Impact of Performance Degradation and Capital Subsidy on the Revenue of Rooftop PV System

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Abstract- Offering capital subsidy is one of the most recognized techniques to promote solar photovoltaic (PV) systems for investors. Most of the nations have offered subsidies to the investors, who are willing to invest and develop the PV systems (system peak capacities ranging from small-scale wattage to large-scale multi-megawatt). This paper tries to investigate the influence of subsidy on the revenue generated by a PV plant. For a clear understanding of the subsidy influence, two PV system cases (the first one is without capital subsidy, and the second one is with 15 % capital subsidy) are considered. The revenue generated by the PV plant is estimated considering the approved grid feed-in tariff rates set by the Electricity Regulatory Commission separately for each case depending on the PV plant capacity. Another known fact is that there exists performance degradation in the PV plant to a maximum extent throughout its lifetime. Hence during the evaluation of revenue, the energy degradation over the PV plant lifetime, i.e., 25 years is considered. Focused results for analyzing the system include energy yield for the first year, energy yields for the rest 24 years of life considering degradation, yield factor, capacity factor, revenue generation, and payback periods. With the analysis of the parameters as mentioned earlier, the revenue benefits of PV systems with and without capital subsidy is discussed, and relevant conclusions were made.

Keywords- Solar photovoltaic system, rooftop solar, PV performance, capital subsidy, energy yields, degradation rate, energy economics, payback periods, grid feed-in tariff.

1. Introduction

Unlike the other renewable energy systems, PV systems have gained a prominent role in the electricity sector. Solar energy being a free source attracts the business people, consumers, schools and educational institutions, military branches, and individual homeowners to have its benefits [1]. It has very good potential and scope in most of the developed and developing nations. Considering the most diversified and fastest growing nation, i.e., India, the importance of solar in its modern electrical utility sector has grown drastically [2,3]. The Ministry of New and Renewable Energy (MNRE), Government of India with an ambitious plan of achieving the target of 100 GW solar power by the end of 2022 under Jawaharlal Nehru National Solar Mission (JNNSM) introduced subsidies for the promotion of solar power across the nation [4]. Apart from the national solar policy, many states Governments in India have different policies regarding capital subsidy, fewer interest rates, debt and equity ratios, longer loan repayment durations, etc. However, in both the national and state solar policies, the subsidy is the most commonly seen method for promoting solar in India. A subsidy is a form of financial aid through cash grants provided to (to ease the high investment and cost burden projects) encourage the investments for developing solar power projects whose capacities range from kW range to MW range. It is evident that the solar PV system adoption or the willingness to use is highly driven by financial aids given regarding subsidy and through other means (policies that reduce the initial financial burdens) [5, 6]. Initial subsidies are more encouraged in India, although a considerable variation in the tariff rates is seen. These tariff rates are mostly varied with respect to the PV plant capacity and subsidy percentage provided as per the Electricity Regulatory Commission.

Considering the scenario in the state of Karnataka, India, the total number solar power projects taken up were 387 (as per the solar progress report till October 2017) with the cumulative capacity of 7033.57 MW. Among these, only 216 projects were commissioned whose contribution is 1492.38 MW. Remaining 170 projects were yet to commission, and this contributes to 5541.19 MW [7]. This tremendous PV installation progress in Karnataka state is only (to maximum extent) due to the benefits offered by the Karnataka Electricity Regulatory Commission (KERC) to the investors regarding grid feed-in tariff rates set for power purchase as well as the capital subsidies.

This paper aims at investigating the revenue benefits to the investors that are possible with the small scale solar PV plants under the current KERC set electricity costs and subsidies. As a first step, performance modeling of the small scale PV system is carried out using the National Renewable Energy Laboratory-System Advisor Model (NREL-SAM) tool. While analyzing the performance of a PV system, a lifetime performance, i.e., for 25 years is considered based on the degradation rate possible in the PV system. At last, a focus is made on evaluating the revenue benefits possible in both the cases (i.e., with and without capital subsidy) and accordingly the payback period of the PV system is estimated.

