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# Technical Barrier to Market Driven Growth of Solar Electricity for Rural Areas of India

Harbans Singh[1], Harmeet Singh[2] and Parm Pal Singh[3]

[1] *Research Scholar, IK Gujral Punjab Technical University, Kapurthala, Punjab, India.*

[2] *Associate Professor, Department of Mechanical Engineering, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India.*

[3] *Former Senior Research Engineer, School of Renewable Energy Engineering, Punjab Agricultural University, Ludhiana, Punjab, India.*

**Abstract: :** Solar electricity is growing fast during last few years but it is not market driven growth because it is being subsidized by the governments. Solar energy is distributed energy source and solar PV power plants are modular in design. As such solar PV systems can be installed as small distributed captive PV systems of few $kW_p$ capacities in or near the premises of the distributed users as well as large utility-scale PV plants of $MW_p$ capacities. At present, utility-scale PV power plants are being used to supply solar electricity to concentrated consumers in the cities as well as distributed consumers in villages. In this paper, a new concept of distributed captive PV power plants of few hundred $kW_p$ capacities near the villages has been introduced. One such captive PV power plant may be installed near a big village or for cluster of smaller villages. It may be noted that market value of solar electricity from utility-scale PV plant is lower than the market value of solar electricity from distributed captive PV power plants near the villages. An illustration shows that distributed captive PV plants can be installed without subsidies in four regions of India with capacity utilization factor of 17.69% or above. However, utility-scale PV power plants require subsidies in all the six regions of India. Therefore, technical barrier to market driven growth of solar electricity in rural areas is the policy of installing utility-scale PV power plants to supply solar electricity to distributed villages in the rural areas.

**Keywords:** Distributed captive PV plants, Grid parity, Market driven growth, Rural PV plants, Technical barrier.

## 1. Introduction

The adverse effects of global warming are apparent. It is well known that the main cause of global warming is significant increase in carbon dioxide in the atmosphere. The major culprits are carbon based fuels such as coal and oil. It is essential to replace these fuels with renewable energy. Solar energy is first among various renewable energy sources. Due to its large potential, solar energy is the only renewable energy source capable of replacing coal and oil. Solar photovoltaic (PV) technology is already a commercially matured technology. During last ten years the cost of solar PV panels has decreased drastically and solar electricity has attained grid parity at many places around the world. Large scale market driven growth of solar electricity without subsidies is required for fast economic growth without the ill effects of global warming.

In the present scenario of electricity market, utility-scale hydro power plants, coal based thermal power plants and few nuclear power plants sell their electricity to utility companies or power exchange at wholesale price. Transmission companies purchase bulk electricity and carry it to large number of substations at 66/132 KV. The distribution companies distribute this electricity from substations to the premises of retail customers in the cities, towns and villages and sell it at retail price. The present electric grid network has developed in this way due to characteristics of hydro and coal based thermal power plants. Both hydro and coal based thermal power plants are always installed as large scale centralized power plants with capacity in the range of few hundred megawatts (MW) to few thousand megawatts (MW) because these power plants enjoy significant economy of scale i.e. cost of electricity reduces significantly with increase in capacity of the power plant. This is true for nuclear power plants also. On the other hand, the characteristics of solar PV power plants are almost opposite. The initial investment per unit of solar electricity does not reduce significantly with increase in capacity. Lack of economy of scale is due to the fact that economy of scale has shifted to automated factories manufacturing PV panels and inverters. The capacity of solar PV power plant also has different meaning than conventional hydro and thermal power plants. A solar PV plant is a cluster of smaller independent PV plants depending upon the capacity of inverters. For example, a one $MW_p$ plant using 500 kW inverters is a cluster of two 500 $kW_p$ plants. With micro inverters, each PV panel is independent PV power plant in itself. These smaller PV power plants can be installed at

