Solar photovoltaic potential and diffusion assessment for Pakistan

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Abstract
In Pakistan, around 58% of current electricity is generated from fossil fuels and only 2.4% is generated using renewable energy (RE) resources even though the country is blessed with enormous RE potential. Among other RE resources, Pakistan’s geographical location offers high solar energy potential, which implies that actual potential assessment should be undertaken. This study, as such, undertakes a comprehensive assessment of solar energy potential and prospects of solar photovoltaic (PV) systems for both off-grid and grid-connected systems. This study also estimates the future available capacity of rooftop and rural off-grid solar PV capacity. Three different types of solar PV modules of the same size, that is, thin-film, premium, and standard were modeled to compare energy outputs. NREL’s System Advisor Model (SAM) is used to estimate the geographical and technical potential of solar PV considering updated data and geographical information. SAM results suggest that an average of 4.5 kWh/kWp/day is obtained from an installed capacity of 1 KWp. The logistic modeling equations are further used to forecast the solar PV penetration over a period until 2090. The research investigation concludes that 2.8 × 10⁶ GWh of electricity can be generated annually in Pakistan. The estimated results prove that solar PV has the potential to meet the present as well as future energy needs of Pakistan.

KEYWORDS
diffusion, prospects, Pakistan, potential assessment, SAM, solar PV

1 | INTRODUCTION
The majority of developed and developing nations are switching swiftly to renewable energy (RE) resources for meeting their energy demand owing to various advantages such as sustainability and low carbon emission. It is estimated by US Energy Information Administration (EIA) in International Energy Outlook 2016 that more than 10 trillion kilowatt-hours of electricity shall be generated by RE sources by 2040. Figure 1 shows the world’s projected energy mix for power generation in 2040 which estimates that a sufficient amount of RE shall be used to meet global energy demand. In addition to on-grid supplies, RE resources like solar, wind, and biomass

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can also be used to provide off-grid electricity to remote areas where investment in large transmission lines is not feasible. Developing countries, where the majority of global RE resources are estimated, could optimize their energy mix by harnessing these resources optimally. Pakistan is sixth largely populated developing country that covers a land area of 803,950 km² and around 1146 km of the coastal belt and has excellent potential for RE resources to harness. The four major sources of RE in Pakistan are blessed with are hydro, solar, wind, and biomass energy resources.

It is pertinent to mention that Pakistan is included among the top 40 globally most attractive countries for renewable investment according to a report issued by Ernst & Young on Renewable Energy Attractiveness Index (RECAI). Ranked at number 26, the country is an attractive option for investors to harness its RE potential including promising solar energy.

Alongside, hydro and wind energy resources solar energy has witnessed sharp growth during the past decades. The development in solar energy harnessing technologies, in particular solar PV, has added greatly to the increased use of daylight to meet energy demand. Pakistan’s geographic location, topography, and climatic conditions are also favorable for solar energy development and utilization on the national level. On average, the country receives about 1900–2200 kWh/m² of global solar radiation intensity annually. This makes Pakistan relatively rich in solar energy potential. The country has a consistent distribution of solar radiation which makes it highly favorable and suitable for the deployment of solar energy-based applications. The diffusion of solar energy resources in the context of Pakistan is assumed to be progressing due to the role of domestic policy on RE that enables adoption and development in the country. Numerous modeling approaches have been considered in the literature such as Jha and Saha forecasted and analyzed broadband diffusion in India having 3G and 4G characteristics. They have been using multiple growth models and found logistics can explain well the diffusion of MBS in India. Shaikh et al., used logistic and logistic population models to forecast natural gas demand in China. Levenberg Marquardt Algorithm (LMA) has estimated the parameters of the logistic model to enhance the forecasting precision. Siemek et al., have estimated long-term natural gas demand by employing logistic modeling for Poland. The parameters of the logistic model have been estimated through Gauss-Newton Algorithm and reported an average error prognosis of up to 20%. Farzana et al., projected natural gas demand for residential and commercial consumers in Iran using a logistic modeling approach. The parameters have been estimated using a genetic algorithm (GA) and nonlinear programming (NLP) with less than 10% average percent error. Melikoglu et al., estimated parameters of the logistic model using SigmaPlot 11 optimization tool and reported enhanced performance to the linear model. Melikoglu estimated parameters of the logistic model using SigmaPlot 11 optimization tool and reported enhanced performance to the linear model. The life-long processes have generally used the logistic modeling approach and have been employed in estimating and projecting the data in different fields. Hussain and Khan developed machine learning models for estimation of global solar radiation and implemented machine learning models to predict diffuse solar radiation for the humid-subtropical climatic zone of India. Harijan used a logistic modeling approach to estimate the long-term diffusion of solar energy in Pakistan and estimated the parameters using the OLS principle.

The diverse climatic conditions and high vulnerability index of Pakistan have pushed the country to consider RE technologies for electricity generation using solar energy as one of key renewable resources. In this context, various studies in the local context have identified the computation of Certified Emission Reductions (CERs), such as Zhang et al., has deployed the difference-in-differences (DID) method for evaluating economic growth and carbon emissions using the emission trading system (ETS) and proposed the carbon trading policy by implementing RE
based projects. Li et al.,\textsuperscript{15} have compared the cost-saving effect before and after implementing the cost-saving certified emission reductions (CCER) scheme. In addition another study by Lin et al.,\textsuperscript{16} evaluated and analyzed the CO\textsubscript{2} emissions for power generation from the year 1978–2017 using the Logarithmic Mean Division Index of Pakistan. It is estimated that approximately 277.9 Mt of CO\textsubscript{2} emissions is expected in 2035 only from the power sector. Sajid et al.,\textsuperscript{17} computed industrial emissions both direct and indirect embodied the magnitude of the final pull effects on intermediate industrial emissions in Pakistan. Another study,\textsuperscript{18} referred to the official electricity demand forecast and proposed four supply-side scenarios for the study period (2013–2035) using Long-range Energy Alternatives Planning System (LEAP) software tool and also estimated the emission under the developed scenario. Yousuf et al.,\textsuperscript{19} have estimated the baseline emission factor of the power generation sector considering net efficiencies of annual fossil fuel consumption, annual energy outputs, and carbon emissions. This study has proposed a baseline emissions factor for power generation weighted average as 0.606 tCO\textsubscript{2}/MWh (tons of carbon dioxide per megawatt-hour) for wind and solar power projects in Pakistan. These findings outline the potential of generating CERs through GHG abatement by deploying renewable-based power projects.\textsuperscript{20} The CERs achieved from these projects are a tradable commodity as defined by the Kyoto Protocol and UNFCCC which shall provide additional capital flows into developing countries like Pakistan thereby accelerating technology transfer, and encouraging penetration and dissemination of cleaner technologies.\textsuperscript{21}

The comparison of various research studies undertaken on the potential and forecasting of solar PV energy based on various models and locations is given in Table 1. The key contributions from this study, as such includes (i) Assessment of technical potential based on the theoretical and geographical aspects using the system advisor model (SAM). (ii) Scenario-based modeling of medium to long-term solar PV energy generation forecasting in Pakistan. The forecasting accuracy and precision have been enhanced with the LMA optimization strategy to optimally find the intrinsic parameters of the logistic modeling approach. (iii) Future available capacity of rooftop and rural off-grid solar PV capacity is estimated. (iv) Effect of capacity utilization factor (CUF), discount rate, lifetime, and initial capital cost (ICC) on the Levelized Cost of solar PV power is analyzed. (v) The CO\textsubscript{2} emission reductions, as a result of the implementation of solar PV-based projects have also been forecasted which may help to earn carbon revenue. It is apparent from Table 1 that this study has considered all major aspects of potential and forecasting of solar PV energy, that is,
theoretical, geographical, technical, future penetration, CO₂ emissions reduction, and levelized cost.

