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Economics of Grid-Connected Distributed Captive PV Power Plants near Villages in India

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Abstract: *Solar energy is most widely distributed renewable energy source as sunshine reaches the doorsteps of the consumers every day. Being distributed energy source, solar energy is more suitable for distributed population in rural areas. Therefore, it will be better to install large number of smaller distributed captive PV power plants near the villages rather than large utility-scale PV power plants. No technology can grow in the market until and unless it is more economical than the existing technologies for the same purpose. In this paper, the economics of solar electricity from distributed captive PV power plants near villages have been evaluated with two types of loans i.e. existing 'equated installment loan' and proposed 'variable installment loan'. The results have been calculated for all the six regions of India. Results show that with equated installment loans, solar electricity from distributed captive PV power plants near villages is more economical than grid electricity in four regions with capacity utilization factor of 17.69% and above. However, with variable installment loans, solar electricity is more economical than grid electricity in all the six regions of India. Hence, banks need to start giving variable installment loans.*

Keywords: *Distributed captive PV plants, Retail grid parity, Equated and variable installment loans, PV plants near villages, Grid parity period.*

I. INTRODUCTION

At present, most of the grid electricity is supplied by hydro power plants and coal based thermal power plants. There is small contribution from solar PV power plants**,** nuclear power plants and biomass based power plants. However, during last few years, solar PV power plants are expanding at fast pace. The limiting factor is higher cost of solar electricity at the time of installation as compared to grid electricity. Therefore solar PV power plants are being installed with subsidies from government. As such unbridled market driven growth of solar PV power plants is being inhibited due to budget constraints. During last few years, the cost of installing solar PV power plants has decreased significantly. Therefore, economic analysis is required with prevailing costs to determine the present price of solar electricity in India.

India is a developing country and majority of population lives in large number of distributed villages in rural areas. At present, large scale utility-scale PV power plants are being installed to supply solar electricity to distributed villages in rural areas. It is better to install large number of distributed captive PV power plants of smaller capacities near the villages as both sunshine and land are available on the periphery of practically all villages. For any technology to grow, it must be cost competitive with existing technologies for that purpose. Therefore, in this paper, distributed captive PV power plants near villages have been considered for economic analysis.

The initial investment required to install solar PV plant is much higher than that for hydro power plants and coal based thermal power plants but fuel cost is zero and maintenance cost is minimal. Therefore cost of repayment of loan constitutes major portion of cost of solar electricity.

At present banks give equated installment loans and loan is repaid back by equated monthly installment (EMIs). The cost of solar electricity from a PV power plants installed with equated installment loan is called 'levelized cost' of solar electricity. It may be noted that levelized cost does not remain exactly same for different years due to decrease in electricity output of PV power plant with time as well as increase in maintenance cost. However, the rate of increase in levelized cost of solar electricity tends to be smaller than the rate of increase in the cost of grid electricity due to inflation. To overcome this problem a new type of loan called 'variable installment loan' has been proposed. In this type of loan, repayment is made by variable monthly installments which increase at prevailing rate of inflation resulting in increase in cost of solar electricity almost like that of grid electricity. With variable installment loan, the cost of solar electricity reduces at time of installation thus making solar electricity more competitive with grid electricity.

In this paper, economic analysis of distributed captive PV power plants near villages have been performed both with 'equated installment loan' and 'variable installment loan' for each of six regions of India with different values of capacity utilization factors.

II. LITERATURE REVIEW

The concept of distributed captive PV power plants near villages is new. Therefore, no literature exists for such PV plants. However, distributed captive rooftop PV systems on the roofs of residential, commercial and industrial buildings are being installed in large numbers throughout the world. Therefore, literature review includes few papers on the performance evaluation of rooftop PV systems followed by papers on economic analysis.

2.1 Performance evaluation of PV systems

The electricity output of solar PV power plants is location specific due to variations in solar energy received per unit area at different places. India has been divided in six regions and capacity utilization factor for each of these six regions has been reported in a report of Central Electricity Regulatory Commission (CERC) [1]. The values of specific electricity output of solar PV power plants in these six regions of India can be calculated based on the given values of capacity utilization factor. The cost of solar electricity generation tends to be different in these six regions.

The study involves performance evaluation of a 2.45 kW_p PV system over a period of 5 years in Mauritius [2]. The performance data was collected during the dry winter season through a mathematical model based on 5 parameters. The result showed overall decrease in all parameters during the period of study. Annual output decreased from 3463.8 kWh to 3370.9 kWh and capacity utilization factor decreased from 16.14% to 15.71%. Also performance ratio decreased from 90% to 70% after 3 months.

