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Keywords: Pakistan, CO2 mitigation, remote rural regions, economic feasibility, off-grid Solar PV power generation

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The off-grid solar photovoltaic (PV) system is a significant step towards electrification in the remote rural regions, and it is the most convenient and easy to install technology. However, the strategic problem is in identifying the potential of solar energy and the economic viability in particular regions. This study, therefore, addresses this problem by evaluating the solar energy potential and economic viability for the remote rural regions of the Sindh province, Pakistan. The results recommended that the rural regions of Sindh have suitable solar irradiance to generate electricity. An appropriate tilt angle has been computed for the selected rural regions, which significantly enhances the generation capacity of solar energy. Moreover, economic viability has been undertaken in this study and it was revealed that the off-grid solar PV power generation system provides electricity at the cost of Pakistani Rupees (PKR) 6.87/kWh and is regarded as much cheaper than conventional energy sources, i.e., around PKR 20.79/kWh. Besides, the off-grid solar PV power generation system could mitigate maximum CO₂ annually on the condition that all of the selected remote rural regions adopt the off-grid solar PV system. Therefore, this study shall help the government to utilize the off-grid solar PV power generation system in the remote rural regions of Pakistan.

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Article

Off-Grid Solar PV Power Generation System in Sindh, Pakistan: A Techno-Economic Feasibility Analysis

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Abstract: The off-grid solar photovoltaic (PV) system is a significant step towards electrification in the remote rural regions, and it is the most convenient and easy to install technology. However, the strategic problem is in identifying the potential of solar energy and the economic viability in particular regions. This study, therefore, addresses this problem by evaluating the solar energy potential and economic viability for the remote rural regions of the Sindh province, Pakistan. The results recommended that the rural regions of Sindh have suitable solar irradiance to generate electricity. An appropriate tilt angle has been computed for the selected rural regions, which significantly enhances the generation capacity of solar energy. Moreover, economic viability has been undertaken in this study and it was revealed that the off-grid solar PV power generation system provides electricity at the cost of Pakistani Rupees (PKR) 6.87/kWh and is regarded as much cheaper than conventional energy sources, i.e., around PKR 20.79/kWh. Besides, the off-grid solar PV power generation system could mitigate maximum CO₂ annually on the condition that all of the selected remote rural regions adopt the off-grid solar PV system. Therefore, this study shall help the government to utilize the off-grid solar PV power generation system in the remote rural regions of Pakistan.

Keywords: off-grid Solar PV power generation; remote rural regions; economic feasibility; CO₂ mitigation; Pakistan

1. Introduction

Electricity is the main source for economic, environmental, and social growth of any country. Electricity is considered to be an ideal invention of humankind and has brought a lot of changes in human lives and society. Nevertheless, approximately 1.1 billion people of the earth are suffering or living without electricity [1]. The majority of the population suffering from this situation are located in rural areas of South-Asia and Sub-Saharan Africa [2]. Similarly, a large proportion of Pakistan are living in rural regions, and the majority of them do not have access to electricity. Pakistan is a developing country facing economic, environmental, and social development challenges which have led the country to an increased power demand. The country's total power demand is 25,000 Megawatts (MW) and this is estimated to be boosted up 40,000 MW by 2030 [3]. Whereas, the electricity supply remains around 17,000 MW, causing an electricity shortage of 8000 MW in the country [4]. In the results, the electricity shortfalls in both urban and rural areas around 12 to 18 h a day [5]. Furthermore, the condition of the remote rural regions of Sindh is very bad, where electricity remains inaccessible for many days.

Pakistan is enriched with a vast potential of energy sources such as oil, gas, coal, and renewable energy (i.e., solar, wind, hydro, and biomass). The estimated potential to generate electricity from

solar energy is 2900 Gigawatts (GW), wind energy (346 GW), hydropower (6 GW), and biomass energy (5 GW) [6]. The province of Sindh is also enriched with renewable energy (RE) sources and the government needs to tap RE to generate electricity [7]. However, most of the rural regions do not have an electricity facility. Forty-eight percent of the population of the Sindh province are living in rural regions, and approximately 13,451 villages are un-electrified [8]. These villages are scattered near and far from the on-grid station, thus connecting to the grid is uneconomic and expensive. The demand for electricity in the rural regions is low when compared to urban areas, from only 50 to 100 Watts (W) per household [9]. Only a small number of lights and one to two fans are required in rural houses because each house is very small and generally built with one room. Providing on-grid transmission to these villages for such a minimum load is expensive and therefore, there is a very minimum chance of grid-connected electricity in the near future. Likewise, electricity generated from diesel generators does not propose an economical option because it is difficult to transport oil to remote rural regions, as well as ineffective for the environment. Pakistan has a structured energy sector for both international and local stakeholders. Moreover, the stakeholders are unwilling to invest in and participate in RE technologies due to high-investment cost, high-discount rates, short-back period requirements, the lack of infrastructural conditions, remoteness regions, and unavailability of the specific region's potential [10]. Currently, due to the worsening economic condition in Pakistan, the government has also called to shut-down all of the on-going RE projects in the Sindh and the Khyber Pakhtunkhwa (KPK) provinces, and this decision negatively affects the development of RE sources and over three billion dollars in investments [11]. The province of Sindh suffers the most from this government decision as its 53 projects are in-progress.