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different places also because the fuel (sunshine) is supplied to the premises of the retail customers by nature every day. The transmission and distribution costs of solar electricity decrease as solar electricity is generated closer and closer to the users. Operation and maintenance costs are quite small. Therefore solar PV power plants can be installed in wide range of capacities ranging from few $kW_p$ to few hundred $MW_p$ in wide spread area. In other words, solar PV systems can be installed as large utility-scale solar PV power plants which generate solar electricity far away from the users as well as small scale distributed captive rooftop solar PV systems which generate solar electricity in the premises of the user. In fact it tends to be economical to install large number of distributed captive solar PV power systems closer to the consumers. This is so because the market value of solar electricity generated in distributed captive PV systems is equal to the retail price of grid electricity while the market value of solar electricity generated in utility-scale PV plants is equal to the wholesale price of grid electricity. Like all other products, the retail price of grid electricity is much more than its wholesale price. Hence, it is essential to select suitable PV systems for different applications. Improper selection of utility-scale PV plants to supply solar electricity to distributed villages constitutes technical barrier to market driven growth of solar electricity in developing countries where majority of the population lives in villages. In this paper, this technical barrier has been investigated and solutions have been provided. Suitable policy changes required to implement these solutions have been suggested.

## 2. Present Scenario of Solar Electricity

The present scenario of solar electricity regarding technical aspects has been discussed. Solar PV systems need to be connected to the existing public electric grid to overcome the problems of variable and intermittent nature of solar energy. Based on the mode of connection to electric grid, solar PV systems can be classified in two categories i.e. off-grid and grid-connected. Grid-connected solar PV systems can be further classified in two categories as these can be connected to grid on supply side as well as demand side.

### 2.1 Off-grid solar PV systems

Off-grid solar PV power systems for un-electrified villages have been subject of investigation of number of investigators. Solar home systems (SHS) consisting of a small solar panel, charge controller and battery along with one or two light bulbs have been installed and studied [1, 2]. Solar home systems have failed at many places because the users were unable to maintain the batteries. In few villages, central charging stations were provided for charging and maintaining batteries instead of providing PV panels to each household. Solar PV mini-grid for villages has been investigated by number of authors [3-7]. Solar PV mini-grid consists of number of PV panels, charge controller and set of batteries. Such systems are useful for un-electrified villages but provide lighting only for 4-5 hours in the evening. The concept of hybrid mini-grid consisting of solar PV panels, wind mill, biogas plant and diesel gen-set has also been studied [8-10]. However such systems rarely work in practice because different energy sources may not be available at one place. Decentralized grid-connected and off-grid systems for villages have been discussed [11-14].

In general, off-grid solar PV systems are expensive due to additional cost of batteries to provide energy storage and larger capacity of PV panels in order to have inbuilt autonomy of 2-3 days to overcome the problem of cloudy days. Batteries are most expensive energy storage and involve recurring cost also as these need to be replaced every 4-5 years. Also, it is not possible to use 100% of solar electricity in such systems due to mismatch between the electricity consumption and solar electricity generation. Only small systems of few watt-peak ($W_p$**)** or kilowatt-peak ($kW_p$) can be used due to limited electricity storage in the batteries. As such off-grid PV systems are recommended as pre-electrification option for very remote villages with no possibility of grid extension in near future. Off-grid solar PV systems have not been discussed further in this paper because such small PV systems do not lead to meaningful economic growth in the villages due to smaller capacities.

### 2.2 Solar PV systems connected to grid on supply side

Utility-scale (centralized) solar PV power plants of few hundred megawatt-peak ($MW_p$) capacities can be installed just like coal based thermal power plants. These are connected to grid on supply side to feed bulk power to the electric grid. Such solar PV power plants are located far away from the cities due to large land requirement and higher cost of land near the cities. It may be noted that conventional utility-scale power plants have capacity of few hundred to few thousand megawatts, while capacity of utility-scale solar PV power plants tends to be much lower i.e. few $MW_p$ to few hundred $MW_p$. In this paper all the solar PV power plants connected to grid on supply side are considered as utility-scale irrespective of the capacity because such PV power plants use grid to carry solar electricity to the consumers.

