

GIS-BASED SPATIAL MODELLING OF HYBRID
RENEWABLE ENERGY POTENTIAL IN THE CASPIAN SEA
ISLANDS: A CASE STUDY OF PIRALLAHI, AZERBAIJAN

Nijat Sohrab Imamverdiyev[✉], Gunesh Rafiq Agakishiyeva^{id},
Natig Gubad Babayev^{id}

Received on July 2, 2026

Presented by K. Stoykova, Corresponding Member of BAS, on September 29, 2026

Abstract

This study presents a geospatial assessment of hybrid wind-solar energy potential on Pirallahi Island, Azerbaijan, using GIS-based spatial constraint and suitability analysis. It employs MERRA-2 reanalysis data (1981–2022), validated with ground observations and complemented by Global Solar Atlas (GSA) and Global Wind Atlas (GWA) datasets. Mean wind speed at 10 m is 4.94 m/s, and annual GHI is 1526 kWh/m². The framework integrates topographic, infrastructural, land-use, and environmental constraints. Power generation was estimated for PV systems and 3.45 MW IEC-class wind turbines, including system losses. Results indicate that 3.2 km² is suitable for solar PV, providing 100.2 MW capacity and 158 GWh/year (CF: 0.18), while 5.6 km² can accommodate 12 wind turbines with 41.4 MW capacity and 120.9 GWh/year gross (weighted CF: 0.333; onshore CF = 0.30, offshore CF = 0.35). Net hybrid generation after separate losses is estimated at 255.6 GWh/year, while a conservative 14% blanket-loss sensitivity case yields 239.9 GWh/year. This study provides the first high-resolution assessment of Pirallahi Island's hybrid wind-solar potential, generation estimates, and demand-surplus dynamics. The proposed system significantly exceeds local demand, revealing a substantial annual surplus available for grid export.

Key words: hybrid energy system, wind energy, solar energy, electricity generation, Pirallahi Island, GIS-based suitability analysis

Introduction. Clean energy sources are essential for sustainable development and reducing carbon emissions. Azerbaijan has committed to greenhouse gas reduction under the 2015 Paris Agreement (COP21) and prioritises renewable energy, reinforced by COP29 (Baku, 2024).

Renewable energy can transform Pirallahi Island's energy strategy by supporting economic development and ecotourism. Smart-grid-integrated hybrid systems improve voltage regulation, frequency response, and demand-side management, while the island's proximity to the Absheron Peninsula facilitates power exchange.

Pirallahi (17.56 km²; population 17 319) is Azerbaijan's largest island. A 2.8 MW PV plant has operated since 2017, generating 3.7 GWh during the 2017–2022 period. Local electricity demand is estimated at 26–35 GWh/year, whereas the proposed hybrid system (255.6 GWh/year after separate losses; 239.9 GWh/year under a conservative 14% loss case) would generate 7.3–9.8 times this demand in the base case, indicating a large theoretical annual surplus relative to local demand.

Although Pirallahi has often been studied together with the Absheron Peninsula, its renewable energy potential has not been comprehensively assessed. Its favourable natural conditions and proximity to Baku support efficient infrastructure deployment and grid integration [1].

Renewable energy assessment requires engineering analysis of meteorological conditions and equipment performance. OZGUR [2] reviewed renewable resource optimization, while ILKILIC [3] emphasized accurate wind assessment for investment planning. BANDO et al. [4] demonstrated the cubic relationship between wind speed and power density, whereas OKEDU et al. [5] confirmed the effectiveness of GIS-based multi-criteria approaches for data-scarce regions.

Recent island studies confirm the effectiveness of hybrid systems. KARIPOGLU et al. [6] proposed a GIS-fuzzy AHP-EDAS framework for offshore wind-solar site selection; ROY et al. [7] analyzed autonomous hybrid systems. Despite increasing interest in renewable energy in Azerbaijan, no comprehensive GIS-based assessment of hybrid wind-solar potential has been conducted for Pirallahi or other Caspian islands. This study addresses this gap by applying GIS-based spatial constraint and suitability analysis, long-term meteorological data, and engineering modelling to assess renewable resources, identify suitable development areas, estimate electricity generation, and evaluate the potential for exporting surplus electricity to the Absheron grid.