On the above-stated factors, the off-grid solar energy is the best option to generate electricity for rural regions of the province. The regions of the Sindh province receive a high amount of solar radiance throughout the year [12]. The province has enormous potential for solar energy and receives high solar irradiation, with more than 300 sunlight days with about 1800–2200 kWh/m² annual global horizontal irradiation [13]. Furthermore, the Asian Development Bank recommended that the off-grid solar photovoltaic (PV) is the best option, as it is easy to install, low-cost, and increases the socio-economic conditions of the rural regions [9,14]. Various studies have proposed the off-grid solar PV system solution to provide electricity in the rural regions [15,16]. Moreover, solar PV evades extra costs, fuel transportation, and makes the project simple by installing on-site resources. In reference [17], it was presented that off-grid solar PV is an appropriate and sustainable choice for rural electrification due to its life-cycle cost, net energy, and local environmental benefits. In another study [18], the authors identified that the development of the solar PV system improves the living standard of the people and also increases the economic and social conditions in the region. The solar PV system is very favorable for the environment because it has no noise impact, mitigates CO₂ emissions, and does not harm human health [19]. Moreover, numerous other studies, such as [20–22], have presented that the off-grid solar PV system is a significant application for electrification and is an economically viable option for the rural regions. In the US, the residential sector has built energy consumption-related heating and air-conditioning, which make-up of a total of 42% of a buildings total energy use [23]. In another study, the authors have assessed the wind energy potential to generate renewable hydrogen energy in the Sindh province [24]. The planning is the most important aspect for energy management and sustainable development, such as social, environmental, and economic [25].

For achieving the target of providing electricity to rural regions, there should be the proper policies implemented for solar PV power generation system. Extensive research is required to evaluate the particular regions for identifying solar energy potential, as well as to assess the economic viability of the regions. To the best of the authors' knowledge, no such research has been conducted for the Sindh province. Thus, this study aims to fill this research gap. In the study, five rural regions of the Sindh province, i.e., Panoaqil, Badin, Nawabshah, Mirpurkhas, and Kambar, are undertaken to investigate the solar energy potential for electricity generation. The main objectives of the study are:

- To evaluate the techno-economic feasibility of an off-grid solar PV system of five regions of Sindh
- To electrify the above-mentioned rural regions by an off-grid solar PV system

Therefore, this study shall help policy and decision-makers to establish solar PV power generation system rural programs in Sindh and also support unwilling stakeholders to invest by providing comprehensive techno-economic analysis. This study is a way forward for developing off-grid solar PV system in the rural regions of Sindh, Pakistan.

2. Electricity Background in Sindh Province

Sindh is the third largest province by area, and the second largest in terms of the population in Pakistan [26]. The location of the Sindh province holds strategic importance due to its long coastal line, as presented in Figure 1. The Karachi port also provides the best, most economical, and shortest route to the neighboring countries for transferring cargo. The geographical location of the port is very significant, thus it has attracted foreign investment, development projects, and overall contributes to both business and economic growth [27]. Therefore, the on-going projects have rapidly increased the electricity demand in Sindh.



Figure 1. Sindh province map [28].

The energy demand is increasing day by day, which results in a huge electricity shortfall in the country [29]. The Sindh province is being the most affected by the increasing electricity deficit as they face a fresh series of load-shedding between 2 to 17 h a day [30]. This situation is even worse in remote rural regions of Sindh, where power is inaccessible for many days. Moreover, the electricity consumption in the rural regions is considered very low, and the transmission lines are a long distance from the rural areas. Thus, it is considered as cost-intensive.

Pakistan has an estimated 2900 GW solar energy potential, however, this renewable source is still waiting to be harnessed [31]. Figure 2 presented the major share in the electricity generation comprised of the gas of 33.6%, oil 32.1%, hydropower 26.1%, nuclear 5.7%, renewable energy 2.2%, and coal 0.2%, respectively [32].

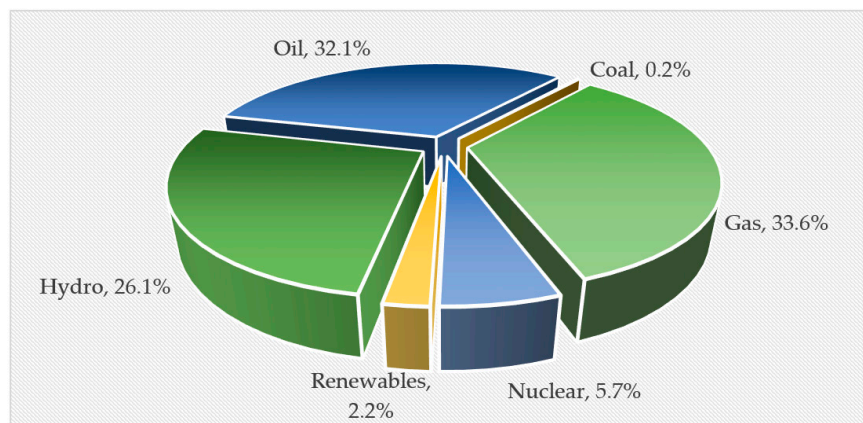


Figure 2. Energy mix of Pakistan.

The Sindh province is rich with renewable energy (RE) sources, such as wind, solar, mini-hydro, and biomass which could be easily utilized for electricity generation. However, the government of Sindh has not taken issues for the development of RE sources seriously, despite increasing demand for electricity. The government had planned a RE policy in 2006, but it is in the infancy stage due to the lack of interest of the government in exploiting these natural resources. Investors are worried and unwilling to invest in the remote rural regions of Sindh since a worse law and order situation, no infrastructure, and a low return on investment are the key factors behind obstructing private investment. However, recently the World Bank has announced that they will finance \$100 million worth of loans for the installation of clean energy in Sindh, the target is to provide off-grid solar PV electricity to 200,000 households, equal to 1.2 million people [30].

Therefore, this study will help government, policymakers, and stakeholders in the implementation of solar PV projects in the rural regions of Sindh.