Different studies have revealed that due to higher solar radiation, half of the country has potential areas for establishing large-scale solar power plants and utilities. One of the richest provinces in terms of solar energy is Baluchistan which receives about 20 MJ/m² daily global insolation. These conditions are ideal for solar energy harnessing using solar PV, solar thermal, and other technologies. However, despite enormous potential, Pakistan lacks the appropriate utilization of solar energy to meet the growing energy demand. Nevertheless, the harnessing of solar energy in the country is encouraging in the country compared to that of the world for the last 10 years as shown in Table 2.

A regional comparison of south Asian countries for solar energy installed capacity place Pakistan in the second position as shown in Figure 2. The overall solar energy installed capacity is although not significant yet progressively encouraging.

This study undertakes a comprehensive assessment of solar energy potential and prospects of solar photovoltaic (PV) as a source of green and sustainable energy to meet Pakistan’s growing energy demand. NREL's System Advisor Model (SAM) is used to estimate the geographical and technical potential of solar PV considering updated data and geographical information. The results of this study would not only provide a realistic estimate of the solar PV energy potential to meet present energy demand yet at the same time would provide a diffusion assessment toward meeting the future energy needs of Pakistan.

This study is organized such that Section 2 of the paper provides an overview of the electricity demand and supply in Pakistan, Section 3 summarizes the solar energy mapping efforts undertaken in Pakistan. The solar PV potential and diffusion assessment methodology are described in Section 4. Section 5 provides the study results pertaining to solar PV potential and diffusion assessment in Pakistan. Prospects of solar PV for meeting the future energy demand of Pakistan is discussed in Section 6 and finally, Section 7 of this study provides the conclusion and recommendations based on this study.

### Table 2

| Year | Total installed capacity (MW) |
|------|-------------------------------|
|      | World | Pakistan |
| 2010 | 40,287 | 9.3 |
| 2011 | 72,045 | 18.6 |
| 2012 | 101,452 | 45.8 |
| 2013 | 135,686 | 100.6 |
| 2014 | 171,590 | 165.4 |
| 2015 | 217,468 | 265.5 |
| 2016 | 291,275 | 589.5 |
| 2017 | 384,362 | 654.7 |
| 2018 | 482,881 | 679.1 |
| 2019 | 580,759 | 713.3 |
| 2020 | 707,494 | 737.3 |

**Figure 2** SAARC solar energy installed capacity (2020)

2 | **OVERVIEW OF ELECTRICITY DEMAND AND SUPPLY IN PAKISTAN**

Pakistan is composed of federating units namely Punjab, Sindh, Khyber Pakhtunkhwa (KPK), Baluchistan, Azad Jammu & Kashmir (AJK), and Gilgit Baltistan (GB).
Except in GB, all areas are connected with the national grid whereas, in GB, electricity is provided by distributed generation. The country is supplied with electricity from thermal, nuclear, hydroelectric, and other RE plants except for some imports from Iran. The share of various energy resources in the electricity supply mix is indicated in Figure 3. This indicates the dominance of thermal resources in energy transformation which increases the price of electricity for the end-consumers as well as a major source of emission. The total electricity generation capability, peak demand, and shortfall for the past 10 years are shown in Figure 4.

It is pertinent to mention here that supply deficit is not only due to poor energy mix but also due to a lack of expansion in supply capability and higher transmission and distribution (T&D) losses. This type of situation particularly explodes in absence of effective energy planning and policy endeavors to ensure sustainable energy supplies. To cope-up the situation, that is, to contain the soaring energy demand; the Government has had been adopting various strategies over the years. In addition, various initiatives including better utilization of RE resources have been undertaken as well. Two key departments established for the purpose are the Alternative Energy Development Board (AEDB) and the Pakistan Council of Renewable Energy Technologies (PCRET). In 2006 Pakistan had set the target to generate 9.7 GW of electricity from renewables and electrify 7874 villages by 2030. It is obvious from Figure 3 that despite these targets in place, there is no substantial progress witnessed in this context. RE has tremendous potential to overcome energy crises and spare Pakistan from investing a huge amount in importing fossil fuel fuels. Solar energy is one of the major RE sources which is examined in terms of availability, capacity, and cost in the following sections. The solar PV technology is quite mature, and the government has already initiated some small-scale projects which are encouraging and have shown promising results.

3 | SOLAR ENERGY MAPPING OF PAKISTAN

Solar energy mapping has attained the greatest ever attention to effectively harness the solar energy potential of any region. With advanced technological intervention,
the mapping task has somewhat become a routine affair which greatly helps decision-making on solar energy installations. To complement the efforts to enhance RE share, World Bank has undertaken solar energy mapping of Pakistan and has recently released the high-quality solar maps for Pakistan, known as Pakistan Solar Atlas, which is based on nine ground-based solar mapping stations located across the country. This solar atlas highlights the tremendous solar potential Pakistan is blessed with.

Pakistan, as such, has become the first country to benefit from high-quality solar maps under the global initiative on RE. A high-resolution annual solar resource map from such an effort for Pakistan is shown in Figure 5. The different colors in the map indicate solar resources in different areas of Pakistan. These maps can be used to identify optimized power calculations for solar PV cells with the angle of elevation and height. This data can also be frequently used for deciding the area and size of PV plates.

These maps also reveal that Pakistan has one of the highest insolation values in the world, with an average of 8.5 h of daylight availability. Most of the areas of Balochistan province have the highest PV potential of 5.8 kWh/day. This is followed by Sindh province and Southern Punjab with a potential rating ranging between 4.5 and 5.4 kWh/day while the areas of Northern Punjab, Khyber Pakhtunkhwa, and Gilgit Baltistan have the referred potential valued between 3.4 up to 4.4 kWh/day. Various research-based studies have indicated that the monthly mean daily Global Horizontal Irradiance (GHI) attributed to Pakistan is 4.44–5.83 kWh/m², thus averaging the annual mean at 5.27 kWh/m². The minimum annual mean daily GHI is 4.44 kWh/m², which is still more than the global annual mean daily GHI, that is, 3.61 kWh/m². In terms of power generation, the solar energy potential associated with the various regions of the country commendably ranges from 2 to 8.5 kWh/m²/day. Despite these favorable indicators, the adaptation of solar energy technologies in Pakistan has been relatively slow in comparison to other countries. Unfortunately, a country with the potential to produce the astounding 2.9 TW of clean energy is merely producing 737 MW of electricity utilizing PV technology.

It is pertinent to mention that solar radiation intensity varies depending upon the specific geographical location, however, the available intensity is sufficient throughout the country to develop and utilize different solar energy technologies efficiently and effectively. Several factors such as source availability, local technology, affordability, public awareness, government policies, and willingness to invest in alternative energy technologies are important for the development and deployment of solar energy applications on the national level.

