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Harnessing photovoltaic solar power in rural regions: A case study of Tehsil Saleh Pat, Sindh, Pakistan

Kırsal bölgelerde fotovoltaik güneş enerjisi kullanımı: Tehsil Saleh Pat, Sindh, Pakistan durum çalışması

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Harnessing Photovoltaic Solar Power in Rural Regions: A Case Study of Tehsil Saleh Pat, Sindh, Pakistan

Highlights

- *Assessing the Potential of Solar Energy*
- *Optimization of plane tilt and orientation ensures the most efficient arrangement*
- *Cost of Electricity Levelization*
- *Carbon Dioxide Emission Reduction via Solar PV Systems*
- *This report makes critical policy recommendations to assist the development of off-grid solar PV systems*

Graphical Abstract

PVsyst tool was used extensively in this study to calculate/simulate power generation and to design of the PV system. The precise computational methodology employed with data containing weather information on an hourly basis, details regarding the project, solar energy exposure, shadow obstructions, simulation of power generation, etc.

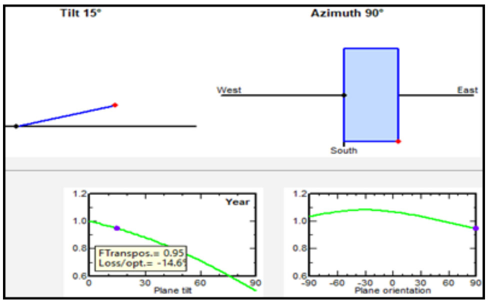

Figure. 4 Optimization of the tilt and azimuth angles in PVsyst

Aim

It is essential to have appropriate policies for generating solar PV power to ensure that electricity reaches rural areas. This study aims to investigate the energy usage patterns in rural regions, exploring both beneficiaries and non-beneficiaries of solar projects.

Design & Methodology

Data collection extended to evaluating the performance of an existing solar power facility in Gagrawara, Sindh, boasting an 8.6 kW power rating. The research included the analysis of extensive data on the solar system's performance and weather conditions over the years. We demonstrated a standard assumption of 30 degrees was adopted to ensure a more cautious and conservative approach for this case study.

Originality

The study conducts a thorough examination, examining crucial aspects such as solar energy potential, solar irradiance characteristics particular to the location, and identifying the best angles for putting solar panels.

Findings

Adjusting the angle of solar panels to the ideal tilt angle was shown to greatly improve energy production while optimizing solar energy consumption. The findings also highlighted that using an off-grid solar PV system is significantly more cost-effective for generating power than traditional methods.

Conclusion

As a result, the government must plan and build a solid policy framework to encourage the installation of off-grid solar systems across Sindh

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Harnessing Photovoltaic Solar Power in Rural Regions: A Case Study of Tehsil Saleh Pat, Sindh, Pakistan

Research Article

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ABSTRACT

The primary objective of this research is to assess the viability and effectiveness of solar energy in rural areas, with a specific focus on Tehsil Saleh Pat, Goth Gagrawara, District Sukkur, Sindh, Pakistan. The study aims to understand the perception of the community towards a solar installation and delve into their opinions. This study aims to investigate the energy usage patterns in rural regions, exploring both beneficiaries and non-beneficiaries of solar projects. Data collection also extended to evaluating the performance of an existing solar power facility in Gagrawara, Sindh, boasting an 8.6 kW power rating. The research included the analysis of extensive data on the solar system's performance and weather conditions over the years. The study also presents an evaluation of the performance of the 8.6 kW solar power facility in Gagrawara, Sindh, providing valuable insights for the solar energy company operating in the region. We demonstrated a standard assumption of 30 degrees was adopted to ensure a more cautious and conservative approach for this case study. This research contributes to the originality of the field by providing a focused examination of the practical application and perception of solar energy in rural Sindh. Furthermore, the assessment of an existing solar power facility's performance contributes valuable, real-world data to the solar energy sector.

Keywords: Solar energy, rural areas, community perception, energy usage patterns, solar installation, solar power facility, performance evaluation.

Kırsal Bölgelerde Fotovoltaik Güneş Enerjisi Kullanımı: Tehsil Saleh Pat, Sindh, Pakistan Durum Çalışması

ÖZ

Bu araştırmanın temel amacı, Tehsil Saleh Pat, Goth Gagrawara, Sukkur Bölgesi, Sindh, Pakistan'a özel olarak odaklanarak kırsal alanlarda güneş enerjisinin uygulanabilirliğini ve etkinliğini değerlendirmektir. Çalışma, topluluğun güneş kurulumlarına yönelik mevcut algı ve görüşlerini incelemeyi amaçlamaktadır Ayrıca araştırma, kırsal bölgelerdeki enerji kullanım modellerini araştırmayı, güneş enerjisi projelerinden hem faydalananları hem de faydalanmayanları keşfetmeyi amaçlamaktadır. Veri toplama aynı zamanda Gagrawara, Sindh'de 8,6 kW güç derecesine sahip mevcut bir güneş enerjisi tesisinin performansının değerlendirilmesini de kapsayacak şekilde genişletilerek güneş sisteminin performansı ve yıllar içindeki hava koşulları hakkında kapsamlı verilerin analizini içermektedir. Çalışma ayrıca, bölgede faaliyet gösteren güneş enerjisi şirketi için değerli bilgiler sunan 8.6 kW güneş enerjisi tesisinin performansını da değerlendirmektedir. Bu vaka çalışması için daha hassas ve denemiş bir yaklaşım sağlamak amacıyla 30 derece standart bir varsayım kullanılmaktadır. Bu araştırma, kırsal Sindh'de güneş enerjisinin pratik uygulaması ve algısının odaklı bir incelemesini sunarak alandaki özgünlüğe katkıda bulunmaktadır. Ayrıca, mevcut bir güneş enerjisi tesisinin performansının değerli, gerçek dünya verilerine katkı sağladığı bir değerlendirme sunmaktadır.

