Solar PV- Diesel Hybrid Energy System For Rural Applications

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Abstract- **This paper describe sizing of solar PV, DG set and battery bank for different configurations for share of solar power. Different configurations for integration of solar with diesel energy systems are explained in detail. The energy availability and reliability of the integrated energy system are highlighted The economics for implementation of different configurations are dealt with detailed discussion in this paper.**

Keywords-integration; optimization; energy; economics

I. INTRODUCTION

The conventional PV system has unstable output characteristic dependent on weather conditions in a short period [1]. The integration of solar PV with other renewable energy source or conventional power will increase the utilization, energetic and exergetic efficiencies of energy conversion systems. Such integration encounters complexities arising from the diverse nature of the solar energy sources, low energy densities, intermittent availability and stochastic elements. Recent developments in processing, control and management of power are enabling stable operation of solar PV-diesel support integrated systems.

II. INTEGRATION OF ENERGY SYSTEMS

The solar power is optimized based on the load requirement and accordingly the size of DG set and battery bank are arrived.

The solar PV with DG set can be integrated in three different configurations i.e., series, switched and parallel [2, 3 and 4]. In series configuration the overall efficiency is low and large capacity of energy storage system is required. The switched and parallel configurations are more suitable for low load, medium load and high load operations [5]. There are three modes and are [6, 7]:

- Solar PV with inverter only – low load operation
- DG set and charging battery by DG set power – medium load operation
- Solar PV with inverter and DG set in parallel – high load operation.

The controller will control the operation of inverter, battery charger and DG set operation. During start-up the controller chooses inverter only operation, if the battery state of charge is above minimum level. When the load increases above the set value, the diesel will be started and operate in parallel with the inverter. In order to get more efficiency of DG set, it is economical to operate the DG set more than 85 % of its capacity. When the load is less than 85 % of DG set rating the excess power is used to charge the battery bank. Depending on the actual site load, the resulting system operation could involve either load sharing or battery charging. When the load on DG set falls below a chosen value, the system will revert to inverter-only operation [8].

Figure 1 gives the flow diagram of the integrated energy system under consideration. The input parameters to the controller are solar (SPV) power, DG set power, Battery power and load. The controller sense the load if solar power is available (i.e., between 0700 – 1800 hours), the SPV supply the power to load. If the SPV power is not there and load is less than battery charge, the battery provides the power supply to load. If the battery charge is lower than the load, the DG set will start and supply the power to the load. The DG set will always run at 85 % of its rating to get better efficiency. The surplus power of DG set is used to charge the battery. In case, the battery is fully charged, the DG set will operate under partial loading. If the load is more than the sum of SPV power & Battery charge, the DG set will start and supply the power to load. When the SPV power is more than load and the battery is fully charged, the power will be drained through dump load, which is a rare case.

III. LOAD PATTERN

A typical village is selected for analysis and its load data are given in Table 1.

The daily average energy requirement is 206.08 kWh/day and the peak power is 14.9 kW for a typical day. The morning peak is between 0700 to 1000 hours and the evening peak is between 1600 to 2200 hours. The energy ratio between peak to non-peak is 56 %, which is normal.

IV. COMPUTATION OF POWER AND ENERGY

A. The Power generated by Solar PV is computed as

i) Solar power is computed as:

$$P_{SPV}(i) = (A_0 + A_1 * h_i + A_2 * h_i^2) * P_{rated\_SPV} \; kW \qquad (1)$$

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Where A_0, A_1 & A_2 are constants based on the site conditions and are A_0 = -3.7136, A_1 = 0.7551 and A_2 = -0.0302 for the selected site, h_i is time in hour, 'i' varies from 7 to 18 & P_{rated_SPV} rated power of Solar PV in kW

