



Feasibility Assessment of Bifacial Rooftop Photovoltaic Systems in the State of Gujarat in India

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Bifacial solar photovoltaic (PV) modules are one of the recent interventions in the widespread commercial deployment of solar energy. This study intends to analyze the adoption of bifacial solar panels in rooftop PV systems to enhance energy generation as compared to their mono-facial counterparts. The technical and economic advantages of a typical 5-kW single-phase solar rooftop photovoltaic system using bifacial Si-modules are presented and compared with those using traditional polycrystalline Si (poly c-Si) modules in the urban location of the state of Gujarat in India. This methodology allows one to find optimal performance under the same irradiation and load conditions. As the majority of terraces in this location have a surface of white or gray tiles, which have a high albedo factor, bifacial modules generate more than 10% excess energy as compared to the poly c-Si systems. Although bifacial modules have an initial cost higher than the polycrystalline counterparts, the cost of their balance of system and space is reduced by 2 to 13%, respectively. Analysis shows that a 5kW bifacial technology can generate an excess of 13 MWh as compared to the traditional poly-Si over a period of 25 years. Finally, it is seen that an optimized bifacial system that is tilted between 15 and 20° will reduce the levelized cost of electricity (LCOE) by 5.5% as compared to the traditional poly c-Si system.

Keywords: rooftop solar, bifacial modules, distributed energy systems, solar efficiency, LCOE, technoeconomic environment, solar in India

1 INTRODUCTION

India has a huge renewable energy potential across the country. Solar energy is one of the key sources of clean energy, and the country has taken various initiatives to promote the utility scale and decentralized or distributed systems as well in the last 5 years. The Indian government has already revised the solar target from 20 to 100 GW, which is promising as well as challenging. Among this 100 GW target, 40 MW will be achieved through the decentralized mode and the rest 60 GW from utility-scale solar projects. Out of 8 GW of solar rooftop deployment in India, Gujarat state has installed around 2 GW, which includes 1.2 GW of residential rooftop systems aggregating to more than 1,00,000 houses. In the decentralized solar project, the rooftop photovoltaic (PV) system has received a priority. The majority of solar PV rooftop systems are expected to be deployed in urban and semi-urban areas. As in India, the majority of residential terraces are flat surfaces, so there is great scope for an elevated structure where one can get the benefits of reflection from the rear side of PV modules. Available open space is always a constraint for the installation of solar PV systems, and in this context, traditional rooftop systems are the best possible solution. It is also proven that the traditional rooftop solar PV system would play a notable role in distributed energy generation to mitigate the energy demand of various load segments. It

