Chapter 19
Performance Analysis of 400 kWp Grid-Connected Rooftop Solar PV System for Technical Institute

Ravindra M. Moharil, Prakash S. Kulkarni, Pranay S. Shete, and Prasad B. Joshi

Abstract In the National Development Council (NDC), India decided to enhance the renewable power share by 40% to its installed capacity by 2030. Indian government has 40 GW rooftop solar installation planned by 2022. Solar energy received by India varies from 4 kWh/m^2 during rainy season months to 7 kWh/m^2 during summer season with total sunny days of 300 per year. In 2015, Maharashtra Energy Regulatory Commission (MERC), Maharashtra state of India, permitted Rooftop Solar PV (RTSPV) system power to be connected to the distribution grid through net-metering. Industrial and commercial sectors preferred to install the SPV panels either on rooftop of building or on barren land in the premises. Various economic models of RTSPV are in place. Availability of solar energy and electricity requirements for academic institutions are coinciding with one another, which eliminates the storage requirement. Technical institutes require a large amount of power as compared to Science and Art institutes. The Maharashtra State Electricity Distribution Company Limited (MSEDCL), a distribution licensee in Maharashtra is charging an educational institute as per the tariff of HT consumer-Public Services category. As per policy of cross-subsidy, tariffs are on a higher side for the institutes. To reduce the financial burden of electricity bills, solar energy is the best option for these institutes. Variation in power generation by RTSPV occurs due to daily and seasonal variation of solar radiation. RTSPV generates active power only which results in different demand characteristics than the customer using grid supply only to meet the existing load. In this chapter, the performance analysis of a 400 kWp grid-tied RTSPV plant for the last 4 years is presented, and various challenges and issues related with interconnection of RTSPV to distribution grids are discussed. Study of system reveals that all solar power generated is consumed in the institute on all working days only on weekends and holidays export of power took place. The active power consumption

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is reduced to more than 50% but the reactive power required has increased. It was found that the payback period is low for net metering as compared to gross metering.

Keywords Rooftop solar photovoltaic System (RTSPV) · Distributed Generation Resources (DGR) · Solar Radiation (SR) · Percentage grid penetration level · Life cycle cost · Net metering · Gross metering · Payback period

Nomenclature

AMC	Annual Maintenance Cost
CEA	Central Electricity Authority
DISCOM	Distribution Company
LCC	Life Cycle Cost
MERC	Maharashtra Energy Regulatory Commission
NDC	National Development Council
RES	Renewable Energy System
SNA	State Nodal Agency
THD	Total Harmonic Distortion
APFC	Automatic Power Factor Controller
DGR	Distributed Generation Resource
IMD	Indian Meteorological Department
LCOE	Levelized Cost of Energy
MSEDCL	Maharashtra State Electricity Distribution Company Limited
O&M	Operation and Maintenance
RTSPV	Rooftop Solar Photovoltaic
SPV	Solar Photovoltaic

19.1 Introduction

Remarkable reduction in solar photovoltaic (SPV) panel cost during the last few years, the world is joining the period of cost competition of solar electricity with conventional electricity tariffs in many countries. Indian government has declared ambitious targets of installing 100 GW of SPV power with 40 GW through rooftop systems. State nodal agencies (SNA) and Distribution Companies (DISCOM) are trying to implement rooftop solar photovoltaic (RTSPV) with the help of solar rooftop project developers (National Solar Mission 2016). Manoj Kr. Behera et al. presented different forecasting models by several researchers for different RES. For developing these models' researchers, we use different meteorological parameters either in time series or statistical form. The availability of resources is predicted by developing suitable algorithms with removal of meteorological inconsistency for planners to design the suitable system (Behera et al. 2018). Moharil and Kulkarni in their paper mentioned that the output from RES is site-specific and depends on various weather parameters. It is difficult to guess the correct amount of power from these RES. Proper forecasting methodology helps in designing a suitable system with minimum imbalance between supply and demand and gap (Moharil and Kulkarni 2010). Mehmet Yesilbudak et al. explained how system operators and power system planners use these SPV power forecasting models as tools to manage the solar PV plants effectively and efficiently in their paper (Yesilbudak et al. 2018). Mandi in his paper described the solar photovoltaic plant of 500 kW installed at university campus of REVA and calculated pay back period and lifetime cost of the plant. He has also calculated specific energy generation of the plant and reduction in carbon emission (Mandi 2017). Nallapaneni Manoj Kumar et al. in their paper mention the design considerations and component selection and provided online monitored data for 95 kWp on grid PV systems and provided simulated energy performance results (Manoj Kumar et al. 2018). Wiles in his paper mentions that for better performance of SPV installations, it is necessary to select the location by using locating tool software and follow instructions given in users manual while installing components like PV modules and inverter. Good workmanship and adoption of National Electric Code helps in further improvement in performance (Wiles 2006). Yi. Guo et al. in their paper addresses the RTSPV economics for electric vehicle parking area site generation for renewable energy. Stochastic approach is used for considering uncertainty of solar energy and model predictive control (MPC) methodology for charging of electric vehicles is used for day ahead time scale pricing (Guo et al. 2016). Ahmed Ouammi in his paper presented a vehicle to building (V2B) model with the Team of Cooperating Microgrids (TCM) to lower the maximum loads with operational flexibilities of EV. MPC is used for optimal operational control of each microgrid. Presented the case study, which achieves reduction in peak load from 67 to 94% for a team of four microgrids by TCM approach (Ouammi 2021). Suresh Singh et al. in their paper done the comparative assessment of two photovoltaic plants technologies at the same location connected to the grid. Various performance parameters are compared. They have discussed various operation and maintenance issues also. They found that for comparison normalized performance indicators like specific yield and performance ratio are useful (Singh et al. 2014). Mahesh Kumar in his paper considered the interconnection issues of the SPV system with the main grid considering two d-q synchronous frames of reference (α–β and dq0) for various faults on the main grid and variation of THD for it (Kumar 2020). Ayompe et al. in their paper presented results of monitoring the RTSPV system for high-rise building in Dublin, Ireland, calculated yield parameters and compared average daily final yield with the results of the other countries (Ayompe et al. 2011). Sharma and Goel in their paper mention findings on the grid-connected solar photovoltaic system of 11.2 kWp (Sharma and Goel 2017). K. C. Rout and P. S. Kulkarni in their paper uses PVsyst V6.84 software for the design of proposed 2 kW RTSPV system in Odisha and demonstrated reduction in carbon emission, available energy, used energy, and excess energy for residential customers (Rout and Kulkarni 2020). Arun Kumar Behura et al. in their paper presented the case study of RTSPV at VIT, Vellore, using

