Assessment, simulation and analysis of PV power generation for educational buildings of a rural women's university in India: a case study

Sonal Sindhu

Panipat Thermal Power Station,
Haryana Power Generation Corporation Limited,
Panipat, Haryana, India
Email: sonalpunia8687@gmail.com

Abstract: The present investigation evaluates the feasibility of grid connected rooftop solar PV system for Faculty of Engineering and Technology (FET), Bhagat Phool Singh Mahila Vishwavidyalya (BPSMV), Khanpur Kalan, Sonepat, Haryana, India. In this investigation, Solargis Photovoltaic (PV) Planner software has been utilised because of its ability to provide access to reliable PV potential information within short span of time. Present study analyses the performance of 160 kWp solar rooftop plant and compares the performances of different PV technologies on the basis of simulated energy yield and performance ratio (PR). Amorphous PV technology performs the best among the four PV technologies in terms of energy yield and PR. Life cycle cost of the proposed PV power plant has also been evaluated to get unit cost of electricity (UCE) of $0.051/kWh. Finally, comparative studies have been carried out with the existing thermal power plants (TPP) in Haryana.

Keywords: photovoltaic; Solargis PV Planner; performance ratio; energy yield; life cycle cost analysis; India.

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Biographical notes: Sonal Sindhu obtained her BTech (ECE) and MTech (ECE) from MDU Rohtak, Haryana, India in 2007 and 2011, respectively. She obtained her PhD in ECE in 2018 from the Faculty of Engineering and Technology (FET), Bhagat Phool Singh Mahila Vishwavidyalya (BPSMV), Khanpur Kalan, Sonepat, Haryana. She started her career as an Assistant Professor at PDM College of Engg, Bgarh, Jhajjar, Haryana in 2012. Currently, she is working as an Assistant Engineer at Haryana Power Generation Corporation Limited, Panipat Thermal Power Station, Panipat. She has professional experience in teaching, research and industry. Her research papers have been published in international journals of repute. She is a life member of professional society such as ISTE. Her areas of interest are solar energy, photovoltaics, multi criteria decision making and reliability modelling.

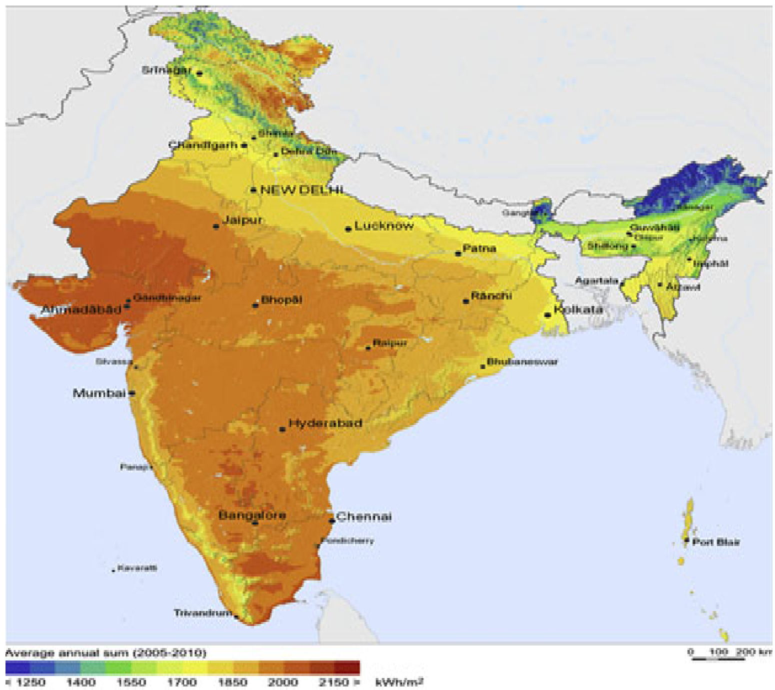
1 Introduction

1.1 Background and rural Haryana

It is a matter of debate and deliberation across globe that fossil fuel resources are standing at the verge of depletion. The present energy needs of India are being fulfilled using fossil fuels and thermal power plants (TPP) are the major player in electricity production, i.e., approximately 70% of the total production. Coal is a dirty fuel that offers high carbon emission coefficient and it causes negative impact on health while mining and using it (Hairat and Ghosh, 2017). Being dependent on coal reserves on large scale, it has caused air and water pollution and has disturbed the natural balance. It has caused 0.08–0.15 million premature human deaths. Moreover, particulate matter up to 10 μm in size (PM10) pollution causing from thermal-based power plants have reportedly caused 20 million asthma cases which is a serious matter of concern (Manju and Sagar, 2017). According to Centre for Science and Environment (CSE), Indian coal-based TPP are not efficiently operated power plants in the world. The centre highlighted that these power plants perform below the global benchmarks and cause stress on nature (Hairat and Ghosh, 2017).

On the other hand, around 81 million households lack access to electricity, which cause major challenge to India's energy security. Therefore, to achieve stable energy options in long run, significant progress in other energy sectors is the need of hours (Manju and Sagar, 2017). It has led to search for non-conventional energy sources for fulfilling the present and future energy demands (Mandal and Panja, 2016). Renewable energy sources have been gaining importance with growing demand of electricity and continuously receding natural resources (Tomar and Tiwari, 2017; Jenniches, 2018). It can help in reducing the dependence on limited reserves of fossil fuels and in mitigating the effects of climate changes (Sindhu et al., 2017a; Shahsavari and Akbari, 2018; Vinod et al., 2018). India having fast growing demand for electricity and increasing concern to emissions reduction is investing strongly in renewable electricity generation (Moallemi et al., 2017). Solar energy is one of the viable, non-polluting, inexhaustible and eco-friendly sources of energy (Sindhu et al., 2016a; Kabir et al., 2018). It may be exploited using one of the techniques viz. solar photovoltaic (PV) and solar thermal technology (Sindhu et al., 2016b). In India, solar energy is gaining much importance due to the several concerns such as energy security, volatility of oil market, climate changes, rural energy needs, and sustainable economic growth (Hairat and Ghosh, 2017). Since independence, Government of India (GoI) has been developing and initiating a wide ranging policies, regulatory instruments, and institutional structures to support the development of solar energy. However, solar energy development in India has gained momentum only after the release of the national solar mission in 2009 which targeted to attain solar generation capacity of 20 GW by 2022 (Yenneti, 2016; Sindhu et al., 2017b, 2017c). Now, GoI has recently approved increasing the target five times to a goal of reaching 100 GW up from 20 GW by 2022 (Yenneti, 2016). Figure 1 depicts the average annual solar energy potential in India.

