

DOI: [https://doi.org/10.71317/kjard.2.9\(s\).2026.625](https://doi.org/10.71317/kjard.2.9(s).2026.625)

Kashmir Journal of Academic Research and Development

Journal homepage: <https://rjsaonline.org/index.php/KJARD>

Design and Development of an Integrated Bio-Solar Hybrid Energy System for Sustainable Rural Electrification in Sindh, Pakistan

Siraj Ahmed

Department of Energy and Environment Engineering, Dawood University of Engineering and Technology, Karachi 74800, Pakistan

Email: siraj.ahmed@duet.edu.pk**Muhammad Azam Usto**

Chemical Engineering Department, Mehran University of Engineering and Technology, Jamshoro, 76062, Sindh, Pakistan

Aurangzeb Junejo

Department of Energy and Environment Engineering, Dawood University of Engineering and Technology, Karachi 74800, Pakistan

Abdul Sattar Jatoi

Chemical Engineering Department, Mehran University of Engineering and Technology, Jamshoro, 76062, Sindh, Pakistan

ARTICLE INFO**ABSTRACT****Received:**

July 31, 2026

Revised:

August 16, 2026

Accepted:

September 04, 2026

Available Online:

September 17, 2026

Keywords:

Village electrification, PV cells, Bioenergy, Hybrid energy system

Corresponding Author:**Siraj Ahmed**Email: siraj.ahmed@duet.edu.pk

Energy supply remains a significant issue for village people in Pakistan, where dependence on existing electrical system and traditional biomass fuels continues to affect energy security, household welfare, and environmental quality. Present study investigates the feasibility of a single house for off-grid bio-solar hybrid energy system for sustainable energy supply in remote area of Sindh, Pakistan, using Karani Village, District Larkana, as a representative case study. Proposed energy system integrates solar photovoltaic (PV) technology for electricity generation with a biogas subsystem utilizing locally available animal dung for cooking and thermal energy purposes. The field survey shows total connected electrical load of approximately 1,595 watts for the single house of village, with an estimated electricity consumption of approximately 9 kWh/day. Village Karani receives favorable solar resources, with an average solar irradiation of approximately 5.5 kWh/m²/day and about 6 h of sunshine/day. Based on the energy data of household assessment, decentralized configuration was designed to utilize solar PV generation for all electrical loads, while biogas was considered for cooking and thermal energy requirements of village house. Current study demonstrates that a decentralized bio-solar hybrid energy system can provide a technically feasible and environmentally sustainable option for village household energy supply in Sindh, Pakistan. Further research involving optimized PV, biogas sizing, energy-storage assessment, life-cycle assessment, pilot-scale field validation is recommended to establish the long-term technical, economic, and environmental performance of the proposed system.

Introduction

Energy is a primary driver of industrial productivity, social development, economic growth, and improvement in life standards [1,2,3]. Reliable and affordable access to energy is particularly important for village communities, where electricity is required for household activities, education, healthcare, agriculture, communication, lighting, and commercial activities [4,5]. However, the availability of a continuous and reliable energy supply remains a major challenge in many rural areas of country [4,6]. In Pakistan, increasing energy demand, dependence on fossil fuels, transmission and distribution losses, and

the higher cost of energy have created significant challenges for sustainable energy development. These challenges are particularly pronounced in rural and remote communities where extension of centralized electricity infrastructure can be technically difficult and economically expensive[7, 8,9].

Accordingly, the development and utilization of local renewable-energy resources can provide an important pathway toward improving energy security and supporting sustainable village development [10,11,12]. Pakistan's energy sector has historically depended substantially on conventional fossil-fuel resources, including natural gas, and oil, coal. Dependency on fossil fuels not only exposes the energy sector to fluctuations in fuel cost and supply-chain constraints but also contributes to atmospheric pollution, greenhouse-gas emissions, and cause of climate change [13]. Diversification of the national energy mix through indigenous available renewable resources has become increasingly important. Several research studies have acknowledged hydropower, solar, biomass, wind, and other renewable resources as promising alternatives for reducing dependence on existing energy sources and improving the long-term sustainability of Pakistan's energy system[14,15]. Pakistan possesses considerable renewable-energy potential because of its diverse geographical and climatic characteristics. Pakistan covers an area of approximately 881,913 km² and includes regions with high solar radiation, livestock production, agricultural activities and significant quantities of biomass resources [16,17]. Including the available indigenous renewable resources, solar energy has particular significance because of Pakistan's favorable solar regime.