PVSyst V6.70 software. Cost analysis with payback period is presented for two different designs with yield factors. They have also carried out the shading analysis and shading losses (Behura et al. 2021). Abhiram S. et al. in their paper focuses on impacts of 30 kW grid-tied RTSPV on secondary distribution systems and studied power quality issues with and without hybrid filters and suggested for installation of harmonic filters to maintain THD within limit (Abhiram et al. 2018). Chandrakant Dondariya et al. in their paper did the feasibility assessment of grid-connected RTSPV using different simulation software like PV*SOL, PVGIS, Solar GIS, and SISIFO. Analysis indicates that PS*SOL found suitable which is fast in operation, easy to use, and reliable as compared to other software (Dondariya et al. 2018). Subhasis Panda et al. in their paper analyzed PV renewable energy from demand side management perspective and presents different measurement index. They demonstrated that adaption of large-scale PV into the system changes load curve from spikes to smooth demand during peak period (Panda et al. 2020). Omkar K. et al. presented performance evaluation of 50 kWp RTSPV at educational institute based on IEC standard 61724 performance parameters (Omkar et al. 2015). M. Chakravarthy et al. in their paper presented the journey of a 200 kWp SPV plant from design to installation and operation at Vasavi College of Engineering, Hyderabad, India. Papers mainly present the sizing of different equipment like SPV modules, inverters, MCCB, cables, etc. They also discussed causes for poor performance and suggested solutions for them (Chakravarthy et al. 2015). Ramkrishna Kappagantu et al. presented RTSPV in smart grid project of Puducherry, India focusing on awareness of people for new technology, doing survey of availability of roof, consumption pattern, impact of government policies, and users experience (Kappagantu et al. 2015). Yash Sharma et al. in their paper presented the technical and economical analysis for the 300 kW RTSPV system installed at Rajasthan Technical University, Kota, India. Simulation is done before the installation of the system. It is concluded that high-power rating modules reduces Levelized cost of electricity (LCOE) compared to the lower power rating modules for the same system load (Sharma et al. 2019). Sandhya Prajapati and Eugene Fernandez proposed a RTSPV installations at commercial buildings for the Electric Vehicle (EV) battery charging and load in commercial building. If the charging time of EV is matched with solar power availability, then it will be more economical and efficient as compare to residential EV charging system, where solar power availability and EV battery charging times are different (Prajapati and Fernandez 2019). Shipla N. and Sridevi HR in their paper carried out the design and study of economical aspects of grid-connected PV system for an educational campus. A comparative study is done for an on-grid and off-grid PV system. Off-grid system uses PV-DG (Diesel generator) system. Proper sizing of battery bank with on-grid PV system is more efficient and economical as compared to the off-grid PV-DG for the same load (Shilpa and Sridevi 2019). Bibhu Padarbinda Mohanty and Moningi Srivalli designed the RTSPV by using System Advisor Model (SAM) and Solar Edge Software. Different operating and weather parameters are used for this designing and optimization of the output of RTSPV system (Mohanty and Srivalli 2020). Rittick Maity and Mobi Mathew in their paper studied the effect of tracking on the power generation of a rooftop PV system with the help of PVsyst simulation software. Authors modeled the SPV for monocrystalline, polycrystalline, and amorphous silicon panels. It was observed that double-axis tracking improves the energy yield of the RTSPV (Maity et al. 2018).

This chapter consider the system with a connected load of 927 kW, Contract demand of 700 kW, and RTSPV capacity of 400 kWp. The RTSPV system was installed in April 2017. For performance analysis various instruments like thermographic imager, power quality analyzer, etc., are used in addition to routine measuring devices. The details of various causes for reduction in the efficiency of the plant and methods for its improvement through proper maintenance are described. Further, economic analysis is carried out to derive the benefits of net metering. Calculations of payback period, net present value, life cycle cost, etc., are determined. Various system parameters like solar fraction, final yield, PV penetration percentage, capacity utilization factor, performance ratio, active/reactive power demand ratio, etc., are used for performance analysis. This case study helps in understanding daytime peak loads management by DISCOM and also discusses how RTSPV plants help in demand response issues with indirect benefits due to installation of RTSPV.

19.2 SPV Performance Monitoring Guidelines

Bureau of Indian Standards has published the photovoltaic system performance monitoring guidelines as IS/IEC 61724:1998, which is discussed in following paragraph and represented in Fig. 19.1.

To monitor the performance of SPV panel, IS/IEC-61724:1998 is used which has listed various meteorological and electrical parameters to be measured. Two types of irradiance data are recorded, one inclined inline with position of array for performance of the system and on horizontal plane to compare with different location

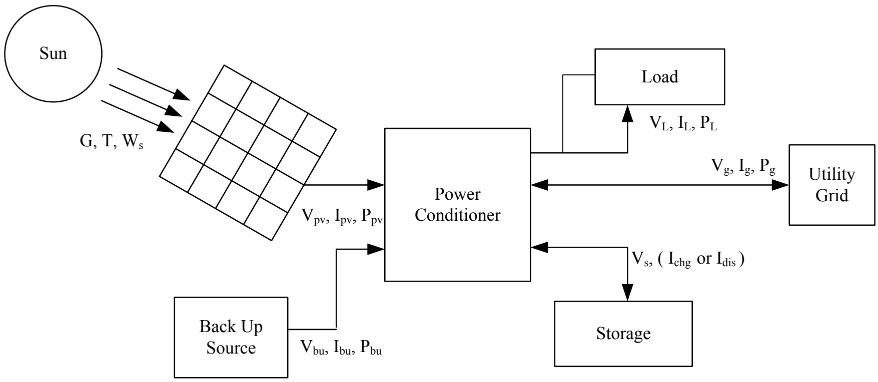


Fig. 19.1 Measurement parameters to be selected for monitoring suggested by Bureau of Indian Standards IS/IEC-61724:1998) (Bureau of Indian Standard 2010)

data. Ambient air temperature is measured with temperature sensors located in solar radiation shields. Wind speed is measured at the location of panels to consider the effects on structures of solar panels. Temperature sensors are connected on the solar panel module back surface to know the array conditions. Voltage and current on PV panel side and converter side are measured with sampling interval between 1 and 10 min. DC power is measured using DC wattmeter and AC power is measured through power sensors which take care of power factor and harmonics. Recording interval of this data is on hourly basis (Bureau of Indian Standard 2010).

