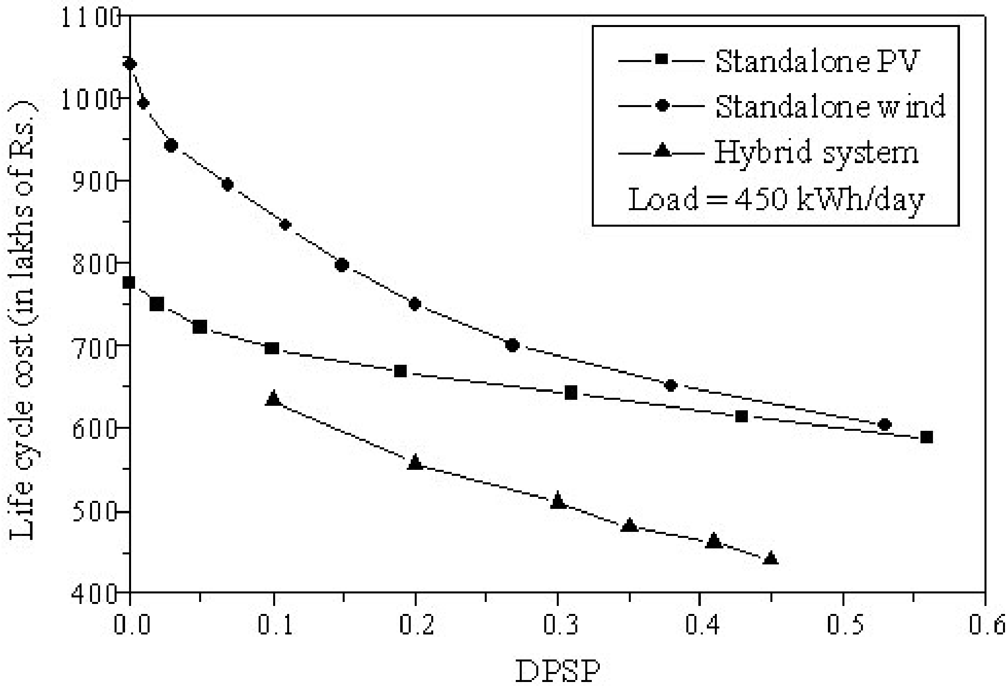

Figure-4. Variation of deficiency of power supply probability with respect to life cycle cost for Standalone photovoltaic, wind and hybrid systems at Poompuhar.