Anahtar Kelimeler: Güneş enerjisi, kırsal alanlar, toplum algısı, enerji kullanım şekilleri, güneş enerjisi kurulumu, güneş enerjisi tesisi, performans değerlendirmesi.

1. INTRODUCTION

Electricity is critical to a country's economic/environmental/social development. It is frequently regarded as one of humanity's greatest inventions, bringing significant improvements to our lives and society. Surprisingly, over 1 billion people worldwide still lack access to energy. Most of these individuals live in rural Sub-Saharan Africa and South Asia [1]. In the same vein, a significant portion of Pakistan's population resides in rural areas, with most lacking access to electricity. Pakistan, a developing country, is confronted with economic, environmental, and social challenges that have increased the demand for additional power. The country currently requires 25,000

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Megawatts (MW), a figure that is predicted to rise to 40,000 MW by 2030. In contrast, the electrical supply remains about 17,000 MW, resulting in an 8000 MW electricity shortage in the country [2]. As a result, there are power outages in both urban and rural areas from 12 to 18 hours every day.

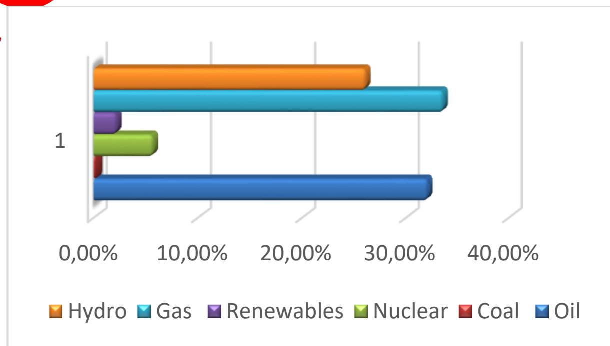
One of the primary benefits of solar PV is its long-term viability and low carbon impact. Solar PV differs from fossil fuels in that it emits no greenhouse gases or other harmful elements, making it an important component in the fight against climate change. Furthermore, it may be put in a variety of settings and provide electricity to remote areas that lack grid connections, making it a viable choice for guaranteeing energy security and resilience. Solar PVs can assist in stabilizing electricity prices by reducing demand for volatile fossil fuels and geopolitical tensions. However, there are several potential disadvantages to solar PV. The initial cost of installing solar panels can be high, though costs have reduced significantly over the last decade. The fluctuation of solar PV is another barrier to overcome, as the amount of electricity generated by the panels changes with the availability of sunshine. Energy storage devices, which allow extra electricity to be stored and used later when sunshine is rare, can help to alleviate this in part. Solar PV is one of the fastest-growing renewable energy sources, with installations increasing all over the world. Solar energy with an installed capacity of 1053 GW in 2022 is the second most installed renewable energy technology [3]. It is essential to have appropriate policies for generating solar PV power to ensure that electricity reaches rural areas. Thorough research is required to assess the solar energy usage in certain places and determine their economic feasibility. In future, there should be additional effective solutions like solar-assisted air conditioning systems [4] or solar assisted heat pump systems for heating residences [5]. So far as the authors are aware, no such study has been conducted for the Tehsil Saleh Pat in the Sindh province.

Figure 1. World Economic Center of gravity (Source. https://www.freeworldmaps.net/asia/pakistan/sindh/#google_vignette)

Its strategic importance stems from its wide coastline, as shown in the Figure 1. Karachi Port, as a critical component, provides the most cost-effective and direct route for freight transfer to adjacent countries. The port's geographical location is critical for attracting international investment and fostering development efforts that considerably increase business and economic growth [6]. As a result, the ongoing developments have caused a rapid increase in electricity demand in Sindh.

Industries as well as consumers should plan some mechanisms to generate energy by utilizing limited resources with a perspective of hybrid energy technologies [7]. The energy demand is constantly increasing, resulting in a substantial shortfall in electricity across the country. This shortfall is especially severe in Sindh. This problem is exacerbated in Sindh's distant rural areas, where electricity is inaccessible for extended periods. Furthermore, power consumption in these rural areas is very low, which is exacerbated by the significant distance between transmission lines and these communities. As a result, it is viewed as a cost-related issue [8]. Pakistan has an estimated solar energy potential of 2900 GW, although this renewable resource is underutilized [9]. The mix of electricity generation in 2015 as shown in Table 1, with gas accounting for 33.6%, nuclear accounting for 5.7%, hydropower accounting for 26.1%, renewable energy accounting for 2.2%, oil accounting for 32.1%, and coal accounting for 0.2% [10], respectively.

Table 1. Electricity Generation Mix by Source



Pakistan had previously undertaken several solar PV projects, the first of which dates back to the 1980s. This initial endeavor, however, did not succeed due to managerial and technical shortcomings. This original initiative, however, did not succeed due to administrative and technical deficiencies [11]. As a result, the country did not actively seek or advocate for any renewable energy projects until 2005. To accelerate the advancement and promotion of renewable energy sources for electricity generation, two bodies were established in 2006: the Alternative Energy Development Board (AEBD) and the Pakistan Commission of Renewable Energy Technology (PCRET). The goal of AEBD is to install solar PV systems in 906 rural households [12]. Furthermore, the government increasingly recognizes the benefits of a solar power framework in supporting socioeconomic progress and safeguarding the environment in sun energy-rich locations (Table 2).

individual community leaders hampered the movement, presumably for personal advantage.