The study depicts the performance evaluation of a 2.07 kW_p rooftop grid connected PV system in Norway [3]. The results show total annual energy output and annual specific output as 1927.7 kWh and 931.6 kWh/KW_p. The paper has further discussed the other parameters like annual average array yield, final yield, PV module efficiency, system efficiency and invertors' efficiency. The overall annual capacity factor and performance ratio calculations also support the technical feasibility of electricity generation of a rooftop grid connected PV system, which can contribute a lot to the future energy mix of Norway.

The performance evaluation of a 1.72 kW_p rooftop grid connected PV system installed in Dublin, Ireland has been reported [4]. The electricity generated was fed into the low voltage supply to the flat. Almost all the parameters like annual energy output, annual average daily final yield, reference yield and array yield were monitored during study. The performance comparison of this system with other systems in different locations showed that the system had the highest system efficiency and performance ratio of 12.6% and 81.5% respectively. The results were found comparable to the results from some parts of Spain but lower than that of Italy and Spain. Ireland's suitability due to high average wind speed and low ambient temperature has been found better.

The performance analysis of two rooftop PV systems installed on two schools in Kuwait has been carried out in the paper [5]. There is high potential of PV technology in Kuwait due to high daily irradiation. The copper indium gallium selenide (CIGS) thin film technology has been used in the two PV systems under study. The results of the study showed that average performance ratio is between 0.74 & 0.85 due to selection of technology and the effect of automated cleaning systems set to run weekly. The minimum monthly energy yield of the PV systems was about 104 kWh/kW_p. Similarly the annual average daily final output was recorded as 4.5 kWh/kW_p/day. The data obtained will be beneficial for research purposes worldwide. School buildings' rooftops are the ideal option for solar PV power generation and to use large unutilized areas. The study reveals that local climate poses challenges to the use of PV technology but further research will lessen the effects of those factors.

2.2 Economic analysis of PV systems

It has been pointed out pointed out that comparison of levelized cost of solar electricity with variable price of grid electricity is not realistic cost comparison because levelized cost remains almost same while variable cost increases several folds during long period of 20-25 years [6]. It is an apple-to-orange comparison. Further, all the products in the market including grid electricity are being sold at variable price. Therefore, solar electricity must be sold at variable price for realistic orange-to-orange cost comparison with grid electricity. To sell solar electricity at variable price, a new type of loan called variable installment loan was proposed and a method to determine variable installments of such loan was given.

The life cycle economic and financial aspect of rooftop PV systems in different states of Australia has been discussed [7]. All the factors relating to manufacturing, purchasing, installation and operation of rooftop systems have been studied. The sensitivity analysis related to electricity cost, feed- in-tariff, battery price, emissions mitigation and cost payback periods without and with battery storage has been carried out. It has been concluded that the decrease in the cost of PV panels has resulted in less payback period. The load profiles have also shown a major effect on payback times. The cost payback and energy payback times have been found to vary between 11 to 25 years and 1.75 to 14 years respectively in different states.

The paper discusses the techno-economic study of roof top solar PV systems across 1000 different locations in United States [8]. To make a solar PV system cost competitive, its cost of electricity generation should be equal to the retail cost of conventional power which is known as 'socket parity'. The analysis reveals that only the location of Hawaii could achieve the socket parity without any state or federal subsidy. Similarly six states achieved socket parity with subsidies. This shows that socket parity of solar PV systems in most of the locations is yet to be attained. The high costs of PV systems along with financing rates have been found to be important barriers to socket parity.

The high cost of solar PV systems has been the major barrier in the development of solar power in Brazil until now [9]. But the reduction in cost in the PV systems has attracted the attention of Brazilian Government. The incentives to provide loans at low interest have yielded positive results in case of residential PV systems where the costs of conventional electricity are higher as compared to the average cost in the country. The outcome of such government policies has been studied in case of rooftop systems for different climatic zones in Brazil.

The feasibility of grid connected PV systems in Algerian dairy farms has been studied in order to optimize the solar power [10]. The energy requirement of Algerian farms with 10-30 cows has been found to be between 330 kWh/cow/year and 560 kWh/cow/year. This requirement of Algerian farms is on the lower side as compared to North European and North American dairy farms consuming up to 2900 kWh/cow/year. The study reveals that the solar electricity generated at the farms can achieve the energy balance between estimated PV generation and farm energy requirement with a cost of electricity ranging from 0.008 $/kWh to 0.033 $/kWh.

The performance of a 110 kW_p SPV rooftop grid connected system installed at a residential hostel building at Bhopal, India has been evaluated through Solargis PV planner software [11]. The output of four different PV technologies has been studied and found that Solargis is fast, accurate and reliable software for simulation of solar PV system. The performance ratio of PV systems has been found to vary between 70% to 88% and the energy output was found between 2.67 kWh/kW_p to 3.36 kWh/kW_p.