has been adopted in a widespread manner across residential, commercial, and industrial users; however, the selection of solar panels is still a concern. In many cases, questions are raised about lower energy production and efficiency issues. Despite the apparent benefits of bifacial modules, their applications still suffer from a lack of visibility into the performance gain that they can provide. On the other hand, self-energy in the same building will be highly accepted in all major urban areas, and the same will be added to rooftop solar potential. The rooftop systems' acceptability is therefore high for the consumption categories, including industrial, commercial, and residential levels. In industries where the sheds or terraces permit the structural load, deployment is expected as it directly saves energy consumption. In the same way, developing rural areas and semi-urban areas are also expected to adopt solar PV rooftop systems (Estimating The Rooftop Solar Potential Of Greater Mumbai, 2015; Press Information Bureau, Government of India Cabinet, 2015). To meet the demand-supply and reduce the transmission and distribution line losses, battery energy storage could be used. In a grid-connected solar rooftop system, a hybrid inverter is used, which is connected to both the grid and the battery. This hybrid inverter-based grid-tie solar rooftop system allows the inverter to store the excess energy in a battery which could be used later on as per the building/house energy demand. However, policy and regulation for the use of battery storage-based hybrid inverters in the rooftop solar system is in the development stage in India (Estimating The Rooftop Solar Potential Of Greater Mumbai, 2015; Thanh et al., 2021). A solar PV rooftop system may comprise various technologies such as thin-film and silicon. In silicon-based technology, polycrystalline, monocrystalline, and bifacial solar module technologies have been found since 1977. Among them, bifacial (BF) module technologies were specially developed for space applications. In BF-modules, Glass-on-Glass technology captures additional light from the rear side, which increases the overall generation. Recently, there has been technological advancement in the production of polycrystalline to bifacial module production from five busbars to multi-busbar (Hubner et al., 1997; Cuevas, 2005; Guerrero-Lemus et al., 2016; Dullweber et al., 2017; Kenny et al., 2018; Ayala, 2019; Baumann et al., 2019; Jang and Lee, 2020). The improvement of silicon module efficiencies is mainly attributed to p-type and n-type PID-free passivated emitter and rear cell technology (PERC) and heterojunction (HJT) solar cell manufacturing. They are also incorporated into bifacial solar cells to achieve analogous efficiencies to the traditional mono-facial ones. A bifacial PV module can absorb irradiance on both sides. The performance of a bifacial PV module is influenced by module tilt and azimuth, similar to a mono-facial PV module. It is, however, more influenced by the diffuse irradiance factor (DIF), height, and albedo than a mono-facial PV module. The performance of the BF module PV system has been analyzed on various reflective surfaces/materials such as white surfaces, multi-color tiles, grass, etc., under different environmental conditions. Due to front and rear side glass, BF modules produce more energy throughout their life at a lower operating cost (Hubner et al., 1997; Cuevas, 2005; Guerrero-Lemus et al., 2016; Dullweber et al., 2017; Kenny et al., 2018; Ayala, 2019; Baumann et al., 2019; Jang and Lee, 2020). Still,

in the laboratory and field, advanced-level research is underway to get higher efficiency and faster deployment in the market (Hubner et al., 1997; Joge et al., 2003; Cuevas, 2005; Branker et al., 2011; Yang et al., 2011; Chu and Majumdar, 2012; Chu et al., 2016; Guerrero-Lemus et al., 2016; Deline et al., 2017; Dullweber et al., 2017; Hansen et al., 2017; Kabir et al., 2018; Kenny et al., 2018; Sun et al., 2018; Ayala, 2019; Baumann et al., 2019; Tahir Patel et al., 2019; Jang and Lee, 2020). To deploy any new technology in the solar market, one has to confirm the levelized cost of electricity (LCOE) as it widely varies with the capital investment, energy generation, post-installation operation, and maintenance cost. Currently, major deployment in India is based on the polycrystalline technology with five busbar technologies. Hence for pushing the bifacial technology, one should compare the LCOE. Bifacial technology will cater to the future market over the traditional polycrystalline market as it requires less space than polycrystalline and delivers higher energy generation than the polycrystalline technology. Overall, we can say that higher generation due to reflection and multi busbar technology results in higher LCOE (Cuevas et al., 1982; Luque et al., 1985; Chieng and Green, 1993; Solar Energy Technologies Office, 2011; Guo et al., 2013; Tyagi et al., 2013; Ueckerdt et al., 2013; Yusufoglu et al., 2014; Janssen et al., 2015; Lo et al., 2015; Castillo-Aguilella and Hauser, 2016; Fertig et al., 2016; Guerrero-Lemus et al., 2016; Ito and Gerritsen, 2016; Green et al., 2017; Stein et al., 2017; Chang et al., 2018; EIA, 2018; ITRPV, 2018; Delano Thierry Odou and Bhandari, 2020; Masrur et al., 2020). Solar radiation is available throughout the year in the Gujarat region of India. In this region, March to June, as well as October to December, are considered to generate higher solar energy than the rest of the months (Guo et al., 2013; Ito and Gerritsen, 2016; Delano Thierry Odou and Bhandari, 2020; Masrur et al., 2020). Researchers across the globe are concerned about the deployment of the bifacial system and installing the small-scale test beds to study the techno-commercial viability, while the classification of bifacial and relevant key technologies needs to be addressed. To the best of our knowledge, representative bifacial PV systems have not been studied yet in terms of their technical performance and economic as well as environmental impact in long-term use.