Table 2. Solar information about five areas within Sindh, Pakistan [12]

Period	Sukkur Region		Badin Region		Nawabshah Region		Mirpurkhas Region		Kumbar Region	
	Daily Solar Irradiation (kWh/m2/day	Earth Temperetature (Celsius)	Daily Solar Irradiation (kWh/m2/day	Earth Temperetature (Celsius)	Daily Solar Irradiation (kWh/m2/day	Earth Temperetature (Celsius)	Daily Solar Irradiation (kWh/m2/day	Earth Temperetature (Celsius)	Daily Solar Irradiation (kWh/m2/day	Earth Temperetature (Celsius)
January	4.10	14.65	4.49	16.92	4.20	14.60	4.41	15.90	3.73	14.70
Feburary	4.97	18.36	5.25	21.03	5.09	18.30	5.06	20.03	4.89	19.26
March	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
August	5.97	39.28	5.14	34.38	5.91	37.44	5.49	36.73	6.00	39.40
September	5.86	39.28	5.47	33.45	5.82	35.75	5.58	34.95	5.82	36.01
October	4.95	30.42	4.97	31.47	5.03	30.88	5.00	31.51	5.47	30.02
November	4.00	22.97	4.31	26.55	4.13	24.37	4.15	25.67	4.22	21.03
December	3.70	16.08	4.02	19.24	3.80	16.90	3.90	18.48	3.68	15.23
Avarage Annual Values	**5.46**	**30.07**	**5.39**	**29.53**	**5.49**	**29.45**	**5.41**	**30.06**	**5.48**	**29.71**

1.1. Assessing the Potential of Solar Energy

The data above reflect the average sun irradiation values in various locations of Sindh province. These locations' optimal average peak sun hours have also been estimated. Table 3 depicts the entire potential for employing solar PV systems in five locations of Pakistan's Sindh province, including Sukkur, Badin, Nawabshah, Mirpurkhas, and Kambar. It emphasizes the tremendous potential for solar PV power generating systems in these locations. For example, with an average solar irradiation of roughly 5.49 kWh/m2/day in Nawabshah and 5.48 kWh/m2/day in Kambar, the projected yearly generation potential is 1503 kWh/kWp and 1500 kWh/kWp, respectively. Furthermore, in each Sindh area, the daily energy production from a solar PV panel surpasses 500 Wh, possibly satisfying main home energy consumption demands.

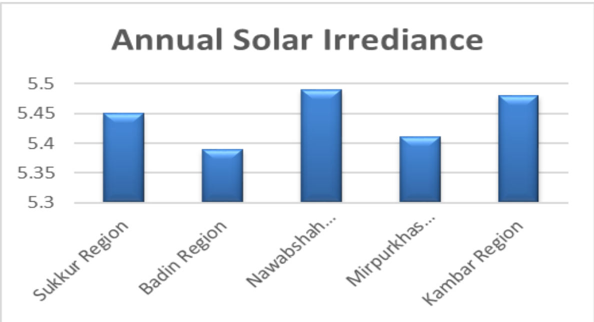
1.2. Power Delivery in Gagrawara via Electricity:

Gagrawara, a rural area in Sukkur District, confronts considerable problems despite signs of its potential. Because of its remote location from the national electricity infrastructure, there are currently no plans to link the village with the grid. According to local reports, the national grid finishes around 50 to 55 kilometers away, providing a significant distance barrier.

In 2013, from local information, a great development occurred when the village obtained a tiny electrical facility, courtesy of the Member of Parliament, aimed at harvesting wind energy. The Tiny Project, which was conducted in 12 to 15 village homes, attempted to brighten critical locations such as stores. Unfortunately, due to the project's inadequate power production, its duration was restricted. According to local reports,

Prior to the wind energy venture, a financially secure individual in the community used a generator to supply electricity to multiple families. This electricity supplier prioritized sales over customer happiness, offering, among other things, a single bulb connection for RS (Indian Rupee). 150 for six hours of lights and RS. 300 for two bulbs for the same time. Customers were required to pay for the daily six-hour service, but the contractor had exclusive access to extra power functions such as phone charging. Other consumers were given additional fees and were not allowed to charge their phones at home (Table 4).

Table 3: Employing solar PV systems in five locations



2. MATERIAL and METHOD

PVsyst tool was used extensively in this study to calculate/simulate power generation and to design of the PV system. One of its key advantages is its ability to not only perform extensive research, design, and data analysis on grid-connected, off-grid, and pumping systems, but also to provide a complete PV system database and compatible to the other solar energy usage tools. We used the program to choose alternative PV components from its product database after entering location and load data, allowing automated simulation of power generation. The complete computation method is depicted in Figure 2.