III. METHODOLOGY OF COST CALCULATIONS

The basis of determination of cost of solar electricity is to convert initial investment into running cost in the form of equated monthly installments. The sum of monthly installments in a given year is divided by the units of solar electricity (kWh) generated in that year to obtain the cost of financing per unit of solar electricity in that year. The only other cost is operation and maintenance (O&M) cost and it is added to the cost of financing to determine the cost of generation per unit of solar electricity for each year of the loan period. The procedure for such cost calculations is given below:

3.1 Generalized capital recovery factor and Capital recovery factor

For variable installment loan, generalized capital recovery factor (C_{rfg}) is used to determine variable monthly installments of the loan. The value of generalized capital recovery factor can be determined for given monthly interest rate (i), number of monthly installments (m) and rate of escalation in installments (e) from Eq (1) and (2):

$$C_{rfg} = (1+i)(1-r) / (1 - r^m) \quad \text{... (1)}$$

$$r = (1 + e) / (1 + i) \quad \text{... (2)}$$

The capital recovery factor for equated installment loan (C_{rf}) can also be calculated from Eqs (1) and (2) by putting rate of escalation in installment (e) equal to zero.

3.2 Annual repayment of loan

For a given value of principal of loan (C), the annual repayment of loan (P_{le}) with equated monthly installments is given by Eq (3).

$$P_{le} = 12\, C\, C_{rf} \qquad \text{(Rs/year)} \quad \text{... (3)}$$

The annual payment of the loan in n^{th} year ($P_{lv}(n)$) with variable installments is obtained by summation of all the variable monthly installments from month m_1 to month m_2 using Eqs (4), (5) and (6).

$$m_1 = 12\,(n-1) + 1 \quad \text{... (4)}$$

$$m_2 = 12\, n \quad \text{... (5)}$$

$$P_{lv}(n) = \sum_{m1}^{m_2} C\, Crfg\, (1+e)^{m-1} \qquad \text{(Rs/year)} \quad \text{... (6)}$$

3.3 Annual solar electricity output

The manufacturer gives the value of maximum possible reduction in output of PV panels (R_m) during the performance warranty period (L). The output of PV panels in base year at a given place is obtained from the available data about capacity utilization factor (C_{uf}) data for different regions. The solar electricity output in base year (E_{ob}) is given by equation (7).

$$E_{ob} = C_{uf}\, 8760/100 \qquad (kWh/kW_p/year) \quad \text{... (7)}$$

The annual solar electricity output during L^{th} year ($E_o(L)$) and annual reduction in electricity output (E_{red}) are given by equations (8) and (9) respectively. Then electricity output for a given year ($E_o(n)$) is obtained from equation (10).

$$E_o(L) = R_m\, E_{ob} \qquad \text{(kWh/year)} \quad \text{... (8)}$$

$E_{red} = [E_{ob} – E_o (L)] / L$ (kWh/year) ... (9)

$E_o (n) = E_{ob} – n E_{red}$ (kWh/year) ...(10)

3.4 Cost of financing of solar electricity

With equated installment loan, the cost of financing per unit (kWh) of solar electricity in a given year (C_f (n)) is given by equation (11).

$C_f (n) = P_{le} / E_o(n)$ (Rs/kWh) ...(11)

3.5 Annual operation and maintenance cost

The value of annual operation and maintenance (O&M) cost per unit capacity (Rs/kW_p) of PV plant in base year (Omc) at a given place is taken from given data. Then operation and maintenance cost per unit of electricity in base year (O_{mb}) is given by equation (12).

$O_{mb} = Omc / Eob$ (Rs/kWh) ... (12)

The annual rate of escalation in operation and maintenance cost (O_e) is also obtained from given data. Then value of annual operation and maintenance cost for n^{th} year is given by equation (13).

$O_m (n) = O_{mb} (1+O_e)^n$ (Rs/kWh) ...(13)

3.6 Cost of generation of solar electricity

The cost of generation of solar electricity in a given year is summation of the cost of financing per unit C_f (n) and O&M cost (O_m(n)). The cost of generation per unit of solar electricity in a given year C_g (n) for equated installment loan is given by equation (14)

$C_g (n) = C_f (n) + O_m(n)$ (Rs/kWh) ...(14)

3.7 Socket cost of solar electricity

The socket cost of solar electricity from utility-scale PV power plant is equal to retail price of grid electricity. For the proposed distributed captive solar PV power plants near the villages, the cost of carrying electricity from power plant to the village is eliminated but the cost of distribution in a village is to be added to the cost of generation to determine the socket cost of solar electricity in a given village. The value of fraction of units generated which are lost during distribution (f) is obtained from data of grid electricity distribution company. Therefore the units of solar electricity supplied at socket in n^{th} year E_s (n) is given by equation (15).