Figure 1 Average annual solar energy potential in India (see online version for colours)

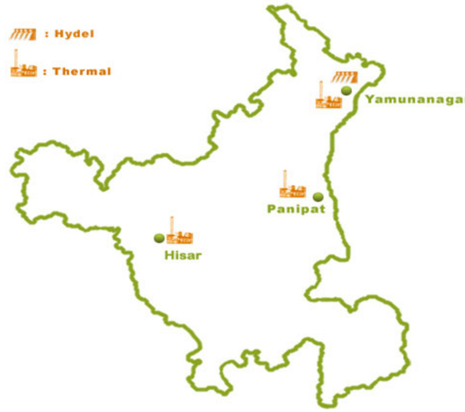


Source: GeoModel Solar

India is having diverse climate, geographical population and is divided into 29 states. Moreover, two third population of India resides in rural area and farming outcome being the only source of income. Haryana is geographically located at 30.73° N and 76.78°, spreading over 44,222 km^2. Administratively, the state is divided into 22 districts and Sonepat City is one of its districts (Chauhan, 2010).

The total human population of the state is around 25.35 million (as per 2011 census), which is about 2% of total population of the country, with 76% residing in rural areas (Chauhan, 2010; Government of Haryana, http://www.haryana.gov.in). The major part of the revenue in the state comes from agricultural sector as well as it shows fast growing industrial and educational sectors. At present, the state has a sound network of technological knowledge producing institutions like central, state, private, deemed, technological Universities, autonomous and self financing institutes. In addition, the state has a diverse type of professional institutions such as engineering, ayurvedic, dental, hotel management, law, nursing, pharmacy and physiotherapy colleges (Nehra et al., 2010). The generating capacity of the state is 4,852.70 MW through thermal and hydel stations at Panipat, Hisar, Yamunanagar and Jhajjar (http://www.hpgcl.org.in). Figure 2 depicts the running power plants of Government of Haryana.

Figure 2 Running TPP in Haryana (State Government) (see online version for colours)



Source: Haryana Power Generation Corporation Limited (HPGCL) official website (http://www.hpgcl.org.in)

Haryana power sector is facing several problems that include theft of power, dependence on power purchase agreements, forced outage of thermal plants and working of discoms. In 2014, the maximum power supply on a single day was 7,616 MW while the maximum demand crossed 8,370 MW which shows a great gap between demand and supply in the state (http://indianpowersector.com/2015/04/haryana-power-sector-problems/). As per present situation of rural Haryana, villagers get electricity supply only for 11 hours out of which only 2 hours supply during the day time (http://www.dailypoineer.com). In such a situation, they are bound to use kerosene or diesel for meeting their fundamental needs. A crucial determinant for the growth of a state is providing access to smooth and adequate energy supply to each and every sector of the economy especially educational sector.

1.2 Related work

In this subsection, the literature review in context of present investigation is discussed. Several researchers have worked in assessment and simulation for PV power generation at various sites. A brief outlook of some of the recent studies has been presented here.

Khatri (2016) proposed to install PV power plant near the Gargi girls' hostel in Malviya National Institute of Technology (MNIT), Jaipur, India. The author carried out cost analysis, economic and environmental viability of the plant in campus area. Mandal and Panja (2016) proposed to install 1 kWp PV system on the roof top of School of Energy Studies Building in Jadavpur University, Kolkata, India and found that the power feeding to the grid is maximum 814 W at the radiation of around 1,003 W/m^2. The overall system efficiencies vary from 12.3% to 18.42% at different level of solar intensity. Shukla et al. (2016a) simulated rooftop grid connected PV system on the campus of Maulana Azad National Institute of Technology (MANIT), Bhopal, India and compared the performance of various PV technologies using Solargis software. Shukla et al. (2016b) designed a standalone rooftop solar PV system to fulfil energy demand of the hostel of MANIT, Bhopal. The study presented detailed cost analysis of this rooftop solar PV system. Kumar and Sudhakar (2015) compared the performance of 10 MW PV grid connected power plant at Ramagundam site with the simulation results obtained using Solargis PV Planner and PVSyst software. Kumar et al. (2014) discussed the details and results obtained from a study carried out on a roof top 20 kWp solar PV power plant in a reputed manufacturing industry in India. Tarigan et al. (2014) analysed the PV power generation for residential house in Indonesia using PV planner. Talavera et al. (2011) estimated the PV potential of the Campus of the University of Jaén in southern Spain. The authors evaluated unit cost of electricity (UCE) using the concept levelised cost of electricity as \$0.13–0.14 per kWh. Kirmani et al. (2010) conducted techno economic feasibility analysis of a stand-alone PV system to electrify a rural area household in India having energy requirement of 1,356 Wp and provided UCE as \$0.74/kWh.

Therefore, with the help of literature review, it has been proposed to install the rooftop PV power plant in the premises of Bhagat Phool Singh Mahila Vishwavidyalya (BPSMV), Khanpur Kalan, Sonepat, Haryana.

After thorough literature survey, objectives framed in context of present study are discussed subsequently.

1.3 Objectives of the study

As the BPSMV is located in the rural belt of Haryana, there is need to empower the grass root rural population about implications of solar energy which offer development ideas and solutions for basic human facilities such as education, employment, health solution, agri information dissemination system, management and automation solution, governance etc. The solar energy offers improved and affordable solution to these basic necessities of rural people at their village doorsteps.