2. Materials and Methods

The description of an investigated rooftop solar PV plant, its performance using simulation model, revenue generations influenced with the subsidy, and payback period estimations are shown in this section. Section 2.1 gives a brief description about rooftop PV system and components, photovoltaic system parameters used in this study. Section 2.2 gives detailed information about the site location, and the simulation modeling did in National Renewable Energy Laboratory-System Advisor Model (NREL-SAM) tool. In Section 2.3, the empirical relation used to evaluate the revenue, and payback periods are described.

2.1. Description of rooftop solar PV system

Land usage is one of the factors that differentiate the PV plants installed either in an open area or on building roof areas. In rooftop solar PV systems, the PV modules or the PV arrays are mounted on the vacant roofs of buildings but whereas in the case open rack installation the PV modules are installed over the ground surface with the help of mounting civil structures by allowing specific value of ground clearance. Schematic view of the grid-connected rooftop PV system is shown in Fig. 1. The schematic view depicts the various components of a grid-connected rooftop solar photovoltaic systems, and these include: PV array (formed by series and parallel combination of PV modules), mounting structure, electrical cables (both the DC and AC cables), protection devices, junction boxes, inverters, isolation transformers, manual disconnect, grid integration provision, and other accessories [8-14]. Depending on the available roof area, the accommodating capacity of the DC PV array is generally decided, and typically it can be ranged from wattage (W) to megawatts (MW) [11]. In rooftop solar PV systems, the primary advantage is the elimination of land cost.

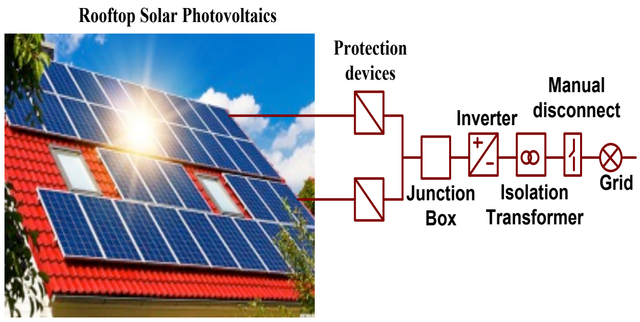

Fig. 1. Grid-connected rooftop solar photovoltaic system.

2.2. Simulation of rooftop solar PV system

The simulation or real-time performance analysis of any PV system starts with the site selection and weather parameter study. Once, these two are known, then the system parameters are identified based on the mathematical sizing approach or based on the simulation tool adopted for investigation. This section provides detailed information about the simulation approach adopted.

2.2.1. Site location

The selected site location is Bengaluru city in the Karnataka State of India. The details about the study location such as latitude, longitude, and time zone are shown in Table 1. While site selection, weather profiles, and their variations, and the government policies towards the solar project implementations are the most important criterion to be remembered. This will help in carrying out the performance analysis of the PV system more accurately and precisely.

2.2.2. Simulation Using "System Advisor Model"

Once the site selection process is over, the next step is the identification of the PV system specification which is mostly carried out mathematically. The selection of PV technology would be based on current PV markets and efficiencies of the available technologies. The specifications of the investigated PV system are shown in Table 2. With these specifications, the simulation modeling is carried out in arriving at the objective of performance assessment. In this study, NREL-System Advisor Model (SAM) tool is used, and it is of performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. It is designed to make predictions on performance and the cost of energy estimates for grid-connected renewable energy systems. The predictions are made based on the inputs given regarding the installation and operating costs and design parameters specified as inputs to the model. SAM's performance models make hourly calculations of the electricity generating a set of 8,760 hourly values that represent the system's electricity production over a single year. Policy makers and designers use the model to experiment with different incentive structures [16, 17].