2.1. Solar PV Power Generation Progress in Remote Rural Regions

Pakistan has installed a small number of solar PV projects in the country, and the first solar PV project was installed in the 1980s. However, the project failed due to the lack of managerial and to technical mistakes [33]. Afterward, until 2005, the country did not develop and promote any RE-based project. Later in 2006, two organizations were established, the Alternative Energy Development Board (AEDB) and the Pakistan Commission of Renewable Energy Technologies (PCRET) to promote and develop RE resources for electricity production [34]. AEDB intends to install a solar PV system in 906 houses of rural regions [35]. Furthermore, the government has understood the advantage of a solar energy framework for enriching socio-economic development and saving the environment in rural regions.

2.2. Solar PV Power Generation Issues in Remote Rural Regions

Solar PV is the appropriate option for providing electricity to off-grid rural regions because of the low-cost technology, easy installation and being environmentally benign. Whereas the development of the solar PV system is substantially very low in rural villages of Pakistan, according to the National Electric Power Regulatory Authority (NEPRA), 40,000 villages in the country do not have access to electricity [36]. There must be robust coordination among organizations is required for a successful solar PV rural electrification programs [37]. Before 2006, no organization was established for developing and planning RE projects, PCRET and AEDB were established in 2006 to coordinate and develop plans for the installation of RE projects in Pakistan. Unfortunately, the progress of both organizations for the development of RE is very poor.

The government has failed to develop and plan innovate strategies and policies for the solar PV system in rural regions, and solar energy productions have failed to take-off, regardless of the

electricity crisis in Pakistan [38]. The common users put themselves at risk by choosing a solar energy solution as an alternative energy. The high up-front cost is also an interruption in the development of solar PV technology. Moreover, the cost of solar PV is significantly higher compared to that in developed countries [31]. In the finance bill 2014–15, the government implemented a 32% tariff on the import of solar PV panels, which results in the low progress of solar PV. Therefore, the government took its decision back and reduced tariffs on solar panels. Despite tariffs on solar inverters, tariffs on batteries are still existing with around 50%. Additionally, the government failed to provide incentives to households on the installation of a solar PV system, which shows the lack of government policies for both investors and customers [39].

3. Research Framework

The research framework of the study has been divided into several sub-sections, which are briefly described as follows:

3.1. Determining the Solar Energy Potential

The average peak solar hours are used to identify and determine the solar irradiation in a particular region when the sunshine at its maximum value for a certain number of hours. The peak solar irradiation is 1 kW/m^2 , the peak hours of sun are equal to the daily solar irradiation in kWh/m^2 . For example, the daily solar array output can be projected to be 545 Wh, if we assume that a 100 Wp solar array is installed in the Panoaqil region with an average solar irradiation of $5.45 \text{ kWh/m}^2/\text{day}$. Therefore, the annual energy output can be computed for monitoring the PV system performance by using the Equation (1) [40]:

$$\begin{aligned} \text{Annual energy output } \left(\frac{\text{kWh}}{\text{kWp}} \right) \\ = \text{Global inplane irradiation} \left((\text{kWh/m}^2) / \text{year} \right) \times \text{Performance ratio} \end{aligned} \quad (1)$$

3.2. Solar Irradiation and Determining the Optimal Tilt Angle

The solar irradiation is generally measured on a horizontal surface of the particular region. The direct solar irradiation received by a solar panel produces a high energy yield. Thus, usually solar panels are angle-tilted to enhance the efficiency of the solar irradiation, and it is necessary to maximize the solar energy yield to determine the optimal tilt angle [41]. The most effective way to increase and improve the solar energy yield is by using solar tracker, solar trackers help in providing maximum energy by changing the angle of solar panels. Nevertheless, solar trackers require high costs, and they utilize more energy for tracking [42]. Furthermore, these solar trackers are a multifaceted nature. Thus it is useless to install in remote rural regions. Consequently, it is more convenient and feasible to change the title angle of solar panels manually rather than installing solar trackers [43]. The various techniques have been employed to compute the ideal title angle of solar panels for exploiting the solar irradiance [44–46]. In this study, a titled horizontal surface obtains a direct beam, some irradiation is diffused, and some are absorbed, while some rays show off the ground, therefore the global horizontal irradiance on a tilted surface I_G^T is described as:

$$I_G^T = I_B^T + I_D^T + I_R^T \quad (2)$$

where I_B^T is a direct beam, I_D^T is diffuse irradiation, and I_R^T is reflected rays of solar energy on a tilted surface.

Let G_B be the ratio for the average daily direct beam on a horizontal surface and average daily direct beam on a tilted surface, then I_B^T can be altered as:

$$I_B^T = I_B G_B \quad (3)$$

where G_B is a geometric parameter, thus the value depends upon the declination angle, horizontal tilt, surface azimuth, and latitude, respectively. Here, the extensively employed Liu and Jordan model [47] is utilized for computing G_B ,

$$G_B = \frac{\cos(L_1 - T_1) \cdot \cos Dsh \cdot \sin i_{ss} + i_{ss} \cdot \sin(L_1 - T_1) \cdot \sin Dsh}{\cos L_1 \cdot \cos Dsh \cdot \sin i_{ss} + i_{ss} \cdot \sin L_1 Dsh} \quad (4)$$

where L_1 is the latitude, T_1 is the tilt angle, and i_{ss} and Dsh are declining angles and the sunshine hours.

For clarity, suppose an isotropic distribution of diffused irradiation. Therefore, the diffused region upon the diffused irradiation on the horizontal surface and the horizontal tilt angle λ :

$$I_D^T = I_D \frac{(\cos(\lambda) + 1)}{2}. \quad (5)$$

Here, a property which is famous as albedo factor ω . The range of albedo varies between 0.1 and 0.9 [48]. Thus the reflected beam can be computed as:

$$I_R^T = \omega(I_B + I_D) \frac{(-\cos(\lambda) + 1)}{2}. \quad (6)$$

3.3. The Economic Viability of Off-Grid Solar PV Power Generation System

The economic feasibility of the off-grid solar PV power generation system in rural regions can be described and identified in the following sub-sections:

3.3.1. Solar PV Power Generation System Size and Battery Storage

A normal solar PV system comprises a solar PV module, load or demand, battery storage, system controller, and DC-AC inverter. The solar PV panels receive solar energy and transfer it to the system controller, then transforming it to DC. Afterward, DC transmits the load to the DC and AC inverter. The electricity produced by a solar PV system relies on the solar irradiance obtained in a particular region. Whereas, several other criteria should be well-measured, such as optimal tilt, efficiency, and solar PV maintenance [49].

