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Life cycle cost analysis of 1 MW power generation using roof-top solar PV panels

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Abstract

Purpose – The purpose of this paper is to focus on life cycle cost analysis (LCCA) of 1 MW roof-top Solar Photovoltaic (PV) panels installed in warm and humid climatic region in Southern India. The effect of actual power generated from solar PV panels on financial indicators is evaluated.
Design/methodology/approach – LCCA is done using the actual power generated from solar PV panels for one year. The net present value (NPV), internal rate of return (IRR), simple payback period (SPP) and discounted payback period (DPP) are determined for a base case scenario. The effect of service life and the differences between the ideal power expected and the actual power generated is evaluated.
Findings – A base case scenario is evaluated using the actual power generation data, 25-year service life and 6 percent discount rate. The NPV, IRR, SPP and DPP are found to be INR 13m, 8 percent, 10.9 years and 18.8 years respectively. It is found that the actual power generated is about one-third less than the ideal power estimated by consultants prior to project bidding. The payback period increases by 70–120 percent when the actual power generated from solar PV panels is considered.
Originality/value – The return on investment calculated based on ideal power generation data without considering the operation and maintenance related aspects may lead to incorrect financial assessment. Hence, strategies toward solar power generation should also focus on the actual system performance during operation.

Keywords Life cycle cost, Roof-top solar PV panel
Paper type Case study

1. Introduction

There is a pressing need to accelerate the development of clean energy technologies to mitigate the global challenges of energy security, climate change and sustainable development. Solar PV is recognized as a key technology to de-carbonize the energy supply and is projected to emerge as an alternate method for power generation at the global level. The total installed photovoltaic power system capacity is about 300 GW, in which close to 75 GW was installed in the year 2016 (IEA, 2016).

India is a tropical country and there are more than 300 sunny days per year. There is greater potential to harness solar energy for power generation (Srivastava and Srivastava, 2013). India has the potential to generate about 748 GW from solar power, which is about 62.5 percent of the total potential for renewable power generation (MoSPI, 2017). As on March 2016, the power generated through solar PV panels is around 2.2 percent of the total electricity produced in India. It is projected that the solar PV panels would meet 10 percent of the total power demand by 2022 (CEA, 2016). The total installed roof-top solar capacity is about 1,247 MW as on December, 2016. The Government of India aims to add 11.9 GW of new roof-top solar panels between 2017 and 2021 (India Solar Handbook, 2017). The Jawaharlal Nehru National Solar Mission (JNNSM) focuses on setting up an enabling environment for solar technology penetration in India and aims to promote sustainable growth while addressing India's energy security challenges. JNNSM aims to create a policy

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framework for 20 GW solar power deployment by 2022 (JNNSM, 2017). A major landmark project is the Kamuthi solar power project completed in September 2016 in the state of Tamil Nadu, India. The area of this plant is 2,500 acres. This plant is expected to generate 648 MW which can meet the electricity demand of 1,50,000 homes. This solar power plant contains 25,00,000 individual solar panels which are cleaned on a daily basis by a solar powered robotic system making it a self-sustaining system. Topaz solar farm in California, USA, which has a capacity of 550 MW, is another largest solar power plant in the world (YourStory, 2016). Recently, the world's largest solar power plant with 2000 MW capacity is set up in the State of Karnataka in India with an investment of INR165bn. These initiatives highlight the huge potential of solar power harnessing in India (*The Hindu*, 2015).

Although the demand for solar power is increasing, not much attention is given to the maintenance of solar PV panels and the associated components installed (CERC, 2011). The actual power generation from solar PV panels is found to be less than the expected ideal power generation due to transformer failure, grid failure and less solar irradiance (CERC, 2011). However, the measures to improve the maintenance of installed solar panels are not discussed in detail. A study on life cycle assessment of 25 kW grid interactive roof-top solar PV power plant finds that the energy payback period is 1.6 years and the carbon payback period is 144 days (Marimuthu and Kirubakaran, 2013). This proves the potential of solar PV technology to mitigate social and environmental impacts. However, this is not sufficient to prove that the solar PV based power generation is completely sustainable because the technology has to prove itself to be economically viable (Kucukvar and Tatari, 2013). In addition to the social and environmental benefits, it is important to address the economic viability.

Majority of the solar power projects in India are formulated by the design consultants for bidding where they prove to the owner that the solar power plant once installed, would give a high return of 12–15 percent with a payback period of 7–10 years (Chandel *et al.*, 2014). This study aims to check the actual economic feasibility of such claims made at the beginning of the contract by estimators. Only a few studies have focused on life cycle cost analysis (LCCA) of solar PV panels installed in the warm and humid climate region in India. Earlier studies on financial analysis of solar PV power plants are based upon the estimated ideal power generation and not the actual power generated where ambitious gains may be arrived. Further, maintenance related issues during operation after commissioning are not considered in LCCA. In developing countries, the effect of improper maintenance may affect the solar power generation and reverse the desired outcome.