Simulation methods are very useful in testing the performance of various components of the PV system before actually installing them hence reduce material and installation cost (Tarigan et al., 2014). Keeping in view the above facts, specific aim of the study is as follows:

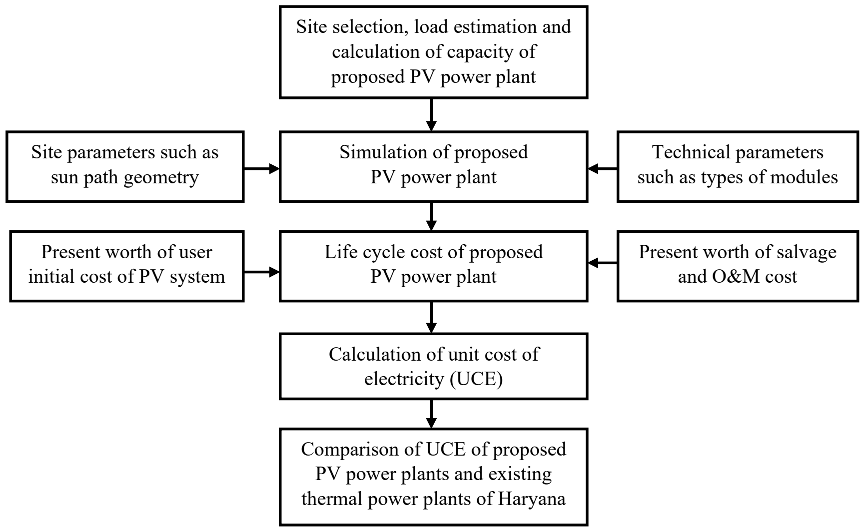
- To assess and evaluate the solar resource potential at BPSMV, Khanpur Kalan, Sonepat, Haryana, India.
- To perform the simulation of proposed capacity of 160 kWp (calculated) of rooftop grid connected PV power plant.
- To evaluate the annual energy yield and PR of the proposed PV power plant.
- To compare the different PV technologies on the basis of simulated results and suggest the best one for building installation.
- To calculate life cycle cost (LCC) of the proposed PV power plant and obtain UCE for it. Finally, carry out comparative analysis with existing TPP in Haryana.

This work presents an assessment of PV power generation for FET, BPSMV, Khanpur Kalan, Sonepat, Haryana using SolarGIS – PV Planner simulation software. Detailed site information is discussed in forthcoming section.

1.4 Methodology adopted

The present investigation utilises the Solargis PV Planner for evaluating the energy yield and PR of the proposed PV power plant for educational building of rural BPSMV, Haryana. Figure 3 illustrates the methodology adopted for conducting the present study.

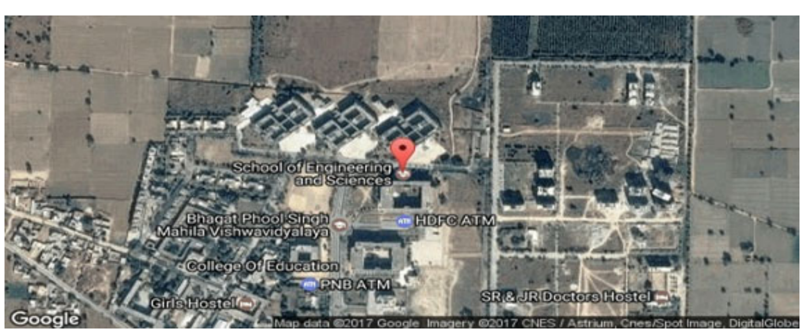
Figure 3 Line diagram for proposed PV power plant



2 Site information: rural women university

BPSMV is the first ever women only state university in northern India established by the Government of Haryana in 2006 at village Khanpur Kalan, District Sonipat. The aim of the University is to provide affordable qualitative higher education to women especially belonging to rural areas. FET erstwhile known as School of Engineering and Sciences (SES) offer multiple discipline in its various departments dedicated for imparting technical education to girls, has a four storey building having almost 50 rooms with provision of modern teaching, library, student activity centre, laboratories, conference hall etc. with a total coverage area of 13,666 m^2 (http://www.bpswomenuniversity.ac.in/ses/). Figure 4 depicts the satellite view of site location.

Figure 4 Satellite view of FET, BPSMV (see online version for colours)



Source: http://suncalc.net/#/29.1554,76.8103,17/2014.09.22/10:49

Table 1 illustrates the monthly average radiation data for Sonepat City located at 28.95 N and 77.05 E in Haryana state of India and Table 2 depicts the various important site parameters.

Table 1 Solar radiation data for Sonepat

Month	*Average (kWh/m²)*
January	3.37
February	4.62
March	6.00
April	6.81
May	7.09
June	6.40
July	5.61
August	5.43
September	5.42
October	5.04
November	3.87
December	3.20
Annual average	*5.24*

Source: Synergy Enviro Engineers (http://www.synergyenviron.com/tools/solar-irradiance/india/haryana/sonepat)

Table 2 Site parameters

Particular	*Value*
Site name	BPSMV, Khanpur Kalan, Sonepat, Haryana, India
Coordinates	29.15, 76.81
Elevation a.s.l	226 m
Slope inclination	0°
Slope Azimuth	0°N
Annual air temperature at 2 m	25°C

Daily solar radiation is an important factor that helps in determination of the proposed capacity to be installed at the site location which has been derived subsequently.

3 Load estimation and calculation of capacity of proposed PV power plant

A thorough investigation was conducted to estimate the overall load consumption in FET in the university. Table 3 depicts the various electrical equipments floor wise.

Table 3 Energy required per floor

S. no.	*Floors*	*Fans*	*Single tubes*	*Double tubes*	*4th set tubes*	*Exhausts*
1	Ground floor	174	91	70	67	06
2	1st floor	172	72	74	50	11
3	2nd floor	146	88	76	-	15
4	3rd floor	185	121	85	-	16
5	Bathroom + toilet + stairs	-	68	-	-	32
Total		*677*		*TUBES = 862*		*80*

Table 4 depicts the electrical equipments along with their rating, hours of operation and overall energy required per day as per survey. The total energy required for the building per day is assessed to be 646 kWh/day.