Moreover, it is essential to calculate the losses suffered during the DC-AC transformation. The various methods are available to forecast solar power yield on a tilted solar PV. The potential of solar PV to produce electricity and S_{pv} (kWh) is computed using Equation (7) [50].

$$S_{pv} = a_{pv} \cdot b_{pv} \cdot c_t \cdot PR \quad (7)$$

where, a_{pv} is the panel area, b_{pv} is the efficiency, c_t is the annual solar irradiation obtained on a tilted PV panel, and PR is the performance ratio used to determine the losses. Further, b_{pv} is computed as [51]:

$$b_{pv} = b_r [1 - \lambda_r (T_A - T_R + (T_N - T_{a.N}) \frac{I_T}{I_N})] \quad (8)$$

where b_r is the efficiency of solar panels, λ_r is the temperature of solar panels, T_A is the ambient temperature and T_R is the referenced temperature of solar panels, T_N is the nominal operating temperature of solar panel cell, $T_{a.N}$ is the ambient nominal operating temperature, and I_N is the solar radiation.

The designing of any solar PV is a very crucial task because it would have to approximate the load that the PV system supports. For any Solar PV, it is necessary to measure the demand of electricity per household, and it can be computed by multiple appliances, i.e., watt ratings, the number of operating hours, and summing up watt ratings. As presented in Table 1, the projected load is about 440 W per household in rural regions, comprising one pedestal fan, one ceiling fan, two charging slots, and three light-emitting diodes (LED) lights.

Table 1. Projected load requirement per household.

Appliance	No. in Use	Operational Hours	Watts Rating	Total Load (Watts-Hour)
Pedestal fan	1	8	12	96
Ceiling fan	1	12	12	144
Charging slot	2	2	5	20
LED light	3	5	12	180
Total Watts per day				440

The front end of the solar PV total electricity produced and demanded is presented here:

$$\text{Electricity difference} = \sum_{i=1}^{365} (S_{pv} - S_d) \quad (9)$$

where i is the day of the year, S_{pv} is the total electricity produced, and S_d is the total electricity demand.

The solar energy can be used in the sunshine hours, thus for the night hours, an energy storage technology is required for providing the electricity to the households. Most of the remote rural regions of Sindh are off-grid, thus, battery storage is required at an extra cost. The benefit of battery storage is that the electricity can be stored in the battery and can be utilized anytime, mostly in night hours or cloudy weather when sunshine is unavailable. If electricity produced is more than its demand, then there will be an electricity surplus, such as $S_{pv} > S_d$, and the additional energy will be kept in the battery. However, if the demand of the electricity is more than the electricity produced then $S_d > S_{pv}$ and the solar PV is supposed to be insufficient to meet the electricity demand and load at a particular period. The electricity required to be saved in a battery annually, K_b , is therefore:

$$K_b = \left(\sum SE - \sum FE \right) \cdot e_b \quad (10)$$

where SE is surplus electricity, FE is shortfall electricity, and e_b is the efficiency of the battery. Simultaneously, the daily storage capacity of a battery, S_b , is considered as:

$$S_b = \frac{K_b}{365} \quad (11)$$

3.3.2. Levelized Cost of Electricity (LCOE)

Levelized cost of electricity (LCOE) is an important metric employed to determine and compare the cost of electricity produced by several technologies and sources. It prioritizes numerous choices dependent on cost-effectiveness. This study compared the electricity generated by the off-grid solar PV system and a conventional on-grid system to determine the total cost of electricity in both systems. Therefore, the study has compared both alternative technologies through the estimated levelized cost of electricity in kWh unit and is computed by a simple LCOE formula [52]:

$$LCOE = \frac{\sum_{\alpha=1}^n \frac{I_{\alpha} + M_{\alpha} + F_{\alpha}}{(1+d)^{\alpha}}}{\sum_{\alpha=1}^n \frac{e_{\alpha}}{(1+d)^{\alpha}}} \quad (12)$$

where, I_{α} is the investment cost, M_i is the maintenance cost, F_i is the fuel cost, α is a year, e_i is the amount of electricity generated in kWh, d is the discounted rate, and n shows the working-life duration of the alternative technology.

3.4. CO₂ Emissions Mitigation from Solar PV Power Generation System

The clean energy is generated from the solar PV system through sunlight, which may help to support minimizing greenhouse gas (GHG) emissions. Therefore, the government should install a

solar PV system in the rural regions, so it may also help to eliminate the use and the need of diesel generators which may possess high-carbon intensity and affect the environment and human health in a bad manner. The solar PV system generates very little or no CO₂ emissions during operation, but suffer emissions in the manufacturing period [53]. Environmental sustainability is a globally challenging issue since CO₂ emissions are increasing from the unwanted activities of humans, such as utilizing fossils fuels, which may directly affect the climate in a bad manner [54,55]. Thus, a solar PV system can significantly mitigate CO₂ emissions if it is replaced with a diesel generator. The amount of mitigating CO₂ emissions and diesel fuel kept or saved, F_k , is calculated by employing a solar PV system [56]:

$$F_k = S_{pv} \times F_R \quad (13)$$

where F_R is fuel required for a diesel generator for producing electricity of 1 kWh. For the solar PV system, the decrease in CO₂ is measured in kilograms (kg), the CO₂ emissions kept or saved is EM_k in the following Equation [56]:

$$EM_k = S_{pv} \times (C_d - C_{pv}) \quad (14)$$

where C_d is the emitted carbon in kg required for a diesel generator for producing 1 kWh of electricity, and C_{pv} is the emitted carbon in kg required for a solar PV system to produce electricity of 1 kWh.

