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Research Article

# Energy, economic and environmental performance assessment of a grid-tied rooftop system in different cities of India based on 3E analysis

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## Abstract

India is very rich in solar energy, with a total of 3000 sunshine hours annually in most places. The installation of on-grid rooftop electricity-generation photovoltaic (PV) systems is currently undergoing substantial growth and extension as an alternate source of energy that contributes to Indian buildings. This paper analyses the viability of mounting solar PV plants in distinct cities of India in various locations with different climate conditions such as Delhi, Bhopal, Udaipur, Ahmadabad, Thiruvananthapuram, Pune and Madurai. The technical feasibility of installing a 100-kWp system is evaluated using PVsyst software under local climatic conditions. The performance ratio is between 70% and 80%, with a capacity utilization factor of 19–21% and estimated energy output of 170 MWh annually at all sites. The system produces 400–500 kWh of energy daily at a per-unit cost of INR 6–7 (Indian rupees) in all locations. The lifespan of the system is ~25–30 years, reducing about 150–170 tons of carbon-dioxide emission to the atmosphere every year. The payback period of the system is ~5–6 years, which defines its feasibility. This information would encourage organizations and individuals to install such PV plants on the rooftops of buildings to use solar electricity for meeting the energy demands of the country.



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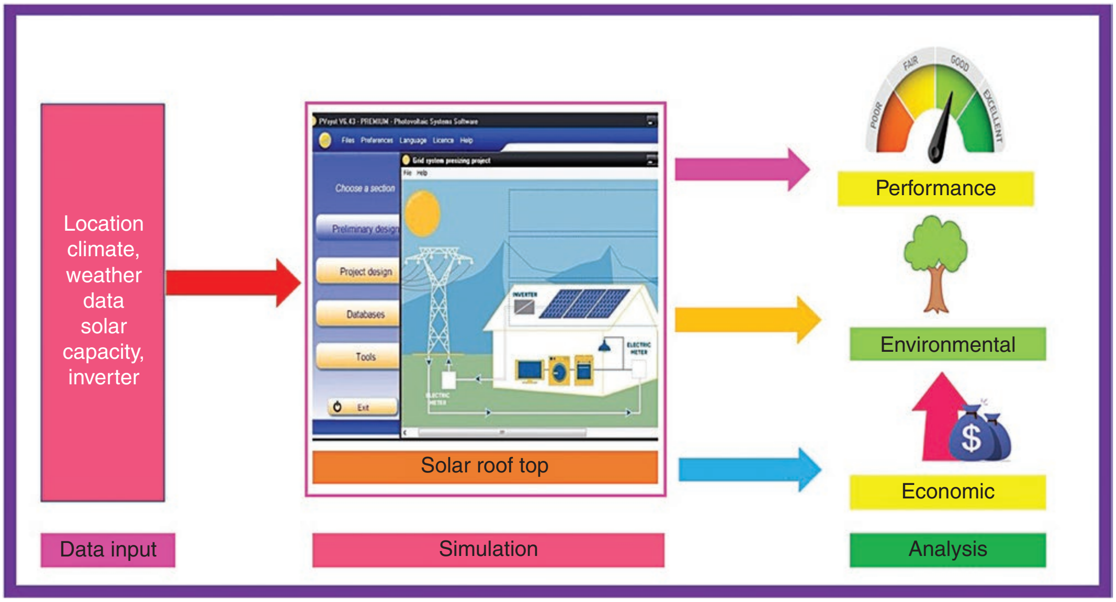
## Graphic abstract




*Keywords*: technical analysis; solar photovoltaic system; plant feasibility; grid-connected system; performance parameters

## Introduction

India is the world's second-most-populated nation, with a population of ~1.36 billion inhabitants. India is a nation with a large number of renewable energy resources available for production. About 86.75 GW of energy is installed from renewable sources, with 34.40-GW capacity from solar energy. The Indian government has set a target to accomplish 100 GW of solar capacity by 2022, including 40 GW from rooftop plants [1]. India has expanded its installed solar power capacity to 37 627 MW. Among these, the largest share is of ground-mounted solar parks, with a capacity of 27 930 MW, followed by 21 141 MW capacity of rooftop solar projects. The smallest share is of stand-alone or off-grid solar projects, having a capacity of 919 MW in villages and areas with no access to grid supply [2]. Large-scale ground-mounted and rooftop projects are mostly grid-connected, supporting the national grid. In recent years, due to awareness and favourable government schemes, many residential, commercial, industrial and agricultural buildings have installed rooftop solar plants. They are grid-interactive projects that may or may not have a two-way net metering supply but are still lowering the burden on the central or local grid.

India is executing the most ambitious renewable-energy expansion programmes for achieving a target of 175 GW of renewable-energy power by 2022 [3]. Newer electricity projects from renewable resources like wind, solar, etc. are developing massively, doubling their power capacities. This would put India among world leaders in green energy. The electricity-generation capacity from renewable sources has reached 35.86% in India, which is 21.22% of the total utility electricity in the country [4]. The fossil fuels are depleting, creating more pollution-causing and global warming. Further, with increasing energy demand, energy production from renewable energy resources has become the best solution in the present context as renewable energy resources are not exhaustible and constitute clean and green energy [5]. The solar power industry is increasing at a very rapid rate. Many solar energy products developed recently have increasingly helped to meet rural needs. For example, solar lanterns that reduce the need for kerosene, solar home and street lighting systems, solar cookers that reduce firewood or coal consumption, solar water heaters, dryers for agricultural and animal products, solar water pumps for irrigation purposes, solar greenhouses for vegetation, etc. encourage the use of the Sun's energy. This growth and expansion of solar power increase the standard of living of the population in the country and lead to economic progress [6]. Further, in recent days, for large-scale projects, the solar tariff has been considerably reduced to INR 2.44/kWh (US$ 0.036/kWh). Fig. 1 shows the chronology of the installed PV capacity of India in the last few years.

Thus, energy demands keep on increasing day by day. India is endowed with an immense solar power capacity of ~5000 trillion kWh each year, with ~300 direct sunshine days [7]. Many solar hotspots are identified in large geographical areas of the country for utilizing this huge energy prospect.