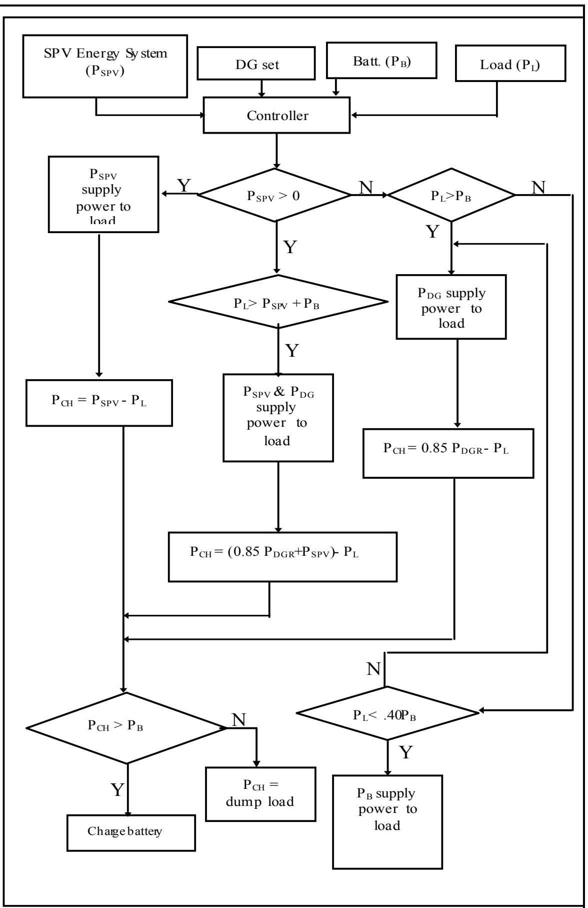

Figure 1: Flow diagram of integrated energy systems

TABLE 1: A TYPICAL LOAD OF A SELECTED VILLAGE

Sl. No	Particulars of load	Power (W)	Quantity (Nos.)	Av. Oper. (h/day)	Energy, (kWh/day)
01	House hold lighting	50	209	7	73.15
02	Community centre lighting	50	29	5	7.25
03	Street lighting	60	12	12	8.64
04	Health centre lighting & heating	1510	1	4	6.04
05	Water pumps	3700	3	4	44.4
06	Small scale industries like flour mills, chiller plants, etc.	3700	3	6	66.60
	Total	**8764**			**206.08**

ii) The solar power used for battery charge is calculated as:

$$C_{SPV}(i) = P_{SPV}(i) - P_L(i) \quad kW \qquad (2)$$

where P_L is load in kW

iii) The total energy supplied by Solar PV to load is given by

$$E_{SPV} = \sum_{i=7}^{18} (P_{SPV}(i) - C_{SPV}(i)) \quad kWh/day \qquad (3)$$

Where 'i' is hour and varies from 0700 to 1800 hours

iv) The total energy supplied by Solar PV for Battery charging is given by

$$EC_{SPV} = \sum_{i=7}^{18} C_{SPV}(i) \quad kWh/day \qquad (4)$$

v) The total energy supplied by Solar PV for both load and Battery charging is given by

$$TE_{SPV} = E_{SPV} + EC_{SPV} \quad kWh/day \qquad (5)$$

B. The power supplied by DG set and Battery bank

When $P_{SPV} \le 0$ and $P_L(i) > 0.40 P_B$

i) The power supplied by DG set to load is computed as:

$$P_{DG1}(i) = P_L(i) \quad . \ kW \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \qquad (6)$$

ii) The power supplied by DG set for battery charging is computed as:

$$C_{DG1}(i) = 0.85 P_{DGR} - P_{DG1}(i) \quad . \ . \ kW. \ . \ . \ . \ . \ . \qquad (7)$$

When $(P_L(i) > (P_{SPV}(i) + P_B(i)))$:

iii) The power supplied by DG set to load is computed as:

$$P_{DG2}(i) = P_L(i) - P_{SPV}(i) \quad . \ kW \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \qquad (8)$$

vi) The power supplied by DG set for battery charging is computed as:

$$C_{DG2}(i) = 0.85 P_{DGR} - P_{DG2}(i) \quad . \ . \ kW. \ . \ . \ . \ . \ . \qquad (9)$$

v) The energy supplied by DG set to load is given by

$$E_{DG} = \sum_{i}^{n} P_{DG1}(i) + \sum_{i}^{n} P_{DG2}(i) + \quad kWh/day \qquad (10)$$

vi) The energy supplied by DG set for Battery charging is given by

$$EC_{DG} = \sum_{i}^{n} C_{DG1}(i) + \sum_{i}^{n} C_{DG2}(i) + \quad kWh/day \qquad (11)$$

vii). Total energy supplied by DG set for both load and battery charging is given by:

$$TE_{DG} = E_{DG} + EC_{DG} \quad kWh/day \qquad (12)$$

C. The power supplied by Battery bank

When $P_L(i) < 0.40 P_B$

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i) The power supplied by Battery bank is given by:

$$P_{B1}(i) = P_L(i) \quad kW \tag{13}$$

When $P_L(i) > P_{SPV}$, $P_L(i) < 0.85P_{DGR}$ and $P_L(i) < (P_{SPV}(i) + P_B(i))$

ii) The power supplied by Battery bank is given by:

$$P_{B2}(i) = P_L(i) - P_{SPV} \quad kW \tag{14}$$

When $P_L(i) > (P_{SPV} + 0.85P_{DGR})$

iii) The power supplied by Battery bank is given by:

$$P_{B3}(i) = P_L(i) - (P_{SPV} + 0.85P_{DGR}) \quad kW \tag{15}$$

iv) The total energy supplied by Battery bank to load is given by

$$TE_B = \sum_i^n P_{B1}(i)) + \sum_i^n P_{B2}(i)) + \sum_i^n P_{B3}(i)) \quad kWh/day \tag{16}$$

V. RESULTS & DISCUSSION

To optimize the use of solar photovoltaic and conventional power (DG set) along with energy storage (Battery bank) three different configurations of Solar PV, DG set and Battery banks are modeled to meet the load requirement by using a simulation tool. The results are discussed with respect to energy system availability, cost and operation & maintenance (O&M).

A. Energy system availability

Table 2 gives the variation of rating and energy supplied by different energy sources for three different configurations.

TABLE 2 : VARIATION OF RATING AND ENERGY SUPPLIED BY ENERGY SOURCES.

Sl. No	Particulars	Int. I	Int. II	Int. III
01	Peak Power Rating of SPV, (kW)	8.0	12.0	16.0
02	Rating of DG set, (kVA)	15.0	12.5	10.0
03	Battery bank capacity, Peak power, (kW)/ Energy, (kWh/day)	4.5/36	6.0/44	7.0/51
04	Energy supplied by SPV to load, (kWh/day)	59.58	75.72	84.29
05	Energy supplied by SPV for battery charging, (kWh/day)	2.50	17.55	40.07
06	Total energy supplied by SPV, (kWh/day)	62.08	93.27	124.35
07	Energy supplied by DG set to load, (kWh/day)	110.7	87.11	71.36
08	Energy supplied by DG set for battery charging, (kWh/day)	33.25	25.70	10.36
09	Total energy supplied by DG set, (kWh/day)	144.0	112.81	81.73
10	Energy supplied by Battery bank to load, (kWh/day)	35.75	43.25	50.43

i) Integration I

Figure 2 shows the power supplied by Solar PV, DG set and Battery bank with time for a typical day. The solar energy is supplied during 0700 to 1800 hours. The total energy supplied to load by Solar PV is 28.91 % of total energy requirement and the excess energy is being used for charging the battery bank, which forms 7 % of battery bank capacity. The Battery bank caters the load during 0100 to 0500 hours, 1100 to 1200 hours and 1900 to 2400 hours. The energy supplied to load by Battery bank is 17.35 % of total energy requirement. The DG set is being switched on during 0600 to 1000 hours and 1600 to 2200 hours. The energy supplied by DG set to meet the load forms 53.74 % of total energy requirement and for battery charging is 33.25 kWh/day (93 % of battery bank capacity)

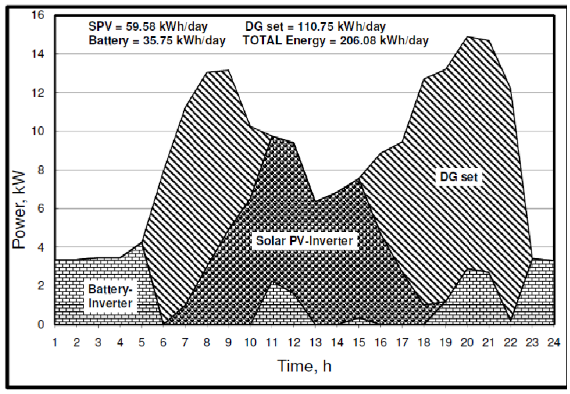

Figure 2: Power supplied by SPV, DG set & battery at Int. I

The total energy supplied by SPV is 16.306 MWh/y (21.93 % of total energy) for the load directly and 0.239 MWh/y for battery charging during surplus power. The energy supplied by DG set to load directly is 44.977 MWh/year (60.52 % of total energy) and 16.357 MWh/y for battery charging. The total energy supplied by battery is 13.038 MWh/y. The round trip efficiency of battery is assumed as 90 % and the battery deep discharge is 40 %.