4. Results and Discussion

The most important step before implementing and utilizing a solar PV system is the determination of the available solar energy in the considered region [57]. The daily solar irradiance values received in all of the five rural regions present the appropriate potential to generate electricity from solar PV energy. Data of solar irradiance is obtained from the NASA database [58]. The data of these five regions, i.e., Panoaqil, Badin, Nawabshah, Mirpurkhas, and Kambar regions, has been provided in Table 2. It is identified from Table 2 that all of the selected remote rural regions have enough daily solar irradiation throughout the year for electricity generation. Further, the daily solar irradiation received on a horizontal surface in each rural region is presented in Figures 3–7. Moreover, the average values of annual solar irradiation in the selected rural regions of Sindh is illustrated in Figure 8. The Nawabshah region receives the highest annual solar irradiation (5.49 kWh/m²) followed by the Kambar region (5.48 kWh/m²), the Panoaqil region (5.45 kWh/m²), the Mirpurkhas region (5.41 kWh/m²), and the Badin region (5.39 kWh/m²), respectively.

Table 2. Solar data for five regions of Sindh, Pakistan [58].

Period	Panoaqil Region		Badin Region		Nawabshah Region		Mirpurkhas Region		Kambar Region	
	Daily Solar Irradiation (kWh/m ² /day)	Earth Temp (°C)	-	-	-	-	-	-	-	-
Jan	4.10	14.65	4.49	16.92	4.20	14.60	4.41	15.90	3.73	14.70
Feb	4.97	18.36	5.25	21.03	5.09	18.30	5.06	20.03	4.89	19.26
Mar	5.71	25.29	5.97	27.85	5.76	26.19	5.88	27.55	5.83	26.04
April	6.65	33.15	6.69	33.97	6.67	34.04	6.61	34.81	6.90	34.14
May	6.88	38.72	6.79	36.06	6.90	37.55	6.78	37.81	6.79	39.60
June	6.76	41.93	6.48	37.31	6.75	39.46	6.55	39.29	6.77	41.12
July	5.91	40.69	5.08	36.15	5.82	37.91	5.52	37.94	5.65	39.92
Aug	5.97	39.28	5.14	34.38	5.91	37.44	5.49	36.73	6.00	39.40
Sep	5.86	39.28	5.47	33.45	5.82	35.75	5.58	34.95	5.82	36.01
Oct	4.95	30.42	4.97	31.47	5.03	30.88	5.00	31.51	5.47	30.02
Nov	4.00	22.97	4.31	26.55	4.13	24.37	4.15	25.67	4.22	21.03
Dec	3.70	16.08	4.02	19.24	3.80	16.90	3.90	18.48	3.68	15.23
Avg. annual values	5.45	30.06	5.39	29.53	5.49	29.45	5.41	30.05	5.48	29.71

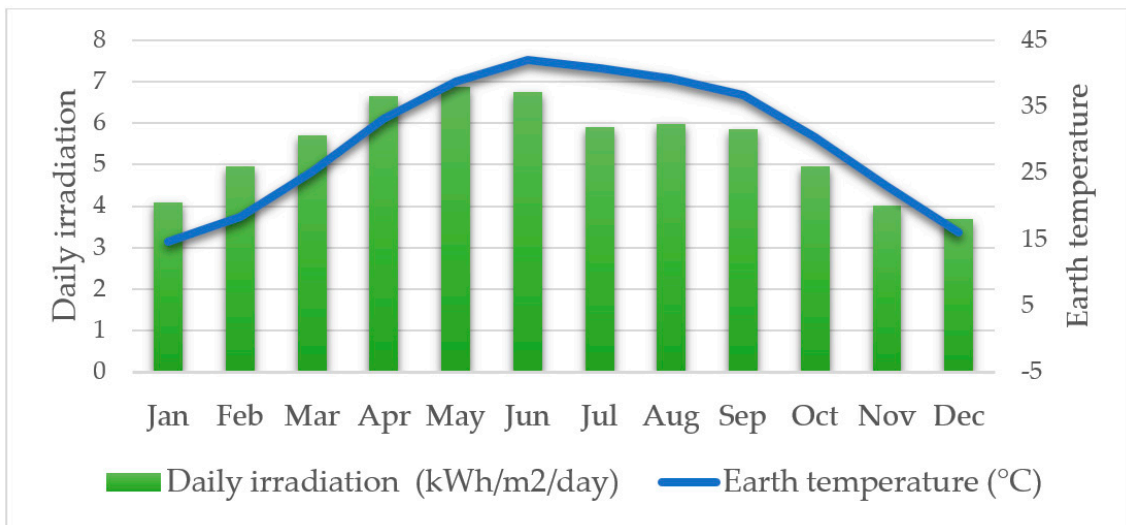


Figure 3. The Panoaqil region daily solar irradiance received.