## 1 Literature review

Chandel *et al.* assessed the architecture, development and performance of one MW on-grid solar power production

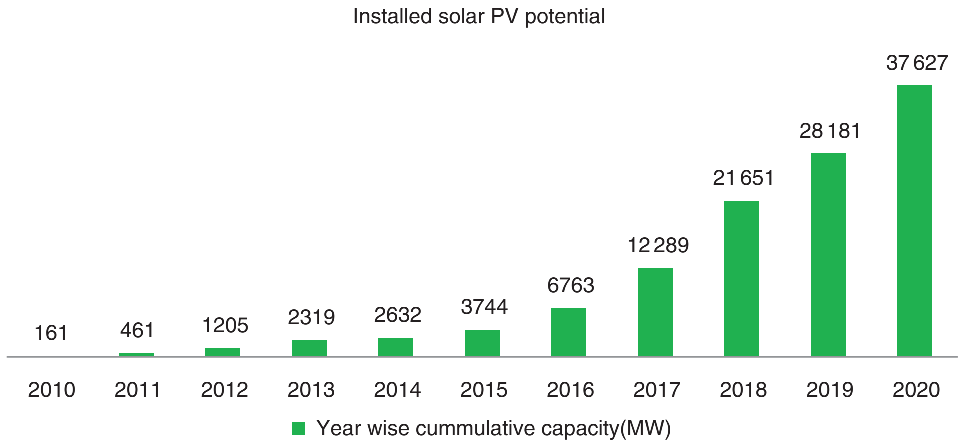



**Fig. 1:** Year-wise cumulative capacity of installed solar PV potential in India

Source: www.mnre.gov.in/reports/2020.

plant at Khordha, Odisha. The total power generated by the plant was ~1 416 200 kWh in 2019 with an annual performance ratio of 80% and capacity utilization factor (CUF) of 16.17% having a payback period of ~8 years. The work assisted in the efficient design and development of grid-interactive systems [6].

Ibrik performed a 12-month efficiency assessment of the 7.68-kWp grid-connected photovoltaic systems on the rooftop of each of the three Palestinian schools: Al-Razi Boys School, Almueh Boys School and Khawleh Bent Al Azwar Girls. The result of deployed photovoltaic systems indicated that the average output ratio (PR) was 78%; the total annual energy provided by each system was equivalent to 10 930 MWh/year. Economic findings were promising to increase the usage of these PV school systems, as the payback period of such a system was <5 years, the cost of the kWh generated was ~US$ 0.1 and the internal rate of return was ~20%. It also addressed the impacts of PV school systems on the power grid in minimizing disruptions and rising voltage levels, as well as the environmental implications of PV systems [8, 9].

Rathore *et al.* highlighted the solar power policies for the cooperative solar rooftop PV market, as well as the various business models and current status in India. Various factors were also studied that encourage the end user to invest in solar rooftop PV. The study also summarized some key obstacles to the growth and development of the solar rooftop PV market in India [10].

Dondariya *et al.* examined the feasibility of a grid-connected photovoltaic solar rooftop network for a residential building in the holy city of Ujjain, India. Various simulation tools such as PV*SOL, PVGIS, SolarGIS and SISIFO evaluated the performance of the 6.4-KW network. The system's annual energy output was 1 528 125 kWh/kWp and the efficiency ratio was 75.01%, which lowered the electricity grid's annual energy consumption by 41.09% [11].

Sharma *et al.* addressed the output of an 11.2-kW grid-connected rooftop solar power system installed at Anusandhan University, Bhubaneswar. The system's various parameters were analysed for a year and the total energy produced during this time was found to be 14 960 MWh with an output ratio of 0.78 [12].

Kumar *et al.* assessed the output of a 10-MW grid-connected solar photovoltaic power plant installed in Ramagundam, Telangana. The configuration of the solar photovoltaic plant operated with a seasonal tilt and its performance was studied along with the annual results. Also, the plant-output outcome was compared with the simulation values derived from PVsyst software and PV-GIS. This demonstrated grid-connected PV systems as the perfect clean-energy options for large-scale generation [13].

### 1.1 Research gap

There have been considerable research findings on large-scale solar projects in India and across the globe. However, a comprehensive performance of the small-scale rooftop system for building areas is less reported in the literature specific to various climatic zones of India. Literature analysis revealed that there is a need to review the techno-economic viability of solar PV systems for rooftop applications on residential, government buildings and educational campuses at different locations in India.

### 1.2 Objective of the study

This study aims at analysing the solar rooftop photovoltaic power generation in seven distinct cities of India. This study also analyses the economic and environmental feasibility of developing solar PV plants at seven Indian sites located at Delhi, Bhopal, Udaipur, Ahmadabad, Thiruvananthapuram, Pune and Madurai.

### 1.3 Key contributions

The key contributions of this analysis are:

(i) assessment of energy performance from rooftop solar PV plants and plant load factor/quality factor;
(ii) estimation of economic parameters including payback and energy cost for the proposed sites;
(iii) valuation of carbon-dioxide-emission reduction due to rooftop solar PV systems.

This research strengthens existing knowledge by undertaking photovoltaic power generation based on the solar rooftop at seven sites.

## 2 Methodology

### 2.1 Site location

India ranges from 8°4’ north and 37°6’ north latitude and 68°7’ east and 97°25’ east longitude to the north of the equator. It is based in the south of the Asian continent. This is the seventh-largest nation in the world, with a gross land area of 3 287 263 square kilometres. Seven distinct Indian cities in different geographical locations with varying climatic forms are considered in this study, as shown in the map of India in Fig. 2. They are as follows:

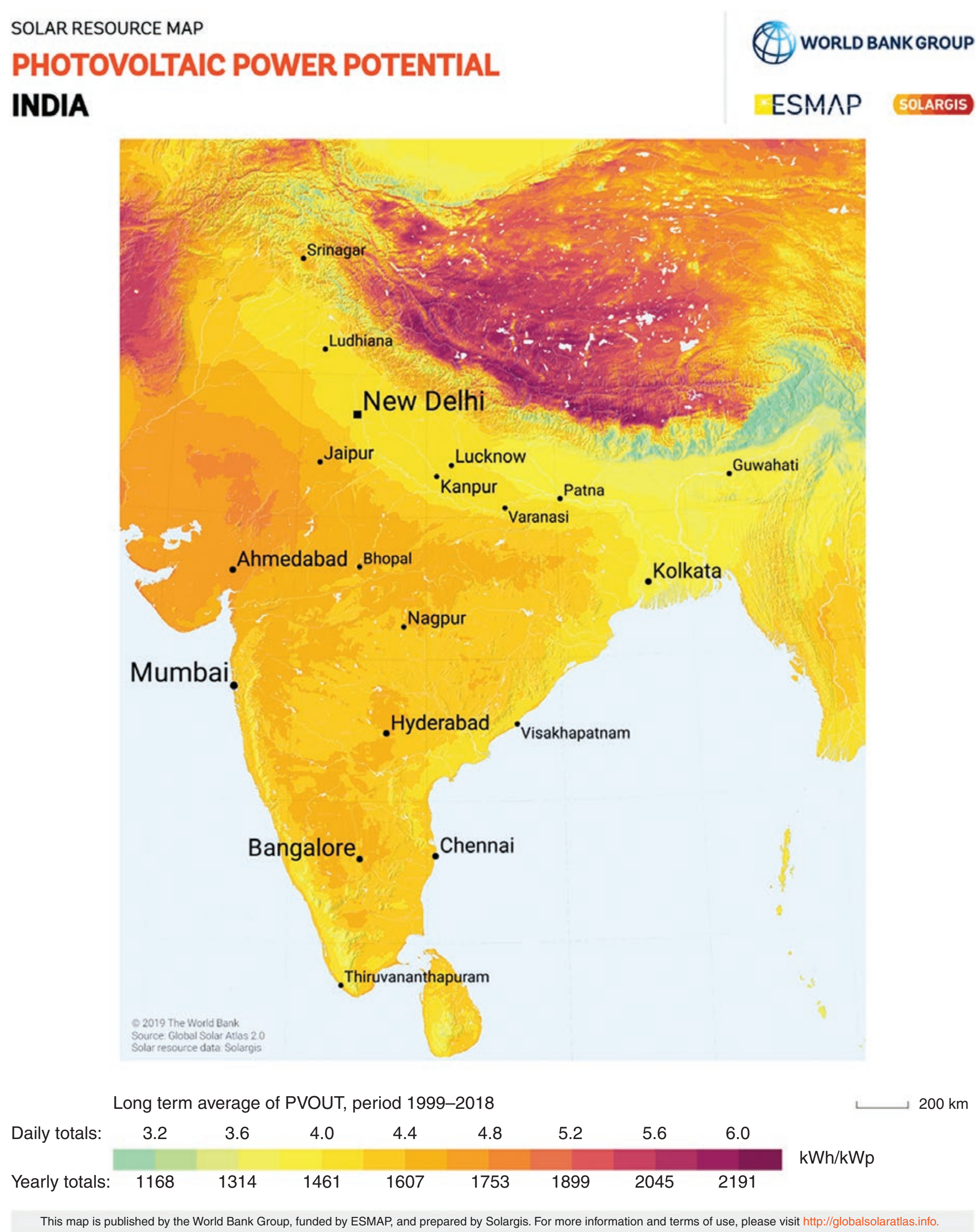



**Fig. 2:** PV power potential map of India

Source: http://www.nrel.gov/rredc/solar_data.html; © 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.

(i) *Delhi* is India's national capital. It is situated in the northern part of India at 28.70° north and 77.13° east, and is 233 m above sea level. The national capital region of Delhi covers an area of 1484 km$^2$ out of which 784 km$^2$ are in the countryside and 700 km$^2$ are portions under the metropolitan sector. Delhi has a moderate dry-hot semi-arid climate. The temperature ranges from 2°C to 47°C, with a mean of 25°C. There is an average rainfall of 886 mm during the monsoon season and heavy fogs during winters.

(ii) *Bhopal* is the capital city of the state of Madhya Pradesh in central India. It is located at an altitude of 511 m, at 23.26° north latitude and 77.41° east longitude. It covers an area of 971 km$^2$ out of which 285 km$^2$ are urban areas and 686 km$^2$ are rural areas. Bhopal has a humid subtropical climate. The temperature ranges from 3°C to 48°C, with a normal of 25°C. The annual rainfall is ~1146 mm, with cold nights in winter and hot, humid days in summer.

(iii) *Udaipur* is situated in the southern region of Rajasthan state in the north-western part of India. It is located at 24.58° north and 73.71° east. It covers an area of 64 km$^2$ and lies 598 m above sea level. The climate is extremely hot, with a temperature varying from 5°C to 49°C. The winter period is pleasant, with bright sunny days and cold nights; monsoons have humid thunderstorms and summers have extremely hot days with dusty sandstorms.

(iv) *Ahmadabad* is situated on the river bank in the northern region of Gujarat state in the western part of India. It is located at 23.07° north and 72.57° east, having an area of 464 km$^2$ and an altitude of 54 m. Ahmadabad has a hot tropical dry climate. The temperature ranges between 13°C in winters to 43°C in summers. The rainfall is marginally less and the weather is hot and dry most of the time.

(v) *Thiruvananthapuram* is the capital city of Kerala Indian state located in southern India. This most populated city is situated on the western coast along with the mainland nation at 8.48° north and 76.95° east. It is spread over an area of 250 km$^2$ with an average elevation of 5 m above sea level. It has a tropical-monsoon climate, with a temperature range of 20°C to 35°C. It receives heavy rainfall of 1827 mm annually, with high relative humidity throughout the year.

(vi) *Pune* is located in Maharashtra state in the western region of India. It is situated between 18.58° north latitude and 73.92° east longitude. Its total area is 332 km$^2$ and altitude is 560 m above sea level. Pune has a hot tropical wet and dry climate with a temperature varying from 20°C to 42°C. The rainfall is moderate, at ~722 mm, with high dusty wind in summers and humid winters.

(vii) *Madurai* is located in the eastern region of Tamil Nadu in the south of India. It is situated at 9.93° north latitude and 78.12° east longitude. It covers an area of 148 km$^2$ and has an average altitude of 101 m above sea level. It has a dry summer tropical climate with an average rainfall of 858 mm yearly. The temperature ranges from 18°C to 30°C in winters and 26°C to 42°C in summer. The weather is mostly hot and dry throughout the year.

The geographical locations of the sites selected for the study are summarized in Table 1.

## 2.2 Simulation software

Simulation software PVsyst version 6 designed at the University of Geneva, Switzerland is adopted for the simulation of rooftop solar PV systems [24]. The PVsyst simulation technique is used to determine the performance and analyse the energy costs of a PV network connected to a grid. Within a specific location, this program involves the compilation of meteorological data, device architecture, shading tests, loss determination and economic assessment. The simulation is conducted on a monthly basis for a full year and produces a complete summary and statement of outcomes. The simulation process requires the following steps:

- The first parameter is the position of the selected site using its latitude and longitude coordinates.
- Climatic data and solar-radiation data are then included from metrological programs like Meteonorm, NASA, etc. from its database.
- Next, the basic system configuration is specified, including the inclination of the PV modules (tilt angle, azimuth angle, direction), the appropriate power output, the available area (land base or rooftop) and the system form (fixed or moving axis).
- The system details are specified by choosing the number and type of PV modules (monocrystalline, polycrystalline or thin-film); size, number and type of inverter; array configuration (number of modules in sequence parallel string combination); transformer capability is performed according to plant requirements.

**Table 1:** Geographical coordinates of selected sites

| | City | State | Latitude (°) | Longitude (°) | Altitude (m) | Area (km$^2$) |
|---|---|---|---|---|---|---|
| 1 | Delhi | NCR | 28.70 | 77.13 | 233 | 1484 |
| 2 | Bhopal | Madhya Pradesh | 23.26 | 77.41 | 511 | 971 |
| 3 | Udaipur | Rajasthan | 24.58 | 73.71 | 598 | 64 |
| 4 | Ahmadabad | Gujarat | 23.07 | 72.57 | 54 | 464 |
| 5 | Thiruvananthapuram | Kerala | 8.48 | 76.95 | 5 | 250 |
| 6 | Pune | Maharashtra | 18.58 | 73.92 | 560 | 332 |
| 7 | Madurai | Tamil Nadu | 9.93 | 78.12 | 101 | 148 |

- The system is then simulated, estimating and visualizing the behaviour of various variants of a solar installation. The simulation results include monthly tables and graphs of normalized values gathered in a report. This also includes a loss diagram showing the energy performance with all system losses indicating system efficiency.
- Finally, the economic and environmental analysis is done mathematically based on the simulated results of the performance of the system.