This study explores the Techno-Economic-Environmental analysis and design optimization of a 5kW bifacial grid-connected solar rooftop PV system and compares it with the polycrystalline system for the Gujarat region. The key objective is to find the techno-economic exploration concerning an ideally designed system with key parameters such as solar radiation (seasonal variation thereof) and performance ratio at the rooftop level.

2 MATERIALS AND METHODS

2.1 Solar PV Rooftop System Design Modeling

A typical grid rooftop system consisting of a solar PV (SPV) array, a solar grid tie inverter/power conditioning unit (PCU), a solar module mounting structure (MMS), and other balance of system (BoS) components, which include AC/DC cables,

earthling protection, lightning protection (LA), a bi-directional meter, and a solar meter, was used. All the components used in the SPV system should conform to the BIS/IEC as per the requirements of the regional electricity authority (Weatherspark, 2015). System capacity has been designed based on the module size, followed by the structure, inverter, and cable design. Here, we have designed the 5 kW rooftop system for the Gujarat region where traditional polycrystalline systems consist of 335 Wp modules which could be installed on an 8×2 table structure, while in the same case with the bifacial system, it consists of 385 Wp of 13 modules which could be installed on a 7×2 table structure. The same will reduce the BoS cost and also use 13% less space on the same terrace.

2.2 Solar Energy Generation

2.2.1 Solar Radiation on the Tilted Surface of the Solar Module

Total solar irradiance (radiation) on the tilted surface of the solar module includes reflected, direct, and diffuse radiation (Weatherspark, 2015; Torrentpower, 2015; Desai et al., 2020a; Desai et al., 20212021; Desai et al., 2020b; Sharma and Goel, 2017; Desai et al., 2019; Desai et al., 2021a).

$$I_{TR} = I_b r_d + I_b r_b + (I_b + I_d) I_r, \quad (1)$$

where r_r, r_b , and r_d are reflected, beam, and diffuse, and I_r, I_b , and I_d are beam, direct radiation, and diffuse instantaneous values, respectively.

2.2.2 Average Annual Solar Radiation on Tilted Solar Panels (Without Shading)

Using an empirical equation, we can measure the beam, direct, and diffuse radiation or estimate the total solar radiation falling on the solar module. Month wise, daily average monthly global radiation on a horizontal surface H_{ga} is given by (IRENA, 2012; Sharma and Goel, 2017; Desai et al., 2019; Desai et al., 2020b; Desai et al., 2021a; Desai et al., 2021b; Bihari et al., 2021; Desai et al., 20212021).

$$H_{ga} = (H_{oa} + H_{ob}) * \{a + b [S_a / S_{ma}]\}, \quad (2)$$

where

H_{oa} = monthly average solar radiation at the horizontal surface,

H_{ob} = monthly average solar radiation at the horizontal surface at the rear surface,

S_a = monthly average daily sunshine hour

S_{maxa} = maximum daily sunshine hours possible at a given location.

a and b are constants.

2.2.3 Plant Performance Ratio

Solar plant performance can be identified on the basis of available solar radiation at the plant location against the generated energy. This performance Ratio (PR) is based on all types of losses, right from the solar module to grid losses, with respect to radiation and local climate conditions. The PR value generally varies between 60 and 80%, but it

depends on the solar PV module temperature, DC cable loss, soiling losses, AC cable loss, transmission loss etc. PR is defined as the ratio of the final yield (Y_f = total energy fed to the grid) to reference yield of the total energy (Y_r) that the system could have produced without any losses in ideal condition (IRENA, 2012; Sharma and Goel, 2017; Desai et al., 2019; Desai et al., 2020b; Desai et al., 2021a; Desai et al., 2021b; Bihari et al., 2021; Desai et al., 20212021).

$$PR = Y_f / Y_r. \quad (3)$$

The performance ratio (PR) is mainly influenced by module mismatch loss, module temperature loss, DC cable loss, AC cable loss, incidence angle modifier (IAM) loss, soiling loss, etc.

