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Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city ☆

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ABSTRACT

In this paper, the potential and the cost-effectiveness of a solar photovoltaic power plant for meeting the energy demand of garment zone at Jaipur (India) is analyzed. Also, the energy demand of garment zone for year 2011has been estimated (2.21 MW) and the design of the solar PV power plant of 2.5 MW capacity has been proposed, which requires about 13.14 acres of land area. Looking at the scarcity and cost of the land near the city, an off-site proposal for the power plant has also been considered and compared with the on-site option. For the on-site solar PV power plant internal rate of return (IRR) is 11.88%, NPV @ 10% discount rate is 119.52 million INR, simple payback period is 7.73 years and discounted payback period @10% is 15.53 years, while for the off-site power plant IRR is 15.10%, NPV is 249.78 million INR, simple payback period is 6.29 years and discounted payback period is 10.14 years. Levelized cost of energy is Rs. 14.94 and Rs. 11.40 per kW h for on-site and off-site solar PV plants respectively @ 10% discount rate, which is quite attractive.

1. Introduction

Garment zone of Sitapura industrial area comprises of 44 industries and the main product of the zone is cotton cloth. These industries use sewing machines, interlocking machines, hydro machines, washing machines and drier machines, which utilize electricity while power presses consume steam. Electricity is also needed for lighting gadgets, fans and air conditioners. Here electricity is outsourced from the state electricity grid and steam is produced locally by diesel fired boilers. Industries also have diesel generators as a standby power supply source.

The average energy demand of the garment zone was 1.84 MW_e in 2011 and it varied monthly. These days getting a continuous and uninterrupted supply of energy has become the largest problem for industries, especially for the garment sector, where production gets affected by frequent power cuts. The backup diesel generators have a very high operation cost and are not a clean source of energy either. So there is great need for a sustainable and clean source of energy; solar energy is the largest available carbon-neutral renewable energy source which can meet the energy demand of garment zone.

A 5 MW SPV power plant was designed [1] for 50 cities of Iran, using RETScreen software and the highest capacity factor was found at Bushehr and lower at Anzali, i.e. 26.1% and 16.5% respectively with a mean capacity factor of 22.27%. A computer program was designed [2] for quick evaluation and optimization of fuel saving, battery lifetime, investment costs, and the total annual cost of the project for a 35 kW hybrid PV–diesel power plant along with the feasibility study under climatic conditions of southern Algeria.

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A viability analysis [3] of a 10 MW PV-grid connected power plant taking 29 metrological sites in Egypt was carried out. Renewable energy production and capacity factor was found to be minimum at Safaga and maximum at Wahat Kharga, i.e. 24.202 GW h/year, 27.6% and 29.493 GW h/year, 33.7%, respectively. Another viability analysis was conducted [4] to find the option of PV power plant in the Gulf Corporation Council (GCC) countries and study showed that the at present PV technology is not a cost-effective option for the GCC countries because of existing lower electricity tariff, higher PV system cost and lower system efficiency. A solar power plant situated in the Kingdom of Bahrain [5] produced 12 MW (32 kW per day) from PV panels installed at the windows and roofs of two buildings along with annual CO_2 reduction of 48,000 t and revenue generation of €4,800,000 annually.

Studies [6] were conducted in Serbia to find out possibilities of generating electrical energy through 1 MW PV power plants by taking different types of solar PV modules available and it was concluded that higher electricity is generated using CdTe solar modules. Researchers [5,6] developed a computer software tool which integrates different types of PV power plants parameters into a single system to verify/compare the performance and dynamic behavior of other researchers' experimental, theoretical and simulation work for PV power plants.

In one study [9] a modular approach was adopted to meet the energy demand of six major cities in India up to year 2025 and solar PV electricity was suggested as the viable solution for meeting future energy demands. Other studies [10,11] also found solar PV system as a reliable substitute to be considered in the Indian process industries, particularly in the garment industry.

Several papers and research have been performed globally in order to evaluate the feasibility and performance of different SPV power plants and it can be concluded that the PV power plant is a viable and feasible option to meet the power requirement at present and in the future. The importance of PV plants is going to increase with the rising electricity tariffs.