Table 1. Details of site location

Parameter	Name/Value
Name of the site location	India IND Bengaluru (SUNY)
Latitude	12.95 °N
Longitude	77.65 °E
SAM station ID	35059
Time zone	GMT 5.5

Table 2. Solar photovoltaic system parameters

Parameter	Name/Value
Photovoltaic array capacity	10 kWp
Module type	Crystalline silicon (c-Si)
DC to AC ratio	0.9
Rated inverter size	~ 11 kW AC
Inverter efficiency	96 %
Array type	Rooftop
Tilt angle	10 ° (close to latitude angle)
Azimuth angle	180 °
Losses	15 %
Degradation rate [15]	1.68%/year for c-Si PV

Step by step procedure that is adapted for carrying out the simulation is as follows [16-18]:

- Open the NREL-SAM and select one of the tools for analyzing the performance of photovoltaic systems. SAM has numerous tools to evaluate the performance of the PV system.
- Solar resource and other weather parameters for the chosen study location must be taken into consideration from the appropriate monitoring station prescribed by the NREL-SAM.
- Technical sizing of the PV system is to be carried out by selecting the capacity of the plant, photovoltaic technology, power electronic converter efficiency.
- Next step is the selection of the installation type with an optimal tilt angle, orientation, and ground coverage ratio.
- Specifying the various possible losses in the PV system (Consider for both the PV cells and PV array, installation method, and electrical components).
- Run the designed PV system to analyze the energy yields. Analyze the parametric considering the age of the PV plant and its influence over the annual energy performance and capacity factors (Considering the degradation rate). This step is done additionally done in this study by considering the degradation rate of the crystalline PV systems for Indian locations.
- Consider the capital cost of the proposed photovoltaic system and analyses the economic parameters that of user's interest.
- Estimate the revenue generated from the plant by considering the approved tariff rates as per the regulatory board.

2.2.3. Weather parameters

As said earlier, the weather parameters of the study location were considered during the performance analysis. The annual averages of the weather data are shown in Table 3. Hourly averages of irradiance parameters in W/m^2 and wind speeds in m/s and temperature in °C (Ambient temperature and PV module temperature) for each month are shown in Fig. 2 and Fig. 3 respectively.

Table 3. Annual averages of weather data

Parameter	Name/Value
Weather file URL	C:\SAM\2017.9.5\solar_resource\India IND Bengaluru (SUNY).csv
Global horizontal irradiance	5.80 kWh/m^2/day
Direct normal irradiance (beam)	4.85 kWh/m^2/day
Diffuse horizontal irradiance	2.32 kWh/m^2/day
Average temperature	23.6 °C
Average wind speed	2.3 m/s

Table 4. Economic Parameters for 10 kWp Rooftop PV Plant Approved by KERC [19] (1 US$ = 70.40 INR as on 12.01.2019).

Economic parameter	Value
Capital cost	10,653.41 US$
Debt: Equity ratio	70:30
Debt	7457.38 US$
Equity	3196.02 US$
Debt repayment tenure	12 years
Interest charges on debt	12%
ROE	16%
Discount factor	13.20 %
Operation & Maintenance expenses	1% of the capital cost with 5.72% annual escalation
Working capital	Receivables (equivalent to revenue generated in one month)
Interest on working capital	12.50 %
Depreciation for the first 12 years	5.83 %
Depreciation for the next 13	1.54 %

Economic parameter	Value
years	
Approved tariff rate with a capital subsidy of 15 %	0.086 US$/kWh
Approved tariff rate without capital subsidy	0.10 US$/kWh