2.2.4 Solar PV Module Efficiency

The instantaneous solar PV module efficiency is given by

$$\eta = P_{dc} / (G * A_m * 100). \quad (4)$$

As a function of temperature, it can be represented as

$$\eta_T = \eta_{Tref} * (1 - \beta_{ref} T - T_{ref}), \quad (5)$$

where

η_{Tref} = PV module efficiency at reference temperature,

β_{ref} = power temperature coefficient,

T_{ref} = reference temperature,

T = cell temperature.

$$T = T_{amb} + \{1.25 * 10^{-3} Gt * (NOCT - 20)\}, \quad (6)$$

where

NOCT = nominal operating cell temperature,

T_{amb} = ambient temperature,

Gt = total solar irradiance in plane (IRENA, 2012; Sharma and Goel, 2017; Desai et al., 2019; Desai et al., 2020b; Desai et al., 2021a; Desai et al., 2021b; Bihari et al., 2021; Desai et al., 20212021).

2.2.5 Estimation of the Electricity Generated by the Output of a Bifacial Photovoltaic System

Bifacial energy generation from both front and back sides is estimated as per the following:

$$E_f = A_t * \eta_{pvf} * H_{ga} * PR, \quad (7)$$

$$E_r = A_t * \eta_{pvrr} * H_{ar} * PR, \quad (8)$$

E_f = energy from the front side (kWh),

E_r = energy from the rear side (kWh),

A_t = total solar panel area (m^2),

η_{pvf} = rear efficiency of the solar module (%),

η_{pvrr} = front efficiency of the solar module (%),

H_{ga} = average annual solar radiation on the shadow free solar module,

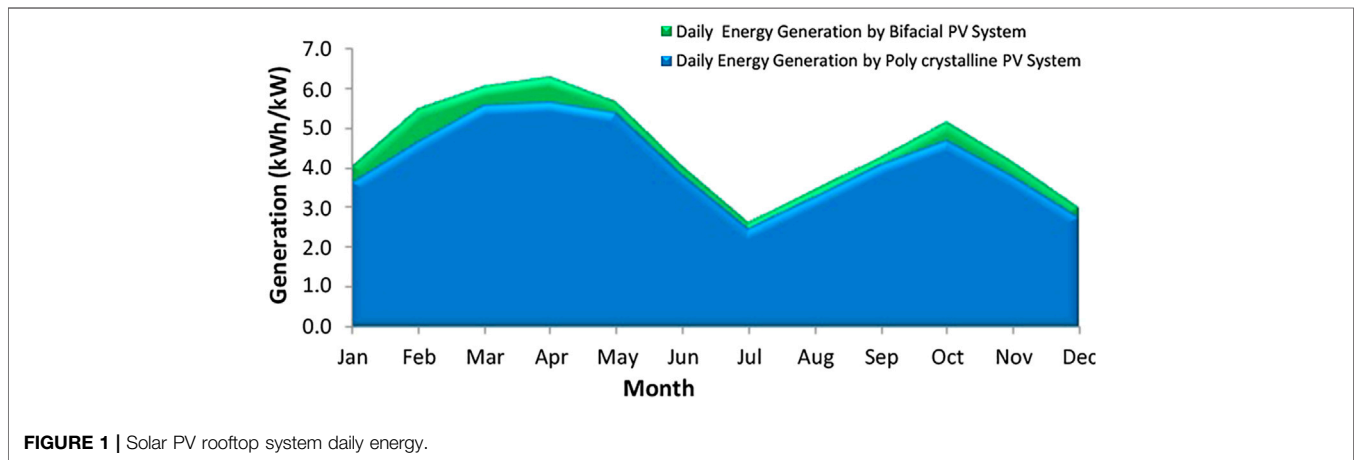
H_{ar} = average annual solar radiation on the solar module due to albedo,

PR = performance ratio (generally vary in the range between 0.5 and 0.9, default value = 0.75) (IRENA, 2012; Sharma and Goel, 2017; Desai et al., 2019; Desai et al., 2020b; Desai et al., 2021a; Desai et al., 2021b; Bihari et al., 2021; Desai et al., 20212021)

TABLE 1 | Component costs (All in INR and USD).