In this paper a 2.5 MW on-site and off-site solar photovoltaic power plant was designed along with the land requirement and economic analysis for the garment zone of industrial area, Jaipur. The solar PV power plant has capacity to generate 10.03 GW h electricity in the first year of operation at 35.23% capacity factor for meeting the energy demand of the sector.

2. Energy demand of garment zone

A questionnaire based survey was conducted from July to September, 2011 for energy demand estimation in garment zone of Sitapura industrial area, Jaipur. After the primary survey the questionnaire was modified and used. The questionnaire comprised of the monthly energy demand in terms of heat and power for each individual industry, number of different type of machines, their energy consumption and duration of operation, etc. The estimated average monthly energy requirement for 44 industries is summarized in Table 1 for the seven months of on-season (January–April and October–December) and five months of off-season (May–September) along with the monthly demand on annual basis.

3. Design of solar photovoltaic power plant

The estimated peak power requirement of the zone was 2.21 MW in the month of February 2011 and considering the expected increase in the future, a 2.5 MW solar PV power plant is considered for the garments zone. Design of solar photovoltaic power plant (Fig. 2) consists of PV module sizing, inverter sizing, battery sizing and module circuit design. The design methodology and technical specifications of the PV power plant are discussed in this section.

3.1. Panel generation factor

Panel generation factor (PGF) is a key element in the size determination of solar photovoltaic cells on the basis of total watt peak rating and then for estimating the number of panels required for a particular SPV plant, which varies with the solar intensity and sunshine period of the site. [12]

$$\text{Panel generation factor} = \frac{\text{Solar irradiance} \times \text{sunshine hours}}{\text{Standard test conditions irradiance}} = \frac{617 \times 9.32}{1000} = 5.75$$

Table 1
Monthly average electricity requirement of the industries.

Average on-season demand (kW h/month)	Average off-season demand (kW h/month)	Average annual demand (kW h/month)
634,175.07	439,643.5	553,120.3

3.2. Energy required from PV modules

Energy required from PV modules can be calculated by multiplying peak energy requirement in kW h/day times 1.3 (the energy lost in the system) to get the total kW h/day which must be provided by the panels

Peak energy requirement of the zone during the on-season period was = 634,175.07 kW h/month = 21,139.169 kW h/day (Table 1)

Energy lost in the SPV system = 30% [12]

Energy required from PV modules = 1.3 × 21,139.169 = 27,481 kW h/day

3.3. Total watt peak rating for PV modules

Total Watt peak rating is calculated using the energy required to be produced from the solar PV modules and the panel generation factor. [12]

$$\text{Total Watt peak rating for PV modules} = \frac{\text{Energy required from PV modules}}{\text{Panel generation factor}}$$

$$\text{Total Watt peak rating for PV modules} = \frac{27481}{5.75} = 4779.30\ \text{kW}$$

3.4. PV modules

SANYO HIT-215NHE5 (Hetero-junction with Intrinsic Thin layer) PV modules are selected for the power plant and the solar cell of the module is made of a thin mono crystalline silicon wafer surrounded by ultra-thin amorphous silicon layers. Characteristics of the HIT cell module are given in Table 2.

3.5. Number of PV modules required

Total numbers of PV modules required in the power plant are estimated by using the total watt peak rating required and the PV module peak rated output. [12].

$$\text{Number of PV modules required} = \frac{\text{Total watt peak rating}}{\text{PV module peak rated output}}$$

$$\text{Number of PV modules required} = \frac{4779.3 \times 10^3}{215} = 22229.30\text{– } 22230\ \text{modules}$$

3.6. Inverter sizing

Size of the inverter used in PV power plant depends on the total peak watts requirement. Total wattage required in the garment zone was 2.5 MW. The inverter must be large enough to handle the total peak watt requirement of the zone at

Table 2
Characteristics of a HIT-215NHE5 PV module.