Average monthly energy generation by SPV and DG set along with share of SPV is presented in Figure 3. The share of SPV is varying between 17.75 % to 27.2 % of total energy supplied to load.

ii) Integration II

In this configuration, the size of SPV is increased, so the power requirement by conventional energy source (DG set) is reduced to 12.5 kVA and the battery bank size has been increased.

Figure 4 shows the power supplied by Solar PV, DG set and Battery bank with time for a typical day. The solar energy is supplied during 0700 to 1800 hours. The total energy supplied to load by Solar PV increased to 36.74 % of total energy requirement and the excess energy is being used for charging the battery bank, which is also increased to 40.58 %.. The Battery bank caters the load

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during 0100 to 0500 hours and 1800 to 2400 hours. The energy supplied to load by Battery bank is increased to 20.99 % of total energy requirement. The DG set is being switched on during 0600 to 1000 hours and 1600 to 2200 hours. The energy supplied by DG set to meet the load is reduced to 42.27 % of total energy requirement and for battery charging is also reduced to 59.42 %.

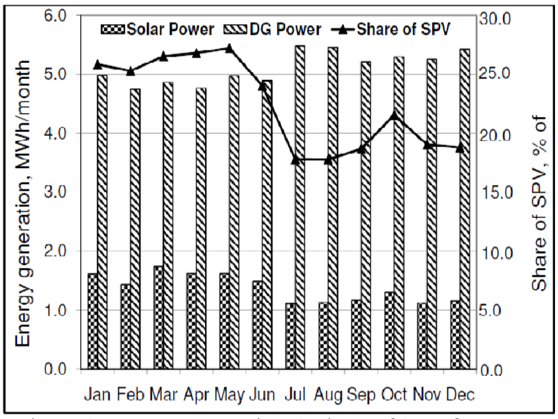

Figure 3: Energy generation & share of SPV for Int. I.

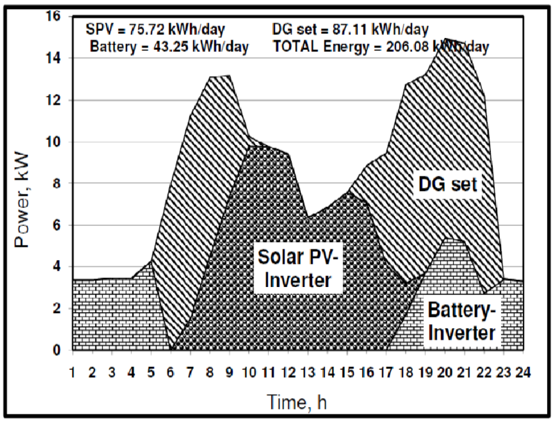

Figure 4: Energy generation & share of SPV for Int. II.

The total energy supplied by SPV is 22.155 MWh/y (29.84 % of total energy) for the load directly and 2.754 MWh/y for battery charging during surplus power. The energy supplied by DG set to load directly is 38.004 MWh/year (51.19 % of total energy) and 14.722 MWh/y for battery charging. The total energy supplied by battery is13.693 MWh/y.

Average monthly energy generation by SPV and DG set along with share of SPV is presented in Figure 5. The share of SPV is varying between 26.64 % to 40.80 % of total energy supplied to load.

iii) Integration III

In this configuration, the size of SPV is increased, so the power requirement by conventional energy source (DG set) is reduced to 10 kVA and the battery bank size has been increased.

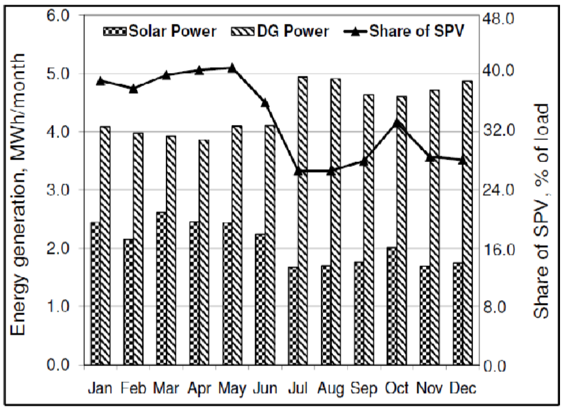

Figure 5: Energy generation & share of SPV for Int. II.