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Utility-scale PV power plants have been investigated by number of investigators. Performance evaluation of 5 $MW_p$ utility-scale PV power plant for 5 years indicates the average annual performance ratio of 0.8 and average annual final yield of 1707 $kWh/kW_p$ [15]. Performance evaluation of 10 $MW_p$ photovoltaic power plants in India shows the annual performance ratio of 86.12% and capacity utilization factor of 17.68% [16].

In general, there are no technological problems and such plants can be installed in a short period of 12-18 months and these can be easily integrated in the existing electric grid without any change. Moreover there is 100% utilization of solar electricity. It is essential to install large solar PV power plants to meet the large concentrated demand of cities and towns. Economically, such solar PV power plants need to compete with thermal power plants and sell their electricity to the nearest power exchange or utility at wholesale price. In other words the market value of solar electricity generated in these PV power plants is equal to the wholesale price of grid electricity and this is a disadvantage. This is so because large solar PV power plants do not make use of the fact that fuel (sunshine) is available virtually everywhere.

**2.3 Solar PV systems connected to grid on demand side**

Solar PV systems connected to grid on demand side are also called captive power plants because such systems supply electricity primarily to captive consumers on the demand side using net-meters. Captive grid-connected rooftop solar PV systems are being installed to tap solar energy falling on the rooftops of residential, commercial and industrial buildings. The capacity of such systems is small (few $kW_p$) depending upon the availability of suitable rooftop area. The captive users have first preference over the solar electricity generated in a given rooftop PV system. Surplus solar electricity flows to the grid and deficit flows from the grid through net- meter. The captive users pay for the difference between the import and export of electricity through net- meter. In this way there is 100% utilization of solar electricity generated on the rooftop.

Rooftop solar PV systems have been investigated by number of authors. Solar PV systems installed on the roofs and facades of buildings in a university in Italy provided more than 80% of its electricity needs [17]. Performance of grid-connected rooftop PV system of 2 $kW_p$ was experimentally evaluated in Serbia. The annual specific yield factor was found to be 1161.7 $kWh/kW_p$ while performance ratio was 93.6% [18]. Performance ratio of two rooftop PV systems consisting of amorphous silicon and mono-crystalline silicon wafer panels in Italy was found to be 89.1% and 82.7% respectively [19]. Performance evaluation of two rooftop PV systems on Kuwaiti schools show performance ratio between 0.74 and 0.85 and annual average daily final yield of 4.5 $kWh/kW_p$/day. Also an automated cleaning system was used to clean PV panels periodically [20].

Rooftop solar PV systems are becoming quite popular. Such systems can be used in both urban and rural areas. The biggest advantage of rooftop solar PV system is that solar electricity is generated in the premises of the user thus eliminating all the transmission and distribution costs. Therefore, the user is paid variable retail price of grid electricity. In other words the market value of solar electricity generated in rooftop solar PV system is equal to the retail price of grid electricity. This is so because such a system makes maximum use of the fact that solar energy is available at the doorstep of every building. The only limitation to the magnitude of solar electricity generated by the rooftop PV systems is the limited availability of suitable rooftop area.

It may be noted that rooftop PV systems are already selling solar electricity to utility companies at retail price of grid electricity using net-meters. Rooftop PV systems have not been discussed further in this paper because such systems do not suffer from the technical barrier to market driven growth discussed in this paper.

## 3. Technical Barrier to Market Driven Growth of Solar Electricity in Rural Areas

In this paper, a technical barrier to market driven growth of solar electricity in rural areas has been identified and investigated. This technical barrier to rapid market driven growth of solar electricity in developing countries is the improper selection of utility-scale solar PV power plants connected to grid on supply side to meet small distributed electric load of the villages. In developing countries, where majority of the population still lives in villages, solar electricity can be generated near the villages as both land and sunshine are available in plenty on the periphery of most of the villages. In this paper the authors suggest a new concept of installing distributed grid-connected captive solar PV power plants near the villages. Such captive PV power plants are to be connected to grid on demand side to supply solar electricity to captive consumers in the villages. In un-electrified villages, grid can be extended and then grid-connected captive power plants can be installed while in electrified villages such captive PV power plants can be installed immediately.