Description	Polycrystalline system	Bifacial system
1. SPV module(Wp)	335	385
Open circuit voltage (Voc) in volts	45.80	48.65
Short circuit current (Isc) in amps	9.50	9.95
Voltage at maximum power (Vmp) in volts	36.70	39.90
Current at maximum power (Imp) in amps	9.13	9.65
Total modules (nos)	15	13
Solar capacity (kW)	5	5
Total module area (m ²)	30	26
Module capex INR (USD)approx.	90,450/- (1,206\$)	102,602/- (1,368\$)
SPV system life (years)	25	25
2. PV inverter		
Inverter capacity (kW)	5	5
Inverter capex INR (USD)approx.	30,000/- (400\$)	30,000/- (400\$)
Inverter lifetime (years)	7	7
Replacement cost from 6 th to 25 th year INR (USD) approx.	45,000/- (600\$)	45,000/- (600\$)
3. BoS cost		
Initial capital INR (USD) approx. for 1 st 5 years	99,500/- (1,326.7\$)	97,000/- (1,293.33\$)
Replacement cost from 6 th to 25 th year INR (USD) approx.	10,000/- (133.33\$)	10,000/- (133.33\$)
Lifetime (years)	25	25
4. Total comprehensive O&M cost INR (USD) approx. for 25 years	65,000/- (866.66\$)	65,000/- (866.66\$)
5. Energy generation for 25 years (kWh) (0.8% Annual degradation considered)	173,400 (2,312\$)	190,740 (2,453.2\$)
6. Tariff INR (USD)approx.		7 (0.093 USD)

(* 1 USD = 75 INR)

**FIGURE 1** | Solar PV rooftop system daily energy.

$$\text{Total Bifacial Energy Yield } E_b = E_f + E_r. \quad (9)$$

In this section, solar generation modeling has been discussed according to this rooftop system, which generates power according to radiation and temperatures as both are the critical parameters for energy generation. Traditional polycrystalline rooftop systems generate power based on the irradiance falling on the front side of the module, whereas in bifacial rooftop systems, energy generation is possible from the front as well as the rear side. Due to this additional rear side irradiance, which is mainly due to albedo based on the color of the roof, the white roof has the highest albedo, and this will help generate more energy.

3 ECONOMIC EXPLORATION

3.1 Levelized Cost of Electricity Generation

Based on the capital investment, O&M expenses, and estimated revenue generation with respect to the energy throughout the life span of the plant, the LCOE of the renewable plant is calculated. As is known, renewable energy is regionally specific and the LCOE varies accordingly in a region-specific manner based on the availability of resources. In our approach, we have shown a constant cash flow analysis considering the ideal generation with the decided degradation and necessary replacement factor. A capital investment-based model is suitable for most renewable energy generation technologies, where in the case of solar or wind power fuel cost as input is zero. We have

TABLE 2 | Monthly energy generation.

Month	Effective irradiance (kWh/m ²)	Monthly energy generation by the bifacial PV system (kWh)	Monthly energy generation by the polycrystalline PV system (kWh)
January	148.4	602	543
February	167	766	651
March	212.5	937	864
April	209.2	943	848
May	201.3	876	834
June	155.2	605	574
July	127.4	406	382
August	135.2	533	505
September	158.8	639	612
October	179.4	799	728
November	152.5	621	568
December	148.4	463	425

taken a simple and constant effort-based approach, given the fact that the model could be applied to different regions and countries according to available resources. The analysis we have conducted in this study is easy to understand and has transparency (Carbon Brief, 2019). The formula used for calculating the LCOE of renewable energy technologies is as follows:

$$LCOE = \sum_{y=1}^{25} \frac{C_y + O\&M_y + R_c}{E_y}, \quad (10)$$

where LCOE = levelized cost of electricity (average lifetime); C_y = yearly capital investment; O and M_y = yearly operation and maintenance cost; R_c = replacement cost; E_y = electricity generation in the year y ;

$$C_y = C_M + C_{BOS} + C_I, \quad (11)$$

$$R_{C_y} = C_{BoS_y} + C_{I_y}. \quad (12)$$

Here, capital coast C_y is the cost of the total system cost which includes the module and balance of supply material (BoS), which are the inverter, structure, cables, earthing, and LA. The

installation cost of the system is also considered the capital cost. Hence, as only modules have a life span of 25 years, there are chances of component replacement during the 25-year time period, which includes the BoS material and installation costs which are considered as a replacement cost. While considering the LCOE of solar rooftop systems, in this majority, two components are available: one is the module cost as the bifacial module cost is higher than the traditional polycrystalline module cost, and the other is the structure cost, which is included in BoS. In this bifacial system the higher efficiency of the module number decreased, which directly reduced the structure size and cost.

In our section, we will estimate the LCOE cost of both polycrystalline and bifacial systems with respect to the capital investment made in each solar rooftop system.

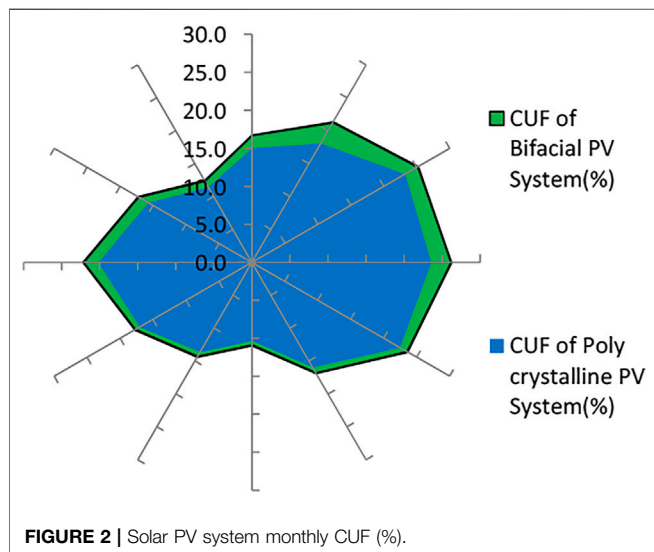
3.2 Components' Cost and Performance Characteristics

Table 1 shows the cost summary of components, including the capital investment, replacement cost, O&M, and specifications [48].

4 RESULTS AND DISCUSSION

4.1 Technical Analysis

The actual energy generation from a bifacial system is analyzed throughout the year, as shown in **Figure 1**. The monthly energy generation is given as per **Table 1** below and is used in the calculation of system performance. From **Table 2**, it is seen that the bifacial solar PV system has a significant effect on energy generation as the collection of radiation is from the front and rear sides. Installing 5 kW rooftop systems at one place and the same orientation at the same place can produce the monthly average energy generation for a bifacial system of 682 kWh while from a traditional poly c-Si system it was 628 kWh. An average of 8% higher generation was observed than the poly c-Si system. The annual solar PV energy yield under the bifacial system was

**FIGURE 2** | Solar PV system monthly CUF (%).

1638 kWh/kWp as compared to the poly c-Si system, which was 1507 kWh/kWp.

Figure 1 also shows that for the rooftop PV system, daily energy for the bifacial mode varies between 2.6 and 6.3 kWh/kW/day. The daily average generation for the bifacial system is 4.5 kWh compared to the traditional polycrystalline system of 4.1 kWh. The monthly yield varies between 81 and 189 kWh/kW. The average yield for the bifacial system is 136 kWh/kW and for the Poly c-Si system it is 126 kWh/kW, as shown in **Figure 1**. The average energy generated by the bifacial system is calculated to be 8% higher than the Poly c-Si system. **Figure 2** shows that the capacity utilization factor (CUF) of the bifacial system is 18.7% whereas it is 17.2% for the poly c-Si rooftop system, which shows that the bifacial-based solar rooftop system CUF is 1.5% higher than the poly c-Si-based solar PV rooftop systems (Sampedro et al., 2020).