Other than solar thermal applications, power generation from solar energy is one of the primary focus these days. In this context, solar PV is a mature technology and over the years is widely used for solar power generation. Following the provision of requisite data available through World Bank’s assisted Solar Atlas, Pakistan could also take advantage of Solar PV technology for power generation to meet its growing electricity demand. In this context, it is essentially required to estimate the long-term averages of solar resources and power generation potential for a specific site. In this study, these estimates, for solar PV installation, for the major cities of Pakistan have been worked out using the SolarGis tool for 2017–2018 data and are briefly discussed as follows. These estimates suggest that Pakistan has adequate solar radiation resources to produce 2.9 terawatts of solar power. It is also revealed that 70% of the 0.8 million

![Solar map of Pakistan](image-url)
km² area of the country receives solar energy radiations of 5.0–5.5 kWh/m²/day. There is a considerable area available in Baluchistan and Sindh provinces that receive 5.5–6.0 kWh/m²/day. The PV potential of Pakistan for major cities from the above-referred estimates is given in Table 3.

As Pakistan is blessed with four seasons due to equatorial zone, therefore, solar irradiance is different in different seasons and this phenomenon is illustrated in Figure 6.

It is evident that Pakistan has average sunshine of 8 h/day. In winter the least sunshine is 6–6.5 h/day, and during peak summer days sun persists for more than 9 h/day. As its longitude and latitude sunshine in the country starts to increase from January to June, then in August, it starts decreasing with a little rise in September and then a sharp decrease in December.

It is pertinent to note that compared to other solar-based technologies, such as solar thermal, solar PV cells are gaining more popularity. In particular, the inclusion of products from China in the market has reduced the prices of solar PV panels. The solar PV cell prices which were 70–80 cent/W in 2011 had substantially reduced to attain about 45 cents/W by 2015. A Levelized cost for installation, operation, and maintenance (O&M), transmission line, along with capacity factor and land area

| TABLE 3 Photovoltaic potential of Pakistan | Mingora | Islamabad | Lahore | Quetta | Bahawalpur | Khuzdar | Turbat | Hyderabad |
|--------------------------------------------|---------|-----------|--------|--------|------------|---------|--------|-----------|
| PVOUT, average daily total (kWh/kWp)       | 4.30    | 4.11      | 3.86   | 5.26   | 4.41       | 5.22    | 4.74   | 4.70      |
| PVOUT, yearly total (kWh/kWp)              | 1571    | 1501      | 1411   | 1921   | 1609       | 1906    | 1729   | 1715      |
| Optimum angle (°)                          | 30      | 30        | 28     | 30     | 28         | 29      | 27     | 26        |
| Annual ratio of DIF/GHI (%)                | 42.3    | 46.4      | 54.0   | 34.6   | 47.1       | 35.4    | 43.3   | 44.2      |
| System PR (%)                              | 77.2    | 76.9      | 75.9   | 78.4   | 74.9       | 77.3    | 74.6   | 74.8      |

FIGURE 6 Month wise Pakistan solar irradiance
requirements for solar PV cells and solar thermal technologies are given in Table 4.

Given the above facts, developing countries like Pakistan essentially need to undertake solar PV potential and diffusion assessment to manage financing and installation of solar PV projects to meet the growing energy demand.

4 | SOLAR PV POTENTIAL AND DIFFUSION ASSESSMENT METHODOLOGY

The estimation of solar energy potential depends on multidimensional indicators. These include but are not limited to local solar energy resources, available land, technological development, the economics of solar products, and governmental policies. Land availability is a major factor in the selection of a suitable area and site for solar PV installation. Technological development directly influences the effectiveness of power transition. The government policies have already been confirmed to leapfrog solar energy penetration in the energy mix. Due to these factors a comprehensive solar energy potential analysis should not be only based on solar energy resources but also consider the geographical, technical potential, and economic feasibility analysis. In this context, the information of theoretical and geographical potential is essentially required and estimated in this study using various mathematical relations ships as follows.

4.1 | Theoretical potential of solar energy

The theoretical potential is the solar energy that is received by the total land of a region in a year and estimated by the following equation:

$$SE_{th} = I \times A \times 365,$$

where $SE_{th}$ is the theoretical potential of solar energy (kWh/m$^2$/day), $I$ is the global average solar irradiation (5.69 kWh/m$^2$/day), $A$ is the total land area ($7.90 \times 10^{11}$ m$^2$) and total days in a year are 365.

4.2 | Geographical potential of solar PV

The geographical potential is the solar energy received by geographically suitable areas for harnessing solar energy.

4.2.1 | Geographical potential of grid connected solar PV

The geography of each region varies and could be complex as well. As such, a suitability factor is generally used for different land types to estimate geographical potential. These suitability factors in respect of Pakistan, for varying geography, considered in this study are provided in Table 5 which is for large Grid-connected solar PV.

| Land use type           | Land-use suitability factor ($f$) | Area per land-use type (million m$^2$) | Land-use area and percentage of total terrestrial area | Suitable area for solar PV (million m$^2$) |
|-------------------------|-----------------------------------|----------------------------------------|-------------------------------------------------------|----------------------------------------|
| Urban areas             | 0.00                              | 1592.2                                 | 0.2                                                   | 0                                      |
| Snow, ice, and water bodies | 0.00                              | 83,590                                 | 10.5                                                  | 0                                      |
| Forests and bio reserves | 0.00                              | 49,358                                 | 6.2                                                   | 0                                      |
| Agriculture             | 0.01                              | 244,401.5                              | 30.7                                                  | 2440                                   |
| Rangelands              | 0.01                              | 160,811.4                              | 20.2                                                  | 1608                                   |
| Wasteland               | 0.05                              | 256,342.9                              | 32.2                                                  | 12,817                                 |
| Total                   |                                   | 796,096                                | 100                                                   | 16,865                                 |
Subsequently, the geographical potential of solar energy can be estimated using the following equation:

\[ SE_{gp} = I \times f \times A \times 365, \]  

where \( SE_{gp} \) is the geographical potential of solar energy (kWh/m\(^2\)/day), \( I \) is the global average solar irradiation (5.69 kWh/m\(^2\)/day), \( f \) is suitability factor, and \( A \) is the total land area (796,096 million m\(^2\)).

### 4.2.2 Geographical potential of roof top and off grid solar PV

Elevated load shedding hours, poor performance of distribution companies, high electricity cost, and grid limitations force the urban population to find alternatives to fulfill electricity demand. Generators and UPS were traditional methods but currently, it is trending to install solar rooftop PV systems not only in domestic areas but also in commercial areas because of decreasing cost of solar PV. Developing countries like Pakistan, therefore, are pushing hard to electrify rural areas of the country using solar PV adoption. The two popular approaches to adopting solar systems are roof top-based installations or rural off-grid solar PV systems. The following section discusses the potential assessment of either of the two.

#### Roof top solar PV potential

The rooftop PV system is referred to as decentralized grid-connected or off-grid PV systems of small to medium scale for domestic electricity supply, installed at or close to houses, utilities, or small industries. The size of the system is related to the available area at and around the settlements mostly rooftops, facades, parking lots, and small surfaces around the house.