This study is practice oriented and aims to create awareness among clients not to just accept the ambitious financial gains projected by consultants. Such projection may not be likely true if the actual power generation is substantially less than the expected power generation. Several maintenance issues related to solar PV power plant operation are often not considered in developing countries and this may reverse the desired outcome in terms of financial performance. The objectives of this study are as follows: perform LCCA of 1 MW roof-top solar PV panels installed over an educational building; determine the differences in the financial gains based on the actual power generated and the ideal power generation estimated by the bidder over the entire life cycle; and study the effect of change in service life and power generation on financial indicators namely net present value (NPV), internal rate of return (IRR), simple payback period (SPP) and discounted payback period (DPP).

2. Literature review

Several studies focused on simulating the performance metrics of Solar PV panels such as the energy output, array yield, final yield, reference yield, PV module efficiency, system efficiency, inverter efficiency, performance ratio, capacity factor, and energy losses (Ayompe *et al.*, 2011; Shiva Kumar and Sudhakar, 2015; Attari *et al.*, 2016; Sharma and Goel, 2017). Software tools namely "PV syst" and "Energy Plus" are used for simulating energy production and energy consumption respectively (Sorgato *et al.*, 2018). "TRNSYS" software is used for sizing and performance assessment of grid-connected PV system (Mondol *et al.*, 2006; Kazem *et al.*, 2017). "RETScreen" software is used for power plant design (Chandel *et al.*, 2014). There are software tools such as "SolarGIS" that integrates solar data and weather data using interactive global maps (SolarGIS, 2019). Solar GIS contains application such as "PV planner" for performance simulation and "PV spot" for performance monitoring.

Studies on techno-economic analysis of grid-connected solar PV panels are limited in literature and are often based upon ideal power generation expected from solar PV panels. The financial performance metrics considered in these studies are buy-back ratio (Celik, 2006), SPP (Chandel *et al.*, 2014; Kazem *et al.*, 2017; Al-Salaymeh *et al.*, 2010), NPV, IRR, DPP (Cucchiella *et al.*, 2015; Sorgato *et al.*, 2018), benefit-cost ratio (Cucchiella *et al.*, 2015), cost payback period (Li and Liu, 2018).

LCCA of solar PV based energy efficient methods in a multi-storied residential building has been investigated and it is found that an additional investment of 3 percent could result in 30 percent savings in the operation and maintenance (O&M) cost (Mahajan *et al.*, 2014). Table I presents the findings of a few studies on LCCA of solar PV system. The results of these studies are mostly similar with some minor variations. Chandel *et al.* (2014) completed LCCA of 2.5 MW on-site solar PV power plant located at Jaipur city and found that the IRR, SPP and DPP at 10 percent discount rate are 11.88 percent, 7.73 years and 15.53 years, respectively. LCCA was performed for a similar type solar PV power plant located outside the city premises (off-site). It is observed that the SPP and the DPP decreases by 19 percent and 35 percent respectively (10 percent discount rate).

Ahir *et al.* (2016) carried out LCCA of a 100 kW roof-top grid-connected solar PV power plant located at Surat, Gujarat. A discount rate of 8 percent was considered. When there is no subsidy considered on the total capital cost, the IRR and DPP are reported as 11.5 percent, and 9 years, respectively. The consideration of 30 percent subsidy on the capital cost is found to increase the rate of return by 77 percent and decrease the DPP by 40 percent.

A study on life cycle costing of 100 kW solar PV system conclude that the SPP is 9.4 years (Bharat *et al.*, 2015). Another study on 100 kW off-grid roof-top solar PV power plant concludes that the NPV at 13 percent discount rate is INR 0.6m (with battery backup) and INR 0.1m (without battery backup). The IRR is found to be 10.6 percent (with battery backup) and 15.0 percent (without battery backup) (Prasanna *et al.*, 2015).

Table II presents the effect of location, solar PV plant size, solar irradiance and orientation of PV panels on cost-benefit ratio and payback period for "hot and dry," "hot and humid" and "temperate(composite)" climatic zones in Mexico (Lopez *et al.*, 2016). The solar PV plant located in the hot and dry climate resulted in high cost-benefit ratio and least payback period due to high solar irradiance. The plant located at the hot and humid climatic zone resulted in minimum cost-benefit ratio and maximum payback period.