S. No.	Parameter	Units	Values
1	Maximum power (P_{max})	W	215
2	Max. power voltage (V_{pm})	V	42.0
3	Max. power current (I_{pm})	A	5.13
4	Open circuit voltage (V_{OC})	V	51.6
5	Short circuit current (I_{SC})	A	5.61
6	Warranted minimum power (P_{min})	W	204.3
7	Output power tolerance	%	+10/-5
8	Maximum system voltage	V_{dc}	1000
9	Temperature coefficient of P_{max}	%/°C	−0.3
10	Temperature coefficient of V_{OC}	V/°C	−0.129
11	Temperature coefficient of I_{SC}	mA/°C	1.68

Note 1: Standard test conditions: air mass 1.5, irradiance = 1000 W/m^2, cell temperature = 25 °C.
Note 2: The values in the above table are nominal.

any time. The inverter size should be 25–30% bigger [12] than the total wattage of the appliances and machines. Inverter size = 2.5 MW × 1.3 = 3.25 MW.

SatCon PowerGate Plus 500 kW 480/3 Inverter [13] is considered for the PV power plant which has an inbuilt maximum power point tracking (MPPT) system.

Number of inverters required = Inverter size/rating of an inverter = 7
Inverter wattage = 7 × 500 = 3500 kW = 3.5 MW

MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. MPPT is not a mechanical tracking system that "physically moves" the modules to make them point directly towards the sun. Additional power harvested from the modules is then made available as increased current [14].

3.7. Battery sizing

Total battery watt hours used per day = 21.14×10^6 W h/day
Battery loss = 15%
Depth of discharge for battery = 40%
Nominal battery voltage = 96 V [12]

$$\text{Battery Capacity (Ah)} = \frac{\text{Total Watt} - \text{hours per day used by appliances} \times \text{Days of autonomy}}{(0.85 \times 0.6 \times \text{nominal battery voltage})}$$

$$\text{Battery Capacity (Ah)} = \frac{21.14 \times 10^6 \times 1}{0.85 \times 0.6 \times 96} = 431781 \text{ Ah}$$

3.8. PV modules circuit

Maximum open circuit voltage = 780 V_{dc}
Open circuit voltage (V_{OC}) of each PV module = 51.6 V_{dc}
Number of modules to be connected in series = (780/51.6) = 15.11–16
Maximum power voltage (V_{mp}) of each PV module = 42 V_{dc}
Maximum power voltage (V_{mp}) at inverter input = 16 × 42 = 672 V_{dc}
Total number of PV arrays to be used for producing 672 V_{dc} = (22230/16) = 1390 arrays

3.9. Land required

Number of PV modules required = 22,230
Dimension of one PV module = 1.57 m × 0.798 m
Number of modules in an array connected in series (Fig. 1) = 16
Total width of each PV array = 16 × 0.798 = 12.77 m
Length of one PV module = 1.57 m
Number of arrays in PV field = 1390
Number of arrays in a row = 16
Width of the solar field = 16 × 12.77 = 205 m
Number of rows in solar field = 87
Pitch distance between two arrays (including module length of 1.57 m) = 3 m [15]
Length of the solar field = 86 × 3 + 1.57 = 259.57 m
Land required for PV field = 205 × 259.57–53,212 m^2 = 13.14 acres
[1 acre = 4047 m^2].

4. Off-site solar photovoltaic power plant

Sitapura industrial area is located in the vicinity of Jaipur city and there is a scarcity of land and the available lands are very costly. Looking at the scarcity and high land prices near the city, off-site proposal of the power plant has also been considered. In off-site solar power plant the design calculations for PV modules, inverter and land requirement are the same except the cost of the land.

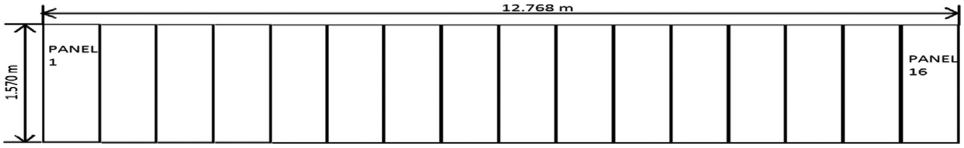

Fig. 1. Arrangement of a PV array consisting of 16 panels.