Mostly areas of the Pakistan country receive high levels of solar irradiation and experience substantial sunshine throughout the year. Several studies have reported approximately 7–9 h/day sunshine in many regions, with more than three hundred sunny days annually under beneficial climatic conditions [18,19]. These conditions provide a suitable basis for PV electricity generation and make solar energy a promising option for decentralized electricity supply, particularly in rural areas.

Biomass represents another important renewable energy resource with considerable relevance to rural Pakistan [20]. In village areas, animal dung has traditionally been used for heating, cooking, and household energy requirements [21]. Depending on the characteristics of the available feedstock, bioenergy can be utilized through technologies such as anaerobic digestion, direct combustion, gasification, thermochemical and biochemical [22].

Present study focuses on the development of a bio-solar hybrid energy system for sustainable village energy supply in Sindh, Pakistan. The study is based on a field investigation of Karani village, including direct site visits and a structured questionnaire survey to characterize existing energy sources, household electricity, cooking, and heating requirements of village people. The collected field data are used to estimate the present and potential energy requirements of the village. In parallel, the potential contribution of locally available solar and biomass resources is assessed based on the prevailing resource conditions and their potential for energy conversion.

Research Methodology

Figure 1 demonstrates the work plan, which is to be accomplished in three stages. First Stage deals with data collection, second stage analysis of the energy resources, and third stage development and utilization of the hybrid system.

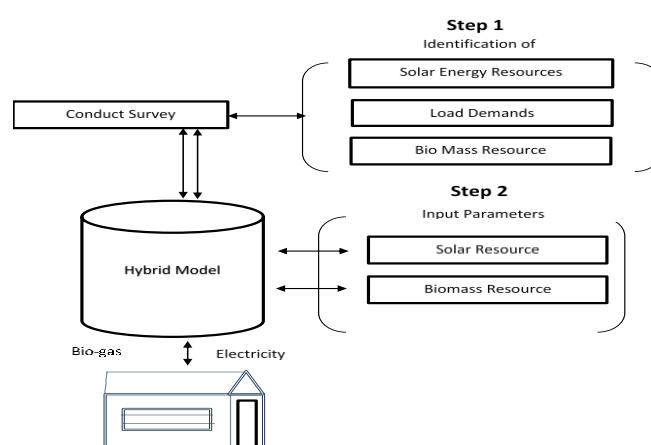


Figure 1: Flow chart of the proposed energy module.

STUDY AREA

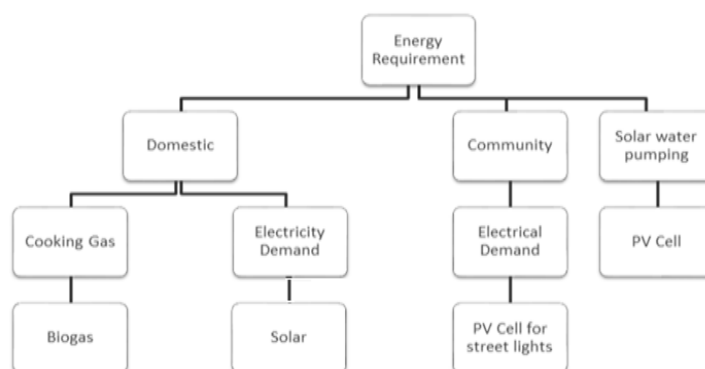
The area of selected Karani village ~40 acres, comprising of houses and shops etc. Karani village profile is given in Table1.