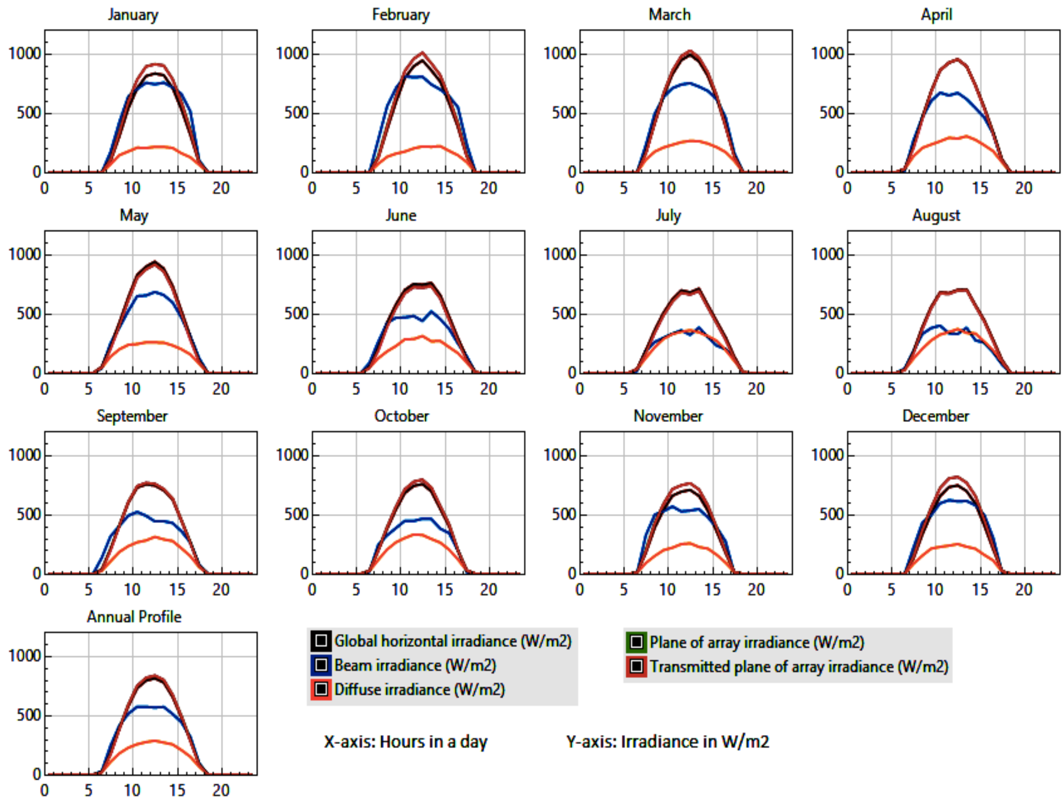

Fig. 2. Solar irradiance parameters at the site location

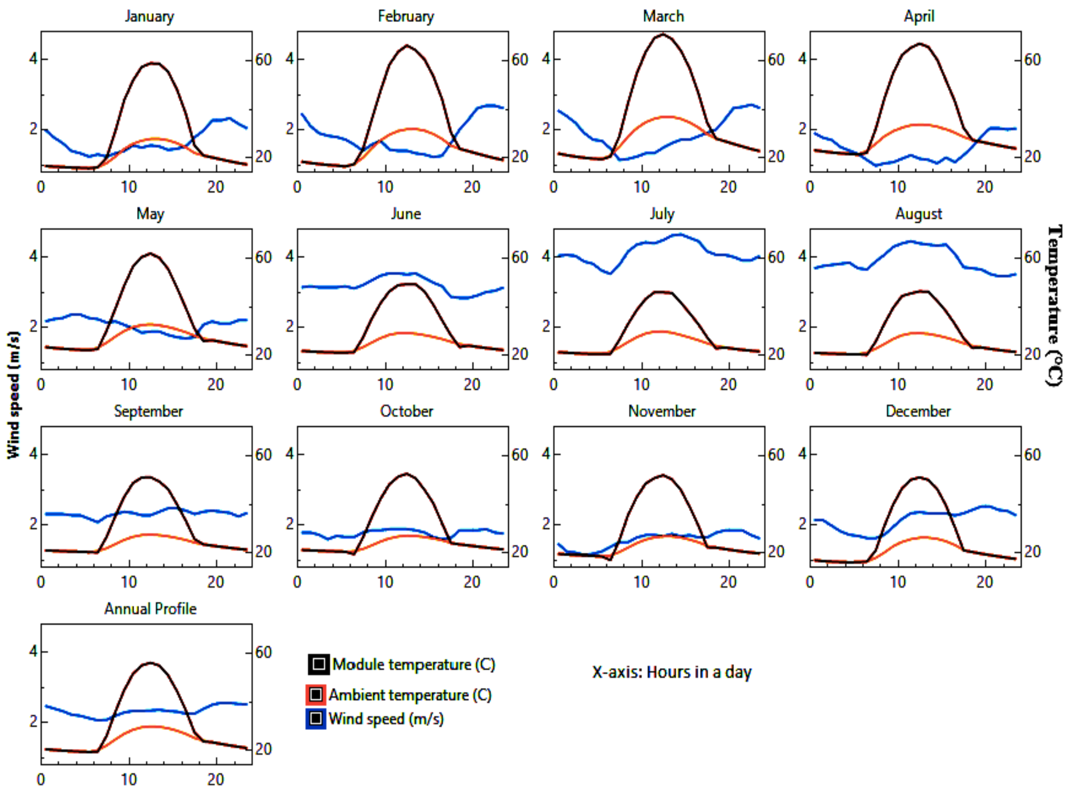

Fig. 3. Wind speed, ambient and module temperatures at the site location

2.3. Economic parameters of rooftop solar PV plant

Karnataka Electricity Regulatory Commission (KERC) has approved the economic parameters as shown in Table 4 for a 10 kWp rooftop solar PV system. The economic parameters by KERC are estimated by considering the cost breakup analysis.