19.3 CEA Grid Code

Central Electricity Authority on 7th October 2013 declared the Technical Standards for Connectivity of the Distributed Generation Resources (DGR) to the grid. The salient features of it are mentioned below:

- Planning, design, construction, reliability, protection, and safe operation of the equipment in the plant is the responsibility of the plant developer.
- Providing the facility for data storage and data communication is with the developer.
- Interconnection facilities and interconnection points with required modifications in existing systems are to be verified by appropriate licensees.
- Maximum net capacity of DGR will be based on capacity of the electric system to which it will be connected and will be finalized after considering the imbalance it will cause, affecting power quality and safety of equipment.
- Before connecting the system to the grid, it is necessary to measure DC current injection, harmonic current injection, and flickers are also to be measured. After installation also once in a year, above measurements are to be done and Flickers should be well below IEC 61000 Standard.
- Single-line diagram of the plant is to be prepared and displayed at the proper location.
- IEEE 519 limit of current injection should not be crossed by any generating station.
- At the interconnection point dc current injection should not be greater than 0.5% from DGR of the full rated output.
- Automatic synchronization device should be available at every DGR. If DGR has inverters with inherently built-in synchronizing devices, then no separate device is required.
- Electronic or electromechanical control circuit breaker shall be available with three-phase generators.
- Following protection are to be provided for DGR:
  - Overvoltage protection if voltages cross the voltage upper limit of 110% of rated voltage and under-voltage protection if the voltage drops down below the 80% of rated capacity. Fault clearing time may be up to 2 s.

  - Over frequency protection if frequency crosses 50.5 Hz frequency and under-frequency if frequency falls below 47.5 Hz with clearing time limited to 2 s. Authorities may prefer the narrower range of operation if desired.
  - Energization of the circuit should be stopped for any faulty circuit by any DGR.
  - Reconnection of DGR will be allowed only after confirming that the voltage and frequency of incoming DGR is within limits and with stable parameters.
  - Unintended islanding of DGR is to be prevented.

- Following conditions must be satisfied by generating station equipments:
  - Any circuit interrupting device should be capable of interrupting maximum available fault current at the site.
  - DGR devices safety and reliability should be such that failure of a single device should not affect the performance of a complete system. Sufficient redundancy is to be provided in the plant.
  - 220% of the rated voltage at the interconnection point should be withstood by a paralleling device of DGR.
  - Voltage fluctuation more than ±5% at the point of interconnection of DGR shall not occur after synchronization of the system with the grid.
  - Provision of the switch is to be made to manually isolate the DGR and the electricity system.

- Distribution licensee may ask the developer of DGR to provide the facility for visible verification of the plant by providing proper indicators to represent ON/OFF of the plant.
- Easy and convenient access to distribution licensee's personnel should be available (Central Electricity Authority (Technical Standards for Connectivity to the Grid) 2013).

19.4 Solar Radiation Data Modeling

The hourly output of a PV generating unit varies with time. India is a tropical country with latitude lying between 7° and 37° N. It receives an annual average intensity of solar radiation between 4.63888 and 8.12777 kW/m^2/day. There are around 300 clear day skies, indicating reception of full solar radiation.

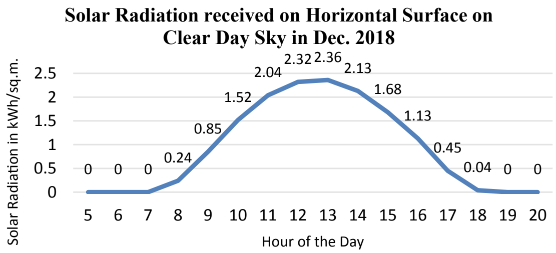
On clear days, there is a cycle symmetrical about solar noon. Solar radiation received on the earth's surface is dependent on (a) duration of day length which depends on different geographical factors, (b) turbidity in the air, (c) solar elevation at noon, and (d) type of cloud, percentage of cloud coverage, and content of water vapour in the air. Moisture contents in the air matters much during absorption of solar radiation and varies the amount of direct or beam and diffuse or scattered solar radiation received on the earth's surface. Summation of beam and diffuse radiation gives the value of global radiation.

Every solar radiation monitoring station measures all the three types of radiations mentioned above by using various instruments. Indian Meteorological Department

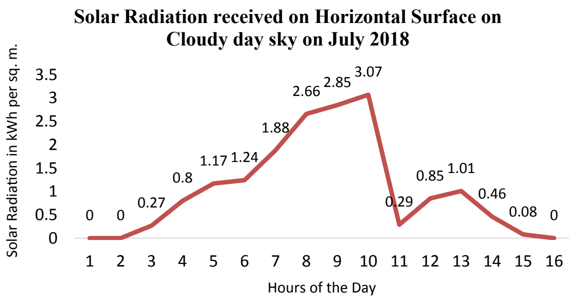
(IMD) is an agency of the Ministry of Earth Sciences of the Government of India, and is accountable for meteorological observations, weather forecasting, and seismology in India. IMD measures different weather parameters like ambient temperature, wind speed, and direction and relative humidity at its station and publishes it as the statistical information. These parameters also matter for solar radiation availability on the solar panels. The graph is plotted between time in hours on X-axis and output radiation in kWh/m^2. Time is plotted from 5th hour of a day to 20th hour (from morning 5 a.m. to evening 8 p.m.). Graph is plotted as shown in Fig. 19.2 for 15 December 2018 and 22 July 2018. December being the month of winter season, the smooth variation is observed from morning 7 a.m. to 6 p.m. Midday values are higher and maximum output reaches 2.36 kWh/m^2 as shown in Fig. 19.2(a) On the other hand, the second graph represented in Fig. 19.2(b), which was plotted for 22 July has a very erratic nature as it was the month of the rainy season and the cloudy weather remarks were observed throughout the day. Also, there is a very drastic fall in output from 2 to 3 p.m. and after that output continues to be less which was due to the rainy weather remarks from 3 to 5 p.m., which directly affects the output.

The solar radiation seasonal variation analysis is shown in Fig. 19.3, which is based on 10 years data collected from IMD, Pune from January 2009 to December 2018. Here, average output variation for the rainy, winter, and summer seasons is plotted against time. The graph clearly shows the seasonal variation with less average values in the rainy season than winter and summer seasons as the number of cloudy days are more in rainy season. The day length is more in the summer season as compared to winter season, which is represented by elongated graphs over time duration for

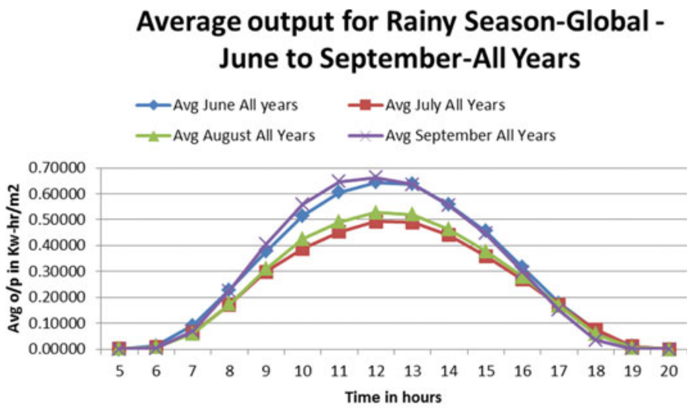
Fig. 19.2 Hourly global solar radiation on clear day and cloudy day