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## 4. 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:

### 4.1 Capital recovery factor

The capital recovery factor ($C_{rf}$) for amortized loan to be paid back in equated monthly installments (EMIs) is given by equation (1). The value of capital recovery factor can be determined for given monthly interest rate (i) and number of monthly installments per year (m).

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

### 4.2 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 equation (2).

$$P_{le} = 12\,C\,C_{rf} \quad \text{(Rs/year)} \quad \text{... (2)}$$

### 4.3 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 (3).

$$E_{ob} = C_{uf}\,8760/100 \quad \text{(kWh/kW}_p\text{/year)} \quad \text{... (3)}$$

The annual solar electricity output during $L^{th}$ year ($E_o(L)$) and annual reduction in electricity output ($E_{red}$) are given by equations (4) and (5) respectively. Then electricity output for a given year ($E_o$ (n)) is obtained from equation (6).

$$E_o\,(L) = R_m\,E_{ob} \quad \text{(kWh/year)} \quad \text{... (4)}$$

$$E_{red} = [E_{ob} - E_o\,(L)] / L \quad \text{(kWh/year)} \quad \text{... (5)}$$

$$E_o\,(n) = E_{ob} - n\,E_{red} \quad \text{(kWh/year)} \quad \text{...(6)}$$

### 4.4 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 (7).

$$C_f\,(n) = P_{le} / E_o(n) \quad \text{(Rs/kWh)} \quad \text{...(7)}$$

### 4.5 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 (8).

$$O_{mb} = Omc / Eob \quad \text{(Rs/kWh)} \quad \text{... (8)}$$

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 (9).

$$O_m\,(n) = O_{mb}\,(1+O_e)^{n} \quad \text{(Rs/kWh)} \quad \text{...(9)}$$

### 4.6 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 (10)

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$$C_g(n) = C_f(n) + O_m(n) \quad \text{(Rs/kWh)} \quad ...(10)$$

**4.7 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 distribution company. Therefore the units of solar electricity supplied at socket in $n^{th}$ year $E_s(n)$ is given by equation (11).

$$E_s(n) = E_o(n)(1-f) \quad \text{(kWh)} \quad ...(11)$$

Therefore, the socket cost of solar electricity in a village from distributed captive power plant near the village is given by equation (12)

$$C_s(n) = P_{le} / E_s(n) \quad \text{(Rs/kWh)} \quad ...(12)$$

**4.8 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 (13) and equation (14) respectively.

$$C_{gw}(n) = C_{gwb}(1+e)^n \quad \text{(Rs/kWh)} \quad ...(13)$$

$$C_{gr}(n) = C_{grb}(1+e)^n \quad \text{(Rs/kWh)} \quad ...(14)$$

**4.9 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 grid parity ratio 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.

**4.10 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.

## 5. Results and Discussion

At present, most of the grid electricity is being supplied by utility-scale coal based thermal power plants followed by hydro power plants. Since last few years large number of utility-scale solar PV power plants with capacity in the range of few $MW_p$ to 500 $MW_p$ each are being installed. Such utility-scale PV power plants are installed far away from the population due to large land requirement at the rate of 5 acres per $MW_p$. These PV plants supply solar electricity to the grid just like coal based thermal power plants. The market value of solar electricity supplied by utility-scale PV plants is equal to wholesale price of grid electricity.

In this paper, it has been suggested by the authors that being distributed energy source, large number of

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smaller distributed solar PV power plants tend to be more suitable for distributed villages rather than large utility-scale PV power plants. Also it may be noted that market value of solar electricity generated by distributed PV power plants near the villages is equal to retail price of grid electricity minus the distribution cost in a village.

The market driven growth of any technology depends on its economics vis-à-vis other competing technologies. Therefore the economics of utility-scale PV power plants and distributed captive PV power plants near villages needs to be determined vis-à-vis market value of solar electricity generated by these power plants. In this paper grid parity period i. e. the time required to reach grid parity has been used as economic indicator to compare utility-scale PV power plants with distributed captive PV power plants near villages to supply electricity in rural areas of India. Further, a solar PV power plant with zero grid parity period will have market driven growth without any subsidies.