## 2.3 Description of a 100-kWp rooftop system

The seven systems considered are of 100-kWp capacity and assumed to be installed on rooftops of government buildings in their specified locations. The PV system is south-oriented, shade-free and fixed according to the tilt angle of the site. The tilt angle is held almost equal to the position latitude for maximum solar-radiation absorption but is marginally modified to reduce energy losses. The PV modules chosen are polycrystalline types covering a surface area of 667 $m^2$ in each system. Their specifications are described in Table 2. The capacity of the inverter is also chosen according to the rating of the plant in each case. The specifications of the inverter are given in Table 3. Other required accessories such as cables, protection equipment, transformers, net meters, etc. are selected with the same specifications and make for the investigation of all the systems. The system is kept attached to the grid because it decreases local energy usage, so the surplus electricity will be pumped back into the grid. Because the system requires no batteries, the total cost of deployment and servicing is smaller relative to that of a stand-alone device (Fig. 3).

Many parameters are used for the evaluation of system performance based on energy generation. They help in comparing the feasibility of solar PV systems at different locations:

- *Tilt angle:* this is the angle between the solar panel and the horizontal line. The tilt angle for PV panels installed on a fixed tilted plane is usually held equal to the latitude of the site for optimum solar power extraction during production. But here it is slightly varied (up to +5° or –5°) during the simulation for reducing the energy losses considering yearly irradiation yield.
- *Azimuth angle:* this is the difference between the orientation of the south and the way the panels are facing. The angle is considered positive to the west and negative to the east. It is held at 0° in this situation.
- *Irradiance:* this is the amount of incidental solar radiation on a surface region of the object. It varies by location, altitude, time, season, precipitation, temperature, deposition of dust and other atmospheric conditions. It is taken as a daily average value from available metrological solar data for a particular location. It is expressed as a power in kWh/$m^2$/day.
- *Solar collection area:* this is the surface area occupied by solar panels used for the production of electric power from solar radiation. Three types of panels, namely monocrystalline, polycrystalline and thin-film, are available. They differ in technology, efficiency and price. Monocrystalline panels work better and need less room but cost more than polycrystalline panels. Thin-film panels are more costly, less effective and require larger space. All the plants require the same amount of area.

## 2.4 Energy analysis

- *Annual energy yield:* this is the final annual solar power output obtained from an installed PV system for an entire year. It can be expressed on a daily, monthly or yearly basis. It depends on component specifications and the solar irradiance of the system at a particular location [17].
- *Daily system output:* this is the average daily energy produced by a particular capacity system. It is the simulated value obtained based on the potential, rated capacity, geographical location and climatic conditions of the place. It is expressed as units of energy generated every day for a particular plant at a fixed site [18].
- *Specific yield:* this is the ratio of a system's annual energy yield to its nominal capacity. This indicates the potential of the system under a standard test condition (STC) considering the irradiance and meteorological conditions for a particular place. It is expressed in kWh/$kW_p$ [19].

**Table 2:** Specifications of PV module [14]

| S. no. | Parameter | Value | S. no. | Parameter | Value |
|---|---|---|---|---|---|
| 1 | PV module type | Polycrystalline | 6 | Open-circuit voltage | 37.8 V |
| 2 | Rating | 295 W | 7 | Short-circuit current | 9.61 A |
| 3 | Manufacturer | Vikram solar | 8 | Maximum voltage | 31.5 V |
| 4 | Number | 338 | 9 | Maximum current | 9.1 A |
| 5 | Operating temperature | –40 to +85°C | 10 | Efficiency | 16.3% |

**Table 3:** Specifications of solar inverter [15]

| S. no. | Parameter | value | S. no. | Parameter | Value |
|---|---|---|---|---|---|
| 1 | Type | Three phases | 6 | Operating voltage | 200–400 V |
| 2 | Capacity | 50 KW | 7 | Apparent power | 55 KVA |
| 3 | Manufacturer | Delta energy | 8 | Frequency | 50/60 Hz |
| 4 | Number of MPPT inputs | 4 | 9 | Current range | 18–24 A |
| 5 | Temperature range | –25 to +60°C | 10 | Efficiency | 98.4% |

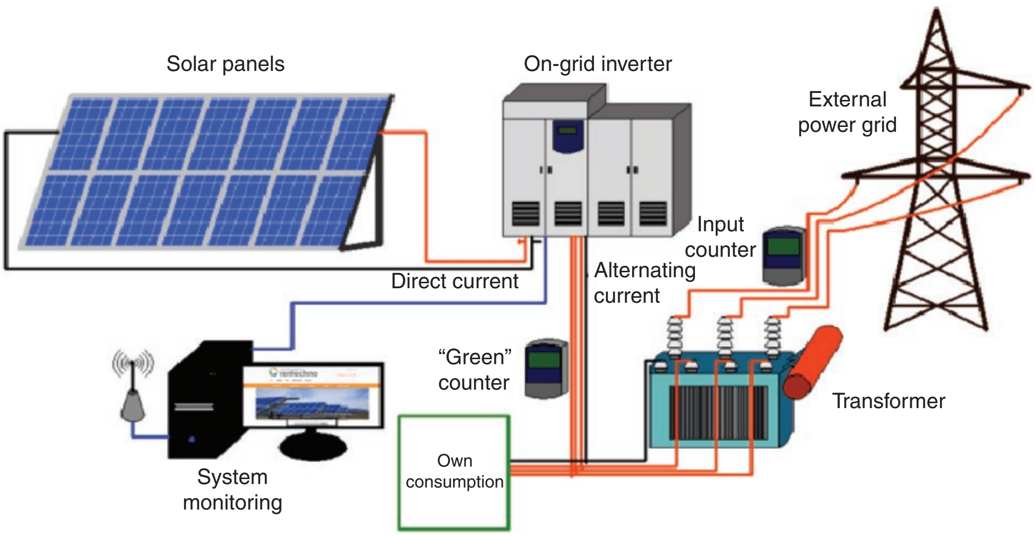



**Fig. 3:** Grid-connected solar PV system

Source: Electrical 4U components of solar electric generation system, https://www.electrical4u.com/components-of-a-solar-electric-generationsystem/.

$$\text{Specific Yield} = \frac{\text{Annual Energy yield}}{(\text{Nominal Power of Array})} \quad (1)$$

where the annual energy yield varies for different locations expressed in kWh/year.