Table 4: The services offered to the residents of Gagrawara along with price

Appliances	*Single Bulb*	*2 Bulb with one Charging socket*	*Single Bulb with TV Connection*	*2 Bulb with a TV Connection*	*Fridge Connection*	*Single bulb and fridge Connection*
Connection Cost for 6 Hours	150 RS	300 RS	350 RS	400 RS	300 RS	400 RS
Connection Cost for 12 Hours	250 RS	500 RS	550 RS	800 RS	500 RS	800 RS
Connection Cost for per day	1000 RS	1400 RS	1500 RS	2500 RS	1000 RS	1500 RS
Connection Cost for 1 Week	4000 RS	5500 RS	6000 RS	7000 RS	5000 RS	6000 RS

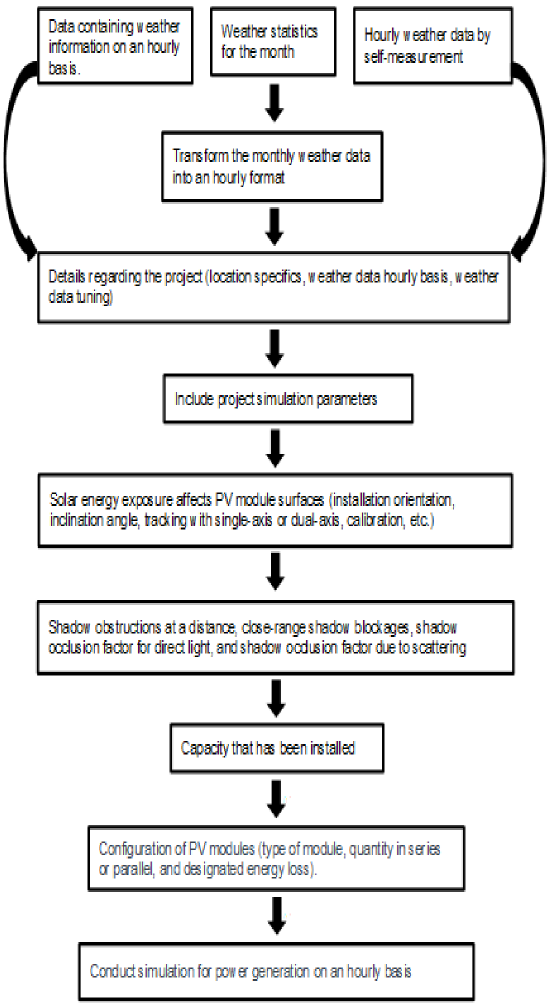


Figure 2. The precise computational methodology employed by the PVsyst software [25]

Figure 3 depicts the 3D representation of the PV system for the near shading analysis in PVsyst tool. Google Earth was used to determine the azimuth angles of the buildings and PV array, as well as the size of shadowing objects. It should be noted that the height and precise positioning of shade items are estimates, as the information acquired from Google Earth is an estimate.

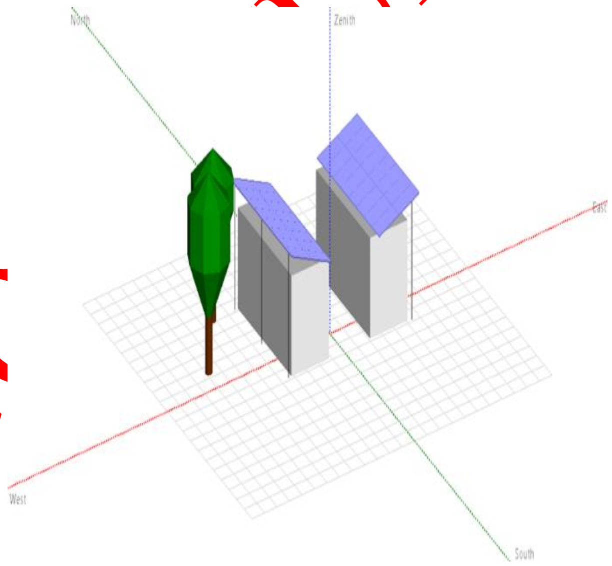


Figure 3. A 3D model of the PV array

2.1. Parameters of PV System

Table 5 shows the tilt and azimuth angle characteristics for the Gagrawara system, which were determined based on the current system's true values. Figure 4 shows how PVsyst's optimization of plane tilt and orientation ensures the most efficient arrangement

Table 5. PVsyst orientation settings for Gagrawara were chosen

Field Type	*Tilt Angle*	*Azimuth Angle*
	15°	-90°
Several Orientation	15°	90°

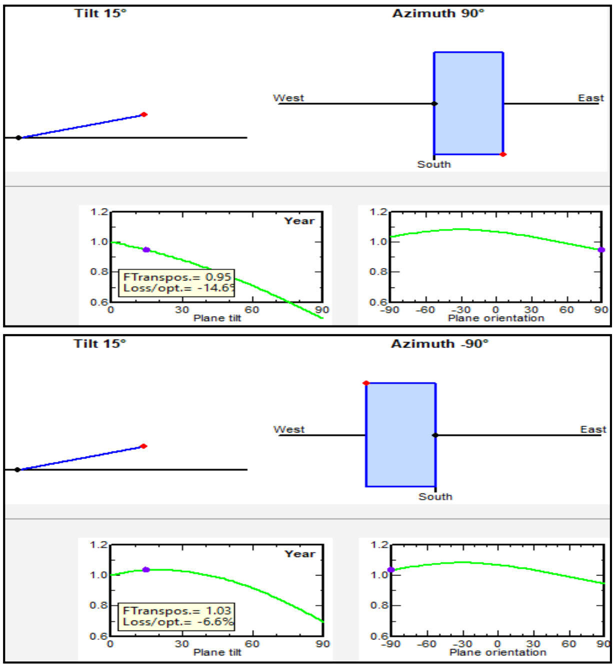


Figure 4. Optimization of the tilt and azimuth angles in PVsyst

2.2. PV Array

Pentra Energy built a PV system on an east-west facing rooftop in Gagrawara in January 2023. The system consists of 32 Q.POWER-G5 270 PV modules and an RPI M8A Solar Inverter (Table 6). The modules are evenly distributed between the east and west sides, with 16 modules linked to each. The installed PV power is calculated 8.6 kWp totally, split into two lines of 16 modules each. For effective power control, the inverter has two Maximum Power Point Trackers (MPPTs).