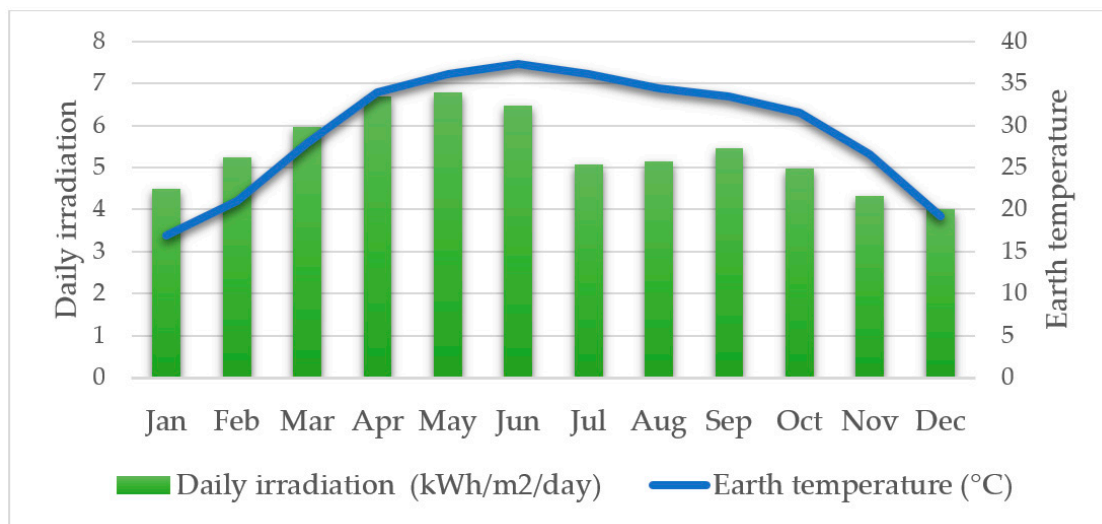


Figure 4. The Badin region daily solar irradiance received.

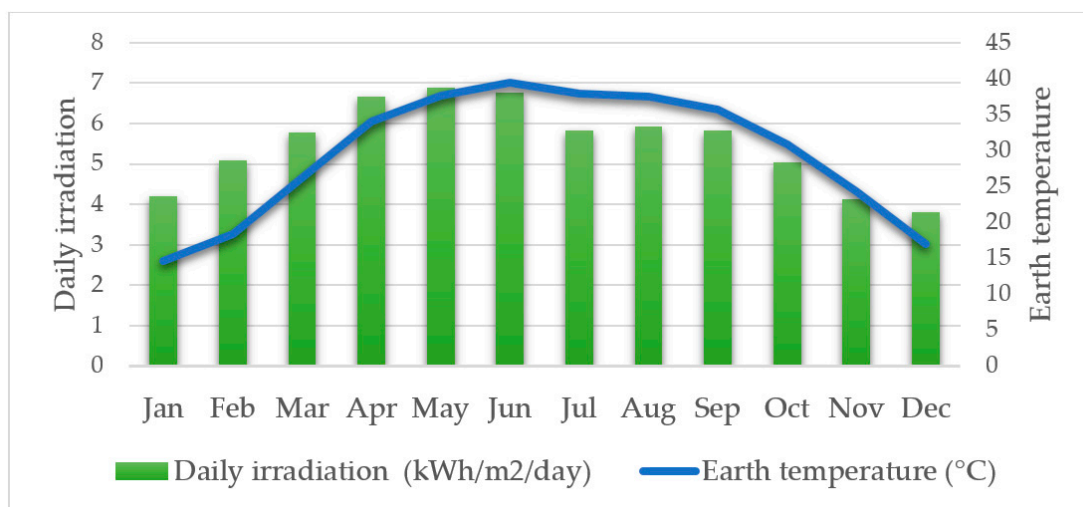


Figure 5. The Nawabshah region daily solar irradiance received.

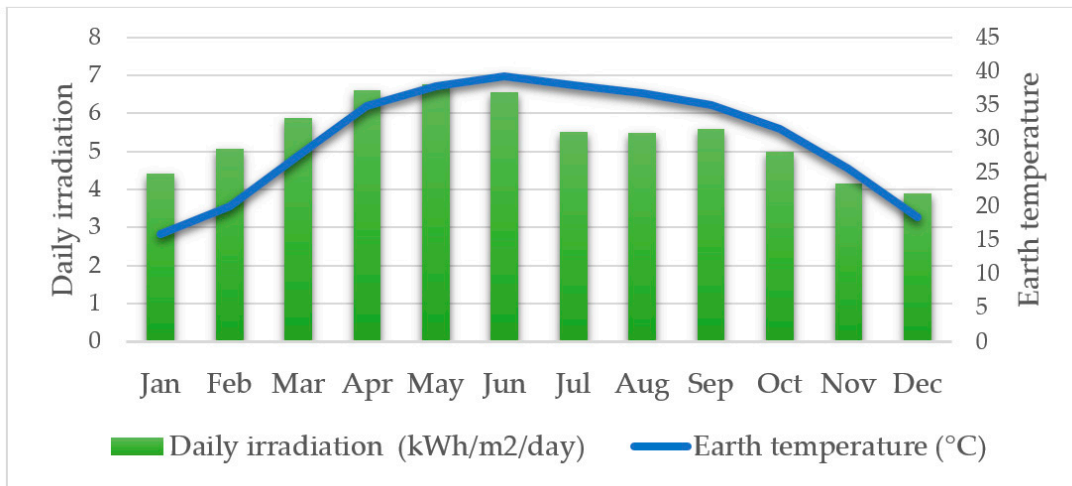


Figure 6. The Mirpurkhas region daily solar irradiation received.