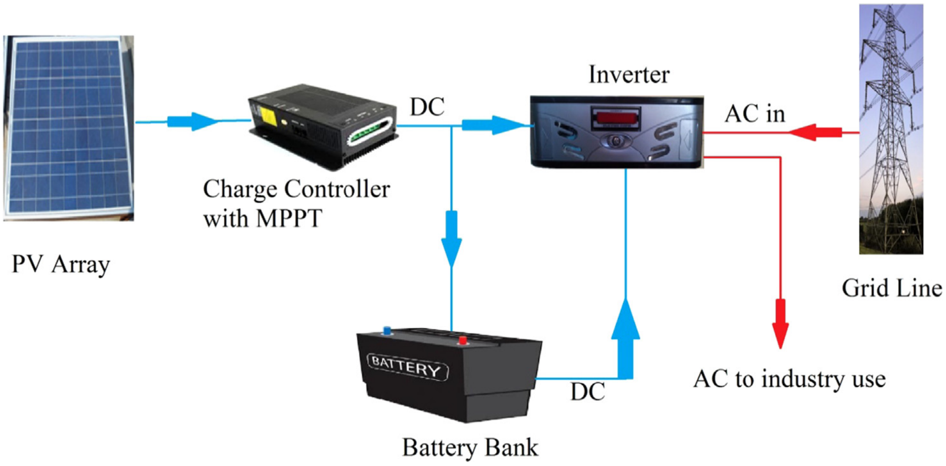

Fig. 2. On-site solar PV power plant.

5. Project cost

5.1. Module and inverter cost

Cost of each PV module = $528.9 [16]
Total cost of 22,230 module used for 2.5 MW ($1 = INR 50) = $11,757,447 = INR 587.87 million
Cost of each inverter of 500 kW capacity = 5.75 million INR [13]
Total cost of 7 inverters = 40.31 million INR

5.2. Design engineering and management cost

Labor cost for design, engineering and project management = Rs. 200/man-hour
Design, engineering and project management hours per kW_p = 2 h [17]
Total design, engineering and project management cost for 2.5 MW = 1.00 million INR

5.3. Installation labor cost

Labor cost for installation = Rs. 50/man-hour
Installation man-hour required for per kW_p = 12 h
Total labor cost for installation of 2.5 MW PV power plant = 1.5 million INR (Table 3)

5.4. Operation and maintenance cost

Fixed O and M cost = INR 5.48 million/MW h [18]
Variable O and M cost = INR 4.95/MW h [18]

Table 3
Project cost of PV power plant of 2.5 MW capacity.

S. No.	Particular for off-site PV power plant	Million INR
1	Module cost	587.87
2	Array structure	23.12
3	Electrical items	32.30
4	Inverters	40.31
5	Design, engineering and project management cost	1.00
6	Total labor cost for installation	1.50
7	Installation hardware—civil, shade, Fencing	5.00
8	Packing and Freight	0.50
	Total cost for off-site plant	**691.6**
	Additional cost for on-site PV power plant	
9	Land cost	207.56
10	Batteries	22.50
	Total cost for on-site plant	**921.66**

Table 4
Levelized cost of energy for SPV plant for different discount rates and project life.

Discount rate (%)	6	7	8	9	10	11	12	15
Life of plant (years)	**(ON-SITE) LCOE (Rs./kW h)**							
25	11.46	12.28	13.14	14.03	14.94	15.88	16.83	19.80
20	12.43	13.22	14.03	14.87	15.74	16.62	17.53	20.35
15	14.15	14.90	15.67	16.46	17.26	18.09	18.94	21.58
	(OFF-SITE) LCOE (Rs./kW h)							
25	8.78	9.40	10.05	10.71	11.40	12.10	12.81	15.04
20	9.51	10.10	10.72	11.35	11.99	12.66	13.34	15.46
15	10.81	11.37	11.94	12.53	13.14	13.76	14.40	16.38

5.5. Capacity factor

Capacity factor is a key driver of the solar PV plant's economics. Majority of the expenses for a PV power plant are fixed in nature and levelized cost of energy is used to correlate the utilization of the power plant. [19]

$$CF = \frac{\text{Annual kilowatt hours generated for each kilowatt AC peak capacity (kWh/kWp)}}{\text{8760 h in a year}}$$