Table 6. PV System parameters

Total PV System Power	8.6 kWp
Modules:	
PV Module	Q.POWER-G5 270 X 32 Module
PV Module Manufacturer	Hanwha Q Cells
MPP Voltage	31.1 V
MPP Current	8.7A
Inverter:	
Inverter	Solar Inverter RPI M8A
Inverter Manufacturer	Delta Energy
Nominal AC Power	8.0 kW
Maximum AC Power	8.40 kW
Nominal AC Current	11.60 A
Maximum AC Current	13.00 A

2.3. Evaluating Solar Power Capabilities

The average peak solar hours are used to calculate the solar irradiation in a certain location, indicating the highest sunshine duration [24]. The peak solar irradiation is 1 kW/m2, which corresponds to the daily sun irradiation defined as kWh/m2.

By assuming an average sun irradiation of 5.45 kWh/m2/day in the Sukkur region, for a 100 Wp solar array, the daily solar array production is predicted to be 68 Wh. Consequently, Equation (1) is used to determine the yearly energy production, which serves as a way of monitoring the PV system's performance [13].

$$\text{Annual energy output}\left(\frac{kWh}{kWp}\right) = \text{GI Irradiation}\left(\frac{kWh/m^2}{year}\right) \text{ x Performance Ratio} \quad (1)$$

whereas, GI is Global Inplane (kWh/m^2)/year).

2.4. Determining the Optimal Tilt Angle and Measuring Solar Irradiance

Solar irradiation is typically measured on a horizontal surface within a defined region. Solar panels receive a lot of energy from direct sunlight. As a result, tilting solar panels is a common strategy to increase irradiation efficiency, aiming to maximize solar energy production by establishing the best tilt angle [14]. Solar trackers are the most effective way to increase energy production since they alter panel angles for optimal efficiency. However, these trackers are expensive and require a lot of energy to track [15]. Despite its versatility, solar trackers are not suitable for installation in distant rural locations. As a result, manually altering solar panel tilt angles is more convenient and cost-effective than installing solar trackers [16].

Direct sunlight is received on an inclined horizontal surface, with some irradiation dispersed and absorbed. Certain rays are also reflected off the earth. As a result, the total horizontal irradiance (Ig) on a titled surface is expressed as follows:

$$I_g^t = I_b^t + I_r^t + I_d^t \quad (2)$$

whereas, I_g^t is a horizontal irradiance, I_d^t diffuse irradiance, I_r^t reflected rays, and I_b^t direct beam of solar energy on tilted surface.

Assuming G_b is the ratio of average daily direct beam irradiation on a horizontal surface to average daily direct beam irradiation on a titled surface, the formula for I_b^t can be changed as follows:

$$I_b^t = I_b \, G_b \quad (3)$$

The Geometric parameter G_b changes depending on latitude, the declination angle, horizontal tilt, and surface azimuth. To compute G_b,

$$G_b = \frac{\cos(L_1 - T_1) \cdot \cos D_{sh} \cdot \sin i_{ss} + i_{ss} \cdot \sin(L_1 - T_1) \cdot \sin D_{sh}}{\cos L_1 \cdot \cos D_{sh} \cdot \sin i_{ss} + i_{ss} \cdot \sin L_1 D_{sh}} \quad (4)$$

whereas,

L_1 = Latitude

T_1 = Tilt angle

D_{sh} = Declining angles

i_{ss} = Sunshine hours

To clarify consider an isotropic distribution of diffused irradiation as an example. This refers to the distribution of diffuse irradiation on the horizontal surface as well as the angle of horizontal tilt, which is expressed by λ:

$$I_d^t = I_d \frac{(\cos(\lambda) + 1)}{2} \quad (5)$$

The albedo factor (ω) is a characteristic used in this context. The albedo factor normally varies between 0.1 and 0.9 [17]. As a result, the computation for the reflected beam is as follows:

$$I_r^t = \omega \, (I_b + I_d) \frac{(-\cos(\lambda) + 1)}{2} \quad (6)$$

2.5. Cost of Electricity Levelization

The cost of electricity levelization is a vital indicator for assessing and comparing the costs of generating electricity from various technologies and sources. It assists in ranking solutions based on cost-effectiveness [18].

$$\text{Cost of Electricity Level.} = \frac{\sum_{\alpha=1}^{n} \frac{I_\alpha + M_\alpha + F_\alpha}{(1+d)^\alpha}}{\sum_{\alpha=1}^{n} \frac{e_\alpha}{(1+d)^\alpha}} \quad (7)$$

Whereas,

I_α = Investment Cost

M_α = Maintenance Cost

F_α = Fuel Cost

α = Year

e_α = Amount of electricity generated in kWh

d = Disconnected Rate

n = The working Life Duration

In addition to photovoltaic (PV) modules, inverters and batteries are critical components of distributed PV systems. Table 7 summarizes the current economic values and major technical issues connected with these essential system components [19]. It is vital to note that other PV system components, such as wiring, control systems, and refurbishing costs, have not been included in the cost evaluation given in the table.