Tariff rates for the FY 2017-2018 were also determined based on the economic parameters for a PV plant without capital subsidy and with 15 % capital subsidy by KERC [19]. These tariff rates were used in this study for analyzing the generated revenues and payback periods from the rooftop solar PV plant at Bengaluru.

Revenue, payback periods, and savings from the proposed PV plant are estimated using the following equations separately for the first year performance case and the PV plant performance considering 25 years of lifetime.

Revenue generated for the first year, without and with 15 % subsidy is estimated by using the Eq. (1), and Eq. (2) respectively.

$$FYR_{without\_subsidy} = EY_{first\_year} \times FiT_{without\_subsidy} \quad (1)$$

$$FYR_{with\_15\%\_subsidy} = EY_{first\_year} \times FiT_{with\_15\%\_subsidy} \quad (2)$$

Where, $FYR_{without\_subsidy}$, and $FYR_{with\_15\%\_subsidy}$ are the first year revenue generated from the PV plant without and with subsidy in US$; EY_{first_year} is the first year energy yield in kWh; $FiT_{without\_subsidy}$ and $FiT_{with\_15\%\_subsidy}$ are the feed-in-tariff rates approved for the PV system without and with subsidy in US$/kWh.

The energy yield of the proposed PV plant for its 25 years lifetime ($EY_{life\_time\,(25\,years)}$) is the sum of energy yields possible every year ($EY_{year1} + EY_{year2} + \cdots + EY_{year25}$) it is given by the Eq. (3).

$$EY_{life\_time\,(25\,years)} = EY_{year1} + EY_{year2} + \cdots + EY_{year25} \quad (3)$$

Similarly, the revenues generated with the consideration of PV plant degradation rate are given by the Eq. (4), and Eq. (5) for without and with 15 % subsidy conditions respectively.

$$LTR_{without\_subsidy+degradation} = EY_{life\_time\,(25\,years)} \times FiT_{without\_subsidy} \quad (4)$$

$$LTR_{with\_15\%\_subsidy+degradation} = EY_{life\_time\,(25\,years)} \times FiT_{with\_15\%\_subsidy} \quad (5)$$

In Eq. (4), and (5), the $LTR_{without\_subsidy+degradation}$, and $LTR_{with\_15\%\_subsidy+degradation}$ are the life time revenues generated from the PV system without and with subsidy when degradation rates are considered.

Payback periods are evaluated using the Eq. (6) For all the considered cases and conditions. Use the capital cost and revenue generated from the systems as per the subsidy, and PV plant life condition.

$$Paybak_{Period} = \frac{Capital\ Cost}{Revenue} \quad (6)$$

Savings from the proposed PV plant is evaluated using the Eq. (7).

$$Savings = Revenue - Capital\ Cost \quad (7)$$

3. Results and Discussion

Results are analyzed to obtain the revenue generations considering the approved tariff rates (without capital subsidy and with 15 % capital subsidy). The analysis includes first-year energy performance and its revenue, and performance degradation with PV plant age and its revenue.

3.1. First year energy performance

First-year energy performance of the proposed 10 kWp rooftop solar PV plant is outlined with the parameters namely: DC array output in kWh, energy yield in kWh, yield factor in kWh/kWp, and capacity factor in %. Fig. 4 shows the brief account of the final electrical energy generated concentrating on the energy difference between the DC array outputs to final energy yield. DC energy from the PV array is 1645.85 kWh records as the maximum generation in March and 1265 kWh as the minimum generation in November. Energy yields at AC side (at the inverter output side) recorded as 1579.35 kWh which is the maximum yield seen for the March month and minimum yield for July, i.e., 1208.86 kWh. There is the difference in energy generation, and this difference is due to the various losses involved in the system. These losses include: soiling-2%, shading-3%, snow-0%, mismatch-2%, wiring-2%, connection-0.5%, light-induced degradation-1.5%, nameplate-1%, availability-3% [20].