Table 4 Total energy required for FET per day

S. no.	*Name of equipment*	*Quantity*	*Rating (W)*	*Hours of operation per day (h)*	*Energy required (kWh)*
1	Tube light	862	40	8	275.840
2	Fan	677	40	10	270.800
3	Exhausts	80	20	5	8
4	Water cooler	4	700	8	22.400
5	Laptop/desktop PC	150	60	6	54
6	Mobile charger	150	5	2	1.5
7	Server (LAN port)	150	15	6	13.5
Total energy consumption per day					*646.04*

Panel generation factor is an important component in determining every watt-peak (Wp) capacity in the panel that can be expected to obtain an average of Wh/day and it varies with the location of the site (Khatri, 2016). For Sonepat City, it has been considered as 5.24 kWh/m^2 as illustrated in Table 1. Panel generation factor is derived in equation (1) as follows:

$$\begin{aligned}\text{Panel generation factor} &= \frac{\text{Daily solar radiation}}{\text{Standard test conditions irradiance for PV panels}} \\ &= \frac{5.24 \times 10^3}{1{,}000} = 5.24\end{aligned} \tag{1}$$

Energy required from the PV module determines the daily energy demand of the building. Generally, 30% system losses are considered and therefore, the energy required comes out to be as follows (Khatri, 2016):

$$\begin{aligned}\text{Energy required } (E_L) &= \text{Energy demand} \times \text{System losses compensation factor} \\ &= 646 \times 1.3 = 839.8 \text{ kWh/day}\end{aligned} \tag{2}$$

Watt peak rating from PV modules is calculated to determine system sizing which is dependent on energy expected from modules and panel generating factor (Khatri, 2016).

$$\begin{aligned}\text{Watt peak rating for PV modules} &= \frac{\text{Energy required from PV modules}}{\text{Panel generation factor}} \\ &= \frac{840}{5.24} = 160 \text{ kWp}\end{aligned} \tag{3}$$

Therefore, 160 kWp is the proposed capacity used in the system simulation discussed in forthcoming sections.

4 Designing of PV modules

In present investigation, ASPL V60 from Ajit Solar manufacturer has been considered for module. It has been selected on the basis of the availability, price and ease to approach. Table 5 provides the complete module specifications.

Table 5 PV module specifications

Module type*	ASPL V60
Peak power output (P_m)	230 (W_p)
Current at peak power output (I_{max})	7.77 A
Voltage at peak power output (V_{max})	29.60 V
Short circuit current (I_{sc})	8.28 A
Open circuit voltage (V_{oc})	37.10 V
Dimensions (mm)	1,665 × 995 × 50
Cell efficiency	16%

Note: *Irradiance of 1,000 W/m^2, spectrum AM of 1.5 and cell temperature of 25ºC.

Source: Ajit Solar (http://www.ajitsolar.com/products.html)

The number of PV modules required for the plant designing depends on the peak rating of the module and is given using equation (4):

$$\begin{aligned}\text{Numbers of module required} &= \frac{\text{Total wall peak rating}}{\text{PV module peak rated output}} \\ &= \frac{160 \times 10^3}{230} = 696\end{aligned} \tag{4}$$

4.1 Sizing of battery

In case of solar PV system, storage medium is required to supply the power when sun is not available (Sindhu et al., 2016a). BPSMV is located at rural location but have low power cuts due to educational infrastructure. So, single day of autonomy is considered for the investigation. Table 6 shows the battery specifications used for the present study.

Table 6 Specifications of battery

Particulars	*Value*
Nominal voltage	48 V
Depth of discharge (DOD)	40%
Capacity of battery	175 Ah
Efficiency of battery	90%
Life of battery	4 years

Source: http://www.atbatt.com/trojan-j185e-ac-12v-deep-cycle-battery.asp?cr_brand=Trojan&cr_product=J185E-AC

Required battery capacity is computed using equation (5) and is given as follows:

$$\text{Battery capacity required} = \frac{\text{Total Wh required} \times \text{Days of autonomy}}{\text{Nominal battery voltage} \times (1 - \text{DOD}) \times \text{efficiency}} \tag{5}$$

$$\text{Battery capacity} = \frac{646 \times 10^3 \times 1}{48 \times 0.6 \times 0.9} = 24{,}923 \text{ Ah}$$

The number of batteries depends on the capacity of individual battery and is evaluated in equation (6) as follows:

$$\begin{aligned}\text{Number of batteries} &= \frac{\text{Battery capacity required}}{\text{Capacity of individual battery}} \\ &= \frac{24{,}923}{175} = 143\end{aligned} \tag{6}$$

4.2 *Sizing of inverter*

The size of the inverter is decided on the basis of calculated peak watt rating of the installed power. The peak watt rating in the present study is 160 kWp. The size of the inverter must be able to handle total amount of watt peak required. The size of the inverter is chosen 25–30% larger than total watt required in order to accommodate the losses.

$$\text{Size of inverter} = 160 \times 1.3 = 208 \text{ kW} \tag{7}$$

Present study considers Solectria PVI 82 kW inverter for the investigation (http://www.pvpower.com/solectriapvi82kwinverter82kw.aspx). The number of inverters is determined on the basis of rated power of the inverter.

$$\text{Number of inverters} = \frac{\text{Inverter size}}{\text{Rated power of an inverter}} = \frac{208}{82} = 3 \tag{8}$$

4.3 *Sizing of module circuit*

Module circuit gives information regarding the array size, number of arrays employed in the system and voltage fed to the inverter. The size of the array determines about the number of modules to be connected in series. It depends on the open circuit voltage of inverter and individual module utilised.

$$\text{Size of an array} = \frac{\text{Maximum open circuit voltage of inverter}}{\text{Open circuit voltage of individual module}} = \frac{600}{37.1} = 16 \tag{9}$$

$$\begin{aligned}&\text{Maximum voltage input to the inverters}\\&\quad = \text{Maximum voltage from a module} \times \text{Number of module in series}\\&\quad = 29.6 \times 16 = 474\ V\end{aligned} \tag{10}$$

$$\text{Total number of array} = \frac{\text{Number of modules}}{\text{Number of modules in an array}} = \frac{696}{16} = 44 \tag{11}$$

4.4 Solargis simulator

Solargis simulator implements four applications viz. iMaps (Kumar and Sudhakar, 2015):

1 utilising high resolution global interactive maps

2 climate data: that provides access to solar irradiation and air temperature

3 PV Planner: basically a simulator implementing several algorithms and data formats

4 PV Spot: a tool for evaluating performance and supervision of PV systems.

Solargis PV Planner is a user friendly simulator having provisions to plan and optimise PV systems by implementing algorithms and by utilising climate and geographic data (Cebecauer and Suri, 2015; Dondariya et al., 2018). It is used for prospecting sites and comparing their energy yields with the usage of different PV technologies options and mounting structures. With the help of the tool, it is easy to know the future PV yield from the system before actually design and construction takes place.