TABLE 1: DETAILS OF KARANI VILLAGE

Village	Moen-Jo-Daro, Karani
District	Larkana
Population	Two thousand five hundred
Average Family Size	Eight persons
Number of Houses	Two hundred ten
Livestock population	Twenty-four hundred thirty
Agriculture land	Three thousand Acres cultivated on tube well and three thousand five hundred Acres cultivated on river water).

Village Load Assessment

Mostly village required the electrical and heat energy for house. During the survey the assessment of electrical load is a critical step in the planning and design of an appropriate energy system for a household or village. Karani village was assessed using the systematic procedure illustrated in Figure 2 for energy requirements of village. Questionnaire was developed to collect primary data on household characteristics, appliances, time in hours, and electricity consumption patterns. The total connected electrical load of the village was estimated at approximately 1595 kW, while the corresponding electricity consumption was approximately 1815 kWh shown in table 2.

**Figure 2: Energy Requirement Flow Chart of the village.****TABLE 2: ELECTRICAL LOAD OF KARANI VILLAGE**

S/NO	Load	Electrical Load (kW)	Electrical (kWh)/day	Consumption
1	Domestic Load	287	1107.7	
2	Commercial Load	81.5	696.5	
3	Masjid Load	3	11	
4	Agriculture Load	1223.44	12174.72	
Total		1594.94	13989.92	

Animal Dung Resources Assessment

Biomass resources are essential for estimating the energy potential of the current study area and for designing a feasible and sustainable energy system. The field survey revealed that existing cooking practices in the Karani village use animal dung as cooking fuel. The use of existing open stoves systems for burning animal dung can result in incomplete combustion, indoor air pollution, impacts on human health and ambient environment. The biomass resource assessment identified 06 types of livestock within the current study area. The livestock population and the corresponding quantity of manure available for potential energy recovery were determined based on the survey data. The estimated livestock population and associated manure production are presented in Table 3. These biomass resource estimates provide a basis for evaluating the available biogas potential and determining the appropriate capacity of the proposed bio-solar hybrid energy system.

TABLE 3: BIOMASS ANIMAL DUNG RESOURCES IN KARANI VILLAGE

S/NO	NAME OF ANIMAL	TOTAL NUMBER	Waste/day	Total Manure/Day
1	Buffaloes	2	15kg	30kg/day
2	Calves	1	12 kg	12kg/day
3	Bullocks	1	12 kg	12kg/day
4	Cows	2	10 kg	20kg/day
5	Goat	2	05 kg	10kg/day

From the Table 3, approximately 84kg of manure are generated in single family houses/day.

Solar Resources Assessment

The solar resource potential of the Karani village was assessed to determine the feasibility of integrating photovoltaic cell (PV) technology into the proposed bio-solar hybrid energy system. approximately 27°15'40" N latitude and 68°06'40" E longitude. Karani village experiences a hot with average temperatures ranging from 40–45 °C during summer, while winter temperatures generally range between 15–20 °C. The study area receives an average of approximately 06hours of sunshine/day, with an average solar irradiation of about 5.5 kWh/m²/day [18]. The availability of substantial solar irradiation throughout the year indicates favorable conditions for PV system for electrical power generation.

Bio-Solar Hybrid Model

Designing of the proposed bio-solar hybrid energy system shown in figure 3. Energy system was designed based on the complementary utilization of available biomass and solar energy resources to meet the electrical and thermal requirements of the Karani village. Biomass is required for biogas subsystem primarily satisfies cooking and thermal energy requirements, while the solar PV subsystem supplies electricity load of village house. The sizing and configuration of the hybrid system were determined based on the estimated energy demand, available biomass resources, and solar energy potential of the present study area.