### 2.4.1 *Plant load factor*

The plant load factor is the ratio of the output power produced by the system to the system output when the plant runs at the maximum rated capacity for a whole year, 24 hours a day. It is also known as the CUF. This is a measure of how well the system is being operated at a particular site under ideal conditions. It is expressed as a percentage [20]:

$$\text{Plant Load Factor or CUF} = \frac{\text{System Output Power}}{(\text{Plant Capacity} * 365 * 24)} * 100 \quad (2)$$

where the system output power is generated energy in kWh/year.

### 2.4.2 *Quality factor*

For a whole year, the quality factor is the ratio of the actual energy provided by the system to the energy created by the system under normal conditions (STC). It is also known as the performance ratio (PR). This is a measure of the system's ability to transform solar energy into electricity. It shows the total effect of conversion losses on the performance of the device (thermal, conduction, inverter, wiring mismatch, soiling). This depends on the environmental conditions (irradiance, temperature), geographical location and atmosphere at a given site. It is expressed as a percentage. It is measured as:

$$\text{Quality Factor or PR} = \frac{\text{Daily Energy Yield}}{(\text{Irradiance} * \text{Collector Area} * \text{PV module efficiency})} * 100 \quad (3)$$

where the daily energy yield is the average power output of the system for a day in kWh/day [21]. Irradiance is solar radiation incident on the surface in kWh/m$^2$/day, the collector area is the active surface of the PV array generating the solar power and the PV module efficiency is taken as specified by the manufacturer.

## 2.5 Economic analysis

### 2.5.1 *Energy cost*

The energy cost is the cost of the electricity produced from the solar power plant installed per unit. This depends on the overall expenditure in building the photovoltaic plant and the working conditions of the facility at a given location [23].

Investment varies according to the type of modules used in the PV array (monocrystalline < polycrystalline < thin-film), the mounting type (flat roof < façade < ground base) and the type of ventilation (free air circulation < semi-integration < fully insulated). The operation of the system depends on the geographical location (latitude, longitude altitude), climatic conditions (temperature, rainfall, humidity, irradiance), system losses (thermal, conduction, inverter, wiring mismatch, soiling, transmission) and output [22].

#### 2.5.2 *Simple payback period (SPP)*

The SPP is normally the time taken to recover the money spent in the project, measured in years. This is based on the system's annual energy savings. The earlier the original investment is returned, the more successful the project becomes:

$$\text{Simple Pay Back Period} = \frac{\text{Initial Investment}}{\text{Annual Savings}} \tag{4}$$

#### 2.5.3 *Levelized cost of electricity (LCOE)*

The LCOE of a photovoltaic system is the aggregate cost of the installation and operation of the system expressed in terms of the prevailing currency per kilowatt-hours. It can be expressed as follows:

$$LCOE = \frac{\textit{total life cycle cost (in Rs.)}}{\textit{Total lifetime energy production (in kWh)}} \tag{5}$$

$$\text{or LCOE} = \frac{\left[\left(\sum_{t=0}^{N} \mathrm{Ct}\right)/(1+\mathrm{r})\hat{}\,\mathrm{t}\right]}{\left[\left(\sum_{t=0}^{N} \mathrm{Er}\right)/(1+\mathrm{r})\hat{}\,\mathrm{t}\right]} \tag{6}$$

where *Ct* is the net cost of the project for time *t* (years) in INR, including the initial investment and operation and maintenance of the project, *N* is the life of the project in years, *r* is the discount rate, *t* is the lifetime of the project and *Er* is the solar energy produced in kWh.

## 2.6 Environmental analysis

The electrical energy that is being used at government buildings and educational campuses is presently supplied from the electricity grid. The grid derives its power from conventional, nuclear, hydroelectric and renewable-power plants. So, a large amount of $CO_2$ is released in the generation of this electricity. As the grid electricity will be replaced by solar PV-based electricity, so the savings in carbon-dioxide emissions by not using grid electricity are estimated by using emission factors as provided by the Central Electricity Authority of India (CEA 2019) [16]:

$$CO_2 \text{ emission factor} = 0.9247 \text{ tCO}_2/\text{MWh} \tag{7}$$

The various input parameters for the study are illustrated in Table 4.

**Table 4:** Input parameters for the study

| Parameter | Value |
|---|---|
| Life of the project | 25 years |
| PV module efficiency | 18% |
| Collector area | 667 $m^2$ |
| Tilt angle | 14–30° |
| Discount rate | 10% |

## 3 Results and discussions

The possibility of a solar PV project is evaluated by its technical and economic performance. Some more factors such as global horizontal irradiance, irradiance on the tilted plane, system output and energy yield of the system also are needed to evaluate the plant feasibility at different locations. The average yearly values of parameters such as specific yield, CUF PR and energy price are observed at different locations and discussed in the previous section.

### 3.1 Solar potential assessment

The result of the monthly performance analysis of simulated data for a year at seven system sites is discussed below.

#### 3.1.1 *Global horizontal incident (GHI) energy*

GHI is the cumulative incidence at a horizontal surface by solar radiation. This is the summation of direct normal irradiance (DNI), diffuse horizontal irradiance and ground-reflected radiation. DNI is solar radiation arriving in a straight line from the direction of the Sun at its present location in the sky, while diffuse horizontal irradiance is solar radiation that does not appear in a direct path from Earth, but has been scattered by molecules while particles in the atmosphere and arrives similarly from all sides. It varies with location, altitude, time, season, humidity, temperature, wind speed, dust accumulation and other atmospheric conditions. It is taken as the average value for a particular site expressed in kWh/$m^2$/day. Fig. 4 shows the monthly variation of GHI at different sites. It is observed that GHI is lower during the monsoon months of July and August at all locations and at a maximum in the summer months of March, April and May.

#### 3.1.2 *Global irradiance on the tilted plane*

Global tilted irradiance (GTI) is the total radiation obtained on a given tilt and azimuth angle, fixed or sun-tracked surface. It is the sum of the primary and transmitted emitted radiation. This is a guide for photovoltaic (PV) applications that may be influenced by shadows sometimes. It varies with location, altitude, time, season, humidity, temperature, wind speed, dust accumulation and other atmospheric conditions. It is taken as the average value for a particular site expressed in kWh/$m^2$/day. Fig. 5 shows the monthly variation in GTI at different sites.

Globally inclined irradiance is found to be lower during the monsoon months of July and August due to rainy days and rainfall at all locations, whereas it is high with sunny skies and adequate sunlight during the summer months of March, April and May during the day.

## 3.2 Energy performance

The simulated energy results at various locations are compared for analysing the operational performance of plants based on the various parameters. Nominal power is the rated capacity of the system; in this case, it is 100 kWp. Table 5 describes the basic energy-performance parameters of the analysed systems at different locations.