Figure 6 shows the power supplied by Solar PV, DG set and Battery bank with time for a typical day. The solar energy is supplied during 0700 to 1800 hours. The total energy supplied to load by Solar PV increased to 40.9 % of total energy requirement and the excess energy is being used for charging the battery bank, which is also increased to 79.46 %.. The Battery bank caters the load during 0100 to 0700 hours and 1800 to 2400 hours. The energy supplied to load by Battery bank is increased to 24.47 % of total energy requirement. The DG set is being switched on during 0600 to 0900 hours and 1700 to 2200 hours. The energy supplied by DG set to meet the load is reduced to 34.63 % of total energy requirement and for battery charging is also reduced to 20.54 %.

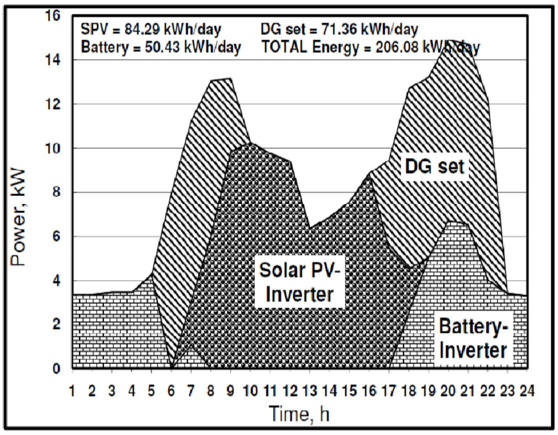

Figure 6: Power supplied by SPV, DG set & battery for Int. III.

The total energy supplied by SPV is 25.433 MWh/y (29.84 % of total energy) for the load directly and 7.74 MWh/y for battery charging during surplus power. The energy supplied by DG set to load directly is 32.843 MWh/year (51.19 % of total energy) and 11.07 MWh/y for battery charging. The total energy supplied by battery is15.576 MWh/y.

Average monthly energy generation by SPV and DG set along with share of SPV is presented in Figure 7. The share of SPV is varying between 35.51 % to 54.40 % of total energy supplied to load.

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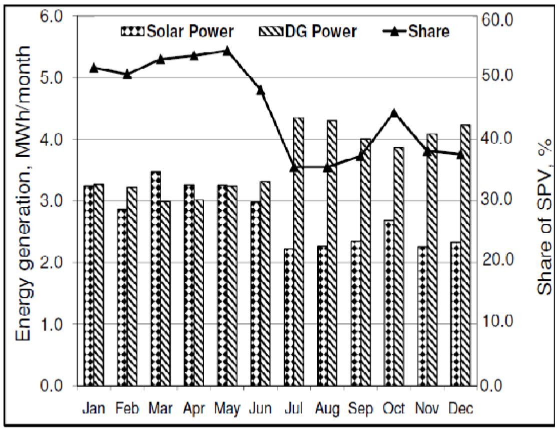

Figure 7: Energy generation & share of SPV for Int. III.

B. *Cost of the system*

The economics for implementation of different configurations are evaluated using HOMER software [9] and results are presented as below:

i) Integration I

Table 3 gives the life cycle cost analysis of the system for *Integration I*. The total initial investment is Rs. 31,39,700, the total annualized cost is Rs. 7,10,170 per year. The levelized cost of energy generation is Rs. 10.46 per kWh with average SPV share of 22.43 %.

TABLE 3: LIFE CYCLE COST ANALYSIS FOR INTEGRATION I.

Component	Annualized capital cost, (INR/y)	Annualized replacement cost, (INR/y)	Annual O&M cost, (INR/y)	Annual fuel cost, (INR/y)	Total Annualized cost, (INR/y)
Solar PV	239700	28106	21808	0	289614
DG set	1739	6439	17907	382768	408853
Battery	705	1739	611	0	3055
Inverter	3384	893	4371	0	8648
Total	245528	37177	44697	382768	710170
Levelized cost of energy : Rs. 10.46 per kWh					

ii) Integration II

Table 4 gives the life cycle cost analysis of the system for *Integration II*. The total initial investment is Rs. 39,13,200, the total annualized cost is Rs. 7,41,754 per year. The levelized cost of energy generation is Rs. 11.55 per kWh with average SPV share of 33.04 %.