The performance of the system is measured using two important parameters viz. system energy yield and system PR as stated here:

a Energy yield

The final yield or energy yield is stated as the ratio of total AC energy output ($E_{PV,AC}$) to the peak power of the proposed PV array power capacity ($P_{\max G,STC}$) at standard test conditions (STC) as given using equation (12) (Kumar and Sudhakar, 2015).

$$\text{Energy yield}\left(E_{AC_{kWh}}\right) = \frac{E_{PV,AC}}{P_{\max G,STC}} \tag{12}$$

b Performance ratio (PR)

The PR is determined by dividing energy yield $(E_{AC_{kWh}})$ obtained in equation (12) to the DC power obtained at STC $(E_{DC_{STC}})$ which is given as follows using equation (13) (Shukla et al., 2016a):

$$\text{Performance ratio}\ (PR) = \frac{E_{AC_{kWh}}}{E_{DC_{STC}} \times irradiation}$$

Various parameters assumed for simulation have been gathered and summarised in Table 7.

Table 7 System information for simulation

	Value
Particulars	
Proposed power capacity	160 kWp
Types of modules	c-Si/a-Si/CdTe/CIS
Mounting system	Fixed mounting, free standing
Azimuth/inclination	180° (south)/29°
Inverter euro efficiency	96.0%
DC/AC losses	5.0%/2.0%
Availability	95.0%
Assumptions	
Phase of system	Start-up phase of a PV project
Tilt angle of the PV array	Same as latitude of the site (Singh, 2010).
Useful life time (N) of the PV system	20 years

Using assumptions in Table 7, simulation in PV Planner has been performed.

4.4.1 Site meteorological and solar radiation data

Solar radiation data is one of key element for accurate assessment of energy yield. Figure 5 shows the path of Sun on annual basis. It also depicts terrain horizon, module horizon, and active area with civil (clock time) and solar time. Module horizon, however, may have shading effect on solar radiation.

Figure 5 Path of sun over the year (see online version for colours)

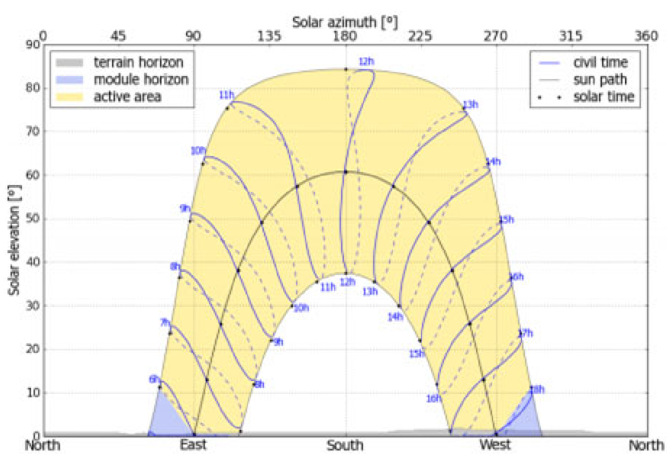
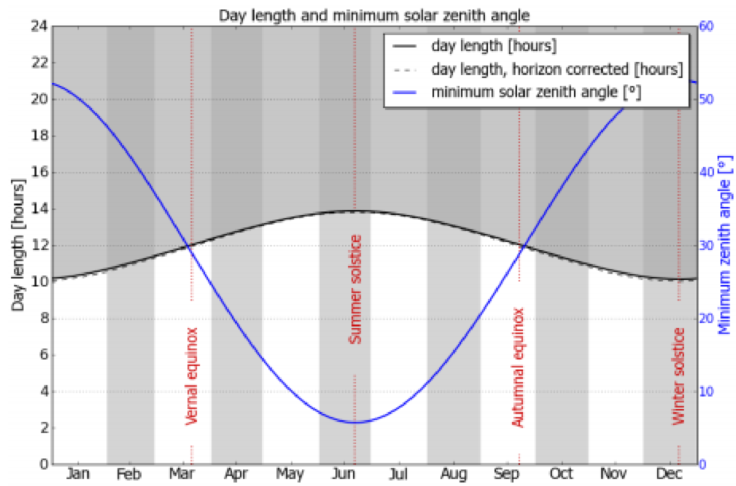


Figure 6 depicts annual change of the day length and solar zenith angle. The local day length, i.e., the time when sun lies above the horizon is short as compared to the astronomical day length, i.e., when obstructed by higher terrain horizon.

Figure 6 Day length and solar zenith angle in FET (see online version for colours)



5 Economic and cost analysis

The economic analysis is not complete if net present value (*NPV*) and the internal rate of return (*IRR*) not evaluated. *NPV* is defined as the difference between the present worth (*PW*) of cash inflows from the system ($CIF(N)_{PW}$) and the *LCC* (Talavera et al., 2011). *NPV* may be expressed as follows:

$$NPV = CIF(N)_{PW} - LCC \tag{14}$$

A PV investment is viewed as favourable if $NPV > 0$. The *PW* of cash inflows from the system ($CIF(N)_{PW}$) is determined as follows:

$$CIF(N)_{PW} = P_u \times E_{PV} \times \frac{K_{PU}\left(1 - K_{PU}^{N}\right)}{1 - K_{PU}} \tag{15}$$

where P_u is the average unitary price per kWh. E_{PV} is the annual electricity generated. K_{PU} is a parameter determined as follows:

$$K_{PU} = \frac{1 + \varepsilon_{pu}}{1 + d} \tag{16}$$

The LCC of a component expresses the total costs of owning and operating an item over its lifetime which is calculated in terms of present value of money (Kirmani et al., 2010). The various costs included in LCC are installing cost, operation and maintenance cost (O&M) cost, repair cost and less salvage cost etc. LCC may be expressed as follows:

$$LCC = PW\left[PV_{UIN}\right] + PQ\left[PV_{OM}\right] - PW\left[PV_S\right] \tag{17}$$

$PW[PV_{UIN}]$ stands for the present worth of initial user investment of PV system, $PW[PV_{OM}]$ is the present worth of O&M cost and $PW[PV_S]$ is the present worth of salvage cost. PW of O&M cost is calculated using follows:

$$PW\left[PV_{OM}\right] = PV_{AOM} \times \frac{K_{PV}\left(1 - K_{PV}^{N}\right)}{1 - K_{PV}} \tag{18}$$