GIS data of roof area of most developing countries including Pakistan is not available and estimating the same is beyond the scope of this study, as such, several authors have explored the relationship between roof area with income and population. In fact, it is considered in the contemporary literature that a high correlation between building density and population can be helpful to estimate rooftop areas. Finally, to estimate the average rooftop area relationship developed by Hoogwijk is used in this study as provided below.

\[ Rt = 0.06(GC)^{0.6}. \]  

where \( Rt \) is the rooftop area in m\(^2\) per capita and grid connected (GC) is the GDP in US$ per capita. Having obtained a rooftop area, it is necessary to reduce this area to that which is available for solar PV applications. There are many factors that influence the fraction of available roof area, including, shading from other applications like ventilation, heating/air conditioning, and shading from other parts of the roof like roof boundaries, water tanks, or neighboring buildings. The available area for rooftop PV is also affected by the orientation of pitched roofs and the installation and racking of the PV panels themselves. In general, a complete rooftop is seldom used for PV installation, as this area may be reserved for other applications and cleaning of PV panels.

It is, therefore, necessary in the calculation of solar PV potential a factor may be introduced that would address these issues. Many authors like Silva and colleagues have used a fraction of available roof area for estimation of Rooftop solar PV potential, however, Wiginton et al., determined coefficients of available rooftop area considering all major aspects of the rooftop as discussed above. So in this study, rooftop area coefficient (\( fr = 0.19 \)) determined by Wiginton et al., is used. Equation (3) can be modified as the following equation:

\[ Rt = 0.06(fr)(Gc)^{0.6}. \]  

The available area for a roof-top PV systems is expressed as the product of available roof-top areas per capita times the population in urban areas.

#### Rural off-grid solar PV potential

Off-grid solar PV systems can be used for a wide range of applications like domestic electricity needs, cooking, supply of telecommunication towers, military applications, mobile charging, and other countless applications. Nowadays it is common practice to use solar home systems (SHS) or solar PV panels along with a charge controller and DC devices in rural areas which are nonelectrified/or have extreme load shedding. This study as such is limited to search for Rural non-electrified households which situate in solar-rich regions and are willing to spend/afford SHS.

### 4.3 Technical potential

The technical potential of solar PV in this study is estimated using SAM. The SAM model is developed by NREL and ESMAP. SAM model has different technical modules along with geographical information. In this study, the solar PV module of SAM is used. The model requires multiple technical data about solar radiations, regional temperature, humidity, and other relevant data. The model is featured in various national databases, yet it
can be updated/customized according to the specific requirement of any study. In this study, three standards (i.e., standard, thin-film, and premium) of solar PV modules are considered because each has different nominal efficiency, power density, module cover, temperature coefficient of power, and fill factor.

Standard and thin-film have glass module covers, however, premium PV modules are designed with antireflective module cover. Approximate nominal efficiencies of standard, thin-film, and premium modules are 17%, 15.6%, and 20.1%, respectively. Thin-film modules are seeking, nowadays, greater attention in the contemporary literature and in the local market for their low cost. Various studies have also recently reported efficiency of around 23.4% of this module.60–62

An important factor that impacts the output of the solar module is the temperature coefficient. It is a measure of the decrease in output power for every 1°C rise in temperature over 25°C of the temperature a solar module receives. In this regard, despite having lower general efficiency, thin-film panels tend to have an excellent temperature coefficient compared to the other two types considered in this study. As such, the temperature coefficient of standard and premium modules is reported to be −0.47%/°C and −0.35%/°C, respectively, while a thin film module has a temperature coefficient of −0.2%/°C. Temperature coefficient, although not a significant parameter for the colder regions, however, in areas with hot climatic conditions like Pakistan can considerably affect the module output.

Based on existing literature, a system size of 1 kW is considered for modeling in this study. The module parameters assumed are given in Table 6.

| Parameter           | Value                  |
|---------------------|------------------------|
| System size         | 1 kW                   |
| Rated inverter size | 0.83 kWac              |
| Inverter efficiency | 96%                    |
| Array type          | Fixed open rack        |
| Total system losses | 14.08%                 |
| Module type         | Standard               |
|                     | Thin film              |
|                     | Premium                |

**4.3.1 | Technical potential of grid connected solar PV in Pakistan**

The total technical potential of solar power generation using solar PV can be estimated using Equation (5) given as under:

\[
SE_{tc} = (A_g /10) \times SP_{ae},
\]  

where \(SE_{tc}\) is the Total technical potential of solar PV, \(SP_{ae}\) is the SAM model output of 1 kWp module and \(A_g\) is the geographical area available for solar PV. Assuming 10 m² area is required for 1 kWp solar PV.

**4.3.2 | The technical potential of roof top PV**

Using the results of SAM in Equation (4), the technical rooftop potential of solar PV for the year 2020 can be estimated and provided in Section 5.

**4.3.3 | Technical potential of rural off-grid solar PV potential**

From the discussion of Section 2.2.2 technical potential of rural off-grid solar PV potential can be estimated using Equation (6).

\[
AE = RHH \times C_p \times CF \times 8760,
\]  

where RHH is the number of rural households who can afford and are willing to install SHS, \(C_p\) is the power rating of a single SHS, CF is the capacity factor of solar PV in Pakistan.

**4.4 | Diffusion and future available capacity of solar PV**

The methodology to estimate diffusion and future available capacity of solar PV for grid-connected rooftop and rural off-grid systems is described in the following sections.

**4.4.1 | Grid-connected solar PV system**

The development of technology over time may confirm an S-curve in a variety of situations and a combination of slow initial growth and rapid growth after a certain take-off point and then again, a slow growth toward a finite upper limit to the dissemination.64,65 Rao and Kishore
have studied the various models for diffusion of RE technologies and concluded that the logistic diffusion model can be optimally used for forecasting the diffusion of RE technologies including solar PV systems in developing countries. Lund has developed and applied the logistic diffusion models for estimating the market penetration rates of solar PV systems and other new energy technologies. These and many other forecasts of solar PV systems' diffusion suggest that the additions of solar PV systems to an installed capacity of power generation will continue to grow exponentially for decades. However, the high growth rate of diffusion of solar PV systems will eventually be replaced by slow growth rates due to the market saturation of PV systems. The growth rates of the solar PV systems capacity addition will decrease after saturation point and finally reach a constant rate of replacement growth.

The diffusion of grid-connected solar PV units in Pakistan can be projected using the PV system's diffusion model as below equation.

\[
N(t) = \frac{M}{1 + e^{-q(t-t')}}.
\]

where \(N(t)\) is the cumulative installed capacity of the grid-connected solar PV system at time \(t\) for the corresponding year, \(M\) is the maximum technical potential of solar PV systems for grid-connected electricity production, \(q\) is the adoption rate of solar PV plants for grid-connected electricity production, and \(t'\) is peak time at the point of inflection.

The parameters of the solar PV diffusion model are estimated using historical installations and expected installations in the near future of grid-connected solar PV systems through Trust Region Algorithm using MATLAB Curve Fitting Toolbox and used to forecast the installation of solar PV plants in Pakistan for grid-connected power supply.

4.4.2 | Future available capacity of roof top solar PV

Since, the exact number of rooftop solar PV installations in Pakistan is not known, therefore, quantifying these is very difficult. In this study, estimation of the future available capacity of the rooftop solar systems for Pakistan is undertaken from the urban population and GDP/CAP data as reported in the contemporary literature. The required data on the urban population is obtained from the United Nations Department of Economics and Social Affairs Population Dynamics. It is also pertinent to note that the GDP of any country is also varying and uncertain as it depends upon various factors.