TABLE 4: LIFE CYCLE COST ANALYSIS FOR INTEGRATION II.

Component	Annualized capital cost, (INR/y)	Annualized replacement cost, (INR/y)	Annual O&M cost, (INR/y)	Annual fuel cost, (INR/y)	Total Annualized cost, (INR/y)
Solar PV	299625	35109	27307	0	362041
DG set	1457	5546	15228	340938	363169
Battery	3384	1645	658	0	5687
Inverter	4277	1128	5452	0	10857
Total	308743	43428	48645	340938	741754
Levelized cost of energy : Rs. 11.55 per kWh					

iii) Integration III

Table 5 gives the life cycle cost analysis of the system for *Integration III*. The total initial investment is Rs. 62,42,000 the total annualized cost is Rs. 8,81,015 per year**.** The levelized cost of energy generation is Rs. 14.07 per kWh with average SPV share of 44.02 %.

TABLE 5: LIFE CYCLE COST ANALYSIS FOR INTEGRATION III**.**

Component	Annualized capital cost, (INR/y)	Annualized replacement cost, (INR/y)	Annual O&M cost, (INR/y)	Annual fuel cost, (INR/y)	Total Annualized cost, (INR/y)
Solar PV	479447	56212	43663	0	579322
DG set	1269	4230	11938	263341	280778
Battery	799	1927	752	0	3478
Inverter	6862	1833	8742	0	17437
Total	488377	64202	65095	263341	881015
Levelized cost of energy : Rs. 14.07 per kWh					

Figure 8 shows the variation of initial capital investment and annualized cost for different configurations. The initial capital investment increase exponential with the increase of share of SPV whereas the annualized cost varies marginally.

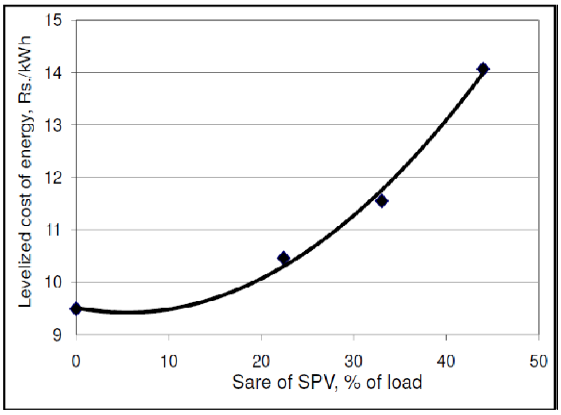

Figure 8: Variation of capital cost & annualized cost with SPV share**.**

Figure 9 presents the variation of levelized cost of energy with share of SPV. The cost of energy per unit increases as the share of SPV increases.

C. *Operation and Maintenance*

Since there are no moving parts in non-tracking SPV system and few moving parts in Tracking system, the maintenance is less [10]. It can be seen from the above Tables 3 to 5 that the annualized O & M cost varies for different components (i.e., for SPV : 0.71 % of capital investment, for DG set : 80 % of capital cost, for battery : 7.5 % of capital cost and for Inverter : 10 % of capital cost). Figure 9 gives the variation of O&M cost as a percentage of capital cost and annualized cost with the share of SPV. It can be seen from the Figure 10 that as the share of SPV increases the O&M cost as percentage of capital cost decreases and the percentage of annualized cost decreases because the O&M

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component for DG set is as high as 80 % of the capital cost.

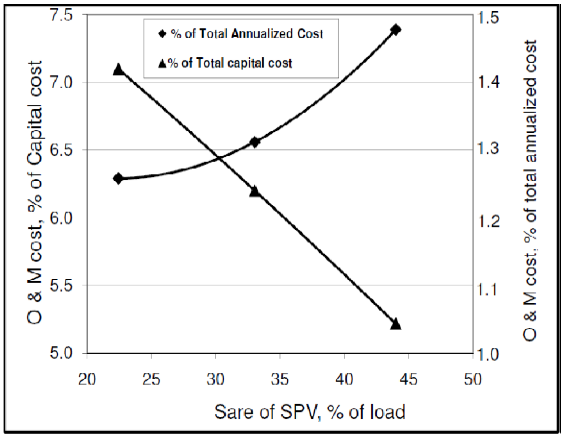

Figure 9: Variation of cost of energy with SPV share.