$E_s (n) = E_o (n) (1-f)$ (kWh/year) ... (15)

Therefore, the socket cost of solar electricity in a village from distributed captive power plant near the village is given by equation (16).

$C_s(n) = P_{le} / E_s(n)$ (Rs/kWh) ...(16)

3.8 Wholesale and retail price of grid electricity

The wholesale price of grid electricity in a given year (C_{gw}(n)) is the price at which thermal power plants sell electricity to nearest utility or power exchange.The retail price of grid electricity in a given year (C_{gr}(n)) is the price charged by the distributed companies from consumers. The wholesale and retail price of grid electricity in the base year (C_{gwb} and C_{grb}) are known for a given place. Also, long term rate of increase (e) in these prices can be calculated from such prices during last 20-25 years.Therefore, wholesale and retail price of grid electricity in n^{th} year is given by equation (17) and equation (18) respectively.

$C_{gw} (n) = C_{gwb} (1+e)^n$ (Rs/kWh) ...(17)

$C_{gr} (n) = C_{grb} (1+e)^n$ (Rs/kWh) ...(18)

3.9 Grid parity of solar electricity

Grid parity of solar electricity is determined differently for the utility-scale (centralized) and distributed captive solar PV power plants because of different market values of their solar electricity. Grid parity of solar electricity generated in a utility-scale solar PV power plant is attained when the cost of generation of solar electricity becomes equal to the present value of wholesale price of grid electricity. It is called wholesale grid parity (generation parity). However, the grid parity of solar electricity generated in a distributed captive solar PV power plant near a village is attained when socket cost of solar electricity becomes equal to the present value of retail price of grid electricity. It is called retail grid parity (socket parity).

The wholesale grid parity is determined from the ' wholesale grid parity ratio' (R_u) which is defined as the ratio of cost of generation of solar electricity from utility-scale PV power plant to wholesale price of grid electricity. The wholesale grid parity is obtained when value of R_u becomes unity. The retail grid parity (socket parity) is determined from 'retail grid parity ratio' (R_d) which is defined as the ratio of cost of solar electricity supplied at socket from distributed captive PV power plants near villages to retail price of grid electricity. The retail grid parity is obtained when value of R_d becomes unity.

3.10 Grid parity period

The grid parity period for utility-scale PV power plants is the time elapsed in months from base year till the value of R_u becomes unity. Similarly the grid parity period for distributed captive PV power plants is the time elapsed in months from the base year till the value of R_d becomes unity.

IV. RESULTS AND DISCUSSION

In this section, economics of distributed captive PV power plants near villages and connected to grid on demand side is elaborated with the help of an illustration for both equated and variable installment loans.

The economics of distributed captive solar PV plants near villages is based mainly on the data supplied by Central Electricity Regulatory Commission (CERC) of India except initial cost [1]. The electricity output of PV power plants is different in different regions of India due to different amount of sunshine received and different environmental temperatures. For this purpose, India is divided into six regions and capacity utilization factors for these regions are given in the Table 1.

Table 1. Region wise capacity utilization factors of solar PV power plants for six regions of India

Solar Zone	Capacity Utilization Factor (%)
Solar Zone-1	14.58
Solar Zone-2	15.63
Solar Zone-3	17.69
Solar Zone-4	19.81
Solar Zone-5	21.92
Solar Zone-6	22.95

The capacity utilization factor in different regions varies from 14.58% to 22.95%. As per CERC report of year 2015-16 [1], the initial investment required to install large utility-scale PV power plants in India is 530×10^5 Rs/MWp. This includes 25×10^5 Rs/MWp as cost of 5 acres of land. The initial investment required to install smaller distributed PV plants of few hundred kW_p capacity is little higher than utility-scale PV plants due to smaller volume of purchase. Based on prevailing prices in India, initial cost of PV power plant of few hundred kW_p capacity including land cost is about 60,000 Rs/KW_p. The only running cost is operational and maintenance (O&M) cost. The O&M cost per unit capacity is given as 7×10^5 RS/MWp with annual increase of 6% [1]. At present, banks give equated installment loan at interest rate of 12.75% for solar PV power plants [1]. The loan period has been taken equal to the performance warranty period of 25 years. Calculations were carried out for each of the six values of capacity utilization factor covering all the six regions of India. The economic criterion used is the cost of solar electricity at socket versus retail price of grid electricity.