PV_{AOM} is annual O&M cost which is taken as 1% of initial investment. KP_V is calculated as follows:

$$K_{PV} = \frac{1 + \varepsilon_{PVOM}}{1 + d} \tag{19}$$

here ε_{PVOM} is the annual escalation rate of O&M cost of the PV system. The PW of salvage value of the plant may be calculated using equation (20), where N is 20 years:

$$C_{SPW} = C_{PV}\left(\frac{1 + i}{1 + d}\right)^{N} \tag{20}$$

It is always desirable to express LCC of the system annually. The annualised LCC (*ALCC*) of the PV system may be expressed in PW using equation (21) as given below:

$$ALCC = LCC\left[\frac{1 - \left(\frac{1 + i}{1 + d}\right)}{1 - \left(\frac{1 + i}{1 + d}\right)^{N}}\right] \tag{21}$$

UCE is calculated using the ALCC in the following relation as given in equation (22):

$$UCE = \frac{ALCC}{365E_L} \tag{22}$$

Another important parameter in economic analysis is IRR. IRR is defined as the value of discount rate at which NPV leads to zero. It is expressed as follows:

$$NPV = CIF(N)_{PW} - LCC = 0 \tag{23}$$

The parameters assumed and utilised for the calculation of LCC, NPV and IRR has been summarised in Table 8.

Table 8 Assumed values of parameters for economic analysis

S. no.	*Particular*	*Symbols*	*Values*
1	Discount rate	D	10%
2	Inflation rate	I	7.23%
3	Salvage cost	C_{PV}	20%
4	O&M cost	PV_{AOM}	1%
5	Price of unit energy	P_u	\$0.13/kWh
6	Escalation in price of unit energy	ε_{pu}	2%
7	Escalation rate of O&M cost	ε_{PVOM}	3%
8	Rs to \$	-----	Rs 64/\$

Solving equations (14)–(23) presented in Subsection 4.5 along with the parameters presented in Table 8, LCC, NPV and IRR may be obtained easily.

6 Life cycle assessment of the PV plant

Usually, four economic indicators are often used for assessment of any renewable energy system, i.e., embodied energy of the system, energy payback time, life cycle conversion efficiency and capacity utilisation factor. The brief description of the same is as follows:

6.1 Energy payback time of the proposed plant

Energy payback time (EPBT) is defined as "how long the PV system is to be operated to recover the energy spent in building it". It is expressed using equation (24) as follows:

$$EBPT = \frac{E_m + E_{mf} + E_t + E_i + E_{mg}}{E_g} \tag{24}$$

Tiwari et al. (2009) has presented the value of energy consumption in materials, manufacture, transport, installing and managing the every m^2 area of the module which is given as follows:

$$E_m + E_{mf} + E_t + E_i + E_{mg} = 1{,}516.59 \text{ kWh/m}^2$$

Total area of module is obtained using number of modules used in an array, length and width of the module which is given as equation (25) as follows:

$$\begin{aligned}\text{Total area of module} &= \text{Number of modules} \times \text{Length} \times \text{Width of modules} \\ &= 696 \times 1.665 \times 0.995 = 1{,}153 \text{ m}^2\end{aligned} \tag{25}$$

$$\text{Total embodied energy } (E_{em}) = 1{,}153 \times 1{,}517 = 1{,}749 \text{ MWh}$$

$$\text{Annual electricity generated } (E_g) = 646 \times (320)^* = 206.7 \text{ MWh/year}$$

where * indicates the number of clear annual sunny days in Haryana (Sindhu et al., 2017b). Energy payback time is obtained using equation (26) as follows:

$$EPBT = \frac{E_{em}}{E_g} = \frac{1{,}749}{206.7} = 8.46 \text{ years} \tag{26}$$

6.2 Energy production factor

Energy production factor (EPF) is the indicator of overall efficiency provided by the proposed plant. It is just the reciprocal of energy payback time of the plant and is given using equation (27).

$$EPF = \frac{E_g}{E_{em}} = \frac{206.7}{1{,}749} = 0.11$$

6.3 Capacity utilisation factor

Capacity utilisation factor (CUF) is defined as the ratio of actual energy generated by the PV plant on annual basis to the equivalent energy output at its rated capacity annually. It is given using equation (28) as follows:

$$
\begin{aligned}
CUF &= \frac{\text{Annual energy generated for each kW peak capacity}}{365 \times 24} \\
&= \frac{\frac{206{,}720}{336}}{8{,}760 \text{ hours}} = 0.070
\end{aligned} \tag{28}
$$

6.4 Life cycle conversion efficiency

Life cycle conversion efficiency (LCCE) determines that the system is how much productive in relation to the solar irradiation over its entire lifetime and is given using equation (29).

$$
\begin{aligned}
LCCE &= \frac{E_g \times N - E_{em}}{E_{sol} \times N} \\
&= \frac{206.7 \times 10^3 \times 20 - 1{,}749 \times 10^3}{4{,}463.628 \times 10^3 \times 20} = \frac{2{,}385{,}000}{89{,}272{,}560} = 0.027
\end{aligned} \tag{29}
$$

N denotes the life of plant which is considered to be 20 years in the investigation. Khatri (2016) has determined E_{sol} to be 4,463.628 in the study and the same has been utilised here.

7 Estimation of carbon credits

Renewable energy sources have sound potential of reducing CO_2 emissions by being perfect substitute of fossil fuels (Vass, 2017). PV system is a neat and clean energy source. Neither it requires fuel for its operation nor does it emit greenhouse gases (GHG) during its entire life time. Presently, India has installed thermal capacity of 302,087.84 MW as per reports of Central Electricity Authority (CEA) (http://www.cea.nic.in/reports/monthly/installedcapacity/2016/installed_capacity-03.pdf) which emits carbon dioxide 0.98 kg per kWh (Sharma and Tiwari, 2013). Carbon dioxide emissions from the PV plant come in picture during the manufacturing and assembling of PV panels (Sindhu et al., 2016b). According to Indian conditions, while considering transmission and distribution losses, the CO_2 emissions per kWh reaches to 1.58 kg (Khatri, 2016). Carbon credits are calculated using following steps:

Step 1 Firstly, CO_2 emission is computed using equation (30).

$$\begin{aligned} CO_2 \text{ emission} &= \text{Embodied energy} \times 1.58 \\ &= 1{,}749 \times 10^3 \times 1.58 = 2{,}763.4 \text{ tonnes} \end{aligned} \tag{30}$$