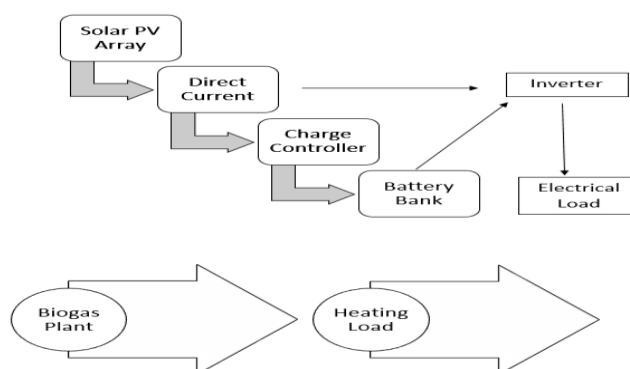


Figure 3: Proposed bio-solar hybrid module.

Village Energy Model

Figure 4 shows the geographical location and spatial layout of Karani Village, as obtained from Google Maps. Based on the existing land-use pattern and energy requirements, the village can be broadly classified into three major sectors: commercial, residential, and agricultural. The residential sector comprises houses of varying sizes, with floor areas ranging from approximately 1,470 to 4,000 ft². Two alternative configurations were considered for meeting the energy requirements of the residential sector. In the first configuration, a single house hybrid energy system is designed and operated independently for each household. In the second configuration, a centralized hybrid energy plant is established to supply energy to multiple households across the village. Considering the household-level energy demand, system flexibility, ease of implementation, and module utilization of indigenous available renewable resources, the present study adopts the single household hybrid energy system model. Accordingly, the proposed system is designed to meet the energy requirements of an individual representative household through the integrated utilization of biogas and solar PV energy.



Figure 4: Karani village.

The average family comprising eight people. Details of estimated quantity of animal dung are presented in Table 3. The energy requirements without considering air conditioning are given in Table 2.

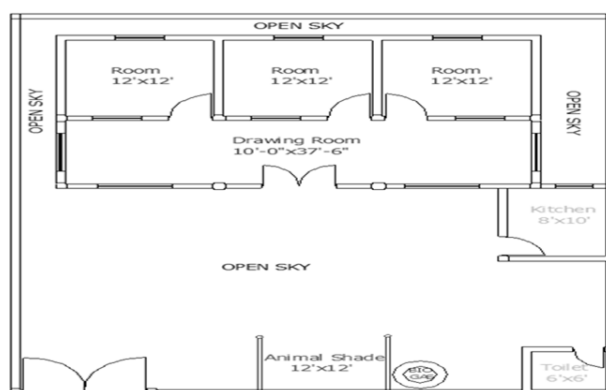


Figure 5: Layout of single-family house of Karani village

Design Of Pv Module

Initial data required for design of Solar PV system electrical connected load and availability of sunshine per unit area. The connected electrical load of village showed in table.2 and solar energy insolation per day are $5.5 \text{ kW h m}^{-2} \text{ d}^{-1}$. The general arrangement of PV system is illustrated in Figure 3.

Table 4: Proposed load of a model house

Load profile						
Name of Appliances	Number of appliances	Power in (Watts)	Total watts of appliances	Time (hrs)	Consumption (kW h/day)	
Saver	10	25	250	6	1.5	
Refrigerator	1	150	150	24	3.6	
Washing Machine	1	500	500	1	0.5	
TV	1	100	100	6	0.6	
Fans	5	100	500	0-6	3	
Total				9.2		

The average daily demand of the modeled house is estimated to be 9.2 kWhd^{-1} . The proposed structure of the module is illustrated in Figure4.

Table 5: Sunshine hours load of a model house.

Load profile						
Name of Appliances	Number of appliances	Power in (Watts)	Total watts of appliances	Time (hrs)	Consumption (kW h/day)	
Refrigerator	1	150	150	6	0.9	
Washing Machine	1	500	500	1	0.5	

TV	1	100	100	3	0.3
Fans	3	100	300	6	1.8
Total				3.5	

Table 6: Batteries/power bank load of a model house.