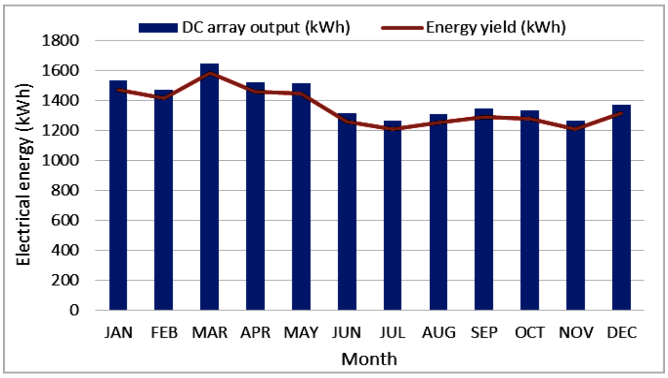

Fig. 4. First-year electrical performance of 10 kWp rooftop solar PV plant

In Fig. 5 the yield factor in kWh/kWp and capacity factor in % are shown. The yield factor of the investigated PV plant varied from 120.89 kWh/kWp (in July) to 157.94

kWh/kWp (in March) with an annual average sum of 1616.58 kWh/kWp. Capacity factors of the PV system are observed to vary in the range of 16.79 to 21.93 % with annual average maintained at 18.71 %.

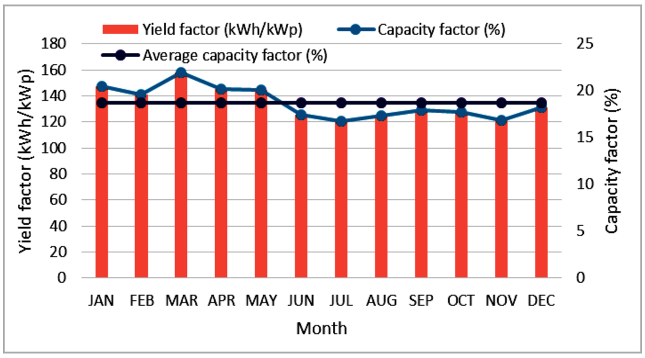

Fig. 5. Yield factor and capacity factor of 10 kWp rooftop solar PV plant

3.2. Revenue considering first year performance

Revenue generated from the 10 kWp rooftop solar PV plant is estimated based on the performance data and approved tariff rates as per the power purchase agreements of the Karnataka Electricity Regulatory Commission (KERC). These were calculated by multiplying the tariff rates to the energy fed into the grid on a monthly basis and later summed up to evaluate annual revenue. Revenue of the plant is thought to be concerning the tariff rates that are differed during the cases of subsidy and non-subsidy. Hence further analysis considering subsidy is evaluated. In Table 5, the grid feed-in payments for the 10 kWp rooftop solar PV plant based on first-year performance are shown.

3.2.1. Without capital subsidy

Revenue generated in the case where capital subsidies were not applicable or not considered was different because of the approved tariff rate variation. Tariff rate approved for 10 kWp rooftop solar PV plant is 0.10 US$/kWh. With this approved rate, first-year revenue is accounted to be 1625.76 US$. There exist variations in the monthly revenues recording the maximum revenue generated in March, i.e., 158.83 US$, and minimum revenue generated in July, i.e., 121.58 US$.

3.2.2. With capital subsidy of 15 %

Tariff rate approved for 10 kWp rooftop solar PV plant with 15 % capital subsidy is 0.086 US$/kWh. With this approved rate, first-year revenue is accounted to be 135.28 US$. There exist variations in each recording, and the maximum revenue is in March, i.e., US$, and minimum revenue is in July, i.e., 103.56 US$. The revenue generated in without subsidy case seems to be higher when compared to with subsidy case.