4.1 Economics of distributed captive solar PV power plants near villages with equated installment loan

The cost of solar electricity generation in distributed captive PV power plants for each of the six regions of India with different values of capacity utilization factor (C_{uf}) has been calculated. The results for distributed captive PV plants near villages for capacity utilization factor of 14.58% are given in Table 2. The equated monthly installments turn out to be 665.42 Rs/month resulting in annual loan repayments of 7985 Rs/year. This annual repayment remains same for each year of loan period. The annual solar electricity generated in the base year by one kW_p PV plant with capacity utilization factor of 14.58% turns out to be 1277 kWh/kW_p-year. The distribution loses in villages have been taken as 20% based on data supplied by Punjab State Power Corporation Limited [12]. Therefore, the annual solar electricity supplied at the socket turns out to be 1022

kWh/kW_p-year in base year and it decreases to 817 kWh/kW_p-year in 25th year resulting in increase in cost of financing per unit of electricity. The cost of financing varies from 7.81 Rs/kWh at the time of installation to 9.76 Rs/kWh in 25th year. The O&M cost per unit of electricity varies from 0.68 Rs/kWh in base year to 3.82 Rs/kWh in 25th year. Adding cost of financing and O&M cost, the cost of generation turns out to be 8.49 Rs/kWh in base year and increase to 13.59 Rs/kWh in 25th year. The present retail price of grid electricity is around 7.00 Rs/kWh. The annual rate of increase in retail price of grid electricity has been taken as 8% based on report of Punjab Energy Development Agency [13]. Therefore, the retail price of grid electricity increases from 7.00 Rs/kWh in base year to 51.38 Rs/kWh in 25th year. The 'levelized retail grid parity ratio' i.e. ratio of levelized socket cost of solar electricity to retail price of grid electricity varies from 1.21 in base year to 0.26 in 25th year. This means that levelized socket cost of solar electricity in village is 1.21 times that of retail price of grid electricity in base year. However, this ratio decreases to 0.26 in 25th year. It may be noted that solar electricity is more expensive than grid electricity at the time of installation of PV power plant but it is much cheaper in 25th year. Similar results for capacity utilization factors of 15.63%, 17.69%, 19.81%, 21.92% and 22.95% were also calculated to determine the socket cost of solar electricity in villages. The results for levelized socket cost of solar electricity in villages from distributed captive PV power plant near villages for different years and all the six values of capacity utilization factor versus retail price of grid electricity are shown in Table 3.

Table 4 shows levelized retail grid parity ratio i.e. ratio of levelized socket cost of solar electricity to retail price of grid electricity in different years for different values of capacity utilization factor. Levelized retail (socket) grid parity is attained when the levelized retail grid parity ratio equals unity. It is apparent from this table that levelized retail (socket) grid parity is attained sometimes before 5th year for capacity utilization factors of 14.58% and 15.63%. The levelized retail (socket) grid parity is attained at the time of installation for capacity utilization factors of 17.69%, 19.81%, 21.92% and 22.95%.

Levelized retail grid parity period is obtained by interpolation of these results and these values are shown in Table 5. Obviously, the levelized retail grid parity period decreases with increase in capacity utilization factor. Levelized retail grid parity period is 37 months and 25 months for capacity utilization factor 14.58% and 15.63% respectively. For capacity utilization factors of 17.69%, 19.81%, 21.92% and 22.95%, the levelized retail grid parity is attained at the time of installation itself. In regions with capacity utilization factor of 14.58% and 15.83%, the distributed captive PV power plants do not attain levelized retail (socket) grid parity at the time of installation and require subsidies from government. However, in other four regions with capacity utilization factors of 17.69% and above the distributed captive PV power plants have attained levelized retail (socket) grid parity at the time of installation and do not require government subsidies resulting in market driven growth.

Table 2. Levelized socket cost of solar electricity generated in distributed captive PV power plants near villages for capacity utilization factors of 14.58% versus retail price of grid electricity for different years

Time period (n) (years)	Annual repayment of loan (P_{le}) (Rs/yr)	Annual solar electricity generated ($E_o(n)$) (kWh/yr)	Annual electricity supplied at socket $E_s(n)$ (kWh/yr)	Cost of financing $C_f(n)$ (Rs/kWh)	O & M cost $O_m(n)$ Rs/kWh)	Cost of solar electricity at socket $C_s(n)$ (Rs/kWh)	Projected retail price of grid electricity $C_{gr}(n)$ (Rs/kWh)	Leveli-zed retail grid parity ratio (R_d)
0	7985	1277	1022	7.81	0.68	8.49	7.00	1.21
5	7985	1226	981	8.14	0.96	9.10	10.43	0.87
10	7985	1175	940	8.49	1.35	9.85	15.54	0.63
15	7985	1123	899	8.88	1.91	10.79	23.15	0.47
20	7985	1073	858	9.30	2.70	12.00	34.49	0.35
25	7985	1022	817	9.76	3.82	13.59	51.38	0.26

Table 3. Levelized socket cost of solar PV electricity from distributed captive PV power plants near villages versus retail price of grid electricity in different years for different values of capacity utilization factor