4.4.3 | Future available capacity of rural off-grid solar PV

The trend of solar PV installation is very common in rural areas where there is no electricity through the grid or the areas with extended load shedding hours. However, the exact number of these installations is not known but an estimation of the available capacity of those installations can be made using the following equation:

\[
AE(t) = RHH(t) \times Cp \times CF \times 8760,
\]

Where \(AE(t)\) is Available Energy potential in year \(t\), \(RHH(t)\) is number of Rural House Holds with SHS in year \(t\), \(Cp\) is the power rating of single SHS, \(CF\) is the capacity factor of solar PV in Pakistan.

4.5 | Emission reductions (base scenario)

Climate change is now a fact and inevitable until efforts are undertaken to contain it. Pakistan is also one of the most affected countries in terms of climate change and facing a daunting challenge to contain it. As a result, hundreds of lives and billions of rupees are lost annually due to its climate change-related calamities. One of the reasons for this change is the excess use of fossil fuels. The burning of carbon-based fossil fuels causes the emission of \(CO_2\) and other pollutants including particulate matter which adversely contribute to climate change. The energy sector is reportedly responsible for about 3/4 of the carbon dioxide emissions, 1/5 of the methane emissions, and a large quantity of nitrous oxide.

Pakistan's energy and power sectors are also adversely contributing to GHG emissions as the majority of power generation is based on fossil fuels. Switching to clean fuels and RE resources can reduce these emissions. The cost of emission reduction is not fully covered by ordinary financial returns and thus climate finance instruments such as the Clean Development Mechanism can be an important tool in increasing the penetration of RE technologies for emission reduction. In this study, the level of GHG emissions that would occur in the absence of a clean energy project is considered as the baseline emission factor. This baseline emission factor determines the potential of GHG

abatement and capacity to generate CERs by setting up clean energy projects. The generated CERs are a tradable commodity as defined by the Kyoto Protocol and UNFCCC which could provide additional capital flows for developing countries.

Solar PV is a clean source of energy, and with implementation, such projects and earning CERs could elevate its penetration in Pakistan. The national baseline emission factor of Pakistan for wind and solar energy projects is estimated as 0.606 tCO₂/MWh. As such, the annual CERs in MT CO₂ for solar PV projects, considered in this study, can be calculated using the following equation:

\[ ACER(t) = EF_{grid} \times AEP(t), \]  

where \( ACER(t) \) is the annual CERs produced in year \( t \), \( EF_{grid} \) is national grid emission factor and \( AEP(t) \) is annual electricity produced from grid-connected solar PV projects.

4.6 | Cost of solar energy

One of the fundamental constraints to harnessing RE resources has had been the higher technological costs and the financial limitation of the developing countries. However, owing to some global financial recession in recent times accompanied by technological development, and reduced taxation/rebates as well as public awareness has caused the RE technologies costs as competitive to conventional energy prices. While the cost of producing RE also depends on several factors like capital cost, fuel cost, Operation and Maintenance (O&M) Cost, plant productivity, and the lifetime of the plant. In this study, the cost of a solar PV project is estimated using Levelized unit cost of energy (LUCE). LUCE is a measure of the average net present cost of electricity generation of a Plant over its lifetime. The LUCE for a solar PV project can be estimated using the expression in the following equation:

\[ LUCE = \frac{Icc[CRF + C_{o&m}]}{AE}, \]  

where \( Icc \) is the initial capital cost, \( CRF \) is the capital recovery factor, \( C_{o&m} \) is the annual operation, and maintenance cost and \( AE \) is the annual electricity output of solar PV system. The \( AE \) can be estimated using the expression:

\[ AE = 8760 \times (Rc) \times (CF), \]  

where \( Rc \) is the rated capacity of the system and \( CF \) is the capacity factor. The \( CRF \) can be estimated using the expression.

\[ CRF = \frac{dr(1 + dr)^t}{(1 + dr)^t - 1}. \]  

The \( CRF \) varies according to the period over which the capital is to be recovered, \( t \) is the years and \( dr \) is the annual discount rate.

5 | RESULTS AND ANALYSIS

The results of this study providing a realistic estimate of the solar PV energy potential and diffusion assessment including emission reduction and cost assessment for Pakistan are given as under:

5.1 | Theoretical potential of solar energy

The area of Pakistan is around 796,095 km² and according to AEDB and ESMAP Global average solar radiation received is 5.69 kWh/m²/day. As such, from Equation (1) the theoretical potential of solar PV for Pakistan is estimated to be 15.525 × 10¹⁴ kWh/year. This theoretical potential is one of the most promising in the region which suggests further study and analysis to determine a feasible solar PV system for Pakistan.

5.2 | Geographical potential of solar PV

5.2.1 | Geographical potential of grid connected solar PV in Pakistan

Pakistan has varying topographical features across its various region, as such, suitability factors as contained in Table 5 were used to estimate the solar energy geographical potential using Equation (2). From these calculations, the geographical potential of solar PV in Pakistan is estimated to be 3.29 × 10¹³ kWh/year. This geographical potential is, however, subject to efficiency and other technical constraints of various solar PV modules in commercial use. It is also pertinent to mention that consumer devices used in Pakistan operate on alternating current (AC) and the power obtained from solar PV is direct current (DC), as such, it requires to be converted to AC which shall cause additional losses.
5.2.2 | Geographical potential of roof top and off grid solar PV in Pakistan

**Roof top solar PV potential of Pakistan**

The rooftop solar PV potential of Pakistan has been estimated using GDP/CAP data in Equations (2) and (4) and the results obtained are summarized in Table 7 below.

It is evident that Pakistan has an estimated 0.1329 PWh/year geographical potential of rooftop solar PV from a feasible rooftop area of 64 million m². However, it should be realized that these estimates are subject to GDP/CAP, as such, varying growth would impact these calculations.

**Rural off-grid solar PV potential**

Considering the current rural population (139 million) and 6.5 persons per rural household (RHH) the number of RHH in Pakistan is estimated to be 21.4 million. Since about 41% of the rural population has no access to electricity, the number of RHH without access to electricity would be around 8.7 million. At this moment, these households are still using traditional ways to fulfill their energy needs, so a solar household system (SHS) could be a valuable solution for this rural population. The key limitation to tapping enormous solar energy for these areas is the higher cost of SHS since Pakistan is a net importer of solar PV modules while the per capita income of the rural population is quite low. Realizing the fact that electricity is an essential commodity in the modern-day world, both rural population and government are striving to electrify these areas. As such, in this study; it is assumed that 50% of the rural population could afford and would be willing to pay for SHS. These households would use electricity for operating various appliances such as fans, lighting, phone charging, and in some cases refrigeration.

Assuming each household is equipped with a 230 Wp, which is sufficient for meeting these basic loads, an estimated capacity of 1000 MW would be adequate to meet the identified demand of this study.

5.3 | Technical potential

In this study, three different types of solar PV modules of the same size, that is, thin-film, premium, and standard were modeled to compare energy outputs. The technical potential assessment of solar PV subsequently estimated using the SAM model, is given in Table 8.

As results indicate the energy output of thin-film and premium modules is higher than the standard module. However, these modules although available in the market are still expensive as compared to standard modules.

It is also pertinent to note that the energy output of different modules varies across the year. The month-wise energy output of the three PV modules considered in this study is illustrated in Figure 7.