The life-cycle cost of solar electricity is primarily influenced by the irradiance condition and the cost of initial investment and financing (Bieri *et al.*, 2017). Further, the adoption of solar power is largely influenced by the financing schemes and interest rates. Although several studies were carried out earlier on LCCA of solar PV plant, many of these studies use the ideal power expected to be generated from solar PV panels for analysis, which may result in incorrect assessment of financial indicators of the solar PV power plant. Some of these studies are generic in nature. For example, there is lack of clarity in terms of the technical details of solar panels, climatic zone and certain input parameters related to cost analysis. This study presents LCCA of solar PV panels considering the actual power generated for one calendar year during operation. Possible reasons for differences between the predicted power generation and actual power generation are identified and a set of recommendations for improving the effectiveness of maintenance operations are presented.

Reference	Location	Climate	Roof-top/ground mounted	Installed capacity (kWp)	Module technoology	Type (on-grid/ off-grid)	Discount rate (%)	NPV (million INR)	IRR (%)	SPP (years)	DPP (years)
Chandel *et al.* (2014)	Jaipur	Composite	Ground mounted (on-site, within city premises)	2,500	Amorphous silicon (Thin film)	On-grid	10	119	11.9	7.7	15.5
Chandel *et al.* (2014)	Jaipur	Composite	Ground mounted (off-site)	2,500	Amorphous silicon (Thin film)	On-grid	10	250	15.1	6.3	10.1
Bharat *et al.* (2015)	Telengana	Hot and dry	Roof-top	100	–	On-grid	–	–	–	9.4	–
Prasanna *et al.* (2015)	Not specific	–	Roof-top	100	–	Off-grid (with battery)	13	0.6	10.6	–	–
Prasanna *et al.* (2015)	Not specific	–	Roof-top	100	–	Off-grid (without battery)	13	0.1	15.0	–	–
Ahir *et al.* (2016)	Surat	Warm and humid	Roof-top	100	–	On-grid (with incentive from Government)	8	3.9	20.3	–	5.4
Ahir *et al.* (2016)	Surat	Warm and humid	Rooftop	100	–	On-grid (without incentive)	8	1.4	11.5	–	9.0

Table I.
Comparison of studies on life cycle cost analysis of solar PV panels in India

Table II.
Life cycle cost analysis of solar PV panels in Mexico

Reference	Location	Climate	Roof-top/ground mounted	Installed capacity (kWp)	Module technoology	Type (on-grid/ off-grid)	Solar irradiance ($kWh/m^2/year$)	Cost-benefit ratio	DPP (years)
Lopez *et al.* (2016)	Mexali, Mexico	Hot and dry	Roof top (commercial building)	4	Multi-crystalline silicon	On-grid	2,204	3.2	13.0
Lopez *et al.* (2016)	San Felipe, Mexico	Hot and humid	Roof top (commercial building)	6	Multi-crystalline silicon	On-grid	2,015	2.8	14.3
Lopez *et al.* (2016)	Tijuana, Mexico	Temperate (Composite)	Roof top (commercial building)	4	Multi-crystalline silicon	On-grid	2,049	2.9	13.9

3. Research methodology

3.1 Case study

This study focuses on 1 MW roof-top solar PV panels installed at Chennai, India. Figure 1 shows the monthly solar irradiance data for Chennai during the period July 2014–June 2015 (NREL, 2015). The annual average direct solar insolation (irradiance) is found to be 5.3 kWh/m^2/day, which is very high compared to other countries like Germany (CERC, 2011). There are six climatic zones in India namely hot and dry, warm and humid, moderate, cold and cloudy, cold and sunny and composite. Chennai belongs to the warm and humid climatic zone. Chennai experiences three major seasons namely summer, winter and monsoon. The summer lasts for 6–7 months with the maximum temperature ranging from 40^0 to 45^{0}C.

The installation details of 1 MW solar PV panels located in three different buildings (blocks) are summarized below:

(1) Building 1 – total area occupied: 8858 sq.ft.; number of panels: 490; power (MW_{peak}): 0.130;

(2) Building 2 – total area occupied: 19,378 sq.ft.; number of panels: 1,072; power (MW_{peak}): 0.284; and

(3) Building 3 – total area occupied: 39,985 sq.ft.; number of panels: 2,211; power (MW_{peak}): 0.586.

In total, the solar power plant consists of 3,773 panels installed over an area of 68,221 square feet. The installed solar panel is 265 Wp mono-crystalline silicon PV with a floor area requirement of about 18 sq.ft. per panel. Figure 2 shows the actual power generated from solar PV panels during the period July 2014–June 2015. It is observed that the actual power generated reaches peak during March–April and it is minimum during September–December.