Step 2 CO_2 mitigation determines reduction in amount of CO_2 due to usage of PV system that would have released by TPP in India. Yearly CO_2 mitigation is given using equation (31) as follows:

$$\text{Yearly } CO_2 \text{ mitigation} = E_g \times 1.58 = 206.7 \times 10^3 \times 1.58 = 326.6 \text{ tonnes} \tag{31}$$

Step 3 Net CO_2 reduction is calculated by subtracting the CO_2 emission and CO_2 mitigation over the entire lifecycle of the proposed power plant using equation (32).

$$\begin{aligned} \text{Net } CO_2 \text{ reduction} &= \left(\text{Yearly } CO_2 \text{ mitigation} \times N\right) - \left(CO_2 \text{ emission}\right) \\ &= (2{,}763.4 \times 20) - 326.6 = 54{,}941 \text{ tonnes} \end{aligned} \tag{32}$$

Carbon credits are obtained against reduction of harmful gases to the environment such as CO_2. One carbon credit corresponds to one tonne reduction of CO_2 (tCO_2e). Khatri (2016) have utilised market price of one carbon credit as \$0.67/tCO_2e. The same has been utilised for the present study and is obtained using equation (33).

$$\text{Carbon credits (\$)} = 54{,}941 \times 0.67 = \$36{,}810.5 \tag{33}$$

The results of the present study of simulation and economic assessment have been discussed in the subsequent section.

7 Results and discussions

Several relevant results have been obtained using simulation such as meteorological and solar radiation data, PV specific energy production and energy yield along with PR using different PV technologies etc. A brief discussion of the same is as follows.

7.1 PV specific energy production

Simulation using Solargis PV Planner was carried out to obtain the optimum specific energy production of the PV system by varying solar geometry parameters and type of PV materials. Figure 7 illustrates that maximum global in-plane irradiation has been recorded in the month of April which results in the highest daily sum of global irradiation. Table 9 shows the maximum global irradiance in the month of May (196 kWh/m^2). The parameters utilised for obtaining PV energy production are fixed surface, azimuth 180° (south), inclination as 29°.

Figure 7 Global in-plane irradiation and air temperature in FET (see online version for colours)

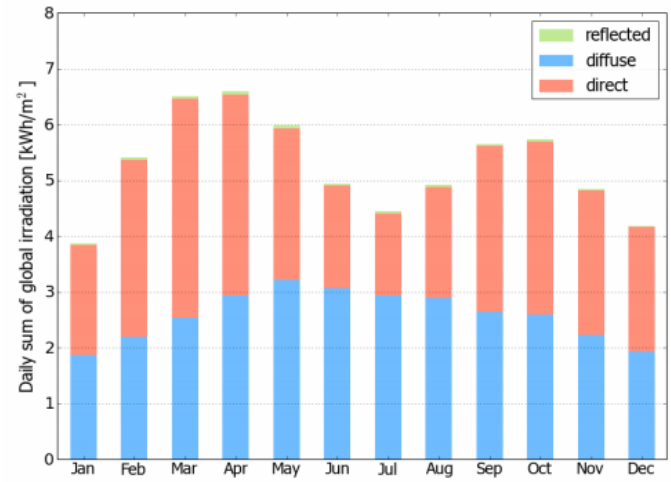


Table 9 Data of GHI and air temperature

Month	Gh_m (kWh/m^2)	Gh_d (kWh/m^2)	Dh_d (kWh/m^2)	T_{24} (°C)
January	92	2.96	1.67	12.7
February	121	4.31	1.97	15.7
March	177	5.71	2.35	21.7
April	194	6.45	2.91	29.2
May	196	6.33	3.38	34.5
June	162	5.40	3.29	35.6
July	148	4.79	3.14	32.7
August	156	5.03	2.99	30.5
September	157	5.24	2.55	28.6
October	149	4.79	2.38	24.6
November	112	3.72	1.96	19.3
December	96	3.08	1.68	14.7

Table 10 depicts the comparative results of average yearly sum of global irradiation by varying types of surface.

Table 10 Average yearly sum of global irradiation

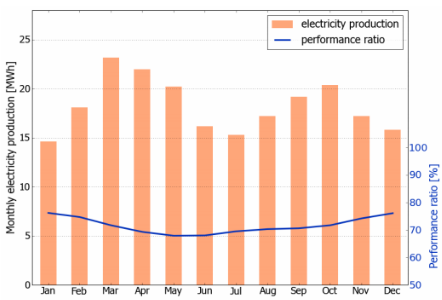
Type of surface	kWh/m^2	*Relative to inclined (%)*
Horizontal	1,758	91.7
Inclined (27°)	1,917	100
2-axis tracking	2,284	119.2
Inclined (29°)	1,915	99.9

The inclination 27° and 29° provide almost similar results. Horizontal mounting provides minimum value whereas 2-axis tracking provides best results solar irradiation.

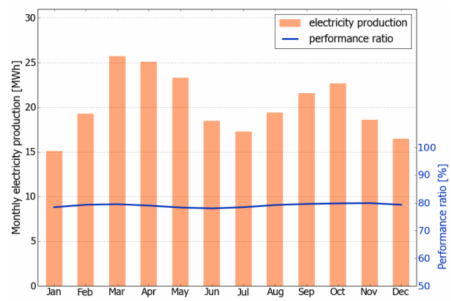
8.2 Energy yield and performance ratio

Energy yield and PR are two significant elements to determine the performance of a system which may be obtained using equations (12) and (13), respectively. Figure 8 depicts the energy yield and PR of four PV technologies viz. crystalline silicon, amorphous silicon, cadmium telluride and copper indium selenide.