3.3. Performance degradation with PV plant age

It is a well-known fact that the performance of the PV plant is degraded with time [15, 21-27]. Hence, the study is extended to analyze the performance degradation of the proposed PV plant over the plant age, i.e., throughout its 25 years lifetime.

Table 5. Grid feed-in payments for the first year

Month	Energy yield (kWh)	Capacity factor (%)	Grid feed-in payments without subsidy (US$)	Grid feed-in payments with 15 % capital subsidy (US$)
January	1470.61	20.42	147.90	125.96
February	1412.94	19.62	142.10	121.02
March	1579.35	21.93	158.83	135.28
April	1454.56	20.20	146.28	124.59
May	1447.27	20.10	145.54	123.96
June	1257.03	17.45	126.42	107.67
July	1208.96	16.79	121.58	103.56
August	1248.51	17.34	125.56	106.94
September	1288.21	17.89	129.55	110.34
October	1275.26	17.71	128.25	109.23
November	1209.53	16.79	121.64	103.60
December	1313.52	18.24	132.10	112.51

For evaluating this, the PV plant age corresponding to its lifetime is estimated. Based on the age considered in percentages, the parametric analysis is done. The annual energy yield and capacity factors were studied carefully starting from year 1 to year 25 until the plant age will become 100 %. Table 6 shows the degradation influenced the performance of the proposed 10 kWp PV plant at Bengaluru location. Here, degradation influenced performance is estimated based on the degradation rate given provided by the All-India Survey of Photovoltaic Module Reliability Report-2016. According to this report, the PV plants whose capacity is <100 kW exhibits a much “higher average linear degradation rate of 1.68 %/year” [15, p.158].

During the first year, the performance is quite higher, the following years the performance tries to decrease gradually resulting in the decrease of annual energy output and capacity factors. At the end of the 13th year when the plant is at the age of 52 to 56%, the performance reduces to a higher value when compared with the first year performance.

This performance reduction is in between 12969.96 to 13191.58 kWh. At the same time, the capacity factors fall in between 14.8 to 15.06 %. At the 25th year, i.e., when the PV plant reaches 100 % of its lifetime, the energy performance is just 10764.64 kWh with a capacity factor of less than 12.29 %.

Table 6. PV plant performance degradation and corresponding revenue

Year	PV Plant age (%)	Energy yield (kWh)	Capacity factor (%)	Grid feed-in payments (without subsidy) (US$.)	Grid feed-in payments (with 15 % capital subsidy) (US$)
1	4	16165.7	18.45	1616.57	1390.25
2	8	15894.12	18.14	1589.41	1366.89
3	12	15627.09	17.84	1562.71	1343.93
4	16	15364.56	17.55	1536.45	1321.35
5	20	15106.43	17.24	1510.64	1299.15
6	24	14852.65	16.95	1485.26	1277.33
7	28	14603.12	16.67	1460.31	1255.87
8	32	14357.79	16.39	1435.78	1234.77
9	36	14116.58	16.11	1411.66	1214.02
10	40	13879.42	15.84	1387.94	1193.63
11	44	13646.25	15.58	1364.62	1173.58
12	48	13416.99	15.32	1341.70	1153.86
13	52	13191.58	15.06	1319.16	1134.48
14	56	12969.96	14.80	1296.99	1115.42
15	60	12752.07	14.56	1275.21	1096.68
16	64	12537.83	14.31	1253.78	1078.25
17	68	12327.20	14.07	1232.72	1060.14
18	72	12120.10	13.84	1212.01	1042.33
19	76	11916.48	13.60	1191.65	1024.82
20	80	11716.29	13.37	1171.63	1007.60
21	84	11519.45	13.15	1151.94	990.67
22	88	11325.93	12.93	1132.59	974.03
23	92	11135.65	12.71	1113.56	957.67
24	96	10948.57	12.50	1094.86	941.58
25	100	10764.64	12.29	1076.46	925.76

3.4. Revenue considering first year performance based on performance degradation

It is known that the revenue generated from the PV plant is a function of energy fed into the grid. The more energy being fed into the grid, the more revenue can be generated, and the investor will be in the profit zone. However, however, when studies conducted on performance degradation, the scenario are observed to be entirely different when compared to the first year performance. Revenue is severely affected by the degradation and grid feed-in payments throughout the PV plant lifetime. Energy performance, capacity factors, and grid feed-in-payment are given in Table 6.