3.2 Life cycle stages of the solar PV power plant

Figure 3 shows the research methodology adopted in this study as well as the life cycle cost components of solar PV panels. The product life cycle of a solar PV plant covers the production of raw materials, processing and purification, manufacture of modules and balance of system (BOS) components, transportation of the modules to the power plant, installation and use of the systems and finally decommissioning and disposal or recycling. The decommissioning phase is not considered in this study because of lack of reliable data.

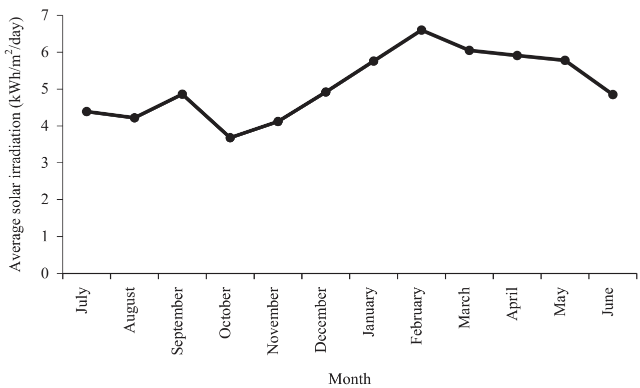

Figure 1.
Monthly solar irradiance in Chennai (July 2014–June 2015)

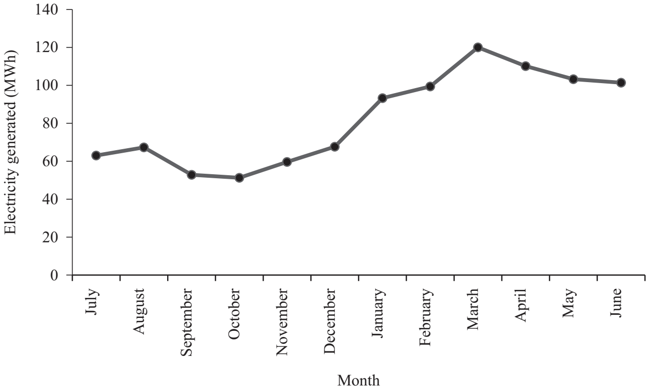

Figure 2.
Actual power generated from solar PV panels (July 2014–June 2015)

3.3 Research process and data collection

The total power generated from 1 MW solar PV panels was determined month-wise. The actual power generated from each building was gathered from data logger for the time period July 2014 to June 2015 (shown in Figure 2). In order to verify the reliability of data gathered from data-logger, the actual power generation data were compared with the solar irradiance data for Chennai (shown in Figure 1). It is noted that the trends observed in solar irradiance is same as the actual power generated.

The ideal average power generation expected from the installed 1 MW solar PV panels is 130 MWh per month and 1,560 MWh per year (CERC, 2011). It is noted that the actual power generation is about 37 percent lower than the estimated power generation. LCCA is performed with the ideal power generation estimated during the planning stage. LCCA is performed again based on the recorded actual data considering the service life of solar PV panels as 25 years and 30 years. The findings based on actual power generated are compared with the findings based on ideal power expected from solar PV panels and significant observations are noted. The reasons for the differences between the actual power generated and the ideal power expected are identified and discussed. Some recommendations for effective O&M of solar PV panels are presented.

3.4 Input data for LCCA

LCCA is a data driven scientific method for evaluating the economic performance of a project, system or a building over its entire life. In this study, the findings of LCCA are presented in Indian rupees (INR). One US Dollar is equivalent to INR64 corresponding to the data collection period mentioned. The scope of the LCCA along with a detailed list of items considered and the assumptions made are presented below.

Initial cost (negative cash flow). The initial cost is based upon the design, engineering, management, supply, installation and commissioning of a solar PV power plant. The design, engineering and management (DM) cost is determined using the man-hours required per kW and the cost per man-hour. It is assumed that the cost per man-hour is INR200 and two man-hours are required per kW (Tidball *et al.*, 2010). The supply, installation and commissioning of roof-top solar PV power plant consists of solar PV modules, inverters, transformers, combiners, low tension panels, cable tray data loggers, sensors, earthing, other accessories/equipment and mounting structures. The initial cost is assumed to cover manufacturing and delivery/transportation in addition to profit margin. The design, engineering and management cost are found to be INR400,000 per MW. The cost of supply,