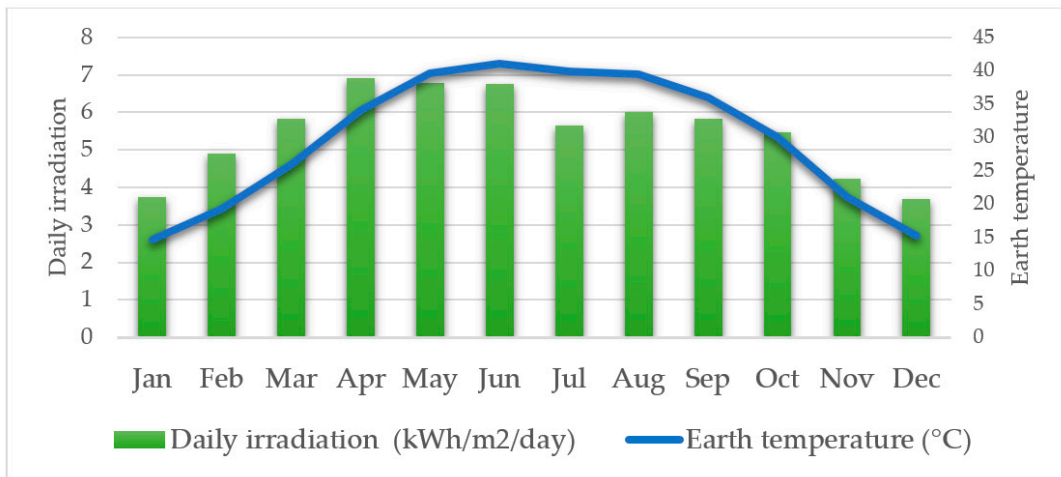


Figure 7. The Kambar region daily solar irradiation received.

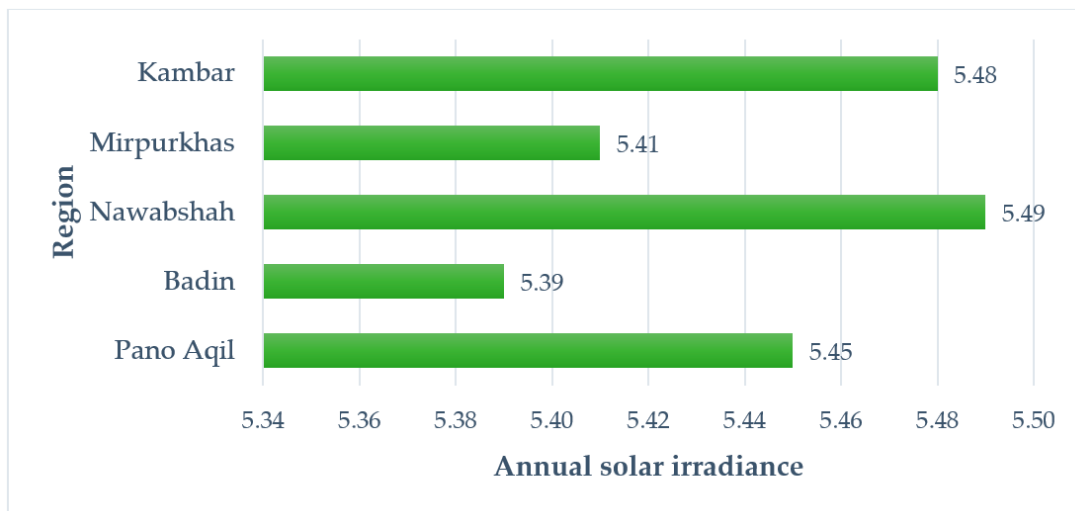


Figure 8. Annual solar irradiance received in five rural regions of Sindh.

4.1. Analyzing the Solar Energy Potential

The above-stated Figures present the average solar irradiation values for the selected regions of the Sindh province. The optimal average peak solar hours are also computed for the selected

regions. Table 3 presents the total potential of using solar PV system in five regions of Sindh province, Pakistan, such as the Panoaqil, Badin, Nawabshah, Mirpurkhas, and Kambar regions. It presents that the potential for the solar PV power generation system is significant in these regions. For example, the Nawabshah and Kambar regions, with average solar irradiation of around 5.49 kWh/m²/day and 5.48 kWh/m²/day, have the probability of generating 1503 kWh/kWp and 1500 kWh/kWp annually. Furthermore, the daily energy produced from a solar PV panel is around more than 500 Wh in each region of the Sindh province, which can satisfy the need for a primary household energy consumption.

Table 3. Potential of solar photovoltaic (PV) power generation in selected regions of Sindh, Pakistan.

Region	Solar Irradiation (kWh/m ² /day)	Avg. Peak Solar Hours	Daily Energy Output (Wh)	Annual Energy Output (kWh/kWp)
Panoaqil	5.45	5.450	545	1492.21
Badin	5.39	5.390	539	1475.782
Nawabshah	5.49	5.490	549	1503.162
Mirpurkhas	5.41	5.410	541	1481.258
Kambar	5.48	5.480	548	1500.424

4.2. Solar Irradiation Obtained at the Optimal Tilt Angle

Using Equations (2)–(6), the mean values of daily solar irradiation received on a tilted angle are shown in Table 4. Similarly, [59] we conducted the techno-economic analysis to check the impact of title angle on the performance of a PV battery storage for a single household in Germany. The results indicate that a substantial percentage of solar energy yield can be annually elevated by changing the angle from 0 to 90 degrees of solar PV panels on the optimal tilt angle. Solar energy yield can be elevated by 9.87% in Panoaqil at the optimal tilt angle of 28.9°. Likewise, 9.98% in Badin on 29.1°, 10.11% in Nawabshah on 29.3°, 11.66% in Mirpurkhas on 30.6°, and 10.43% in Kambar at 29.5°.

Table 4. Daily solar irradiation (kWh/m²/day) received on a tilted varying between 0 and 90 angle degrees.