It was observed that the annual average PR for the bifacial system is 81 and 75.54% for the polycrystalline system. October, February, and April have a PR that is around 90% which is at par in comparison to the traditional solar PV rooftop system. Monthly average yield, annual average daily yield, annual average PR, and annual average CUF for the bifacial system and polycrystalline system are 136 kWh/kWp, 4.5 kWh/kWp, 81, and 18.72% and 126 kWh/kWp, 4.1 kWh/kWp, 75.5, and 17.22% for the solar PV System, respectively. According to the latest research conducted in the world still, we can get more than 20 to 30% higher generation in the bifacial system by modifying the roof and using the seasonal tilt-based structure, which will help to get the maximum irradiance from the rare side.

4.2 Economic Analysis

For the acceptance of the bifacial System in the market, a techno-economic-environmental analysis is needed in parallel. The economic analysis gives an idea about the internal rate of return, economic viability concerning the payback period of the project on which investment is made. To identify the economic viability we have conducted the economic analysis of the project on two financing conditions, one with the 100% equity investment and the other with a price of seven INR (0.0933 USD)/kWh. The internal rate of return (IRR) for the bifacial system is 24% against the 23% of the polycrystalline solar system which is very attractive looking to the current global financing scenario. We get the payback of the bifacial system 2 months earlier than the polycrystalline system. The LCOE for the bifacial rooftop solar system is 1.88 INR (0.0250 USD), which is 5.5% higher than the traditional polycrystalline rooftop system.

4.2 Environmental Analysis

India is the third-largest in the world for greenhouse gas emissions as the main source is coal for energy generation. Every year India emits about 7% of global emissions (IRENA, 2012; Carbon Brief, 2019; GHE, 2014; Environment and U. N.

(2019-11-19), 2019; downtoearth, 2018). These emitted gases or particles are the following: monoxide (CO), carbon dioxide (CO₂), etc. Our analysis shows that throughout life, a bifacial system saves 916,525 kg of CO₂ from adding to the atmosphere and prevented 224,444 kg of uses of coal compared to the polycrystalline system which is 8% higher.

5 CONCLUSION

Bifacial module technology, which is expected to dominate PV installations in the near future, presents an emerging trend in terms of technical and economic feasibility in rooftop PV systems for energy generation. Annual average daily yield, annual average monthly yield, annual average PR, and annual average CUF for a typical 5kW bifacial PV system are found to be 4.5 kWh/kWp, 136 kWh/kWp, 81%, and 18.72%, respectively for a flat rooftop. This system can generate an excess of 13 MWh than the traditional poly-Si technology. A tilt angle between 15° and 20° will reduce LCOE by INR 0.11 (0.0015 USD), which is 5.5% higher than the traditional poly-Si rooftop system. This can be reduced further by the larger deployment of the bifacial rooftop system, as in regions such as Gujarat, which have more than 3 GW of rooftop potential, which could be enhanced by 400 MW as bifacial modules require less space. The deployment of 3 GW bifacial in place of polycrystalline silicon modules leads to a generation of 39 TWh throughout its life. The bifacial rooftop technology of the proposed scale can save 13% space, 9,16,525 kg of CO₂ emission throughout its life, and prevents the use of 2,24,444 kg coal, which is advantageous as compared to polycrystalline systems.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors without undue reservation.

AUTHOR CONTRIBUTIONS

AD and IM have conceptualized the article. AD has collected and analyzed the data. Also, AD was involved in writing the first draft, followed by corrections and proofreading. IM and AR have corrected and modified the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenrg.2022.869890/full#supplementary-material>

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