**5.1 Economics of utility-scale solar PV power plants**

The economics of utility-scale solar PV plants is based mainly on the data supplied by Central Electricity Regulatory Commission (CERC) of India [21]. The economic comparison is based on cost of solar electricity versus wholesale price of grid electricity.

As per CERC report of year 2015-16 [21], the initial investment (C) required to install utility-scale PV power plant in India is 530 x$10^5$ Rs/MWp. This includes 25×$10^5$ Rs/MWp as the cost of 5 acres of land at the rate of 5×$10^5$ Rs/acre. The only running expenses are operation and maintenance (O&M) cost. The O&M cost per unit capacity ($O_{mc}$) is given as 7×$10^5$ Rs/MWp with annual increase ($O_e$) of 6%. 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. The capacity utilization factor in different regions varies from 14.58% to 22.95%. The present wholesale price of grid electricity sold in India varies from 3-4 Rs/kWh. So the present wholesale price of grid electricity is taken as 3.5 Rs/kWh. The annual rate of increase in the price of grid electricity has been taken as 8% based on information supplied by Punjab Energy Development Agency (PEDA) [22].

The costs of solar electricity generation in utility-scale PV power plant for each of the six regions of India with different values of capacity utilization factors have been calculated. The results for capacity utilization factor of 14.58% are given in Table 2. Initial investment including land cost is 53000 Rs/KWp. At present, banks give amortized loan with repayment through equated monthly installments.

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 |

Table 2
Cost of generation of solar electricity in utility-scale PV power plant for capacity utilization factor of 14.58% versus wholesale price of grid electricity for different years.

| **Time period** **n** **(years)** | **Annual repayments of loan** $P_{le}$ **(Rs/yr)** | **Annual electricity supplied** $E_o(n)$ **(kWh/yr)** | **Cost of financing** $C_f(n)$ **(Rs/kWh)** | **O & M cost** $O_m(n)$ **(Rs/kWh)** | **Cost of solar electricity** $C_g(n)$ **(Rs/kWh)** | **Projected wholesale price of grid electricity** $C_{gw}(n)$ **(Rs/kWh)** | **Whole-sale grid parity ratio** $R_u$ |
|---|---|---|---|---|---|---|---|
| 0 | 7054 | 1277 | 5.52 | 0.55 | 6.07 | 3.5 | 1.73 |
| 5 | 7054 | 1226 | 5.75 | 0.77 | 6.52 | 5.21 | 1.25 |
| 10 | 7054 | 1175 | 6.00 | 1.08 | 7.08 | 7.77 | 0.91 |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15 | 7054 | 1123 | 6.28 | 1.53 | 7.81 | 11.57 | 0.68 |
| 20 | 7054 | 1073 | 6.57 | 2.16 | 8.73 | 17.24 | 0.51 |
| 25 | 7054 | 1022 | 6.90 | 3.06 | 9.96 | 25.69 | 0.39 |