Year	Capacity Utilization Factor (C_{uf})						Projected retail price of grid electricity C_{gr} (n) (Rs/kWh)
	14.58 (%)	15.63 (%)	17.69 (%)	19.81 (%)	21.92 (%)	22.95 (%)	
0	8.49	7.93	7.00	6.25	5.66	5.41	7.00
5	9.10	8.40	7.50	6.70	6.06	5.78	10.43
10	9.85	9.19	8.12	7.25	6.55	6.26	15.54
15	10.79	10.07	8.89	7.94	7.18	6.86	23.15
20	12.00	11.20	9.89	8.83	7.98	7.63	30.49
25	13.59	12.68	11.20	10.00	9.04	8.64	51.38

Table 4. Levelized retail grid parity ratio for distributed captive PV power plants near villages in different years for different values of capacity utilization factor

Year	Capacity Utilization Factor (C_{uf})					
	14.58 (%)	15.63 (%)	17.69 (%)	19.81 (%)	21.92 (%)	22.95 (%)
0	1.21	1.13	1.00	0.89	0.81	0.77
5	0.87	0.81	0.72	0.64	0.58	0.55
10	0.63	0.59	0.52	0.47	0.42	0.40
15	0.47	0.44	0.38	0.34	0.31	0.30
20	0.35	0.32	0.29	0.26	0.23	0.22
25	0.26	0.25	0.22	0.19	0.18	0.17

Table 5. Levelized retail grid parity period for distributed captive PV power plants near villages for different values of capacity utilization factors

	Capacity Utilization Factor (C_{uf}) %					
	14.58 (%)	15.63 (%)	17.69 (%)	19.81 (%)	21.92 (%)	22.95 (%)
Levelized retail grid parity period (months)	37 months	25 months	zero months	zero months	zero months	zero months

4.2 Economics of distributed captive solar PV power plants near villages with variable installment loans

With variable installment loan, loan is paid back by variable monthly installments as compared to equated monthly installments. The initial investment, loan conditions as well as solar electricity output remains same. Only cost of financing will change and this will change the cost of solar electricity in different years. As before, based on prevailing prices in India, initial cost of PV power plant of few hundred kW_p capacity including land cost is about 60,000 Rs/kW_p. The O&M cost remains same. Calculations were carried out for same six values of capacity utilization factor and variable loan conditions. The economic criterion used is the cost of solar electricity at socket versus retail price of grid electricity.

The cost of solar electricity generation in distributed captive PV power plants for each of the six regions of India with different values of capacity utilization factor (C_{uf}) has been calculated. The results for distributed captive PV plants near villages for capacity utilization factor of 14.58% are given in Table 6. The variable annual repayments based on variable monthly installment turns out to be 4274 Rs/year in base year and increases to 28965 Rs/year in 25th year. As before, the annual solar electricity supplied at the socket in the base year by one kW_p PV plant with capacity utilization factor of 14.58% turns out to be 1022 kWh/kW_p-year and it reduces to 817 kWh/kW_p-year in 25th year. The cost of financing varies from 4.18 Rs/kWh at the time of installation to 35.45 Rs/kWh in 25th year. The O&M cost per unit of electricity varies from 0.68 Rs/kWh in base year to 3.82 Rs/kWh in 25th year. Adding cost of financing and O&M cost, the variable socket cost of solar electricity turns out to be 4.86 Rs/kWh in base year and increase to 39.27 Rs/kWh in 25th year. The retail price of grid electricity in the base year is 7.00 Rs/kWh with annual increase of 8%. Therefore, the retail price of grid electricity varies from 7.00 Rs/kWh in base year to 51.38 Rs/kWh in 25th year.

Table 6. Variable socket cost of solar electricity generated in distributed captive PV power plants near villages for capacity utilization factors of 14.58% versus retail price of grid electricity for different years

Time period (n) (years)	Annual repayment of loan (P_{le}) (Rs/yr)	Annual solar electricity generated ($E_o(n)$) (kWh/yr)	Annual electricity supplied at socket $E_s(n)$ (kWh/yr)	Cost of financing $C_f(n)$ (Rs/kWh)	O & M cost $O_m(n)$ (Rs/kWh)	Cost of solar electricity at socket $C_s(n)$ (Rs/kWh)	Projected retail price of grid electricity $C_{gr}(n)$ (Rs/kWh)	Vari-able retail grid parity ratio (R_d)
0	4274	1277	1022	4.18	0.68	4.86	7	0.69
5	5879	1226	981	5.99	0.96	6.95	10.43	0.67
10	8759	1175	940	9.32	1.35	10.67	15.54	0.69
15	13049	1123	899	14.52	1.91	16.43	23.15	0.71
20	19441	1073	858	22.66	2.7	25.36	34.49	0.74
25	28965	1022	817	35.45	3.82	39.27	51.38	0.76

The ratio of variable socket cost of solar electricity to retail price of grid electricity varies from 0.69 in base year to 0.76 in 25th year. This means that variable socket cost of solar electricity in village is 0.69 times that of grid electricity in base year and 0.76 times in 25th year. Similar results for capacity utilization factors of 15.63%, 17.69%, 19.81%, 21.92% and 22.95% were also calculated to determine the variable socket cost of solar electricity in villages. The results for variable socket cost of solar electricity in villages from distributed captive PV power plant near villages for different years and all the six values of capacity utilization factor versus retail price of grid electricity are shown in Table 7.