Load profile					
Name of Appliances	Number of appliances	Power in (Watts)	Total watts of appliances	Time (hrs)	Consumption (kW h/day)
Saver	10	25	250	6	1.5
Refrigerator	1	150	150	18	2.7
TV	1	100	100	3	0.3
Fans	2	100	200	6	1.2
Total				5.7	

Design of PV array

PV system was designed based on the estimated electrical demand of a representative single house in Karani village. The calculated house connected load was approximately 1.5 kW. To account for system losses, including inverter losses, wiring losses, temperature effects, and operational losses, a 25% design margin was incorporated. Thus, the adjusted design load was estimated as:

$$P_{design} = 1.5 \times 1.25 = 1.875 \text{ kW}$$

Solar irradiation period was assumed to be approximately 6 h/day, corresponding to the period between 10:00 AM and 4:00 PM. Accordingly, the estimated daily energy requirement was:

$$E_{PV} = 1.875 \times 6 = 11.25 \text{ kWh/day}$$

PV array capacity of approximately 1.9 kW was considered suitable for a representative single house. A commercially available 585 W solar PV module was selected based on its suitability and local market availability. The required number of modules was calculated as:

$$N = \frac{1900}{585} = 3.25$$

Therefore, four 585 W PV modules, with a total installed capacity of 2.34 kW, would be required to provide approximately 1.9 kW of minimum design capacity while allowing an additional generation margin.

The proposed PV configuration can therefore be expressed as:

$$P_{PV} = 4 \times 585 = 2340 \text{ W} = 2.34 \text{ kW}$$

Battery capacity

Battery bank was incorporated into the solar PV system to supply electricity during periods of insufficient solar shine and nighttime. Based on the single house load assessment, the daily electrical energy requirement to be supplied through battery storage was estimated at approximately 5.7 kWh.

The required battery capacity can be estimated from:

$$C_{Ah} = \frac{E_{bat}}{V_{sys} \times DOD \times \eta_{bat}}$$

where C_{Ah} is the required battery capacity (Ah), E_{bat} is the required stored energy (Wh), V_{sys} is the nominal battery-bank voltage, DOD is the allowable depth of discharge, and η_{bat} is the battery efficiency.

Minimum theoretical battery capacity of approximately 475 Ah at 12 V is required. However, in practical system design, battery efficiency and allowable depth of discharge should also be considered. Therefore, the final battery-bank capacity should be selected according to the manufacturer's recommended operating conditions.

If 150Ah, 12V batteries are selected, the required number is:

$$N = \frac{475}{150} = 3.17$$

Inverter

Inverter capacity was selected based on the maximum simultaneous single house electrical load. The estimated maximum load was approximately 1.500 kW. A 10% safety margin was incorporated to accommodate short-term load fluctuations and starting currents associated with electrical appliances:

$$P_{inv} = 1500 \times 1.10 = 1650 \text{ W}$$

Biogas plant

For village life, energy is required mostly for cooking purposes, water heating. Single family house of Karani village requirement of biogas is considered the following steps.

Total member of average family of village Karani is eight.

Gas required per person/day is 0.3m³.

An average 2.4 m³ units of heat are required on daily basis (8×0.3=2.4m³/day).

The total quantity of dry matter 10kg/day (m₀=10kg/day).

Volume of fluid, V_f=10/50=0.2m³/day (V_f=m₀/ρ_m).

Volume of digester, V_d=0.2×25=5m³ (V_d=V_f×t_r).

Volume of biogas, V_b=0.24×10=2.4m³/day (V_b=cm₀)

Energy from available digester, E=0.6×28×0.8×2.4=32.2MJ/day (E=ηH_bf_mV_b).

Volume of the 5m³ biogas digester will be adequate to meet the requirements of the Single-family house.

COST ANALYSIS

Solar

Solar PV system economic assessment was conducted by considering the initial installation cost and estimated maintenance expenditure over the system's operating life. The estimated installation cost of the PV system was Rs. 847,500, while the maintenance expenditure over the assumed 25-year operating period was estimated at Rs. 211,875.