Region	0 Tilt Angle Degree	15 Tilt Angle Degree	30 Tilt Angle Degree	45 Tilt Angle Degree	60 Tilt Angle Degree	75 Tilt Angle Degree	90 Tilt Angle Degree
Panoaqil	5.8	6.2	6.3	6.1	5.6	4.8	3.9
Badin	5.5	5.9	6.0	5.8	5.4	4.6	3.7
Nawabshah	5.7	6.2	6.3	6.2	5.7	4.9	4.0
Mirpurkhas	5.8	6.2	6.3	6.1	5.6	4.8	3.9
Kambar	5.8	6.2	6.3	6.1	5.6	4.8	3.9

4.3. The Economic Viability of Solar PV Power Generation System

An off-grid solar PV system is proposed in the study to provide electricity to rural households in the Sindh province. In Table 5, the simulation of the parameters has been employed and provided by [60]. Based on Equations (7)–(11), it is identified that the PV module area is 1.2 m², whereas maximum voltage and current are 26.3 V and 7.61 A. The solar PV system can be used for the electrification of one household, having a production capacity of 200 W or less [61]. Therefore, for a solar panel of 200 W with a 140 Ah/12 V battery is appropriate for the load of one household. Moreover, the conversion efficiency of a solar panel is 16%. Maximum electricity is produced in all of the selected rural regions from April to June, however, due to monsoon season, a slight decline is observed from July to October in the rural regions of Sindh. The cost specifications for the off-grid solar PV system are shown in Table 5. It was identified using Equation (12), that the levelized cost of energy (LCOE) of the proposed off-grid solar PV system is PKR 6.87/kWh, however, the electricity cost from the conventional energy sources is PKR 20.79/kWh [60]. Thus, electricity produced by the solar PV system saves each household approximately PKR 13.92 per kWh.

Table 5. Parameters employed in the study.

Parameter	Unit	Value
Panel area	m ²	1.2
Max: power current	A	7.61
Max: power voltage	V	26.3
PV panel power rating	WP	200
Ambient temperature	°C	20
Panel referenced temperature	°C	25
Panel referenced efficiency	%	16
Solar radiation for NOM	W/m ²	800
PV panel life	Year	25
Panel capital cost	PKR/WP	110
Battery efficiency	%	85
Battery cost	PKR/Ah	120
O/M cost	% of the total cost	4
Discount rate	%	9
Battery duration	Year	5

4.4. CO₂ Emissions Mitigation from the Solar PV Power Generation System

A 20 kW diesel generator produces the electricity of 4 kWh/liter. The annual demand of the electricity for the household mentioned above is 160 kWh, so the diesel generator would consume a total of 41.43 L/year. Therefore, based on Equation (14), as per household, the proposed solar PV system could mitigate CO₂ at about 97.50 kg/year. According to the sixth population and housing census of Pakistan, there are 4,185,828 households in rural regions of Sindh [62]. If the off-grid solar PV system electrified 100% of the rural areas, then the high level of CO₂ could be mitigated annually.

5. Conclusions and Policy Recommendations

5.1. Conclusions

An off-grid solar PV system is recognized as the optimal choice to provide electricity in remote rural regions. However, it is very necessary to assess the techno-economic feasibility of the particular region for installation of an off-grid solar PV power generation system. Therefore, this study has evaluated the techno-economic feasibility of five rural regions of the Sindh province, i.e., the Panoaqil, Badin, Nawabshah, Mirpurkhas, and Kambar regions. The study also suggests that by installing the off-grid solar PV system in the above-mentioned regions it would help to mitigate the CO₂ emissions from the particular regions. The solar energy potential, solar irradiance, and optimal tilt angles of solar panels have been evaluated. For maximizing the solar energy, it was found that the output of energy could be significantly increased by varying the solar panels angle on the optimal tilt angle. The results also revealed that the off-grid solar PV system is a much cheaper option for electricity compared to other conventional electricity sources. This study identified that all five regions of the Sindh province have good potential for solar energy and are technically and economically feasible for producing electricity. Therefore, the government must plan and build a strong policy framework to install an off-grid solar system in the Sindh province. Meanwhile, this study provides key policy recommendations for the implementation of an off-grid solar PV system in the rural regions of Sindh.

5.2. Policy Recommendations

The following policy recommendations can be employed to develop an off-grid solar PV power generation system in remote rural regions of the Sindh province, Pakistan.

- The results of this study indicate that rural regions have a very good potential for solar-based electricity generation. Therefore, off-grid solar PV rural programs must be started with critical

action plans and strategies and the concerned authorities must formulate planning and policies to implement such projects.

- According to the investigation, all of the selected regions have suitable solar energy potential to generate off-grid solar PV electricity. However, the Nawabshah is the most favorable due to its higher solar energy potential. Also, the geographical location of Nawabshah is technically and economically the best option for generating PV electricity.
- As the review of the existing scientific studies and government policies indicate, lack of supportive policies and political will are the main hurdles in the deployment of solar electricity generation systems in rural areas of the country [63,64].
- It is suggested that supportive policies must be planned for stakeholders so that stakeholders can easily invest in rural regions for developing a solar PV power generation system.
- The financial constraints due to poverty and a huge budget deficit are also recognized as another hurdle in the deployment of the solar PV system. Therefore, the government tries to ensure the availability of micro-financing projects which may aid rural communities to install an off-grid solar PV system.
- The policy framework should be formulated by giving high preference to a renewable-based solar power system instead of the conventional power generation system.
- The upfront cost of a solar PV system must be minimized, so that rural communities install and electrify with a solar PV system.
- The quality standards should be taken into account for the off-grid solar PV system.
- It is important that householders should be given loans and subsidies to utilize solar PV power generation systems at the domestic level.
- Educate people by organizing training and campaigns about the drawback associated with conventional energy and make them aware of the advantages related to the deployment of solar energy.
- Priority must be given to the local communities and train them to install, operate, and maintain the solar PV system.

5.3. Limitations of the Current Study and Future Research Direction

This study has considered only five particular regions of Sindh province, thus the results of the study are not feasible for other regions of Sindh and other provinces of Pakistan. Therefore, the techno-economic feasibility analysis must be carried out for other regions to identify solar power potential. In the future, the hybrid renewable energy system, solar and wind, can be developed in the potential regions of Pakistan because the hybrid renewable energy system is a more reliable and effective source of energy. The hybrid solar–wind energy system shall be employed in the remote rural regions of Pakistan to make them independent of grids. The government can play a pivotal role to end the energy crisis by facilitating rural regions with such a hybrid energy system.

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