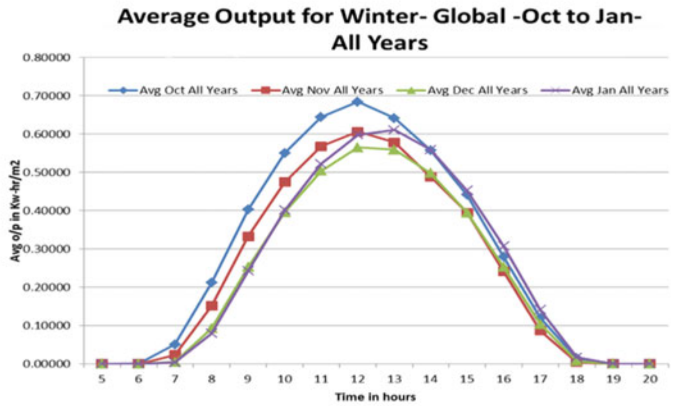
(a) Clear day sky global radiation



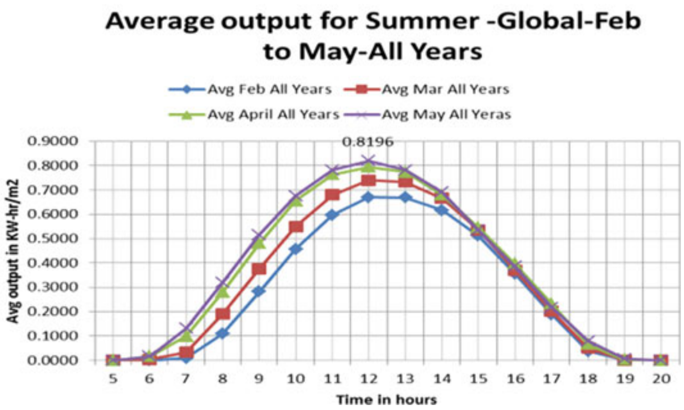
(b) Cloudy day sky global radiation



(a) – Rainy season variation in Solar Radiation



(b) – Winter Season variation in Solar Radiation



(c) – Summer season variation in Solar Radiation

Fig. 19.3 Seasonal variation of Solar radiation at the site

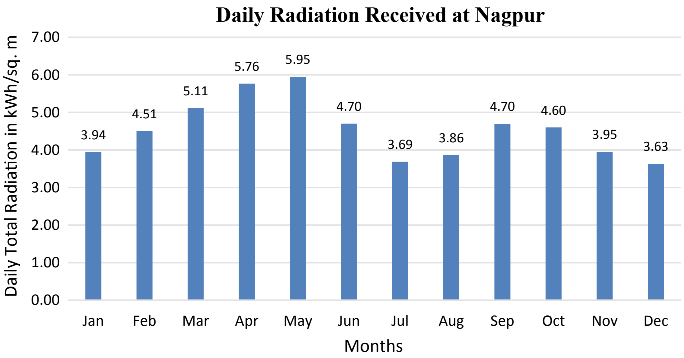


Fig. 19.4 Daily solar radiation received in different months at Nagpur

summer and rainy seasons. Daily average solar radiation in summer months is varying from 5.114 to 5.95 kW/m^2/day. Daily average solar radiation in the winter season is varying from 3.63 to 4.35 kW/m^2/day. Day temperature of Nagpur in the winter season is in the range of 25–30 °C and 40–45 °C in the summer months. The effect of temperature was observed on power output of solar PV panels during these months.

The monthly variation of solar radiation received on the earth's surface at Nagpur, which is located at latitude 21.0929° N and longitude of 78.98° E is represented in Fig. 19.4.

19.5 Site Details and Infrastructure Developed

The institute, Yeshwantrao Chavan College of Engineering (YCCE) is located in Nagpur, Maharashtra, India. The solar photovoltaic panels are installed on roofs of various buildings of the institute. Total roof coverage by PV panels is 2590.98 m^2. Figure 19.5 represents the google map of the institute representing installed solar panels. These panels were functional from April 2017. Figure 19.6 represents the predicted and power generated from date of installation to till date. It can be observed that the rainy season months are with low power generation, whereas the highest power generation took place in the summer month May, this is due to higher day length and more intensity of the beam radiation. For months of October and May the generation is very close to expected demand. In the month of April 2017, the variation in expected and generated power is large due to the teething problems of the system. Smooth power generation started from May 2017 onwards. Failure of the grid is not an issue for the institute as it has 11 kV express feeder benefit. The variation of the generated power with respect to expected power is in the range of ±20% except for a few months.

The plant rated capacity is 400 KWp. It is distributed on four different buildings with 100 kWp capacity on each. Each building has 334 panels of multi-crystalline

Fig. 19.5 Google map representing solar panel installation on various buildings at YCCE

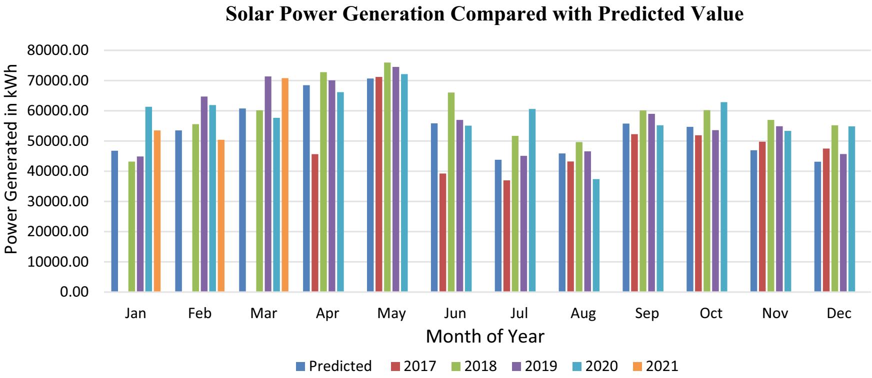


Fig. 19.6 Solar generation in various months over the years from date of installations

silicon PV modules of 300 Wp each. These panels are connected to two inverters of 50 kW each. The DG set backup is provided to take care of lighting load. Details of Solar PV panel and inverter are given in Annexure. Figure 19.7 represents installed PV panels on the science department building of the institute.