Therefore, the total estimated life-cycle cost was:

$$\begin{aligned} C_{PV} &= 847,500 + 211,875 \\ C_{PV} &= \text{Rs. } 1,059,375 \end{aligned}$$

Assuming an operating life of 25 years and an average daily electricity generation of 13.5 kWh/day, the estimated levelized energy cost was calculated as:

$$\begin{aligned} C_{unit} &= \frac{1,059,375}{25 \times 365 \times 13.5} \\ C_{unit} &\approx \text{Rs. } 8.6/\text{kWh} \end{aligned}$$

The estimated electricity generation cost of the proposed PV system was approximately Rs. 9/kWh.

Biomass

The estimated initial installation cost of the biogas plant was Rs. 100,000, while the total maintenance expenditure was estimated at Rs. 250,000 over the assumed maintenance period. Therefore, the total estimated expenditure was:

$$C_{BG} = 100,000 + 250,000$$

$$C_{BG} = \text{Rs. } 350,000$$

Per unit cost = $350000 / (15 \times 365 \times 2.4) = \text{Rs. } 16$

Conclusion

The present study investigated the development of a bio-solar hybrid energy system for sustainable rural energy supply in Sindh, Pakistan, using Village Karani, District Larkana, as a representative case study. Overall, the study demonstrates that a household-scale solar-biogas hybrid energy system can provide a technically feasible pathway for sustainable rural energy supply in Sindh, Pakistan, particularly in communities with favorable solar resources and substantial livestock populations. The proposed model can serve as a basis for further research and pilot-scale implementation. Future studies should incorporate detailed optimized PV, biogas-system sizing, battery, life-cycle environmental assessment, economic, and environmental performance of the proposed hybrid energy system.

References

- L. Berridy-Segade, A. Mortera-Canga, D. Iribarren, M. Prodanovic, and M. Martín-Gamboa, "Assessing the social life cycle impacts of future energy mixes: the illustrative case study of power generation in Spain," *Energy Convers. Manag.*, vol. 349, Feb. 2026, doi: 10.1016/j.enconman.2025.120790.
- Y. Khan, H. Yousafzai, and T. Hassan, "Transmission losses, import dependence, and political instability: A Co-integration perspective on Pakistan's energy crisis," *Energy Strategy Reviews*, vol. 64, Mar. 2026, doi: 10.1016/j.esr.2026.102142.
- A. Feroz and I. A. Rana, "Conceptualizing urban heat resilience through capacities and a multidimensional perspective: Empirical evidence from formal and informal settlements of Lahore, Pakistan," *J. Environ. Manage.*, vol. 405, Apr. 2026, doi: 10.1016/j.jenvman.2026.129683.
- S. Ahmed, Y. Huang, M. Kinjo, T. Senjyu, D. Song, and M. H. Elkholy, "Sustainable and reliable energy management for urban hybrid energy systems: A case study in Islamabad Pakistan on hydrogen and battery integration using transient search optimization algorithm," *Results in Engineering*, vol. 27, Sep. 2025, doi: 10.1016/j.rineng.2025.106272.
- S. S. Viridy *et al.*, "Integrated assessment of multi-fuel energy demand, load profiles, and greenhouse gas emissions in an unelectrified rural community in Zambia," *Results in Engineering*, vol. 32, p. 112493, Dec. 2026, doi: 10.1016/j.rineng.2026.112493.
- A. C. P. Brasil Junior, R. C. F. Mendes, and J. Lavaquial, "Small (and not-so-small) villages in the Amazon: The challenge of access to electricity infrastructure," *Energy Res. Soc. Sci.*, vol. 132, Feb. 2026, doi: 10.1016/j.erss.2026.104550.
- A. SALIM, S. U. REHMAN, W. M. ABDULKAWI, and H. Y. AHMED, "Overcoming barriers to solar energy adoption in Pakistan: Current status, policy gaps, and institutional reforms," *Results in Engineering*, vol. 29, Mar. 2026, doi: 10.1016/j.rineng.2025.108537.
- J. Cai, G. Shen, W. Zhang, and F. Chen, "Cost-effective hybrid microgrid for sustainable energy and hydrogen production in remote area," *Appl. Therm. Eng.*, vol. 302, Aug. 2026, doi: 10.1016/j.applthermaleng.2026.131798.
- A. Mujeeb, J. Oladigbolu, M. S. Bakare, and A. A. Ibrahim, "Pathways to environmental sustainability through energy efficiency: A strategic next energy vision for sustainable development by 2050," Dec. 01, 2025, *Elsevier B.V.* doi: 10.1016/j.sciaf.2025.e03053.
- M. Hussain *et al.*, "Regional and sectoral assessment on climate-change in Pakistan: Social norms and indigenous perceptions on climate-change adaptation and mitigation in relation to global context," *J. Clean. Prod.*, vol. 200, pp. 791–808, Nov. 2018, doi: 10.1016/j.jclepro.2018.07.272.
- S. Bilgen and I. Sarikaya, "Exergy for environment, ecology and sustainable development," Jul. 30, 2015, *Elsevier Ltd.* doi: 10.1016/j.rser.2015.07.015.
- H. Togun *et al.*, "Pathways towards a carbon-free energy system: Technological advances, policy barriers, and integrated decarbonization strategies," Dec. 01, 2026, *Elsevier Ltd.* doi: 10.1016/j.apenergy.2026.128548.
- O. Jafarli, "Assessment of renewable energy potential for heating applications in Azerbaijan: A review and regional perspective," May 01, 2026, *Elsevier Ltd.* doi: 10.1016/j.ecmx.2026.101908.