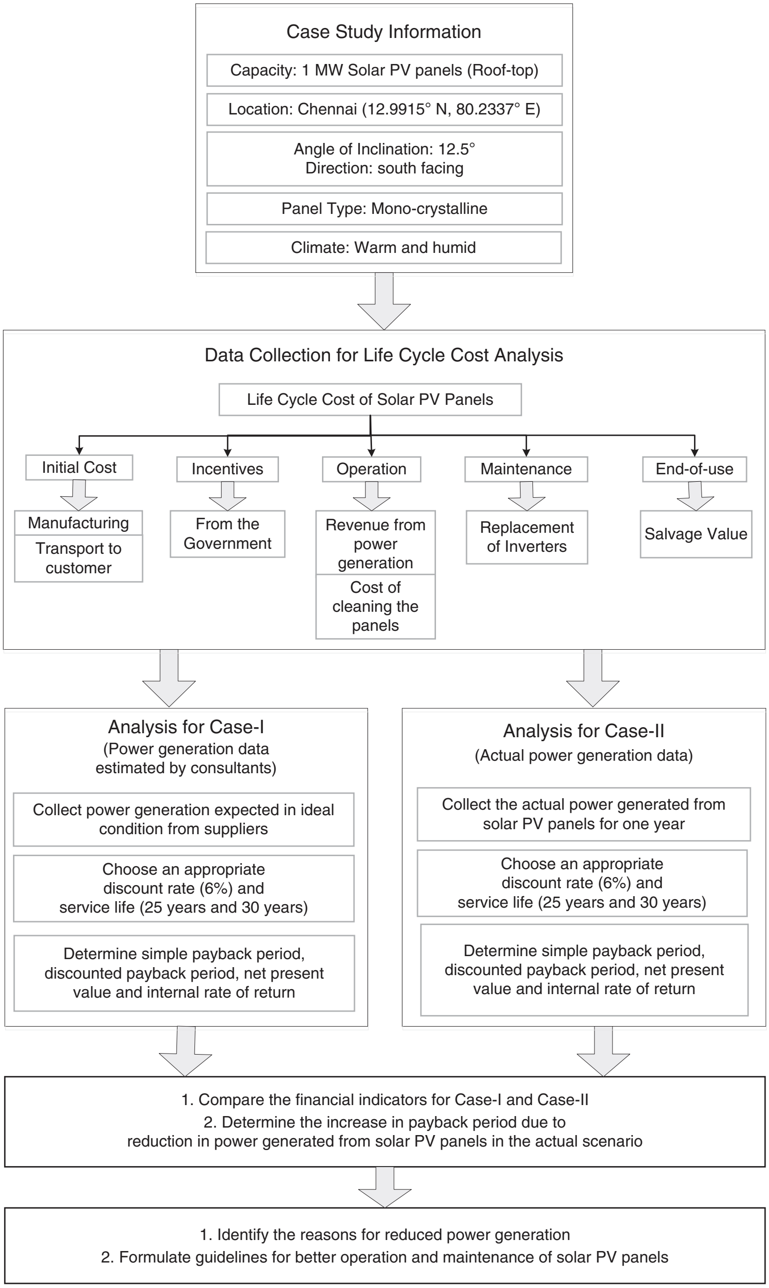

Figure 3.
Research methodology

installation and commissioning is found to be INR70,513,825 per MW. The initial cost is in the range of INR60 to 70m per MW of solar PV installed.

Incentive from the Ministry Of New And Renewable Energy (MNRE) (positive cash flow). There is no subsidy for installing solar PV panels in public education institutions from

MNRE. However, pre-conditioned incentive is granted for this purpose. The return incentive provided by the MNRE is INR16,250 per kW upon the completion of at least 80 percent work within 8 months (MNRE, 2017). In this study, it is observed that 80 percent work has been completed within 8 months. Hence, the incentive is taken into account for analysis.

Operation and maintenance cost (negative cash flow). The O&M cost is considered as $11.68 (INR748.64) per kW per year based on a previous study (Tidball *et al.*, 2010).

Savnings from power generation (positive cash flow). The cost of power generated from solar PV panels is INR6.5 per kWh. Practical observable degradation in the actual power generation from solar PV panels in India is considered as 2.5 percent in the first year and 0.5 percent in the subsequent years (CERC, 2011; Solar Mango, 2016).

Replacement cost (negative cash flow). The service life of inverters is usually 25 to 30 years. It is observed that 10 percent part-replacement is done in inverters every 10 years (IEA, 2011). This study considers the part-replacement cost of all inverters. The inverter cost is INR11,098,050 per MW. Hence, the replacement cost (every 10 years) is INR1,109,805 per MW.

Salvage value (positive cash flow). The maximum salvage value of mono-crystalline solar PV cells is noted as $0.33 (INR21.15) per watt in 2010 (McCabe, 2011). Most of the solar PV cells used in India are imported. Hence, this study uses the salvage value reported in the literature.