It is evident that the output of all modules is highest in the month of May since PV output is directly proportional to the solar radiation and inversely proportional to temperature. The efficiency comparison analysis of all three modules has also been undertaken and is summarized in Table 9.

The above results indicate that the thin-film module has higher power output and superior efficiency as compared to the other two modules considered. However, it is somewhat costlier than premium and standard modules.

5.3.1 | Technical potential of grid connected solar PV in Pakistan

The technical potential for a grid-connected solar PV system has been calculated using Equation (5) and found to be 2.8 PWh/year for standard, 2.9 PWh/year for premium, and 3 PWh/year of thin-film PV module.

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**Table 7** Suitable area for rooftop solar photovoltaic and associated potential

| Gc (US$) (at constant FC 2010) | fr | Per capita roof top area (Rt) (m²) | Suitable area for roof top PV (million m²) | Geographical potential of roof top solar PV (PWh/year) |
|-----------------------------|----|---------------------------------|----------------------------------|-----------------------------------------------|
| 1168                        | 0.19 | 0.42                           | 64                               | 0.1329                                        |

**Table 8** SAM model results

| Parameter           | Output (standard) | Output (thin film) | Output (premium) |
|---------------------|-------------------|--------------------|------------------|
| Annual energy (SE_{ae}) (kWh/year) | 1664              | 1793               | 1725             |
| Capacity factor     | 19%               | 20.5%              | 20.5%            |
| Energy yield        | 1664 kWh/kW/year  | 1793 kWh/kW/year   | 1725 kWh/kW/year |
5.3.2 | Technical potential of roof top solar PV potential

In this case, considering the financial limitation of households, the technical potential of the standard module has been estimated alone. As such, from the efficiency comparison data of Table 8, using Equation (4), the rooftop potential of solar PV has been estimated to be 0.01065 PWh in a year.

5.3.3 | Technical potential of rural off-grid solar PV potential

The technical potential of rural off-grid solar PV for a year has been estimated, using data from Table 8 in Equation (6), to be around 1.66 TWh for a standard type solar PV module.

The technical potential assessment of solar PV modules for power output, efficiency, grid-connected system, and their rooftop feasibility were undertaken.
These results of this assessment reveal that although the thin-film module has superior performance, however, its availability in the market is low as the same is still not well accepted by the stakeholders in Pakistan. As such, its large-scale supply and production both are limited here. As regards the premium modules, their higher costs are a key limitation for its market penetration. In the meantime, the Standard solar PV modules have a higher market stake as they are low cost and their technical assessment too is not far below when compared to the two other modules assessed in this study.

5.4 | Diffusion and future available capacity of solar PV in Pakistan

Based on the technical potential assessment undertaken in the foregoing section, the diffusion and future available capacity of solar PV in Pakistan have been estimated as follows in the subsequent sections.

5.4.1 | Grid-connected solar PV system

The diffusion of a grid-connected solar PV systems has been undertaken using Equation (7) defined in the methodology section of this study. It is pertinent to mention that precise estimation of the parameters of the referred relationship is significant for successful modeling and forecasting the diffusion. In this context, the Trust-region Algorithm (TRA), which is one of the most important numerical optimization methods in solving nonlinear problems, has been considered in this study. TRA works in a way that first defines a region around the current best solution, in which a certain model to some extent could approximate the original objective function. Then algorithm moves forward within the model’s defined region. Unlike the line search methods, TRA usually determines the step size before improving direction. If a notable decrease is gained after the step forward, then the model is believed to be a good representation of the original objective function. If the improvement is too subtle or even a negative improvement is gained, then the model is believed to be a poor representation of the original objective function within the defined region. The convergence can be ensured by the size of the “trust region” (usually defined by the radius in Euclidean norm) in each iteration and would follow the improvement previously made to provide final results.\(^{70,71}\) The estimated parameters for Equation (7), as such, are given in Table 10.

It is evident from Table 10 that the maximum installation capacity of grid-connected solar PV would be approximately 827 GW, that is, about 50% of the total technical potential, with a growth rate of approximately 20% and maximum capacity diffusion in the year 2058 \((t' = 40.37)\).

Subsequently, using these parameters in Equation (7) the grid-connected Solar PV installed capacity has been estimated with respect to existing (actual) solar PV installations and their growth. Both growth patterns of grid-connected solar PV, that is, the estimated and actual are illustrated in Figure 8.

The above illustration reveals that the estimated model growth pattern of grid-connected solar PV follows and duly fits the actual growth pattern. The goodness of fit of the proposed model has been statistically verified with R square \(R^2 = 0.89, R^2_{adj} = 0.84\) which depicts dependent variable percentage variance and measures the model and dependent variable relationship strength.

In addition, based on Equation (7) parameters estimated in Table 10, in this study three sets of scenarios have been developed for grid-connected solar PV diffusion. A business as usual (BAU) scenario, which suggests the adoption rate following the past trends is shown in Figure 9. This scenario is taken as the base scenario in this study. The other two scenarios are solar energy potential utilization (SEPU), other energy alternative (OEA) scenarios. In SEPU, the adoption rate of grid-connected Solar PV units in Pakistan is set at 10% higher than the BAU while in the OEA scenario adoption rate is set to be 10% lower than the BAU. The installed capacity of grid-connected solar PV power plants in Pakistan has been subsequently projected using the logistic growth model and the solar PV diffusion model of Equation (7) for these study scenarios up to 2090. The projected results of the installed capacity of solar PV system for grid-connected electricity generation for the BAU scenario are depicted in Figure 9.

The S-shape characteristics of the curve indicate that during the early years of the forecasting period, the diffusion of solar PV power for grid power supply is very slow (2021–2035) and after this slow growth region, the growth for grid power supply increases exponentially.

| Parameter | Value |
|-----------|-------|
| \(M\)     | 827,400 (MW) |
| \(Q\)     | 0.204  |
| \(t'\)    | 40.37  |
Finally, the growth in cumulative capacity for grid power supply again slows down (2061–2090) and approaches the upper technical potential limit. The projected annual capacity addition is also shown in Figure 9. It infers that the annual installation of solar PV for grid-connected electricity in Pakistan shall be increasing up to the peak or inflation point and shall be decreasing gradually as the installed capacity of solar PV plants approaches the upper limit. The projected cumulative installed capacity of grid-connected solar PV and associated electricity generation under each scenario of this study for the period 2021–2090 is summarized in Table 11.

It is projected that about 6.86, 4.66, and 3.73 GW of solar PV systems could be added to the national grid in Pakistan up to 2030 under each SEPU, BAU, and OEA scenario, respectively. These projected results indicate that only 0.41%, 0.28%, and 0.22% of the total technical potential of solar PV plants for grid power supply, for each scenario respectively, could be harnessed by the year 2030. However, results indicate that after 2030 the pace of installation would increase rapidly and may reach a saturation point by 2090 which is estimated to be around 50% of the total technical potential.

The above forecasted solar PV diffusion appears somewhat optimistic while the ground realities may add some constraints to such diffusion. These constraints may contain diffusion include increased urbanization due to population growth thus high-rise buildings may limit solar PV rooftop space. In addition, rural population growth and their reliance on agricultural crops and the overall demand for these crops may also curtail available space for the diffusion of solar PV. However, realizing the fact that climate change could be effectively contained with such RE resources, as such, ways and measures, such as technological improvements,
smart grids, off-grid systems and offshore systems, needs to be explored for maximum PV installations for a sustainable future of the country.