Table 7. Variable Socket cost of solar PV electricity from distributed captive PV power plants near villages versus retail price of grid electricity in different years for different values of capacity utilization factor

Year	Capacity Utilization Factor (C_{uf})						Projected retail price of grid electricity E_{gr} (n) (Rs/kWh)
	14.58 (%)	15.63 (%)	17.69 (%)	19.81 (%)	21.92 (%)	22.95 (%)	
0	4.86	4.54	4.01	3.58	3.24	3.10	7.00
5	6.95	6.49	5.73	5.12	4.63	4.42	10.43
10	10.67	9.95	8.80	7.86	7.10	6.78	15.54
15	16.43	15.32	13.53	12.08	10.92	10.43	23.15
20	25.36	23.65	20.91	18.66	16.87	16.11	30.49
25	39.27	36.64	32.35	28.88	26.11	24.95	51.38

Table 8 shows variable retail grid parity ratio i.e. ratio of variable socket cost of solar electricity to retail price of grid electricity in different years for different values of capacity utilization factor. Variable retail (socket) grid parity is attained when the value of variable retail grid parity ratio equals unity. It is apparent from this table that variable retail (socket) grid parity is attained at the time of installation for all the values of capacity utilization factors. Variable retail grid parity period is obtained by interpolation of these results and these values are shown in Table 9. Obviously, the variable retail grid parity period is zero for all the six values of capacity utilization factors.

Table 8. Variable retail grid parity ratio for distributed captive PV power plants in different years for different values of capacity utilization factor

Year	Capacity Utilization Factor (C_{uf})					
	14.58 (%)	15.63 (%)	17.69 (%)	19.81 (%)	21.92 (%)	22.95 (%)
0	0.69	0.65	0.57	0.51	0.46	0.44
5	0.67	0.62	0.55	0.49	0.44	0.42
10	0.69	0.64	0.57	0.51	0.46	0.44
15	0.71	0.66	0.58	0.52	0.47	0.45
20	0.74	0.69	0.61	0.54	0.49	0.47
25	0.76	0.71	0.63	0.56	0.51	0.49

Table 9. Variable retail grid parity period for distributed captive PV power plants near villages for different values of capacity utilization factors

	Capacity Utilization Factor (C_{uf}) %					
	14.58 (%)	15.63 (%)	17.69 (%)	19.81 (%)	21.92 (%)	22.95 (%)
Variable retail grid parity period (months)	zero months	zero months	zero months	zero months	zero months	zero months

4.3 Comparison of distributed PV power plants financed with equated and variable installment loans

In solar PV power plants, the initial investment required is very high while O&M cost is small and fuel cost is zero. As such the cost of financing is major component of the cost of generation of solar electricity. Therefore, different types of loans with different modes of repayment of loan have significant effect on the cost competitiveness with grid electricity. Economic analysis has been performed for distributed captive PV power plants with two types of loans. Therefore, we have economic comparison of two cases namely.

- Distributed captive PV power plants financed with equated installment loan
- Distributed captive PV power plants financed with variable installment loan

The values of levelized and variable retail grid parity ratios at the time of installation for distributed captive PV power plants with equated loan installations and variable loan installments respectively for different values of capacity utilization factors are shown in Figure 1. This figure shows that with equated installment loans, levelized retail grid parity is not attained in base year for distributed captive PV power plants near villages in two regions with capacity utilization factors of 14.58% and 15.63% because value of levelized retail grid parity is more than one. However, solar electricity from such PV power is cost competitive with grid electricity in other four regions. It is apparent that with variable installment loans solar electricity from such PV power plants is cheaper than grid electricity in base year in all six regions of India.