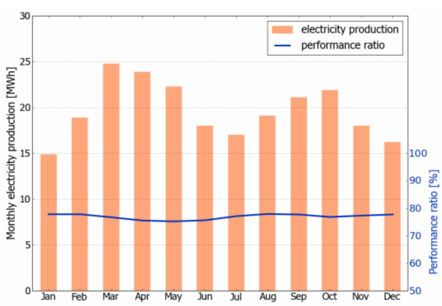
Figure 8 PV electricity production and performance ratio, (a) c-Si module (b) a-Si module (c) CdTe module (d) CIS module (see online version for colours)



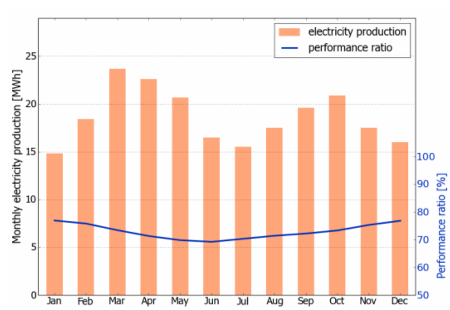
(a)



(b)



(c)



(d)

Table 11 represents energy output and average PR using four PV technologies. It is interesting to note that system energy yields varies from 1,371 kWh/kWp (c-Si module) to 1,518 kWh/kWp (a-Si module) and the system PR ranges from 71.4% (c-Si module) to 79.1% (a-Si module).

Table 11 Energy output and average performance ratio

S. no.	*PV technology*	*Energy Output (kWh/kWp)*	*Average performance ratio (%)*
1	c-Si	1,371	71.4
2	a-Si	1,518	79.1
3	CdTe	1,475	76.8
4	CIS	1,398	72.8

Amorphous PV technology performs the best among four PV technologies in terms of energy yield and PR. High PR is a desirable feature as it leads to high economic benefits.

8.3 Results of economic analysis

The results of economic and cost analysis have been summarised in Table 12. The results of cost and economic analysis recommend the installation of PV power plant at the premises of BPSMV Khanpur Kalan, Sonepat. The IRR and NPV are positive for the investment. The price obtained for UCE is $0.051 per kWh. It gives an indication that PV systems are going to be competitive in near future.

Table 12 Economic analysis results

S. no.	*Parameter*	*Value*
1	LCC ($)	248,638.86
2	UCE ($/kWh)	0.051
3	NPV ($)	17,659.86
4	IRR (%)	1.9
5	EPBT (years)	8.46
6	EPF	0.11
7	CUF	0.070
8	LCCE (%)	0.027
9	Carbon credits ($)	36,810.5

After comparing the present study with the similar studies conducted so far, it may be concluded that with the passing time UCE of the PV power plants is coming down. Of course, it is true that as compared to TPP it is still a costly option as depicted in Table 13 but GoI is offering subsidy to lower down the initial cost of PV power plants and giving boost to establish the plants in educational buildings and many other applications.

Table 13 Cost comparison of proposed PV power capacity and existing TPP

Plants in Haryana	*Unit cost of electricity (UCE/kWh)*	*Remark*
PTPS, Panipat (Unit 7)	3.10/- ($0.048)	As per data available for the month of Jan 2017.
PTPS, Panipat (Unit 8)	3.12/- ($0.048)	
DCRTPP, Yamunanagar	3.09/- ($0.0478)	
RGTPP, Khedar, Hisar	3.03/- ($0.0469)	
Proposed PV power plant	3.26/- ($0.051)	Calculated

Several significant conclusions may be drawn from the present investigation discussed subsequently.

9 Conclusions

In present investigation, the technical performance of a 160 kWp grid connected roof top solar PV system for supplying electricity to educational building of Women University in rural India has been attempted. A brief summary of findings of the present study are as follows:

- Various four types of PV modules have been simulated for determining the energy output and PR. The PR varies from 71.4% to 79.1% for crystalline silicon and amorphous silicon respectively.
- The energy yield varies from 1,371 kWh/kWp to 1,518 kWh/kWp for crystalline silicon and amorphous silicon respectively.
- Out of the four PV technologies, amorphous silicon and cadmium telluride depicts their PR higher than 76%. Although, all technologies performs satisfactorily under all weather conditions.
- UCE came out to be $0.051/kWh, in Indian rupees it is equivalent to Rs 3.26/- per unit. Although it is high as compared to UCE obtained from thermal power generation stations in Haryana such as Panipat, Hisar and Yamunanagar, i.e., maximum Rs. 3.12/- per unit (as per January 2017). But as the cost of PV panels is decreasing day by day and due to clean nature of solar power, it is a good alternative for fulfilling present and future energy demands. With this cost it can be inferred that it is best alternative for electricity generation in remote and rural sites.

10 Suggestions for future work

The present work may be expanded using the actual implementation of the simulated and proposed power plant in the BPSMV University and actually comparing the theoretical and practical results. Moreover, any other PV software apart from Solargis may be used such as PV SYST, SAM, Sunny Design or Blue Sol and the different results may be compared.

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Nomenclature

Abbreviations and symbols	*Description*
FET	Faculty of Engineering and Technology
BPSMV	Bhagat Phool Singh Mahila Vishwavidyalaya
PV	Photovoltaic
PTPS	Panipat Thermal Power Plant
DCRTPP	Deen Bandhu Chhotu Ram Thermal Power Plant
RGTPP	Rajiv Gandhi Thermal Power Plant
GoI	Government of India
JNNSM	Jwahar Lal Nehru National Solar Mission
STC k	Standard test conditions
kW	Kilowatt
kWh	Kilowatt hour
O&M	Operation and maintenance
kWp	Kilowatt peak
Gh_m	Monthly sum of global irradiance (long-term monthly average)
Gh_d	Daily sum of global irradiance (long-term monthly average)
Dh_d	Daily sum of diffuse irradiance (long-term monthly average)
T_{24}	Daily (diurnal) air temperature (long term monthly average)
N	Useful life time of power plant
D	Interest rate/ discount rate
I	Inflation rate
PVS	Salvage cost
LCC	Life cycle cost
ALCC	Annualized life cycle cost
UCE	Unit cost of electricity ($/kWh)
P_u	Price of unit energy ($/kWh)
ε_{pu}	Escalation in price of unit energy (%)
PR	Performance ratio
PW	Present worth
EPV	Annual PV electricity generated (kWh/yr)
IRR	Internal rate of return
NPV	Net present value ($)
PVAOM	Annual O&M cost of the PV system ($)
ε_{PVOM}	Annual escalation in O&M cost of PV system (%)
EPBT	Energy payback time
LCCE	Life cycle conversion efficiency

Nomenclature (continued)

Abbreviations and symbols	*Description*
EPF	Energy production factor
E_m	Energy for materials
E_{mf}	Energy for manufacturing PV system
E_t	Energy for transport
E_i	Energy for installation
E_{mg}	Energy for management
E_g	Annual energy generation
E_{sol}	Solar energy
E_{em}	Embodied energy (kWh)