To summarize the major cost components, the total initial cost for the design, engineering and management as well as the supply, installation and commissioning of solar PV panels is found to be INR70,913,825 per MW. The O&M cost are determined as INR748,640 per MW per year. The replacement cost (every 10 years) associated with inverter is found to be INR1,109,805 per MW.

3.5 Key parameters used in LCCA

The financial assessment of a solar PV power plant is performed using the following indicators in this study: SPP: SPP refers to the number of years required to recover the initial investment considering only the net annual saving. It is influenced only by the net cash flow of the system and the total service life; DPP represents the number of years required to recover the initial investment considering the time value of money. It is influenced by the net cash flow of the system, total service life, and the discount rate considering the time value of money; NPV is the difference between the present value of cash inflows and the present value of cash outflows. It is used in project capital budgeting to analyze the profitability of an investment. This is sensitive to the reliability of future cash inflows that an investment will yield. NPV should always be greater than zero or positive for a project to be profitable or at least feasible. A project is financially not profitable when NPV is negative; and IRR refers to the discount rate used at which the NPV of a particular project is equal to zero. A higher IRR indicates that it is more desirable to undertake the project. Hence, IRR is used to rank alternate project execution scenarios. The scenario with highest IRR is considered as the best possible option to undertake. IRR implies the rate of return that an investment is expected to yield.

4. Results and discussion

Two cases are considered for LCCA based on power generation data. There are two scenarios under each case based on service life. These are listed below.

Case I (power generation data estimated by consultants during planning phase):

- Scenario 1: ideal power generation estimated and service life = 25 years.
- Scenario 2: ideal power generation estimated and service life = 30 years.

Case II (actual power generation data gathered from site during operation):

- Scenario 3: actual power generation from solar PV panels and service life = 25 years.
- Scenario 4: actual power generation from solar PV panels and service life = 30 years.

Based on trial and error basis, a discount rate of 6 percent is considered for analysis. Figure 4 shows the analysis of SPP and DPP for the above four scenarios. Figures 5 and 6 show the analysis of net present value and IRR, respectively.

4.1 Comparison of Scenario 1 and Scenario 3

There is substantial reduction in the NPV of about INR45m when the actual power is considered instead of ideal power estimated at a discounted rate of 6 percent. The IRR decreases from 14.6 to 8 percent when the actual power generation is considered instead of ideal power estimated. It is observed that the financial parameters calculated based on ideal power is too ambitious and it may not be feasible to achieve in the actual case. In simple terms, if an institution decides to implement 1 MW solar PV plant by taking credit from the bank at 11 percent interest expecting a return of 14.6 percent, then it may run on debt because the actual return is just 8 percent. Hence, the loan from the bank should be at an interest rate of at least less than 8 percent for the project to be just profitable. The SPP increases from 6.4 to 10.9 years when the actual power generation is considered instead of