Table 7. The financial implications and technical specifications of each component

Components	*Economic Cost PKR/kW*	*Technical Parameter*
PV System	100000 – 300000 / kW	Utilizes monocrystalline or polycrystalline panels (15%-20%) efficiency.
PV Panel	30000 – 60000 / kW	Typically rated 250W – 400W
Batteries	15000 – 30000 / kWh	Utilizes lead acid or Lithium-ion capacity based on storage need.
Inverters	20000- 50000 / unit	Convert DC to AC.

2.6. Carbon Dioxide Emission Reduction via Solar PV Systems:

Solar PV systems capture clean energy from the sun, providing an option for reducing greenhouse gas emissions. The government's installation of these systems in rural regions might remove reliance on high-carbon diesel generators with a negative impact on the environment and human health. When solar PV systems produce little to no CO_2 during operation, it is critical to recognize their emissions throughout the production process [20]. Addressing CO_2 emissions, a significant worldwide challenge, is caused by human activities such as the use of fossil fuels, which directly influences unfavorable climate consequences [21]. As a result, replacing diesel generators with solar PV systems has the potential to significantly reduce CO_2 emissions.

As a result, using a solar PV system instead of a diesel generator can help to minimize CO_2 emissions. A solar PV system determines the quantification of reduced CO_2 emissions and saved diesel fuel, denoted as Q_k [22].

$$Q_k = S_{pv} x f_n \quad (8)$$

f_n denotes the amount of fuel necessary for a diesel generator to create one kWh of electricity and S_{pv} (kWh) is the potential of solar PV to produce electricity. The decrease in CO_2 emissions for the solar PV systems is indicated as D_e in the supplied equation [23, 24].

$$D_e = S_{pv} x (C_n - C_{pv}) \quad (9)$$

C_n is the amount of carbon in kilograms (kg) necessary for a diesel generator to create 1 kWh of electricity, whereas C_{pv} is the amount of carbon in kilograms (kg) required for a solar PV system to generate 1 kWh of energy.

Table 8. Estimated Electricity Consumption for a rural Household

Appliances	*Number Of Use*	*Working Hours*	*Watts ratting*	*Total Load (Wh)*
LED Lights	3	6	12	216
Charging Slots	2	3	5	30
Ceiling Fan	1	14	12	168
Pedestal Fan	1	7	12	84
			Total=	**498 (Wh)**

In Table 8, the total electricity produced with this kind of solar PV and the total electricity demanded is given by;

$$\text{Difference of electricity} = \sum_{i=1}^{365} (P_p - P_d) \quad (10)$$

Here i, P_p, and P_d are the day of the year, total electricity produced and total electricity demanded, respectively.

$$BRA = \frac{\text{BA}}{f} \quad (11)$$

The availability factor (η_a) is defined as the proportion of the effective surface occupied by solar PV panels installed on the roof over the full building area to calculate the effective PV-available roof area (PVRA) from the rural building area (BRA) [25].

$$\eta a = \frac{PVRA}{\text{BRA}} \quad (12)$$

The addition of the availability factor accounts for constraints in utilizing the full roof space for PV system installation owing to several influencing variables, namely:

1. Shadows cast by surrounding objects such as buildings, trees, or structures on the roof itself.

2. Use of the roof surface for other uses: hosting additional home utilities such as exterior air-conditioning units.

3. Setting aside a section of the space for personnel control and maintenance of the PV modules.

2.7. Optimal Installation of PV Modules on Sloped Roofs

Sloped roofs are prevalent in the rural areas of Pakistan, mainly due to the country's high levels of rainfall, which make them effective for proper drainage. To install photovoltaic (PV) modules on these roofs, it's crucial to align them parallel to the roof's incline. The pitch of these roofs can vary between 25 to 35 degrees, but for this study, a standard assumption of 30 degrees was adopted to ensure a more cautious and conservative approach to analyzing the data (Figure 5). By strategically placing PV modules on the southern, southeastern, southwestern, eastern, and western sides of these sloping roofs, there are notable advantages to be gained. This selective placement allows for optimal exposure to sunlight, maximizing the energy-generating potential of the PV system. Consequently, when calculating the area conversion factor for PV module installation, the focus is placed on only one side of the sloped roof, considering the most advantageous orientation for solar energy capture and efficiency. The following formula was created to compute the installable area of PV modules generating energy on certain sloping roofs.

$$E_g = \frac{\text{BFA}}{\cos \Theta} \times \eta_b \times \eta_a \times (1 - \eta_p) \quad (13)$$

where the slop of the roof is represented as Θ and the house's area conversion factor is η_b while η_a and η_p are the availability factor and the panel loss factor, respectively.