### 3.2.1 *Specific yield and system output*

From the results, it is can be observed that specific yield is highest at Pune followed by Delhi due to high solar irradiance at these sites. Bhopal, Udaipur and Ahmadabad have good potential as having suitable weather conditions, while Thiruvananthapuram and Madurai, being coastal areas, have the lowest energy yield for the generation of solar electricity. System output is the average annual output power produced by a particular capacity system. It depends on the solar radiation, system components, rated capacity, operational losses, geographical location and climatic conditions of the place. Fig. 6 shows the monthly variation in system output at different sites. It is observed that the output of the system is lower for the monsoon period in July, August and June due to cloudy days and rainfall at all locations and is at a maximum in March, April, February and May due to clear skies, ample sunshine and pleasant weather conditions.

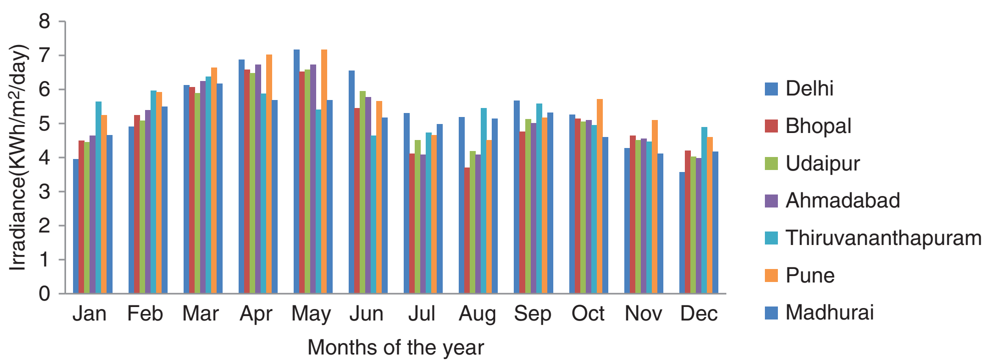



**Fig. 4:** Monthly variation in global horizontal irradiance at different sites

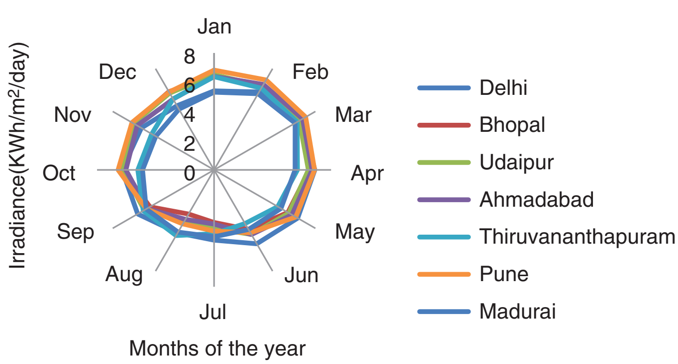



**Fig. 5:** Monthly variation in global tilted irradiance at different sites.

**Table 5:** Energy-performance parameters at different locations

| City | Tilt angle (°) | Irradiance (kWh/m²/day) | Daily system output (kWh/day) | Annual energy yield (MWh/year) | Specific yield (kWh/KW$_p$) |
|---|---|---|---|---|---|
| Delhi | 25 | 5.40 | 494.8 | 181 | 1806 |
| Bhopal | 29 | 5.08 | 476.1 | 174 | 1738 |
| Udaipur | 30 | 5.16 | 486.2 | 177 | 1774 |
| Ahmadabad | 26 | 5.19 | 480.5 | 175 | 1754 |
| Thiruvananthapuram | 14 | 5.33 | 456.5 | 167 | 1666 |
| Pune | 23 | 5.62 | 506.7 | 185 | 1849 |
| Madurai | 14 | 5.10 | 436.8 | 159 | 1594 |

### 3.2.2 *Energy yield*

The energy yield is the cumulative yearly solar energy produced from the photovoltaic system. It depends on the requirements of the materials, solar irradiance, rating power, geographical location and climatic conditions of a specific place. Fig. 7 shows the monthly variation in the energy yield of the PV plants at different sites. The energy yield of the system is observed to be lower during the monsoon months of June, July and August due to rainy days and rainfall at all locations, whereas it is strong during the months of March, April, October and November due to the high-temperature intensity and tremendous sunshine, but has modest energy yield during the months of January, February, May and December due to good weather conditions.

### 3.2.3 *PLF or CUF of the system*

The plant capacity of the system at full load, in this case, is 100 $kW_p$. The plant load factors (or CUF) of systems at different locations are shown in Fig. 8.

From this figure, it can be observed that the plant load factor is highest at Pune followed by Delhi due to excellent solar irradiance available at the sites. Bhopal, Udaipur and Ahmadabad have fine