5.4.2 | Future available capacity of rooftop solar PV in Pakistan

The future available capacity of rooftop solar PV systems has been forecasted under three GDP/CAP scenarios which are BAU, high economic growth (HEG), and low economic growth (LEG) scenarios. BAU is a basic scenario that is based on and driven by the existing policy endeavors and measures. In HEG scenario GDP/CAP is assumed to rise at an average rate of 6% per annum while the LEG scenario assumes a future in which the national GDP/CAP would be marginally low and averaged at a growth rate of 3% per annum.

Subsequently, the GDP/CAP growth for all three scenarios, the urban population, and available rooftop space has been estimated using Equation (4) while associated solar PV generation has been estimated using Equation (5) considering standard solar PV technology. All these results are summarized in Table 12.

It is obvious from the results contained in Table 12 that as the urban population and income would increase; the rooftop area would also increase. As such, solar PV generation from the domestic rooftop is estimated to be 11.5, 11.4, and 11.3 TWh during 2021 and 25, 22, and 19.3 TWh during 2035 in each HEG, BAU, and LEG scenarios, respectively. These estimates of rooftop solar PV may be sufficient to meet around 50% of domestic electricity demand which was 54 TWh.

### Table 11: Projected cumulative installed capacity of GC solar PV power and associated electricity generation in Pakistan

| Year | Installed capacity (GW) | Associated generation (TWh) |
|------|-------------------------|-----------------------------|
|      | SEPU BAU OEA | 19% Cap 20% Cap | SEPU BAU OEA | 19% Cap 20% Cap | SEPU BAU OEA | 19% Cap 20% Cap |
| 2021 | 0.92 0.75 0.72 | 1.53 1.61 | 1.24 1.31 | 1.20 1.26 |
| 2025 | 2.25 1.69 1.50 | 3.74 3.94 | 2.81 2.96 | 2.49 2.62 |
| 2030 | 6.86 4.66 3.73 | 11.41 12.01 | 7.76 8.17 | 6.21 6.54 |
| 2035 | 21 12.80 9.28 | 34.44 36.25 | 21.30 22.42 | 15.45 16.26 |
| 2040 | 60 34.53 22.85 | 100.49 105.78 | 57.47 60.49 | 38.03 40.03 |
| 2050 | 352 207 125 | 586.39 617.25 | 345.23 363.40 | 208.03 218.98 |
| 2060 | 724 596 436 | 1204.68 1268.09 | 991.42 1043.60 | 725.99 764.20 |
| 2070 | 815 787 724 | 1356.51 1427.91 | 1310.7 1379.74 | 1204.68 1268.09 |
| 2080 | 826 822 809 | 1374.91 1447.27 | 1368.1 1440.11 | 1346.37 1417.23 |
| 2090 | 827 827 825 | 1376.89 1449.36 | 1375.9 1448.36 | 1372.12 1444.34 |

### Table 12: Future available capacity of Rooftop area in Pakistan and associated power generation capacity

| Year | Urban population (million) | Future GDP/CAP (US$) | Roof top available (million m²) | Associated generation (TWH) |
|------|---------------------------|----------------------|---------------------------------|-----------------------------|
|      | HEG BAU LEG | HEG BAU LEG | HEG BAU LEG | HEG BAU LEG |
| 2021 | 84.225 | 1238.444 1220.918 1203.393 | 68.876 68.290 67.700 | 11.5 11.4 11.3 |
| 2025 | 92.183 | 1563.506 1455.968 1354.430 | 82.577 79.121 75.762 | 13.7 13.2 12.6 |
| 2030 | 103.278 | 2092.324 1814.401 1570.155 | 111.344 102.219 93.725 | 18.5 17.0 15.6 |
| 2035 | 115.051 | 2800.002 2261.074 1820.240 | 150.063 131.998 115.893 | 25.0 22.0 19.3 |
| 2040 | 127.507 | 3747.034 2817.709 2110.157 | 202.277 170.479 143.325 | 33.7 28.4 23.8 |
| 2045 | 140.649 | 5014.377 3511.378 2446.251 | 272.519 220.066 177.161 | 45.3 36.6 29.5 |
| 2050 | 154.484 | 6710.368 4375.816 2835.875 | 361.157 279.437 215.408 | 60.1 46.5 35.8 |

Abbreviations: BAU, business as usual; HEG, high economic growth; LEG, low economic growth.
in the year 2018–2019. It is expected that passionate technological improvements and reduced technology and installation costs would help out to overcome the limitation of rooftop space due to vertical construction in urban areas.

5.4.3 | Future available capacity of rural off-grid solar PV

The future available capacity of rural off-grid, that is, the SHS PV system and associated power generation, estimated using Equation (8), is given in Table 13. The key data pertaining to the rural population, for this purpose, has been obtained from and the size of a rural household is kept as seven persons per household. In addition, for the purpose of consistency, the capacity factor of standard solar PV modules has been considered while calculating the future available capacity of the rural off-grid solar PV system.

It is evident that the estimated future available capacity of rural off-grid, that is, the SHS PV system does not show any promising increase from the base year (2020) to the end year (2050) of this study. This marginal growth of SHS is mainly attributed to the anticipated rural population migration and increased urbanization thus limiting the increase of rural households. As such, the estimated SHS capacity could be used to meet the electricity demand of rural areas where grid connectivity is not possible.

5.5 | Emission reductions (base scenario)

This study estimates, using Equation (9), the potential of CO₂ emission reduction and capacity to generate CERs by setting up solar PV-based projects. Future annual CO₂ emission reduction estimates as a result of the anticipated installation of standard (19% capacity factor) and thin film (20% capacity factor) solar PV systems are shown in Figure 10.

Although this study has considered the anticipated installation of a standard solar PV module with a capacity factor of 19%, however, for the purpose of comparison CO₂ emission reduction has also considered thin-film PV modules in these analyses. It is apparent from Figure 9 that with a gradual increase in solar PV installations, there is a marked reduction in CO₂ emissions following the year 2036 and onward. The

| Year | Rural population (million) | No. of RHH (million) | RHH with SHS (million) | Associated electricity generation from SHS (TWh) |
|------|---------------------------|---------------------|------------------------|---------------------------------------------|
| 2021 | 140.975                   | 20.139              | 4.129                  | 1.580                                       |
| 2025 | 138.990                   | 19.856              | 4.070                  | 1.558                                       |
| 2030 | 144.888                   | 20.700              | 4.243                  | 1.624                                       |
| 2035 | 148.609                   | 21.230              | 4.352                  | 1.666                                       |
| 2040 | 150.133                   | 21.448              | 4.397                  | 1.683                                       |
| 2045 | 149.353                   | 21.336              | 4.374                  | 1.674                                       |
| 2050 | 146.711                   | 20.959              | 4.297                  | 1.645                                       |

**FIGURE 10** Projected CO₂ emission reduction from solar photovoltaic electricity
estimated CO₂ emission reduction for the standard PV module during 2090 is 840 Mt while for the thin-film PV modules these are estimated to be 2080 Mt. In either case, the overall CO₂ emission reduction for both modules is substantial and noteworthy.