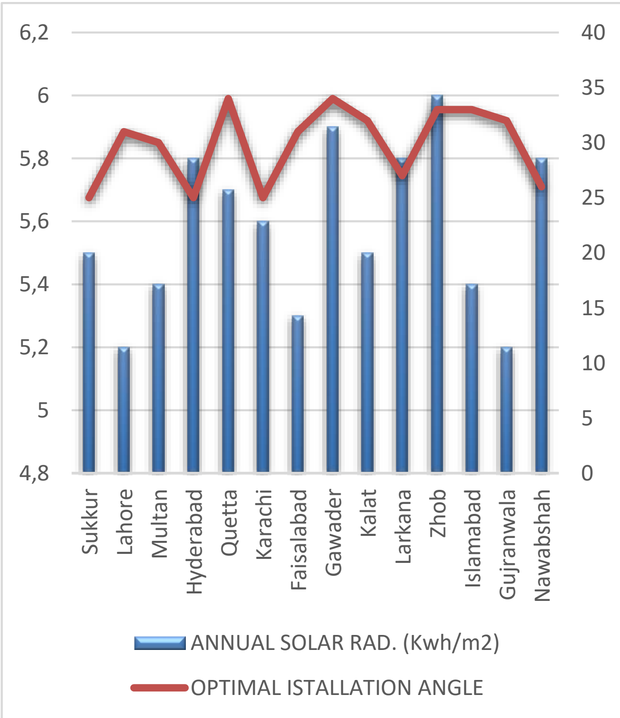


Figure 5. Comparison between Optimal Angle and Annual Solar Radiation

2.8. Small-Scale Solar Power Plant in Gagrawara Village

A solar power plant on a small scale has been established in Gagrawara village as shown in Figure 6 to generate electricity using solar energy. A mini-grid solar project has been established in Gagrawara village to provide electricity to a minimum of 60-70 households as per its design. The solar power plant has a maximum capacity of 8.6 kW, which is generated through the installation of 32 solar panels, each with a rating of 24 V, 8 A and a peak power output of 270 Watt. Following the solar panels, a power bank has been installed comprising of 120 batteries, with each battery rated at 2 V and 1000 Ah. The batteries have been connected both in series and parallel to create a 48 V DC bus-bar.

Figure 6. In Gagrawara, solar panels have been set up to form a mini- power plant that generates and distributes electricity

Gagrawara has recently installed a solar panel system that plays a crucial role in powering the village's electricity needs. The solar panels charge battery banks through charger controllers with a rating of 48 V and 140 A DC. The stored energy in the battery bank is then used to generate electricity through an inverter that converts DC to AC. This inverter has a rating of 48 V DC input and 230 V AC output, with a capacity of 12 kVA. Additionally, powerhouses at this scale should contain switch gears and protection, charger controller, inverter for each AC and DC sides to satisfy the safety conditions. With this setup, the village can now rely on a steady and sustainable source of electricity (Figure 7).

Figure 4. The powerhouse installed in Gagrawara

3. RESULTS AND DISCUSSION

Conclusion:

In remote rural regions, the provision of electricity remains a pressing challenge, and among the various available options, an off-grid solar photovoltaic (PV) system emerges as a promising and practical solution. However, establishing such a system necessitates a detailed assessment of its technological capabilities as well as its economic viability within a given geographic setting. As a result, this research was carried out to thoroughly examine the techno-economic feasibility of establishing an off-grid solar PV power generating infrastructure in the Sukkur district of Sindh. The evaluation of the research extends beyond just analyzing the feasibility of a solar PV system. It adopts a broader perspective, taking into account environmental conservation activities. Implementing the recommended off-grid solar PV system in Sukkur and surrounding areas has the potential to significantly reduce CO_2 emissions, marking an important step toward environmental sustainability.

The study conducts a thorough examination, examining crucial aspects such as solar energy potential, solar irradiance characteristics particular to the location, and identifying the best angles for putting solar panels. These aspects form the foundation of the techno-economic analysis, offering a comprehensive knowledge of the feasibility and possible advantages of implementing an off-grid solar PV system in Sukkur, Sindh. Adjusting the angle of solar panels to the ideal tilt angle was shown to greatly improve energy production while optimizing solar energy consumption. The findings also highlighted that using an off-grid solar PV system is significantly more cost-effective for generating power than traditional methods. This study emphasizes the significant solar energy potential in Sindh province, confirming its technological and economic viability for power generation. As a result, the government must plan and build a solid policy framework to encourage the installation of off-grid solar systems across Sindh. Simultaneously, this report makes critical policy recommendations to assist the development of off-grid solar PV systems in Sindh's rural areas.

Limitation:

We need to discuss about the research's limitations. It only focused at Sukkur, especially a hamlet in Sindh called Gagrawara. As a result, what they discovered may not be applicable in other parts of Pakistan. Future studies should look at other sections of the country to discover if off-grid solar power is available there as well. They might also consider developing systems that employ both wind and sun electricity. These kinds of devices might assist rural communities in becoming self-sufficient from the main power grid. The government must also intervene. They can address Pakistan's energy difficulties by supporting these new rural networks. This study only looked at total additional energy and energy required, which is a drawback. We'd receive more comprehensive data if we tracked how much energy we used and produced every hour. However, in this study, we only utilized average data to determine how much power we consumed and generated. That's a significant omission. In the future, it will be critical to examine how power supply and demand fluctuate hour by hour in order to have a better understanding.

AUTHOR CONTRIBUTIONS

Yusuf ÖZTÜRK: Literature Review, Conceptualization, Methodology, Writing Original Draft, Review and Editing

Muhammad Nouman ABBASI: Literature Review, Modelling, Data Curation, Analysis, Writing Original Draft.

CONFLICT OF INTERESTS

No potential conflict of interest was declared by the authors.

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COMPLIANCE WITH ETHICAL STANDARDS

It was declared by the authors that the tools and methods used in the study do not require the permission of the Ethics Committee.

ETHİCAL STATEMENT

It was declared by the author(s) that scientific and ethical principles have been followed in this study and all the sources used have been properly cited

REFERENCES

[1] Warner, K. J., & Jones, G. A., "A population-induced renewable energy timeline in nine world regions", ***Energy Policy***, 101(August 2016), 65–76, (2017).

[2] Ur Rehman, S. A., Cai, Y., Fazal, R., Walasai, G. Das, & Mirjat, N. H., "An integrated modeling approach for forecasting long-term energy demand in Pakistan", ***Energies***, 10(11), 1–23, (2017).