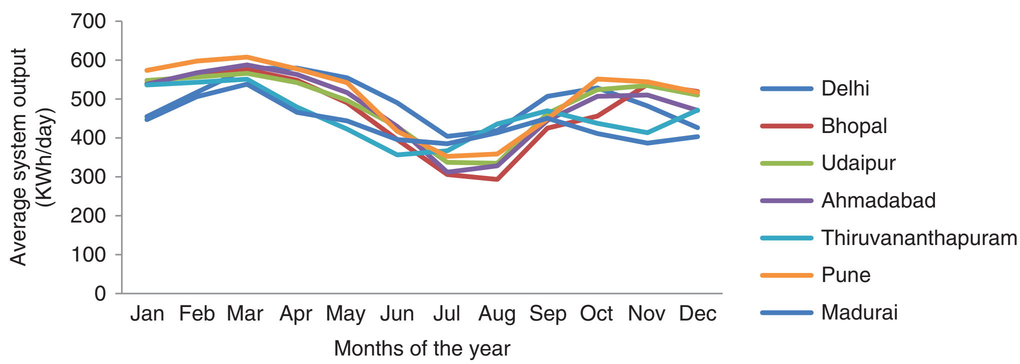



**Fig. 6:** Monthly variation in system output at different sites

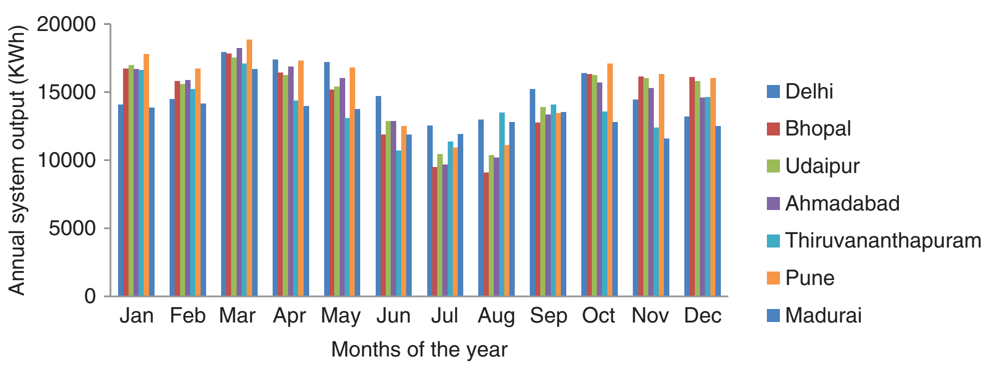



**Fig. 7:** Monthly energy yield of the systems at different sites

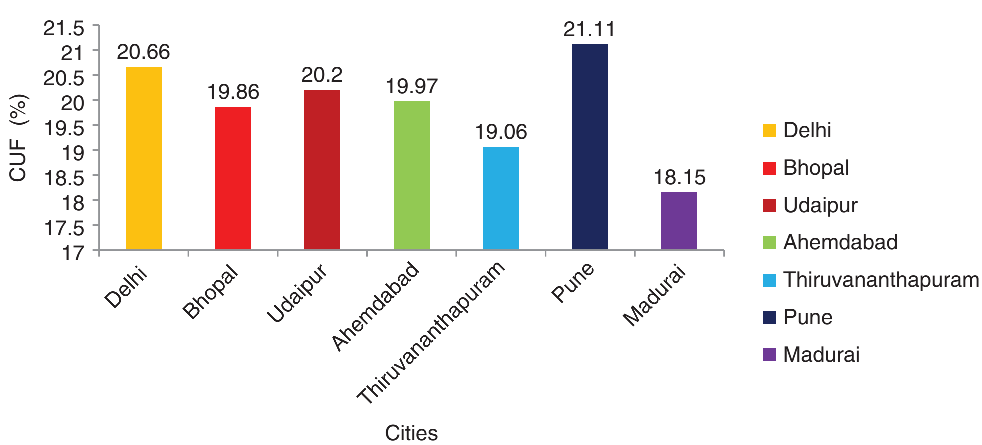



**Fig. 8:** Plant load factor (or CUF) of the solar PV system at different locations

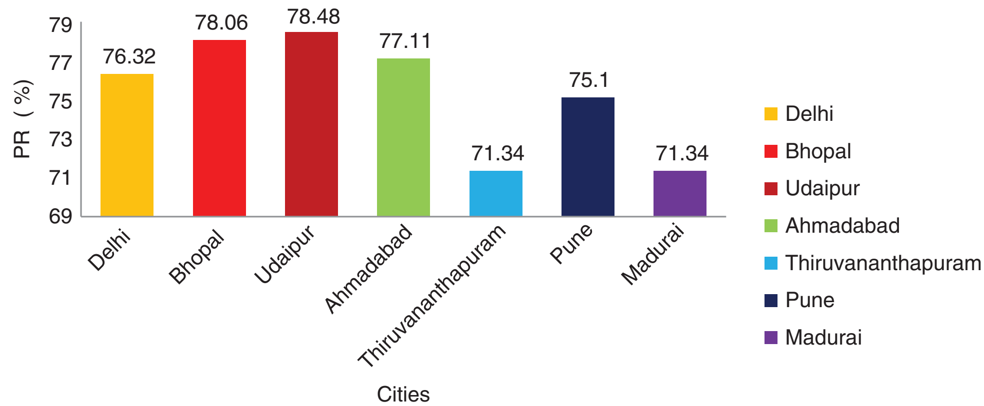



**Fig. 9:** Quality factor (or PR) of the solar PV system at different locations

**Table 6:** Cost break-up of solar PV plant

| S. no. | Particular | Capital cost in INR |
|---|---|---|
| 1 | PV modules cost | 4 620 265 |
| 2 | Supporting cost | 566 739 |
| 3 | Inverter and wiring | 605 790 |
| 4 | Transport and mounting | 615 216 |
| 5 | Total investment | 6 408 010 |
| 6 | Annuities | 76 320 |
| 7 | Maintenance | 52 812 |
| 8 | Total energy cost | 6 537 144 |

potential as having suitable weather conditions, while Thiruvananthapuram and Madurai, being coastal areas, have the lowest CUF for the generation of solar electricity.

#### 3.2.4 *PR or quality factor of the system*

The quality factors (or PR) of systems at different locations are shown in Fig. 9.

From Fig. 9, it can be observed that the quality factor is highest at Udaipur followed by Bhopal due to excellent solar hotspot sites having adequate ambient temperatures for the operation of the system. Ahmadabad, Delhi and Pune have good potential, having suitable weather conditions with more sunshine hours, but Thiruvananthapuram and Madurai, being coastal areas, have fewer sunny days and more rainy days, so the quality factor for the generation of solar electricity is lowest.

### 3.3 Economic performance

Economic analysis indicates the profitability of the installed PV system. It gives an idea about the recovery of the invested amount and profit gain in any system. The overall cost break-up of the proposed system is given in Table 6 as per simulation results.

The Indian government offers a 30% subsidy to install grid-connected rooftop solar power plants to encourage the use of green energy and also reducing the country's national-grid load. The excess generated electricity is added back into the system's grid credit revenues. These are simulated values, not actual values, when subsidies, taxes and the actual cost of equipment are considered based on different locations. The recovery period is greatly reduced and the system becomes profitable for the next 20 years. Thus, the energy price and SPP vary accordingly for different locations, as shown in Figs 10 and 11, respectively.

From Fig. 10, it can be inferred that electricity generated from the system is most expensive in Madurai, followed by Thiruvananthapuram; this is because of high rains in these areas. Whereas Bhopal, Ahmadabad and Udaipur have lower costs due to suitable weather conditions, Delhi and Pune, having a greater number of sunny days in a year, show the cheapest cost of solar power generation.

From Fig. 11, it can be seen that the time taken to recover the initial investments for the installation of the solar PV plant is the highest in Madurai, followed by Udaipur and Ahmadabad. This is because the cost per unit of electricity is higher in this case. While Bhopal and Thiruvananthapuram have the lowest payback due to suitable weather conditions, Delhi and Pune, having a greater number of sunny days in a year, show the cheapest cost of solar power generation, thereby quickly recovering the initial investment cost.