3.4.1. Without capital subsidy

Performance degradation impacts on the revenue when the PV system is developed without considering the capital subsidy is studied here. The revenue drops critically with a reduction in energy generation. If the first year scenario continues to be the same for the rest of the PV plant life, the revenue might be 40644.00 US$, but this is not possible. The revenue generated from 10 kWp rooftop solar throughout its lifetime is just only 33225.65 US$ which is quite less.

3.4.2. With capital subsidy of 15 %

Degradation impact on the energy revenues when the proposed PV system is developed considering the 15 % capital subsidy, shows the gradual reductions in the revenue generation. The total revenue generated is observed to be around 28574.06 US$ which is quite less if the PV system is assumed to be operated with the first year performance throughout the lifetime.

3.5. Summary

Results are summarized in Table 7 for first-year separately and for the entire PV, plant lifetime considering the degradation separately. It is observed that there exist a significant difference in the revenue generations and payback periods based on plant degradation during its lifetime of 25 years. It is also observed that there is less impact of capital subsidy on the payback periods. The capital cost considered in this study is the sum of equipment cost and fixed operation & maintenance cost (O&M). The capital cost for the PV system under the first year performance category is around 10759.94 US$, and 9145.95 US$ for without subsidy case and with 15 % capital subsidy case respectively. For the first year, the revenue generated in without subsidy case and with subsidy case is 1625.76 US$ and 1384.65 US$ respectively with a payback period of ~6.62 years and ~6.60 years. In this case, savings cannot be obtained as the revenue is constrained to first year only.

Considering, the performance degradation case without subsidy and with the subsidy, the revenue generated by the PV plant in its lifetime is 33225.65 US$ and 28574.06 US$ respectively with payback periods of ~8.10 years and ~9 years.

Table 7. Results summary

Parameter	First year		PV plant lifetime with degradation (25 years)	
	Without capital subsidy	With 15 % capital subsidy	Without capital subsidy	With 15 % capital subsidy
* Capital cost (US$)	10759.94318	9145.951705	13316.76136	11702.76989
Energy yield (kWh)	16165.75		332256.48	
Yield factor (kWh/kWp)	1616.58		33225.65	
Average capacity factor (%)	18.71		15.17	
Revenue (US$)	1625.76	1384.65	33225.65	28574.06
Savings (US$)	Not possible in the first year		19908.89	16871.29
Payback period (Years)	~ 6.62#	~ 6.60#	~8.10	~9

*Capital cost includes the fixed operating and maintenance cost/year (assumption)
#It is strictly based on the first year possible revenue

During this savings are possible, and the saving accounts to be around 19908.89 US$ and 16871.29 US$ for without subsidy and with 15 % capital subsidy cases respectively.

4. Conclusion

An extensive study was done in this paper for evaluating the impacts of performance degradation and subsidies on the revenue generations from the small scale rooftop solar PV system at Bengaluru city of Karnataka State in India. From this study, the following conclusions are drawn:

- It is observed that the PV plant performs efficiently for the specific location weather conditions with an annual energy yield and capacity factor as 16165.75 kWh and 18.71 % respectively for the first year.
- The age of the PV plant will have an impact on energy generations, and that directly affects all another factor of the system. While with the plant age consideration the cumulative energy yield for 25 years is seen to be 332256.48 kWh.
- The average capacity factor during the performance degradation condition is 15.17% which is much lesser when compared to the first year capacity factor (18.71%).
- Performance degradation of the PV plant led to reductions in the generated revenue thereby increasing the payback periods from ~6.62 years to ~8.1 years and ~6.6 years to ~9 years.
- It is observed that the subsidy might be a favorable option in the initial stage of the PV plant establishment, but in the long run, it affects the revenue slightly. The reason for this is observed to be with the variation of FiT (feed-in-tariff) rates for subsidy and without subsidy conditions.

However, it is advisable to have clear cut studies about the various influential factors on the PV system before one proceeds with the practical or commercial plant.

Future work will be on improving these results considering the optimization methods and incorporating various other parameters that would directly or indirectly affect energy and economic performance.

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