- S. A. Soomro, M. A. Raza, N. H. Mirjat, Y. Z. Alharthi, and L. Kumar, "Unlocking Pakistan's wind energy potential for sustainable energy transition: A comprehensive review," Feb. 01, 2026, *Elsevier B.V.* doi: 10.1016/j.indic.2025.101056.
- A. U. Rehman *et al.*, "Analysis of renewable energy resources (RERs) under the China-Pakistan economic corridor (CPEC) initiative: A proposed solution for optimized and sustainable energy management," *Sustainable Futures*, vol. 10, Dec. 2025, doi: 10.1016/j.sftr.2025.100826.
- A. W. Bhutto, A. A. Bazmi, and G. Zahedi, "Greener energy: Issues and challenges for Pakistan-Solar energy prospective," Jun. 2012. doi: 10.1016/j.rser.2012.02.043.
- A. Raheem, W. A. K. G. Wan Azlina, Y. H. Taufiq Yap, M. K. Danquah, and R. Harun, "Thermochemical conversion of microalgal biomass for biofuel production," Oct. 01, 2015, *Elsevier Ltd.* doi: 10.1016/j.rser.2015.04.186.
- M. Ashraf Chaudhry, R. Raza, and S. A. Hayat, "Renewable energy technologies in Pakistan: Prospects and challenges," Aug. 2009. doi: 10.1016/j.rser.2008.09.025.
- I. A. Mirza, S. Ahmed, and M. Shahid Khalil, "RENEWABLE ENERGY IN PAKISTAN: OPPORTUNITIES AND CHALLENGES." [Online]. Available: www.irena.org
- A. H. Fathima and K. Palanisamy, "Optimization in microgrids with hybrid energy systems - A review," 2015, *Elsevier Ltd.* doi: 10.1016/j.rser.2015.01.059.
- R. Pode, "Battery charging stations for home lighting in Mekong region countries," 2015, *Elsevier Ltd.* doi: 10.1016/j.rser.2015.01.003.
- J. L. Easterly and M. Burnham, "OVERVIEW OF BIOMASS AND WASTE FUEL RESOURCES FOR POWER PRODUCTION," 1996.
- Available next action: Create a downloadable DOCX file here in this chat containing the editable prose above



2026 by the authors; Journal of The Kashmir Journal of Academic Research and Development. This is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).