The interest rate of 12.75% has been used [21].The loan period has been taken as equal to performance warranty period given by the manufacturers i.e. 25 years. Using above data the equated monthly installments turn out to be 587.83 Rs/month resulting in annual repayments ($P_{le}$) of 7054 Rs/year. This annual repayment of loan 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/kWp-year. As per the performance warranty given by the manufacturers, the solar electricity output in $25^{th}$ year will not be less than 80% of the solar electricity output at the time of installation i. e. maximum possible reduction of 20% in 25 years. Distributing the 20% reduction linearly, the annual reduction in output turns out to be 0.8% This means that solar electricity output of 1277 kWh/kWp-year at the time of installation reduces to 1022 kWh/kWp-year in $25^{th}$ year. Therefore the cost of financing ($C_f$ (n)) varies from 5.52 Rs/kWh at the time of installation to 6.90 Rs/kWh in $25^{th}$ year. The O&M cost in the base year as per CERC report is 700 Rs/kWp and it increases at annual rate of 6%. Therefore, the O&M cost per unit of electricity $O_m$(n) varies from 0.55 Rs/kWh in base year to 3.06 Rs/kWh in $25^{th}$ year. Adding cost of financing and O&M cost, the cost of generation of solar electricity Cg(n) turns out to be 6.07 Rs/KWh in the base year and increase to 9.96 Rs/kWh in $25^{th}$ year. The wholesale price of grid electricity in the base year ($C_{gwb}$) is 3.50 Rs/kWh with annual increase of 8%. Therefore, the wholesale price of grid electricity varies from 3.5 Rs/kWh in base year to 25.69 Rs/kWh in $25^{th}$ year. The 'wholesale grid parity ratio' i. e. the ratio of cost of solar electricity to wholesale price of grid electricity ($R_u$) varies from 1.734 in base year to 0.387 in $25^{th}$ year. This means that the cost of solar electricity is 1.734 times that of grid electricity in base year. However, this ratio decreases to 0.387 in $25^{th}$ year indicating that solar electricity is much cheaper than grid electricity. Similar results for capacity utilization factors of 15.63%, 17.69%, 19.81%, 21.92% and 22.95% were also calculated to determine the cost of generation of solar electricity. The results for cost of solar electricity from utility-scale PV power plant for different years and all the six values of capacity utilization factor versus wholesale price of grid electricity are shown in Table 3.

Table 3
Cost of generation of solar PV electricity (Rs/kWh) from utility-scale PV power plants versus wholesale price of grid electricity in different years for different values of capacity utilization factors

| **Year** | **Capacity Utilization Factor ($C_{uf}$)** | | | | | | **Projected wholesale price of grid electricity $C_{gw}$(n)** |
|---|---|---|---|---|---|---|---|
| | **14.58 (%)** | **15.63 (%)** | **17.69 (%)** | **19.81 (%)** | **21.92 (%)** | **22.95 (%)** | **(Rs/kWh)** |
| 0 | 6.07 | 5.66 | 5.00 | 4.46 | 4.03 | 3.86 | 3.5 |
| 5 | 6.52 | 6.09 | 5.37 | 4.80 | 4.34 | 4.14 | 5.21 |
| 10 | 7.08 | 6.61 | 5.84 | 5.22 | 4.71 | 4.50 | 7.77 |
| 15 | 7.81 | 7.28 | 6.43 | 5.74 | 5.19 | 4.96 | 11.57 |
| 20 | 8.73 | 8.14 | 7.19 | 6.43 | 5.81 | 5.55 | 17.24 |
| 25 | 9.96 | 9.20 | 8.21 | 7.33 | 6.62 | 6.33 | 25.69 |

Table 4 shows wholesale grid parity ratio ($R_u$) i. e. the ratio of cost of generation of solar electricity to wholesale price of grid electricity in different years for different values of capacity utilization factor. Wholesale grid parity is attained when the value of wholesale grid parity ratio i.e. ratio of generation cost of solar electricity to grid electricity equals unity. It is apparent from this table that wholesale grid parity is attained somewhere between $5^{th}$ and $10^{th}$ year for capacity utilization factors of 14.58%, 15.63% and 17.69%, while the wholesale grid parity is attained before $5^{th}$ year for capacity utilization factors of 19.81%, 21.92% and 22.95%.

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Table 4
Wholesale grid parity ratio for utility-scale 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 | 1.734 | 1.617 | 1.428 | 1.274 | 1.151 | 1.102 |
| 5 | 1.251 | 1.168 | 1.030 | 0.921 | 0.833 | 0.794 |
| 10 | 0.911 | 0.850 | 0.751 | 0.671 | 0.606 | 0.579 |
| 15 | 0.675 | 0.629 | 0.555 | 0.496 | 0.448 | 0.428 |
| 20 | 0.506 | 0.472 | 0.417 | 0.372 | 0.337 | 0.321 |
| 25 | 0.387 | 0.361 | 0.319 | 0.293 | 0.257 | 0.246 |