19.6 Analysis of Solar PV System and Load Profile of Institute

Table 19.1 represents the connected load of different buildings of the institute. The institute starts its functioning from 9 a.m. to 4 p.m. with a lunch break from 12 noon to 1 p.m. Administrative department works from 10 a.m. to 5 p.m. Figure 19.8 represents the typical load curve of the institute. This load curve is plotted for the actual load on

Fig. 19.7 Solar photovoltaic panels installed on Science Department Building of institute

Table 19.1 Building-wise load distribution of institute

Building	Total load (W)	Building	Total load (W)
Science Department Building	24,088	IT Department Building	35,362
Mechanical Department Building	32,497	Civil Department Building	48,948
Administrative Block	73,028	Central Computing Center	88,737
Electronic Department Building	79,262	EP & CT Department Building	110,914
Mechanical workshop	21,320	Auditorium Building	16,680
Canteen	7424	Pump load and Machine	210,740
Total campus load/connected load = 749000 W (749 kW)			

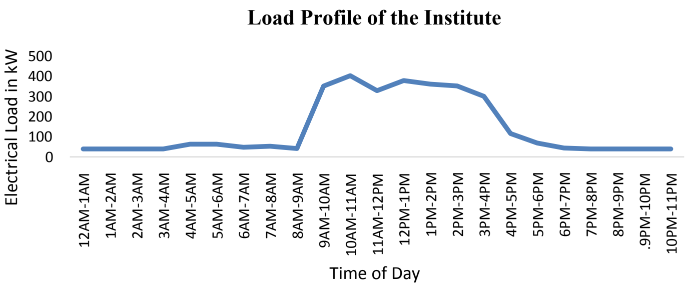


Fig. 19.8 Typical load profile of the institute on Thursday 18 January 2018

Thursday, 18 January 2018. Pump load is normally operated in the morning hours from 4 to 7 a.m. Teaching learning process begins from 9 a.m. onwards. From 4 to 5 p.m., only administrative office load is present; 5 pm onwards only essential street lighting, building lighting, and hostel load are present. When we compare the solar radiation curves for all the seasons shown in Fig. 19.3 and the load curve in Fig. 19.8, it is found that the power output of solar PV can supply the power requirement of the institute load.

Figure 19.9 represents the active power import from the distribution company before and after installation of RTSPV. It can be observed that the kWh has reduced to 50% for almost all months after installation of panels.

Table 19.2 represents the reactive power demand in kVARh lag, before and after

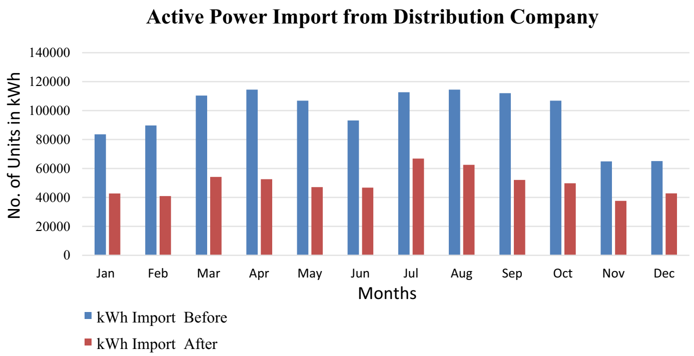


Fig. 19.9 Change in the active power import before and after installations of SPV panels

Table 19.2 Reactive power kVARh lagging drawn from distribution company

Month of the year	KVARh lag consumption		
	Before	After	After APFC installation
Jan	2240	6768	2100
Feb	2320	9415	2230
Mar	3323	11,699	2230
Apr	6423	9643	2300
May	6375	11,956	3750
Jun	3461	8655	1000
Jul	7949	15,831	1095
Aug	7430	13,518	2220
Sep	5177	13,531	1325
Oct	10,246	21,294	1260
Nov	1611	4111	820
Dec	1977	6046	365

installation of RTSPV panel. The reactive power demand has increased to 1.5 times for April to 4.1 times in the month of February. Rise in reactive power demand is highest for winter season and lowest in summer season. It can be observed that the reactive power demand has increased after the installation due to reactive power drawn from the supply by inverter and increase in harmonics due to solar power inverters. Even the power factor has reduced as active power demand has reduced but reactive power demand remains the same for load connected. To compensate for this reactive power demand, an automatic power factor controller (APFC) was installed in the control room with a capacity of 60 kVAR in addition to earlier fixed capacitors of 100 kVAR. APFC installation has reduced the reactive power demand in large amounts which is now well below before installation of RTSPV.

Figure 19.10 represents the change in kVA demand before and after the installation of RTSPV. It can be observed that kVA demand has reduced with the variation from 38% in February to 78% in June month. Figure 19.11 represents the bill demanded by the distribution company for 2016, before the installation of RTSPV and for 2019, after installation of RTSPV. The per unit charges for consumption is Rs. 9.10 for year 2016 and Rs. 9.70 for year 2019. The drop in bill demand varies from 9% for September to almost 60% in the month of February.

Table 19.3 represents the variation in solar panel voltage (V_{pv}), solar panel current

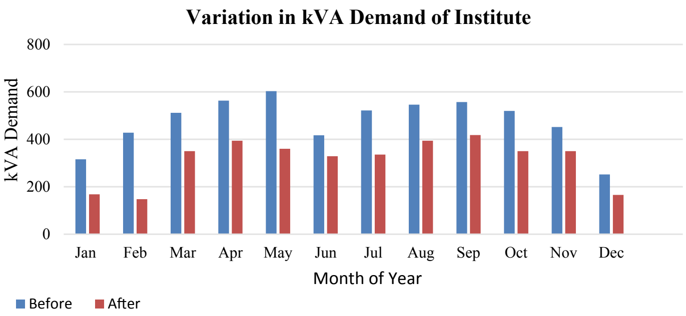


Fig. 19.10 Change in the kVA demand of institute before and after the installation of SPV panels

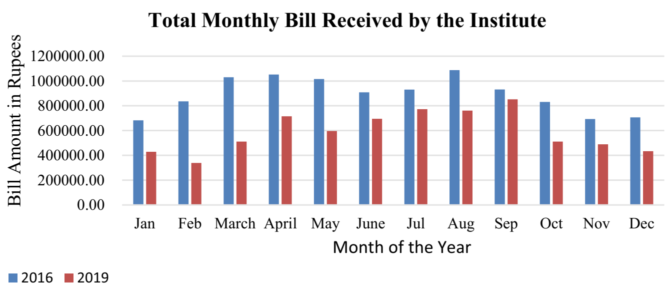


Fig. 19.11 Total electricity bill before and after installation of RTSPV at Institute