[3] Pourasl, H. H., Barenji, R. V., & Khojastehnezhad, V. M., "Solar energy status in the world: A comprehensive review", ***Energy Reports***, 10, 3474-3493, (2023).

[4] Akyüz, A., Yıldırım, R., Gungor, A., & Tuncer, A. D., "Experimental investigation of a solar-assisted air conditioning system: Energy and life cycle climate performance analysis", ***Thermal Science and Engineering Progress***, 43, 101960, (2023).

[5] Sezen, K., & Gungor, A., "Comparison of solar assisted heat pump systems for heating residences: A review", ***Solar Energy***, 249, 424-445, (2023).

[6] Kazmi, S. A. Z., Naaranoja, M., & Kantola, J., "Reviewing Pakistan's Investment Potential as a Foreign Investor", ***Procedia - Social and Behavioral Sciences***, 235(October), 611–617, (2016).

[7] Naz, M. Y., Bou-Rabee, M., Shukrullah, S., Ghaffar, A., Gungor, A., & Sulaiman, S. A., "A review of hybrid energy technologies tenets, controls and combinational strategies", ***Cleaner Engineering and Technology***, 5, 100340, (2021).

[8] Ghafoor, A., & Munir, A., "Design and economics analysis of an off-grid PV system for household electrification", ***Renewable and Sustainable Energy Reviews***, 42, 496–502, (2015).

[9] Iqbal, W., Yumei, H., Abbas, Q., Hafeez, M., Mohsin, M., Fatima, A., Jamali, M. A., Jamali, M., Siyal, A., & Sohail, N., "Assessment of wind energy potential for the production of renewable hydrogen in Sindh Province of Pakistan", ***Processes***, 7(4), (2019).

[10] Harijan, K., Uqaili, M. A., & Mirza, U. K., "Assessment of Solar PV Power Generation Potential in Pakistan", ***Journal of Clean Energy Technologies***, 3(1), 54–56, (2015).

[11] Shaikh, P. H., Shaikh, F., & Mirani, M., "Solar energy: Topographical asset for Pakistan", ***Applied Solar Energy (English Translation of Geliotekhnika)***, 49(1), 49–53, (2013).

[12] Xu, L., Wang, Y., Solangi, Y. A., Zameer, H., & Shah, S. A. A., “Off-grid solar PV power generation system in Sindh, Pakistan: a techno-economic feasibility analysis”, ***Processes***, 7(5), 308, (2019).

[13] Borhanazad, H., Mekhilef, S., Saidur, R., & Boroumandjazi, G., “Potential application of renewable energy for rural electrification in Malaysia”, ***Renewable Energy***, 59, 210–219, (2013).

[14] Benghanem, M., “Optimization of tilt angle for solar panel: Case study for Madinah, Saudi Arabia”, ***Applied Energy***, 88(4), 1427–1433, (2011).

[15] Barker, L., Neber, M., & Lee, H., “Design of a low-profile two-axis solar tracker”, ***Solar Energy***, 97, 569–576, (2013).

[16] Shah, S. A. A., Valasai, G. Das, Memon, A. A., Laghari, A. N., Jalbani, N. B., & Strait, J. L., “Techno-economic analysis of solar PV electricity supply to rural areas of Balochistan, Pakistan”, ***Energies***, 11(7), (2018).

[17] Kotak, Y., Gul, M. S., Muneer, T., & Ivanova, S. M., “Impact of Ground Albedo on the Performance of PV Systems and its economic analysis”, ***International Conference on Solar Radiation and Daylight SOLARIS***, April, 21–22, (2015).

[18] Baurzhan, S., & Jenkins, G. P., “Off-grid solar PV: Is it an affordable or appropriate solution for rural electrification in Sub-Saharan African countries?”, ***Renewable and Sustainable Energy Reviews***, 60, 1405–1418, (2016).

[19] Zhang, W., Zhao, Y., Huang, F., Zhong, Y., & Zhou, J., “Forecasting the energy and economic benefits of photovoltaic technology in china’s rural areas”, ***Sustainability (Switzerland),*** 13(15), (2021).

[20] 20. Jabeen, M., Umar, M., Zahid, M., Ur Rehaman, M., Batool, R., & Zaman, K., “Socio-economic prospects of solar technology utilization in Abbottabad, Pakistan”, ***Renewable and Sustainable Energy Reviews***, 39, 1164–1172, (2014).

[21] Ikram, M., Mahmoudi, A., Shah, S. Z. A., & Mohsin, M., “Forecasting number of ISO 14001 certifications of selected countries: application of even GM (1,1), DGM, and NDGM models”, ***Environmental Science and Pollution Research***, 12505–12521, (2019).

[22] Baurzhan, S., & Jenkins, G. P., “On-grid solar PV versus diesel electricity generation in sub-Saharan Africa: Economics and GHG emissions”, ***Sustainability (Switzerland)***, 9(3), (2017).

[23] Ullah, H., Kamal, I., Ali, A., & Arshad, N., “Investor focused placement and sizing of photovoltaic grid-connected systems in Pakistan”, ***Renewable Energy***, 121(2018), 460–473, (2018).

[24] Xu, L., Wang, Y., Solangi, Y. A., Zameer, H., & Shah, S. A. A., “Off-grid solar PV power generation system in Sindh, Pakistan: a techno-economic feasibility analysis”, ***Processes***, 7(5), 308, (2019).

[25] Zhang, W., Zhao, Y., Huang, F., Zhong, Y., & Zhou, J., “Forecasting the energy and economic benefits of photovoltaic technology in China’s rural areas”, ***Sustainability***, 13(15), 8408, (2021).