### 3.4 Environmental performance

The greatest environmental impact of using solar power for the generation of electricity is that it replaces the energy produced by the conventional thermal power plant. This not only conserves the non-renewable fossil fuel, but also prevents degradation of the environment by the emission of harmful greenhouse gases (GHGs). The carbon-dioxide reduction per MW power to the atmosphere is determined as per Equation (7). Thus, it can be estimated that this 100-kWp solar system can generate ~180 MW of green power, thereby reducing ~160 tons of carbon emissions to the atmosphere per year at the selected locations. This reduction

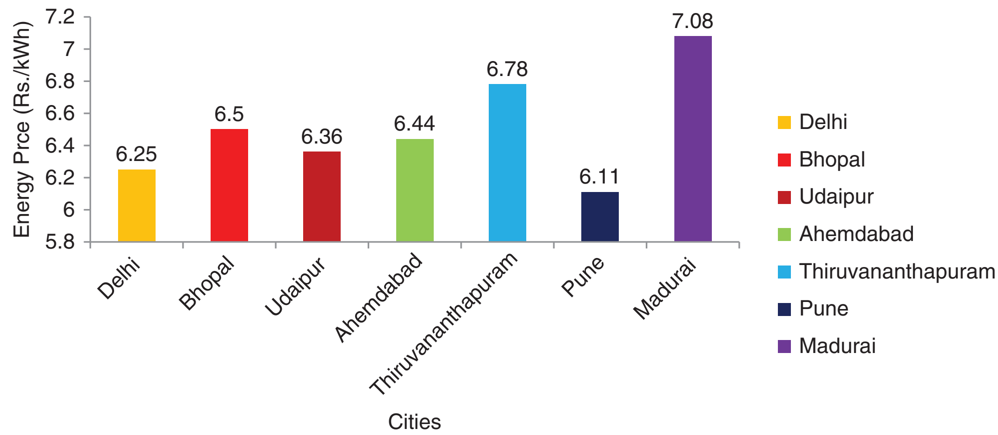



**Fig. 10:** Energy price of the solar PV system at different locations

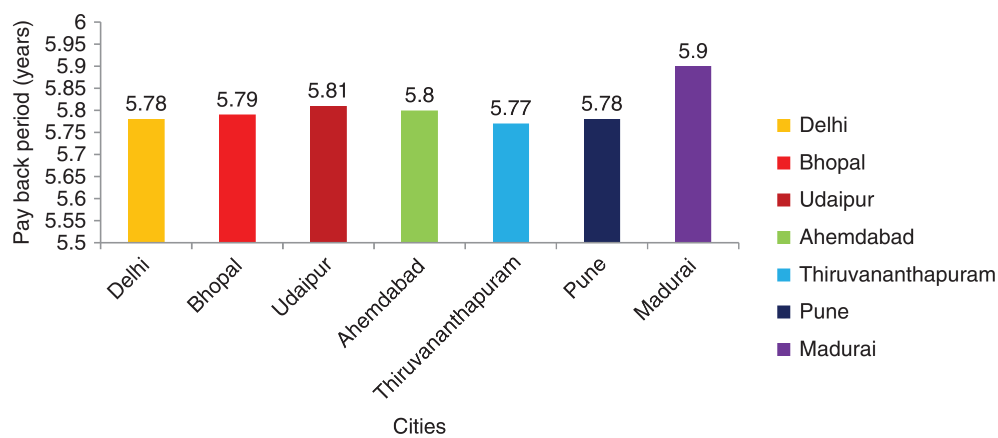



**Fig. 11:** Simple payback period of the solar PV system at different locations

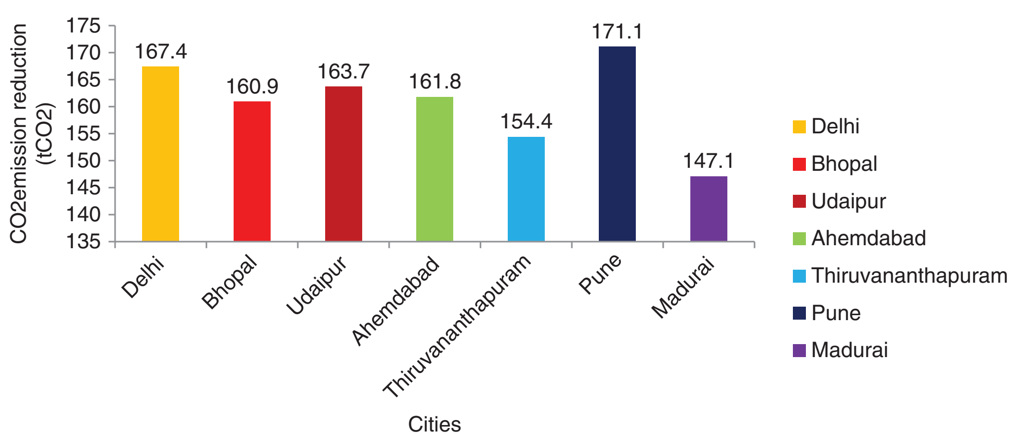



**Fig. 12:** $CO_2$-emission reduction of the solar PV system at different locations

in carbon-dioxide emissions contributes to the reduction in ambient greenhouse gases demonstrating the sustainability aspects of this pollution-free energy generation for a green economy.

From Fig. 12, it can be concluded that the reduction in carbon emission by the PV plant is the highest in Pune, followed by Delhi. This is because they have a greater number of sunny days in a year and high solar power production. Whereas Bhopal, Ahmadabad and Udaipur have suitable moderate weather conditions for energy production, Thiruvananthapuram and Madurai, having a humid climate with a higher rainfall, generate lower amounts of solar power.

## 4 Conclusions

The energy, economic, and environmental performances of grid-tied solar photovoltaic (PV) rooftop systems are determined in different cities of India using the PVsyst simulation tool. For this study, solar PV systems are selected with the same capacity of 100 kWp having the identical type of module array and inverter. The evaluation of various 3E parameters of these PV systems yields the following results:

- The PR of the PV plants at different locations is between 70% and 80%, with Udaipur and Bhopal giving the highest values.
- The CUF is in the range of 19–21%, with Pune and Delhi having excellent values.
- The estimated energy yield for all the sites is >170 MWh annually, with Delhi and Pune showing extremely good production.
- The output of the system is between 400 and 500 kWh/day of energy generated at all locations except for on rainy days. Thiruvananthapuram and Madurai, being coastal areas, have more rainfall and humidity as compared with the other locations during the monsoon season.
- The cost of electricity produced by PV plants per unit is in the range of INR 6–7/kWh, depending on the generation and operation of the plant at a specific place.
- The economic analysis of the present systems showed the payback period to be ~5–6 years, which is financially attractive but could be reduced further considering subsidies and GHG benefits.
- The environmental analysis indicates that each of these systems reduces ~150–170 tons of carbon-dioxide emission into the atmosphere per year at different locations. With a lifespan of ~25 years, a substantial amount of $CO_2$ can be mitigated compared to conventional energy use.
- The limitation of the study includes the predictive capability of the software simulation and cost assumptions in which taxes and subsidies are excluded. Further, such standards can vary widely at different places, as each state has its own policies and prices. Therefore, a much easier economic analysis is conducted by considering a simple period of payback for the system. The study does not consider the actual installation, operation and maintenance costs at different locations of the solar PV system.
- Thus, the Indian government needs to provide attractive capital subsidies and generation-based incentives, and encourage educational institutions and individuals to install such PV plants on rooftops of buildings to harness solar energy as an alternative source of electricity for meeting the future energy demands of the cities.

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## Conflict of Interest

None declared.

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