Energy required to be generated from the plant$=$21,139.17 kW h/day
Annual energy to be generated from the plant$=21{,}139.17 \times 365 = 7.716 \times 10^6$ kW h
Peak capacity requirement of the PV plant$=2.5 \times 10^3$ kW_p

$$CF = \frac{7.716 \times 10^6 / 2.5 \times 10^3}{8760} = 0.3523 = 35.23\%$$

5.6. Levelized cost of energy

Levelized Cost of Energy (LCOE) is equivalent to the average price consumers would have to pay to exactly repay the investor for the capital, O&M and fuel costs with a rate of return equal to the discount rate. For this SPV power plant LCOE are Rs. 14.94/kW h and 11.40/kW h for on-site and off-site PV power plant respectively, taking the 25 year life of the power plant @ 10% discount rate (Table 4).

6. Financial analysis

Four scenarios are considered for financial analysis of the power project viz (i) pre-tax scenario, (ii) post-tax scenario, (iii) pre-tax with equity and (iv) post-tax with equity for both on-site and off-site options. The financial analysis is carried out considering the 25 years of plant life. In pre-tax scenario financial performances for the project are determined without

Table 5
Financial analysis for proposed SPV (Price in million INR).

Analysis	Pre-tax		Post-tax		Pre-tax with equity		Post-tax with equity	
	On site	Off site	On site	Off site	On site	Off site	On site	Off site
NPV @ 10%	119.52	249.78	108.39	238.49	135.30	211.37	124.09	200.16
NPV @ 15%	−142.48	3.39	−147.76	−1.95	−17.36	60.24	−22.67	54.93
IRR (%)	11.88	15.10	11.88	14.94	14.18	18.92	13.91	18.64
Simple payback period (years)	7.73	6.29	7.73	6.29	10.39	6.27	10.39	6.27
Discounted payback period (years) @ 10%	15.53	10.14	15.53	10.14	15.21	9.65	15.44	9.65
Discounted payback period (years) @ 15%	Never	17.18	Never	17.50	26.33	13.24	28.61	13.24

considering the tax and duties. For post-tax scenario 0% tax is taken for first 10 years and 4% afterwards is specified for the solar power plant in Rajasthan. Also, 7% depreciation is considered for first ten years and 1.33% afterwards [20].

Pre-tax and post-tax analysis with equity share of 70% of total investment is considered by taking loans from financial institutions with 11.75% interest rate. Loan term and interest rate is taken as specified by World Bank [21]. An additional cash flow i.e. yearly installment of the loan has also come into the analysis (Table 5).

7.. Conclusion

Study has been carried out to assess the technical feasibility and economic viability of a 2.5 MW capacity solar photovoltaic power plant for meeting the energy demand of garment zone, Jaipur considering on-site and off-site options. For this power generation total 22,230 PV modules are required with 16 modules in each row. Seven inverters with MPPT controller of 3.5 MW capacity and battery bank of 431,781 Ah are required to supply the power and the total land area required is 13.11 acres.

In on-site power plant PV modules are placed also on the roof of industries and modules are connected to a centralized battery bank and inverter. For off-site SPV power plant no battery bank is required as all the power generated is supplied to the grid simultaneously and a centralized inverter is used with a step-up transformer.

The power plant can generate 10.03 GW h electricity in first year at 35.23% plant capacity factor. After 25 years, considering cumulative degradation of 11.01%, electricity generation from the plant will be i.e. 8.96GW h. Levelised cost of energy (LCOE) is Rs. 14.94/kW h and 11.40/kW h for on-site and off-site PV power plants respectively, considering 25 years of plant life @ 10% discount rate.

Financial performance indicators (internal rate of return (IRR), net present value (NPV) and payback periods) are analyzed for four financial cases i.e. pre-tax analysis, post-tax analysis, equity analysis pre-tax and equity analysis post-tax. Financial analysis shows that the off-site PV power generation option is better because of land scarcity near the city.

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