The grid parity period i.e. the time required to reach grid parity is obtained by interpolation of these results and these values are shown in Table 5. Grid parity period is 104 months, 92 months and 67 months for capacity utilization factors of 14.58%, 15.63% and 17.69% respectively. For capacity utilization factors of 19.81%, 21.92% and 22.95%, the grid parity period is 47 months, 29 months and 20 months respectively. It is apparent that the value of grid parity period for six regions in India varies from 104 months to 20 months. Obviously grid parity period decreases with increase in capacity utilization factor. Further, utility-scale PV power plants have not attained grid parity at the time of installation of plant anywhere in India. Therefore such PV plants cannot have market driven growth because government subsidies are required at the time of installation of utility-scale PV power plants.

Table 5
Grid parity period for utility-scale PV power plants for different values of capacity utilization factors

| | Capacity Utilization Factor ($C_{uf}$) | | | | | |
|---|---|---|---|---|---|---|
| | **14.58 (%)** | **15.63 (%)** | **17.69 (%)** | **19.81 (%)** | **21.92 (%)** | **22.95 (%)** |
| Grid parity period (months) | 104 months | 92 months | 67 months | 47 months | 29 months | 20 months |

**5.2 Economics of distributed captive solar PV power plants near villages**

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 [21]. The initial cost of smaller distributed PV plants of few hundred $kW_p$ capacity is little higher than utility-scale PV plants of 10-500 $MW_p$ capacity. The higher initial cost is 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 O&M cost remains same. Calculations were carried out for same six values of capacity utilization factor and same loan conditions. In other words the only change in conditions is initial cost of 60,000 Rs/$KW_p$ for distributed PV plants as compared to 50,000 Rs/$kW_p$ for utility-scale PV plants. 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 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. As before, 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

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distribution loses in villages have been taken as 20% based on data supplied by Punjab State Power Corporation Limited [23]. 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 $25^{th}$ year. The cost of financing varies from 7.81 Rs/kWh at the time of installation to 9.76 Rs/kWh in $25^{th}$ year. The O&M cost per unit of electricity varies from 0.68 Rs/kWh in base year to 3.82 Rs/kWh in $25^{th}$ 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 $25^{th}$ 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 $25^{th}$ year. The retail grid parity ratio i.e. ratio of socket cost of solar electricity to retail price of grid electricity varies from 1.21 in base year to 0.26 in $25^{th}$ year. This means that socket cost of solar electricity in village is 1.21 times that of grid electricity in base year. However, this ratio decreases to 0.26 in $25^{th}$ 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 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 6
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)** | **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 7
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 8 shows retail grid parity ratio i.e. ratio of socket cost of solar electricity to retail price of grid electricity in different years for different values of capacity utilization factor.The retail (socket) grid parity is

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attained at the time of installation for capacity utilization factors of 17.69%, 19.81%, 21.92% and 22.95%. Grid parity period is obtained by interpolation of these results and these values are shown in Table 9. Obviously, the grid parity period decreases with increase in capacity utilization factor. 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 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 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 retail (socket) grid parity at the time of installation and do not require government subsidies resulting in market driven growth.

Table 8
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 9
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 (%)** |
| Grid parity period (months) | 37 months | 25 months | zero month | zero month | zero month | zero month |

**5.3 Comparison of utility-scale and distributed captive PV power plants**

The utility-scale PV power plants and distributed captive power plants near the villages have an advantage and disadvantage relative to each other. The initial investment for utility-scale PV plant is lower due to larger volume of purchase. However the market value of electricity generated in utility-scale PV plants is lower (wholesale price of grid electricity) than that of distributed captive PV power plant (retail price of grid electricity minus the distribution cost). Therefore, only economic analysis taking all these facts into account can show which of these systems is economical. For economic comparison, the time periods in which these power plants attain grid parity are determined. The plant which attains grid parity earlier tends to be more economical.

The values of grid parity period for utility-scale and distributed captive PV power plants for different values of capacity utilization factors are shown in Table 10 and Figure 1.