It is pertinent to mention that generally, natural gas and RFO remained the dominant contributors to CO₂ emissions from the power sector, but with coal preferred policies and the addition of coal-based power plants now the main contributors to emissions are natural gas and coal. Natural gas and coal contribute around 90% of CO₂ emissions from the power sector of Pakistan. Overall CO₂ emissions of the power sector are around 55 Mt during the year 2018–2019 while the electricity demand of the country is increasing rapidly. As such, the installation of grid-connected solar PV systems can share a large portion of future power needs and contain the carbon footprints of the power sector.

5.6 | Cost of solar energy

The cost of solar PV technology over the years has witnessed a descending trend globally which is attributed to technological development and reduced cost of the raw material. As such, in the recent past the initial capital cost (ICC) of solar PV is reported to vary from 0.5 to 0.9 US$/W.

However, Pakistan is an importer of solar PV panels, therefore, an average ICC of 0.7 US$ is considered under the base case scenario of this study. The O&M cost of the solar PV system is generally considered 2% of ICC and the same is considered in this study. The lifetime of a solar PV system varies from 20 to 30 years depending on the quality of the system and climatic conditions. As Pakistan has moderate climatic conditions, as such, for the base scenario lifetime of 25 years is considered.

Finally, the discount rate of 10% is considered as the system may be leased. These technical details and assumptions are used to estimate the solar PV LUCE and undertake its sensitivity analysis as shown in Figure 11.

The sensitivity analysis of the LUCE is based on various uncertainties/assumptions related to different ICCs, different cost utilization factors, varying lifetimes, and discount rates. These analyses reveal that LUCE is most sensitive to the CUF, though it is also largely affected by ICC. In contrast to the CUF, which intensifies the effects of certain factors toward determining the LUCE, the lifetime is a moderating variable for the calculation of LUCE. As CUF increases, the marginal cost savings due to other factors, that is, discount rate, ICC, and lifetime are compensated. However, as the lifetime is varied its effect on LUCE is noticed to be the least. Finally, the LUCE is also found to be sensitive toward varying discount rates, with higher rates the future savings are devalued though its effect is evidently low.

The above cost-related analysis of solar PV-based power generation reveals that they are highly competitive compared to the cost of power generation from thermal power plants which varies from 4.3 to 6.3 cents/kWh. Alone, in the based case scenario the cost of power generation from solar PV is 4.5 cents/kWh with a descending trend of ICCs. As such, it is most likely that in future power generation a considerable share of solar energy is evident.

6 | PROSPECTS OF SOLAR PV

It is evident from the contemporary literature and findings of this study that RE harnessing is already taking its ground mainly for climate change concerns,
increased costs, and diminishing reserves of fossil fuels. Among, various RE resources solar PV system stands out as the most sustainable solution to the aforementioned challenges. The solar PV system offers various competitive advantages in contrast to other RE technologies despite the fact that its deployment, in the national/regional grid, requires special arrangements to achieve the expected performance.\textsuperscript{73,74} The primary advantage of solar energy-based systems is also the possibility of the widespread application of PV technology in almost every geographic region of the world.\textsuperscript{75} In addition, the implementation of PV systems at a small scale is extremely feasible and convenient. At the same time, the replacement and relocation of these systems are also quite easy to meet specific load requirements of household, commercial, and medium-scale consumers.\textsuperscript{76} The PV systems, as such, being modular in nature have emerged as the most feasible energy systems with the lowest technical losses, reduced maintenance, and a life span of approximately 25 years.\textsuperscript{77} The disruption of one unit of a PV system does not necessarily damage or affect the output of other connected PV units in the arrayed system, but only requires repairing or replacement of that specific unit.\textsuperscript{78,79} Hence, PV systems relatively have easy maintenance and management.

In terms of attaining expected power outcomes, several factors determine the energy output of a PV system. One of the major factors is the material used in the PV units’ development. The greater the quality of material used, the greater is the energy conversion efficiency of the developed unit.\textsuperscript{80} As such, the availability of sunlight for longer periods would assure a greater amount of energy generated from such PV units. The energy availability would, therefore, sufficiently increase for an extended period of time in the areas that receive large amounts of sunlight during the daytime.

This study finding, in terms of solar PV technology, emission reduction potential, and reduced cost of generation from such system has also established that solar PV has significant prospectus in the future energy mix. The improved technological developments and reduced costs of such technologies would bring a revolutionary change in the energy landscape accompanied by the environmental benefits of these systems.

While the prospects of solar PV, as discussed above, are generally promising yet there are some impediments that may constrain its exponential deployment. One of these is the intensity of climate change, which can affect the overall performance of installed PV systems. In addition, the PV systems output could also be compromised in the regions with relatively lesser insolation and in the hotter temperature regions, the lifespan of the PV panels could be reduced. Besides this, higher humidity levels, dense soiling effect, and higher altitudes with less available light time can reduce the expected energy outcomes of the PV units as well.\textsuperscript{81,82} However, the majority of these impediments could be resolved through technological innovation in the PV system development.

7 | CONCLUSION AND RECOMMENDATIONS

This study thoroughly reviewed the literature pertaining to solar PV system development statistics and undertook its potential and diffusion assessment for Pakistan using SAM and logistic modeling equations. The study results reveal that solar energy has huge potential to overcome future energy demand and supply gaps. It is expected that under the view of ongoing projects, RE enthusiastic policies, and accelerated research and development along with institutional support solar energy will also be one of the lead energy sources in the energy mix of Pakistan. In particular, solar PV deployment has a promising future as its potential assessment and diffusion duly establish that it can reduce energy import bills and assist the country to achieve its nationally determined contributions to meet global climate change obligations.

It is, therefore, well established that solar PV potential and prospects in Pakistan can ensure a sustainable energy future based on a theoretical and geographical potential assessment undertaken in this study. The theoretical and geographical potential of solar PV systems is estimated to produce $15.525 \times 10^8$ and $3.29 \times 10^7$ GWh/year, respectively. A detailed assessment of solar PV potential using the System Advisor Model suggest the technical potential of 1682 GW. Based on these results, this study concludes that around $2.8 \times 10^6$, $2.9 \times 10^6$, and $3 \times 10^6$ GWh of electricity can be generated annually with standard, premium, and thin-film solar PV, respectively in Pakistan. Following recommendations, as such, are devised based on these results:

(1) As, most parts of the PV systems are imported which not only increases the price but also drains foreign reserves of the country, therefore, an indigenous market of PV systems should be developed.

(2) RE supportive infrastructure, that is, technology advancement, repair-maintenance facilities, and capacity building should also be undertaken to effectively ensure PV system operation in the country.

(3) Central and scheduled banks should encourage and facilitate sustainable energy financing with minimum interest for solar PV installations.
(4) Rate of returns on investment should also be enhanced based on spillover incomes/development to attract maximum foreign direct investment in the solar PV.
(5) Solar PV-friendly policies along with institutional support should be developed.
(6) Public awareness regarding sustainable energy technologies should be enhanced.
(7) Local R&D teams and research centers should be developed to encourage universities/public institutions to conduct solar PV research and include the same in the curriculum.

It is anticipated that considering the results of this and other relevant studies; and the recommendations given above, the solar PV system would become a key energy carrier in the overall energy mix of Pakistan. It is also expected that an increased share of solar PV and other RE resources would help to contain climate change and ensure sustainable development.

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