Table 19.3 Variation in parameters of inverter

S.N	Active power P_{PV} (Watts)	Array voltage	Array current	Inverter line voltage in Volts			Inverter line current in Amps			Reactive power drawn from supply in VAR		
		V_{pv} (V)	I_{pv} (A)	V_{L1}	V_{L2}	V_{L3}	I_{L1}	I_{L2}	I_{L3}	Q_1	Q_2	Q_3
01	3061	716.9	4.59	425	427	429	4.33	4.35	4.36	3	4	3
02	3124	715	4.70	427	426	433	4.43	4.37	4.34	4	4	3
03	3739	692.2	5.81	429	427	425	5.37	5.41	5.38	5	6	5
04	3749	729.9	5.52	426	424	424	4.88	4.84	4.89	6	5	6
05	3921	710.8	5.93	426	424	422	5.12	5.11	5.11	8	7	8
06	4491	700.6	6.89	434	433	431	6.49	6.43	6.48	10	8	7
07	4725	690	7.30	429	428	426	6.8	6.83	6.69	9	12	10
08	5661	710	8.57	437	433	433	8.1	8.1	8.4	12	15	17
09	7259	692	11.27	431	429	426	11	11.21	11.2	18	15	18
10	7821	670	12.55	429	428	426	8.9	9.09	9.19	22	17	19
11	23,420	625	40.28	427	426	424	8.8	8.9	8.9	54	56	54

(I_{pv}), inverter side voltages (V_{L1}–V_{L3}), and currents (I_{L1}–I_{L3}) and reactive power drawn from the grid when active power from solar panel is varying.

After observing the different parameters, line voltage, and currents from the output side of the inverter are balanced. The reactive power requirement for the inverter rises with the increase in the power output from the inverter.

$$Solar\ Fraction = \frac{Energy\ Provided\ by\ Solar\ generation\ system}{Total\ Energy\ required\ by\ the\ institute} \tag{19.1}$$

$$Final\ Yield = \frac{System\ Energy\ Output}{System\ rated\ power\ dc} \tag{19.2}$$

$$Reference\ Yield = \frac{Total\ inplant\ solar\ insolation\ (H_T\ in\ \frac{\mathrm{kWh}}{\mathrm{m}^2})}{Reference\ irradiation\ \left(1\frac{\mathrm{kWh}}{\mathrm{m}^2}\right)} \tag{19.3}$$

$$Performance\ Ratio = \frac{\text{Actual reading of plant output in kWh}}{\text{Calculated, nominal plant output in kWh}} \tag{19.4}$$

$$Capacity\ Utilization\ Factor = \frac{Actual\ Energy\ Output\ of\ PV\ system}{(No.\ of\ Hours\ in\ month) \cdot Rated\ power} \tag{19.5}$$

$$Percentage\ Grid\ Penetration\ Level = \frac{Solar\ Energy\ Exported}{Solar\ Energy\ Generated} \cdot 100\% \tag{19.6}$$

The various performance parameters are as given below and represents in Table 19.4. The solar fraction is varying from 0.51 to 0.84 indicating that more than 50%

Table 19.4 Performance parameters of solar generation system

S. N	Month	Solar fraction	Final yield	Reference yield	Performance ratio	Capacity utilization factor	% Grid penetration level (%)
01	Jan	0.74	1.21	3.94	0.87	0.190	32.77
02	Feb	0.79	1.21	4.51	0.92	0.241	45.82
03	Mar	0.75	1.23	5.11	0.90	0.252	67.52
04	Apr	0.63	0.93	5.76	0.78	0.222	22.36
05	May	0.67	0.93	5.95	0.77	0.222	30.18
06	June	0.72	1.13	4.70	0.70	0.219	25.27
07	July	0.51	1.22	3.69	0.88	0.179	18.47
08	Aug	0.60	1.39	3.86	0.92	0.215	18.76
09	Sep	0.74	1.36	4.70	0.71	0.264	10.79
10	Oct	0.73	1.32	4.60	0.95	0.243	34.66
11	Nov	0.84	1.05	3.95	0.83	0.171	54.19
12	Dec	0.70	0.98	3.63	0.88	0.142	44.19

energy need of institute is satisfied by RTSPV. Final yield is varying from 0.93 to 1.39, which indicates satisfactory performance. The values of performance ratio is varying from 0.70 to 0.95, which indicates the power loss is taking place due to temperature rise in summer seasons and better PR values for winter season. Capacity utilization factor indicates variation from 0.171 to 0.264, these calculations are based on (24 h × days of month). Percentage grid penetration level indicates that lowest grid penetration took place in September and highest penetration in the Month of March.

19.7 kWh and kVA Billing

In kWh billing, only active power consumption is charged and no charges for reactive power consumption. To reduce reactive power demand from consumer, power factor incentives and penalty are levied if power factor falls below 0.9 lagging. The highest incentives are available for maintain unity power factor. If customers draw leading power factor power, it is ignored by distribution company, which tempts customers to overcompensate during lean period by using fixed capacitors which is harmful for both distribution company and customer. Some customers used hybrid compensation of fixed and switch capacitors using automatic power factor controller.

$$kVAh = \sqrt{\sqrt{(kWh)^2 + (kVARh_{lag} + kVARh_{lead})^2}} \tag{19.7}$$

$$True\,Power factor = (displacement\,power factor) \cdot (distortion\,power factor)$$

$$True\,Power factor = cos\varnothing_i \frac{1}{\sqrt{1 + (THD)^2}} \tag{19.8}$$

In kVAh billing, the customer is charged on the customer's kVAh consumption. Customer has to maintain the power factor to unity for optimum kVAh value. Equation (19.7) is represented the calculation of kVAh. Equation (19.8) represents the effect of THD on true power factor. In this billing, no separate pf incentive is awarded. Computation of kVAh is affected due to harmonics as calculation is the rms values of parameters. The distortion power factor increases with the increase in harmonics, reduces true power factor, and increases kVAh consumption.

19.8 Maintenance and Audit of Solar PV Panels

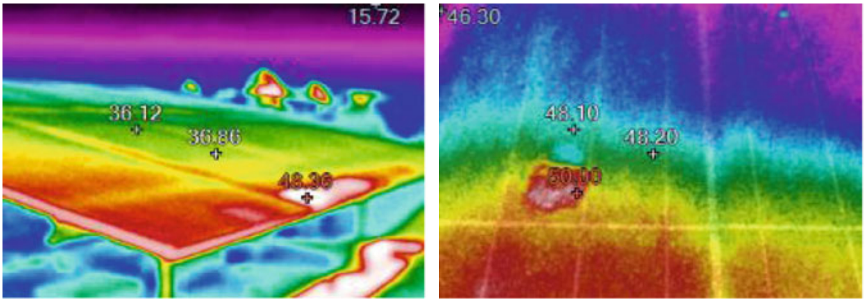
Smooth functioning of solar PV panel and associated circuitry is possible by proper maintenance of it. It also enhances output from solar PV panels over the years.