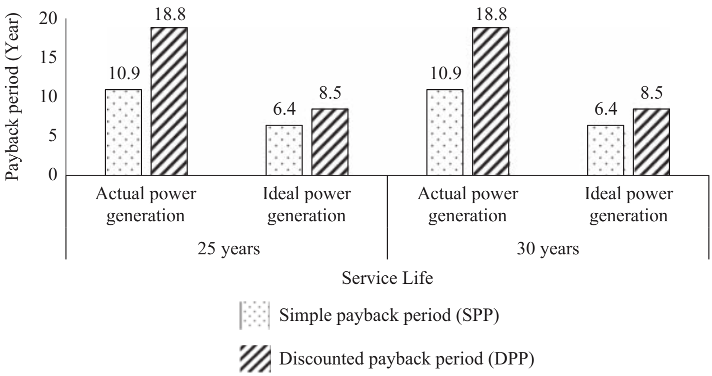

Figure 4. Analysis of simple and discounted payback periods for four scenarios

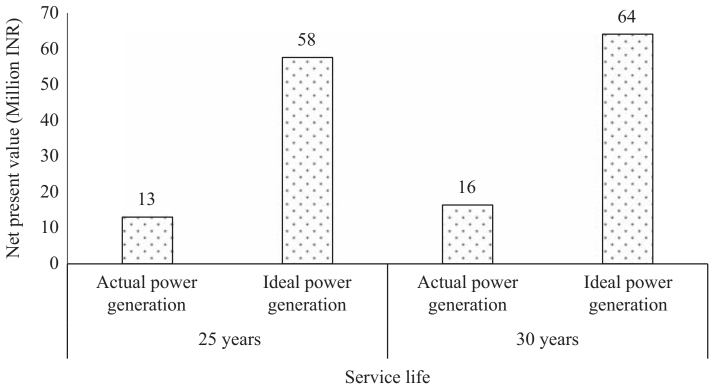

Figure 5. Analysis of net present value for four scenarios

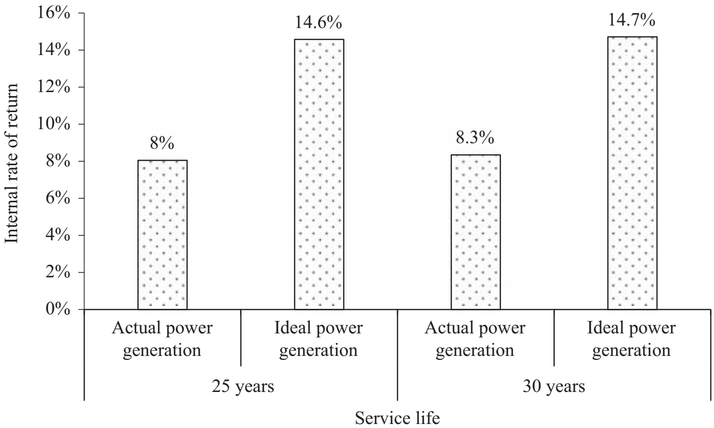

Figure 6. Analysis of internal rate of return for four scenarios

ideal power estimated. The DPP increases from 8.5 to 18.8 years when the actual power generation is considered. Hence, the ideal payback period seems to be highly optimistic which may not be feasible in the real case. For example, if an institution goes for this project assuming that the power plant is required only for 15 years and the initial investment would be recovered in 8.5 years, then the project would probably be run on loss because the actual DPP is more than 15 years.

The SPP and DPP obtained in this study based on ideal power data are comparable with the payback period reported in the literature (Cucchiella *et al.*, 2015; Kazem *et al.*, 2017). However, the findings vary with other studies. For example, Al-Salaymeh *et al.* (2010) determined that the SPP of a standalone solar PV and grid-connected solar PV is 50 and 30 years, respectively. Sorgato *et al.* (2018) found that the DPP for different cities in Brazil ranges from 7 to 23 years.

4.2 Comparison of Scenario 2 and Scenario 4

There is substantial reduction in the NPV of about INR48m when the actual power is considered instead of ideal power estimated at a discounted rate of 6 percent. The IRR decreases from 14.7 to 8.3 percent when the actual power generation is considered. The IRR calculated based on ideal power generation looks too ambitious and may not be possible to achieve in practice. The SPP increases by 4.5 years when the actual power generation is considered. The DPP increases by 10.3 years when the actual power generation is considered. The trends in the LCCA results for 30-year service life is similar to 25-year service life with marginal variations which are not significant.

4.3 Reasons for reduced actual power generation compared to estimated power generation

The main reasons assessed during site investigation for decreased actual power generation are as follows: Improper maintenance of inverters: Inverter failures are recorded very often and this results in the shutdown of some stretches of the power plant; lack of immediate response to inverter failures: Immediate action to replace or repair inverter is not done gradually losing the power generation potential of the plant from few weeks to few months in some cases.

The other reasons are: broken cells and interconnects: some crystalline silicon cells and interconnection between the modules are broken because of repeated thermal expansion and contraction or due to mechanical stress leading to open circuits; and glass breaks: in many cases, glass breaks are caused by external factors like hail storm, lightning, falling trees and sometimes because of poor packaging during transportation.

One of the easiest ways to avoid broken cells and interconnects is to pay due diligence and conduct panel quality test before procurement from the manufacturer and shifting. There are many testing methods available for detecting micro cracks. Electroluminescence (EL) or electroluminescence crack detection (ELCD) testing is one of the most applied methods. It is an image analysis and helps in locating potential inherent defects present in solar PV panels. This test would incur cost, time and manpower which are the main reasons for PV suppliers not investing on quality testing. However, there could be many other reasons for the broken cells which can be examined in future studies. Cleaning solar panels regularly with micro-fiber cloth can reduce the impact of fallen debris over the panels.

4.4 Guidelines for better maintenance of solar PV plant

Some guidelines for successful operation of a solar PV power plant are: data acquisition and analysis, plant control, alarm-management, documentation control, reporting, warranty claim management and spare parts management have to be taken into consideration during operation and monitoring; and maintaining environmental health and safety, proper periodic maintenance of modules, inverters, transformers, mounting, cabling, landscape, cleaning and timely communication are mandatory. To maintain quality control and safety standards, only qualified personnel should be permitted to work on PV installation. Inverters that are offline can have a dramatic negative impact on the return on investment. An adapted version of commonly reported inverter errors and the corresponding corrective actions are presented in Table III (Kaco, 2009).