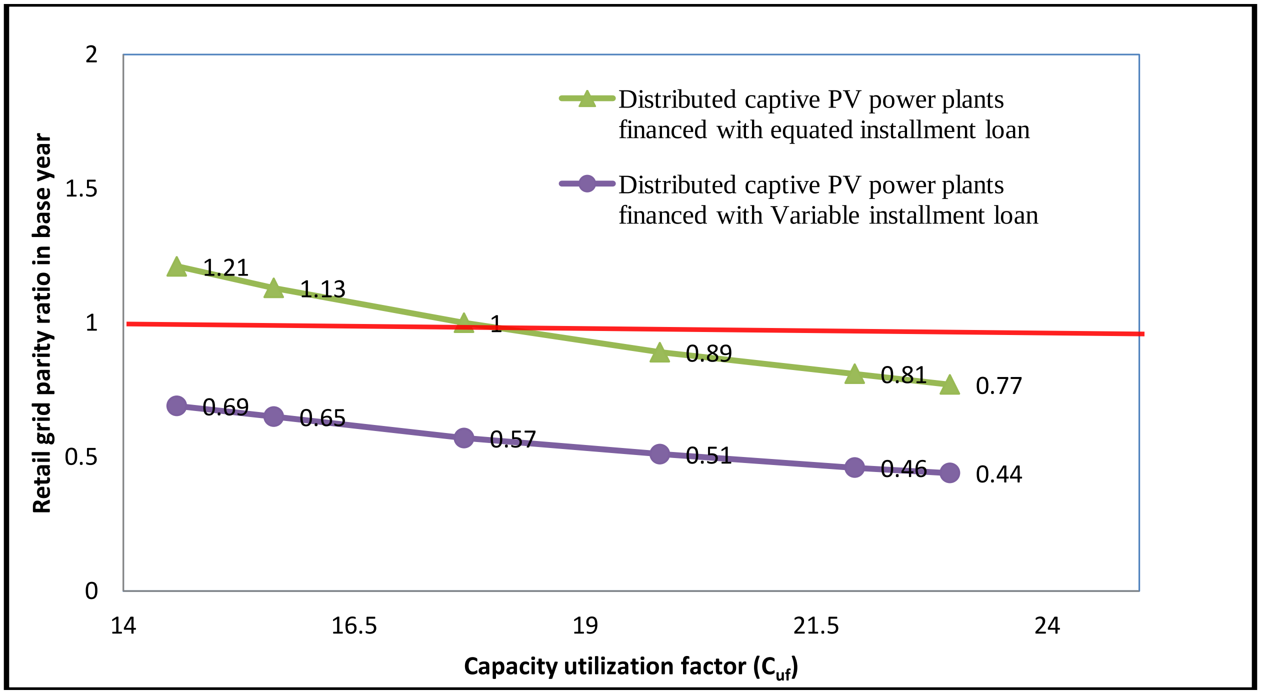

Figure 1: Comparison of levelized and variable retail grid parity ratio in base year for distributed captive solar PV plants for different values of capacity utilization factor with equated and variable installment loans.

The values of levelized and variable retail grid parity period for distributed captive PV power plants near villages with equated and variable installment loans respectively are given in Table 10. With equated installment loans, the levelized retail grid parity period is 37 months and 25 months for capacity utilization factor of 14.58% and 15.63% respectively. Hence, with equated installment loans subsidies are required to install such PV power plants in these two regions while no subsidies are required in other four regions of India. It may be noted that with variable installment loans, grid parity period is zero in all the six regions of India thereby indicating that solar electricity is cheaper than grid electricity in base year and no subsidies are required.

Table 10. Levelized and variable retail grid parity period of distributed captive solar PV power plants for different values of capacity utilization factors for different systems

Type of PV power plant	Capacity Utilization Factor (C_{uf})					
	14.58 (%)	15.63 (%)	17.69 (%)	19.81 (%)	21.92 (%)	22.95 (%)
Distributed captive PV power plants near villages with equated installment loan	37 months	25 months	zero months	zero months	Zero months	Zero months
Distributed captive PV power plants near villages with variable installment loan	zero months	Zero months	zero months	zero months	Zero months	Zero months

V. CONCLUSIONS

1. Cities require large scale utility-scale PV power plants to meet the large electric load of concentrated consumers in the cities. However, distributed captive PV power plants tend to be more suitable for distributed villages with smaller electric load because both sunshine and land are available on the periphery of villages.

2. With equated installment loans, distributed captive PV power plants near villages need subsidies in two regions of India with capacity utilization factor of 14.58% and 15.63%.

3. With equated installment loans, distributed captive PV power plants near villages can be installed without subsides in four regions of India with capacity utilization factor of 17.69% and above. In these four regions the distributed captive PV power plants will have market driven growth without subsidies.

4. With variable installment loans, distributed captive PV power plants near villages can be installed without subsides in all the six regions of India. Therefore, such PV power plants will have market driven growth without subsidies throughout India.

5. The financial barrier to market driven growth of solar electricity is higher cost of solar electricity vis-à-vis grid electricity at the time of installation of PV power plant though it becomes cheaper after few years. This financial barrier can be eliminated by giving variable installment loans instead of equated installment loans.

6. Policy change is required for the banks to start giving variable installment loans for unbridled market driven growth of solar PV power plants without any subsidies.

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