Following are few tips to be followed for better performance of RTSPV system (Bureau of Indian Standard 2010):

- Regular visual inspection of the RTSPV for physical wellness of the panels.
- Solar cells and PV panels cleaning on a fortnightly basis with water.
- Thermal scanning of all thermal based components.
- Measurement of electrical parameters on ac and dc side of the solar system.
- Measurement of earthing resistance of solar system and electrical system.
- Collection of real-time data and its comparison with manufacturer's product catalogue on a consistent basis. Deviations may be analyzed.
- Timely performance of critical and non-critical repairs.
- Management of inventory and spares.
- Identifying and tracking key performance indicators for best performance.
- To check the interconnections of solar panels and electrical terminals for possible damages due to open to sky conditions.

Guidelines for doing the audit of Solar PV panels installed as per IS/IEC 61724:1998:

- To check the availability of various drawings/diagrams/manuals necessary for operation and maintenance of plant.
- Schedule of Module cleaning. To check the record keeping of solar panel cleaning.
- To check the availability of the operation and maintenance manual.
- To check the availability of design documents for panel mounting structure.
- To check the module connection integrity with tong tester.
- To check the junction/string combiner boxes condition (electrical and safety aspect both).
- To inspect mechanical integrity of mounting structures (Visual inspection).
- Checking fuse and cable connections
- String currents with the help of Clamp meter.
- To verify the V_{oc} and I_{sc} of an individual panel with a data sheet of manufacturer.
- To measure output power from inverter.
- Use of thermal imager to check:
  - To detect string faults with hot spot images.
  - Damages in the solar module
  - Heat loss and temperature rise issues in inverters.
- To reduce the downtime and early fault detection, cable fault locator may be used.
- Power Analyzer to check Solar PV system as per IEC 61,000 for
  - voltage flicker.
  - Harmonic variation, Voltage fluctuations, etc.
  - No DC current injection at interconnection point.
- Meter reading at point of coupling for various parameters.
- To check the labelling of different components.



(a) Corner dirt collection (b) Dirt spot on SPV panel

Fig. 19.12 Thermal imaging of solar PV panel

- To check the various protective devices used in the system (overcurrent, overvoltage/under-voltage relay, residual current, surge and lightning protection, etc.)
- To check the earthing, insulation, and islanding condition of the system.
- To check the solar radiation recorded in the system with a solar radiation measurement device.

Figure 19.12(a) shows the thermal image of a solar PV panel. Here, the cold temperature is 15.72 °C and temperature at various locations on temperature indicates that at the corner of the panel the temperature is around 48.38 °C as compared to temperature at other spots as 36.12 °C or 36.26 °C. The reason for having higher temperature at the corner is because of deposition of dust at the corner. Figure 19.12(b) represents the spot of dirt at the middle of the panel. The spot has a temperature of 50.0 °C and cold temperature is 46.3 °C. It represents sticking dirt on the panel which did not get removed in water cleaning. After observing such a hot spot on the panels, it is the responsibility of the maintenance team to clean it with special efforts so that the corresponding part of the panel will not get permanently damaged.

19.9 Net and Gross Metering

Maharashtra state government has approved the net metering policy for individual customers through the MERC (Net Metering for Rooftop Solar Photovoltaic Systems) Regulations, 2015. The institute net meter billing is done as per this policy document. For 11 kV customers it is permitted to connect a RTSPV up to 1 MW but not more than its sanctioned load. Institute has a sanctioned load of 700 kVA and permission to install 100% of the sanctioned load, i.e. 700 kVA RTSPV. Considering the shadow free area, four buildings are identified for installation with a 100 kWp RTSPV system on each building considering availability of rooftop space. The total installed capacity is 400 kWp.

Following points from the policy are to be noted:

- High tension consumer is allowed to connect RTSPV to a low-tension busbar and the net meter is necessary to be connected to the high tension side of the consumer transformer.
- It is permissible to install RTSPV at different locations within the same premises.
- Safe operation of RTSPV with proper maintenance and necessary updates in hardware and software is the responsibility of the consumer.
- Renewable generation meters are to be maintained by distribution licensees.
- Islanding prevention for grid-connected solar inverter is to be ensured as per IEC 61000/IEEE 519 standards.
- Before injection of power into the grid, it is necessary to properly filter out harmonics and other distortions by connecting suitable filters at the inverter end so that only good quality power will be injected into the grid.
- IEEE 519 standard is to be followed for the presence of harmonic voltage and current penetrated into the grid. All meters should have advanced metering infrastructure (AMI) with RS 485 communication port.
- Before net metering if the consumer is billed as per time-of-day metering. After net metering also his consumption and generation are to be measured as per the time-of-day metering.
- Bill raised by the distribution licensee should include the following:
  - Renewable energy generation recorded by renewable energy generation meter.
  - Details of unit's consumption on time-of-day basis.
  - Active and lagging and leading var consumption during the billing period.
  - Number of units exported to distribution company, Number of units banked by distribution licensee and number of units adjusted against the solar generation units.
  - Number of units adjusted against renewable power obligations.
- If exported units are more than the imported units then after adjustment of imported units remaining units will be banked by distribution licensee and its settlement will be done at the end of financial year.
- If the imported units are more than exported units then the distribution licensee can raise the bills for units remaining after adjustment of exported units. Customer has to pay the bill before the due date.
- Payment for all the banked units in the financial year with distribution licensee will be calculated and adjusted in the first bill of the new financial year as per the tariff approved by the regulatory commission.
- For the time-of-day meter consumer, solar unit generation will be adjusted first in the same time zone. Excess unit generation will be adjusted in the off-peak period zone or banked considering generation is in the off-peak period (MERC 2015).

Institute installed its RTSPV system in April 2017. From installation till date, the number of units generated from RTSPV is 27,84,586 units. Out of these 10,44,050 units were used by the institute, 8,70,268 were exported out of that 77,651 units were adjusted, and 7,92,617 units were banked.

Presently, the distribution company has connected net meter and charges the number of units consumed at the average rate of Rs. 9.41 and purchases the solar energy generated at rate of Rs. 3.5. Considering this, saving due to solar installation is Rs. 9.41 $\times$ (10,44,050 + 77,651) + Rs. 3.5 $\times$ 7,92,617 = Rs. 1,33,29,352/- If in place of net metering if gross metering is used, then whole solar power generated is purchased by MSEDCL, a distribution licensee at Rs. 3.50, which pays (Rs. 3.5 $\times$ 27,84,586 units = Rs. 97,46,051/-. Hence, the institute will be at loss if gross metering is done to the tune of Rs. 35,83,301/-.