The periodic maintenance of PV system is essential and more care has to be given for maintenance of Inverter system.

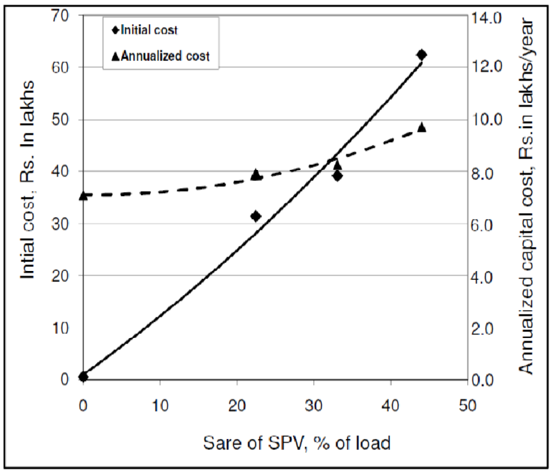

Figure 10: Variation of O&M cost with SPV share.

When a module is placed outdoors, airborne particulates (i.e., dust, debris) settle on the glass surface of the module. This is called "soiling". These particulates block the amount of light energy reaching the cell and therefore reduce the power output of the module. The power output is reduced by 0.78 at dust coverage of 25 %. Therefore, it is essential to bring down the dust coverage below 1 % by periodic cleaning. A module installed in a wet weather climate would have less "soiling" compared to drier climate [11].

VI. CONCLUSIONS

The integration of Solar PV with conventional power i.e., DG set along with storage battery works out to be costly as compared to only DG set operation. At present the cost generation for DG set is Rs. 14.30 per kWh. Since the cost of diesel is increasing drastically, the solar PV – diesel integration may become economical at later dates. As the share of SPV increases the levelized cost of energy, initial cost and annualized cost increases. The availability and reliability indices are good. The failure rate of inverter is more in PV system. If these failures are addressed, the SPV system will become more popular.

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REFERENCES

[1] Hong-Sung Kim, Naotaka Okada, Kiyoshi Takigawa, "Advanced grid connected PV system with functions to suppress disturbance by PV output variation and customer load change", Solar Energy Materials & Solar Cells 67 (2001) 559-569.

[2] Fouad Kamel, "Perspectives on Grid-connected Photovoltaic solar generators", Renewable energy, vol.6, No.5-6, pp. 515-520, 1995

[3] Langworthy, "Intelligent power station control systems for remote area power supply", Electric Energy Conference, Darwin, 1991, pp. 68-74.

[4] G. Ernest Palomino, "Performance of a grid connected residential photovoltaic system with energy storage", 26th IEEE photovoltaic Specialists Conference, Sept. 29 – Oct.3, 1997.

[5] B. Wichert, "PV-Diesel Hybrid Energy Systems for Remote Area Power Generation – A Review of Current Practice and Future Developments", Renewable and Sustainable Energy Reviews, Vol.1, No.3,pp.209-228, 1997.

[6] K. Peippo and P.D. Lund, "Optimal sizing of solar array and inverter in a grid-connected photovoltaic systems", Solar Energy Materials and Solar Cells 32 (1994), pp. 95-114.

[7] C.V. Nayar, "Recent Developments in Decentralized Mini-Grid Diesel Power Systems in Australia", Applied Energy 52 (1995), pp. 229-242.

[8] C. Christober Asir Rajan, "Stand-alone Wind-Solar Photovoltaic integrated power generation system for rural areas", 'Proc. Of National Conference on Application of Solar Energy – Recent Developments' , 20-21, Nov. 1997, at ERC, CPRI, Trivandrum, pp. 18-21.

[9] HOMER home page, http://www.nrel.gov/international/tools/HOMER/homer.html

[10] J. C. Wiles, B. Brooks, B-O. Schultze, "PV Installations, A Progress Report," *Proceedings of the 29th IEEE Photovoltaic Specialist Conference*, 2002, pp. 1461- 1464.

[11] Grid-tied Photovoltaic System Performance Conversion efficiency Factors, http://www.solarexpert.com/grid-tie/system-performance-factors.html.

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