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Table 10
Grid parity period of utility-scale and distributed captive solar PV power plants for different values of capacity utilization factors

| **Type of PV power plant** | **Capacity Utilization Factor ($C_{uf}$)** | | | | | |
|---|---|---|---|---|---|---|
| | **14.58 (%)** | **15.63 (%)** | **17.69 (%)** | **19.81 (%)** | **21.92 (%)** | **22.95 (%)** |
| Utility- scale | 104 months | 92 months | 67 months | 47 months | 29 months | 20 months |
| Distributed captive | 37 months | 25 months | zero month | zero month | zero month | zero month |

It is apparent that grid parity period for distributed captive PV plants is lower for all the six regions of India i.e. for all the values of capacity utilization factors, indicating that such plants are more economical. Further utility-scale PV plants require subsidy to install in all the six regions because grid parity period is more than unity for all the six regions. However distributed captive PV plants can be installed without subsidy in four regions of India with capacity utilization factor equal to or above 17.69%. Hence, we should go for distributed captive PV power plants near villages for rural area and such PV plants will have fast market driven growth in most of India.

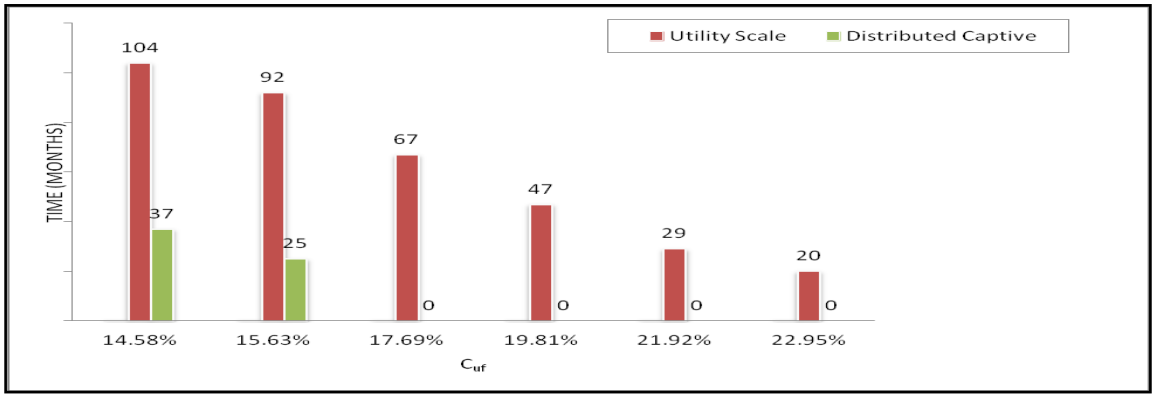


Fig. 1
Comparison of grid parity period for utility-scale and distributed captive PV plants for different values of capacity utilization factors

## 6. Conclusions

1. Cities require large scale utility-scale PV power plants to meet the large electric load of concentrated consumers in the cities. However, for distributed villages with smaller electric load, it is possible to use utility-scale PV power plants as well as smaller distributed captive PV power plants near the villages.
2. The utility-scale PV power plants of large capacities have lower initial investment as compared to smaller distributed captive PV power plants. However market value of solar electricity generated in utility-scale PV plant (wholesale price of grid electricity) is lower than that of distributed captive PV power plants near villages (retail price of grid electricity minus distribution cost in village)
3. Utility-scale PV power plants cannot be installed without subsides in any of the six regions of India because their wholesale grid parity ratio in base year is more than unity for all the six values of capacity utilization factors.
4. 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.
5. The distributed captive PV power plants are always more economical than utility-scale PV power plants as indicated by their lower grid parity ratio.
6. The technical 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 technical barrier has been eliminated for distributed captive PV power plants in four regions of India.
7. Policy change is required to give first preference to installation of distributed captive PV power plants

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near villages in rural area. In other words distributed energy sources like solar energy should be used through distributed captive PV power plants for consumers in distributed villages.

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