19.10 Life Cycle Cost of RTSPV and Tariff Decision

Regulatory bodies in India, has following guidelines for doing the calculations of life cycle cost and there on the tariff for the respective resources. Following points are to be noted for the RTSPV system calculations:

To start any renewable project requires huge funding, which normally raises through debts, equity, loan amount, etc. Regulatory commission has sanctioned a single part tariff with considerations for interest on loan and working capital, returns on equity fund and debentures, depreciation amount for developer on his own investment, O&M expenses, etc. Levelized-based tariff is decided for this. The must run priority is given to all renewable projects indicating that all the renewable energy generated from the plant will either be consumed by the customer or may be exported to the distribution licensee. When the capital cost of a renewable plant is to be considered then it includes the land cost if it is to be exclusively purchased for development of the project. In case of RTSPV, land cost investment is not required. But funds are required for infrastructure modification, plant and machinery purchased. Pre- and post-operative expenses of the project are also considered as a part of capital investment. Regulatory commission permitted for 70:30 debt: equity ratio while deciding tariff. Though the life span of project is 25 years, loan tenure is permitted up to 12 years only. Loan repayment schedule is to be considered from the first year of commercial power generation from the plant. For the first 12 years, depreciation rate of 5.83% is applicable and remaining amount will be spread over the useful life of the plant. For receiving carbon credits/renewable energy, purchase–sale obligations or any other matter related with clean energy development must be initiated by the developer. While determining tariff if the developer is getting benefits like generation-based incentive, accelerated depreciation, additional depreciation, it will be considered. Failure of renewable projects to generate guaranteed power needs to compensate for under-generation units by paying 75% of approved tariff. Excess generation than guaranteed power will be rewarded distribution licensee at the rate of 75% of tariff for excess generation.

Table 19.5, represents the costing for capital equipment. The interest rate is considered here as 8% and inflation rate 5%. The life of solar PV is considered as 25 years. The present worth of capital cost as

Table 19.5 Equipments needs capital investment

S. N	Name of equipment	Unit cost (Rs.)	No. of units	Total cost in lakhs
01	Solar panels, 300 Wp, 36 V	Rs. 16,500/-	1336	220.44
02	Inverter, 50 kW	Rs. 6,25,000/-	08	50.00
03	Module mounting structure			36.00
04	Control structure			24.00
05	Cables, lightning arrestors			04.00
06	Transportation and logistic			08.00
07	Installation charges			22.04
	Total capital cost			364.48

$$Present\ Worth = S_o = C_0\left(\frac{1+f}{1+i}\right)^n = 180.2238620\,\text{Lakhs}$$

$$Replacement\ cost = \frac{S_o}{(1+i)^n} = 26.3159\,\text{Lakhs}$$

$$Maintenance\ Cost = AMC \cdot \left(\frac{1}{i} \cdot \left(1 - \left(\frac{1}{(1+i)^n}\right)\right)\right) = 25.619\,\text{Lakhs}$$

The maintenance cost permitted by regulatory authority is 0.006 or 0.6% of the capital cost. The depreciation cost is considered for the first 15 years only as per the directives of regulatory authorities. To clean the solar panels energy is required. It is assumed that 200 units per month are required to clean the panels. Energy cost and scrap cost is assumed as zero.

$$Average\ Energy\ Generated\ per\ year = 676358.5\ units$$

$$No.\ of\ units\ used\ for\ cleaning\ panels\ per\ year = 200 \times 12 = 2400\ units$$

$$\frac{Total\ units\ to\ be\ used\ for\ billing}{25\ years = (676358.5 - 2400) \cdot 25}$$

$$= 16848962.5\ units$$

Considering the inflation and interest rate, the revenue generation from RTSPV at present rate of Rs. 9.65 per unit is

$$Total\ revenue\ generation = 16848962.5 \cdot \left((9.65) \cdot \left(\frac{1.05}{1.08}\right)^{25}\right)$$

$$= 803.96856\ \text{Lakhs}$$

Considering above factors the Life Cycle Cost (LCC) is calculated as (Abu-Rumman et al. 2017):

$$LCC = Capital\ Cost + Replacement\ Cost + Maintenance\ Cost + Energy\ Cost - Scrap\ Cost$$

$$LCC = 180.223686 + 26.3159 + 25.619 + 0 - 0 = 232.158762\ Lakhs$$

$$Levelised\ cost\ of\ energy\ (LCOE) = \frac{Life\ Cycle\ Cost\ (LCC)}{Life\ Cycle\ Energy\ Produced\ (LCEP)}$$

$$LCOE = \frac{232.158762}{803.96856} = Rs.0.2887$$

$$Pay\ back\ period = \frac{Levelised\ Capital\ Cost\ over\ 25\ years \cdot 25}{Total\ levelized\ Revenue\ generation\ in\ 25\ years} = \frac{180.2238620 \cdot 25}{803.96856} = 5.6042\ years$$

The above calculations have been carried out considering net metering. If all the generated units are purchased by the distribution company under gross metering at the rate of Rs. 3.5 per unit, then

$$Total\ revenue\ generation = 16848962.5 \cdot \left((3.50) \cdot \left(\frac{1.05}{1.08}\right)^{25}\right) = 291.5948152\ Lakhs$$

$$LCOE = \frac{232.158762}{291.5948152} = Rs.0.79616$$

$$Payback\ period = \frac{180.2238620 \cdot 25}{291.5948152} = 15.45157\ years$$

19.11 Conclusions

Institute installed RTSPV 4 years ago in April 2017. This chapter has analyzed the performance of RTSPV. Solar power generation and load curve are matching with one another. It was found that the active power drawn from the distribution company reduced to halved, similarly kVA has also reduced but the reactive power requirement increases. Installation of APFC brought down the reactive power demand also. Most of the times the exported power is adjusted with imported power and banking of power takes place during the vacation period only. Installation of RTSPV helps the institute in reducing bills. When the overall kWh consumption is reduced, other charges like wheeling charges, electricity duty, etc., also reduces. Energy bill charged by distribution licensee reduces in the range of 8–60% for various months. Grid penetration percentage varies from 10 to 60%. Though regular cleaning is done, some dirt was not removed, and special efforts are needed to remove them and save the panel from hot spot and damage. It was observed that net metering is beneficial to customers as compared to gross metering. Payback period for net metering is 5.6 years as compared to gross metering which is around 15.45 years. For further expansion in load, there is no need to take the additional sanction of load from the distribution licensee as maximum kVA demand has already dropped due to installation of RTSPV.

Annexure I

A-1 Solar panel and inverter specifications

Solar panel specification		Inverter specifications	
Watt	300 W-peak	Type of inverter	Grid tie solar inverter
Voltage	36.6 V	Model No	RPI-M 50A
Current	8.2 A	AC capacity of individual Inverter (KW)	50 kW
Type	Multi-crystalline	No. of inverters installed	8 No
Efficiency	14.3%		
Temperature	25 °C		
Dimensions (mm)	1955 × 992 × 38 mm Area of single panel = 1939.36 m^2		
Tilt angle (slope) of PV Module	18°	Total AC capacity of inverter (KW)	400 KW
Mounting	Fixed type	No. of phases	3-φ

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