Few suggestions for better maintenance of a solar PV power plant are (Solar Mango, 2015) solar PV panels need to be cleaned to get rid of dust, debris and any animal infestation accumulated over time. The presence of cracks or other mechanical defects need to be checked. Annual cleaning would be sufficient in regions with frequent rainfall. In general, quarterly cleaning is recommended. Visual inspection is recommended every week;

Inverter error	Action
DC under-voltage	Diagnose the underperforming systems
DC over-voltage	Test the strings
DC ground fault	Adopt the ground fault detection procedure
AC under-voltage	Confirm that all the breakers are ON Check the AC voltage with voltmeter Perform a manual restart if voltage is within range Contact utility if the voltage is outside of range
AC over-voltage	Check the AC voltage with voltmeter Perform a manual restart if voltage is within range Contact utility if the voltage is outside of range
Low power	The reason for low power can be mainly because the system is just shutting down due to lack of sufficient sunlight Diagnose underperforming systems if the weather is sunny
Over temperature when fan is not operating	Check for the power supply to fan If the supply is proper, replace fan If the supply is not proper, replace power supply
Over temperature when fan is operating	Check to verify sensor readings Replace sensors if they are found to be in poor condition If sensors are found good, further investigation is necessary
Overtemperature when fan is operating with accurate sensors	Check for intake and exhaust filters for excessive buildup of dust; clean or replace if necessary
Software fault	Contact the manufacturer

Source: Adapted from Kaco (2009)

Table III. Commonly reported inverter errors with remedial actions mounting structures with tracking systems have moving parts and these parts need to be lubricated as per the manufacturer's guidelines; and cables have to be checked for any cracks, breaks or deterioration in insulation. Physical damages to cables or junction boxes need to be addressed.

5. Conclusion

Solar PV is emerging as one of the promising technologies in the renewable energy sector. Significant investment is expected in establishing solar PV power plant in the next decade in India. Although the design, installation and commissioning of solar PV power plant is technically feasible, the financial feasibility should be evaluated. This practice-oriented study aims to educate the client/owner not to just accept the optimistic financial gains predicted by designers/consultants. Such projections may not be likely true if the actual power generation is substantially less than the expected power generation due to lack of attention given to operation & maintenance related issues.

Although data related to financial indicators may be obtained from PV suppliers, these may not reflect the real scenario during operation where the actual power generation is substantially less compared to predicted power generation expected due to operation related aspects. Hence, the payback period obtained from solar PV suppliers may not present a true understanding of the financial viability of a proposed solar PV power plant.

It is observed that the actual power generated from 1 MW roof-top solar PV panels is about one-third less compared to the ideal power generation estimated during the planning phase. LCCA based on the actual power generation data reveals that there is an increase in the payback period by 70–120 percent. In few cases, there is a chance that the payback period is close to the service life of the solar PV panels which makes the investment least profitable. Major reasons of drop in power generation during operation are frequent inverter failures and delay in responding to fix the inverter failures. This study highlights that there could be a substantial reduction in the actual power generated from solar PV panels due to O&M related issues. To overcome this, systematic implementation of O&M related procedures is required in the use phase. Effective periodical O&M of solar PV panels and the associated electrical and electronic components would bridge the gap between the actual power generated and the ideal power estimated.

Installation of a solar PV power plant and commissioning alone may not promise sustainable outcome. Any organization that plans to install a solar PV plant must have carried out cost analysis based on real-time performance data before entering into contract. The O&M related issues and consequent drop in the actual power generation need to be taken into account in arriving at the return on investment and payback period during the planning phase.

The results presented in this study are valid for roof-top mono-crystalline solar PV panels with south facing direction and 12.5 degrees angle of tilt. The findings of this study are valid for solar PV panels installed in the warm and humid climatic zone in India. More case studies are required to understand the actual power generation data from multiple climatic zones. Further, actual power generation data may be gathered over multiple years to determine decrease in power generation over the life of a solar PV power plant. Sensitivity analysis is needed to study the effect of each parameter on LCCA (e.g. variation in the discount rate by 10 or 20 percent). There are few limitations which may affect the findings of this study. Parameters like O&M cost of a solar PV power plant over 25 years' service life need a detailed study and documentation by the client to arrive at accurate projection, which is challenging in real scenario in developing countries. Further, it is challenging to gather exact details of capital cost associated with solar PV power plant installation. Contractors prefer not to share the cost details due to highly competitive bidding process.

Potential directions for further research are as follows: a comprehensive study on maintenance issues related to solar PV power plant is required; more case studies are required to understand the financial performance based on the actual power generated during operation. This will help to appreciate the benefits of solar power harness from the economical aspect rather than just going with the consultant's projections; and based on the findings of a large number of case studies, a mathematical model can be developed to predict the actual power generation and arrive at realistic life cycle cost.

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