Materials and methods. The methodology integrates climatic resource analysis, spatial suitability assessment, and engineering modelling based on long-term meteorological data and equipment parameters. The following sources were used: NASA POWER (MERRA-2) reanalysis (1981–2022) [8, 9], Global Solar Atlas (GSA) [10], Global Wind Atlas (GWA) [11], global photovoltaic power potential data [12], local wind measurements, and topographic data. The stages of

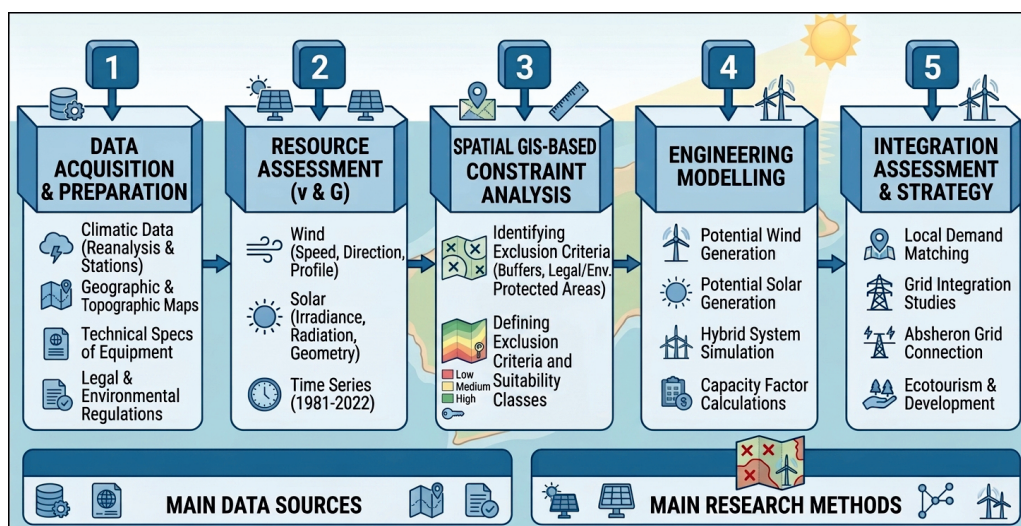


Fig. 1. Research database, methodology and workflow

the methodology are: (1) climatic data collection and processing; (2) solar and wind resource analysis; (3) spatial GIS-based constraint and suitability analysis; (4) engineering calculation of potential generation; (5) evaluation of grid integration prospects (Fig. 1).

GIS-based constraints and exclusion analysis. The spatial analysis was implemented as a GIS-based constraint and exclusion assessment. No weighted MCDM aggregation was applied; therefore, the mapped areas represent technically feasible zones rather than weighted suitability classes. Suitable areas were identified through the application of exclusion criteria, including settlement buffers, transportation infrastructure restrictions, environmental constraints, coastline setbacks, and topographic limitations. The resulting suitability map represents areas that satisfy all predefined technical and environmental criteria. Technically feasible zones were identified using spatial exclusion criteria: 100–200 m buffers around settlements; 50 m road and 100 m power line buffers; exclusion of oil wells and pipeline areas; 50 m coastline setback; exclusion of slopes $> 15\%$ for solar PV; exclusion of environmentally sensitive and historical sites.

Since Pirallahi has predominantly flat topography, solar radiation potential is provided for horizontal surfaces. The optimal fixed tilt for ground-mounted PV is 29° at 180° azimuth. The Solar Electrical Potential is calculated as:

$$(1) \quad W_{\text{power}} = G_{\text{avg}} \times A \times \eta_{\text{solar}} \times PR.$$

PV systems on suitable sites (3.2 km^2) are estimated at 100.2 MW of capacity with 158 GWh of annual generation, with a capacity factor (CF) of 0.18; the ground coverage ratio was applied separately to estimate installed capacity. Criteria thresholds follow Bandoc et al. [4] and Okedu et al. [5]. The capacity

factor was derived by integrating the turbine power curve over the site-specific wind-speed distribution using a Weibull probability density function ($k = 2.0$, $A = 5.5$ m/s), following the methodology of GARDASHOV and GARDASHOV [13]. This approach accounts for the non-linear relationship between wind speed and power output and provides a more defensible estimate than the simplified equation

$$(2) \quad W_{\text{power}} = 0.5 \times \rho \times A_{\text{rotor}} \times V^3 \times C_p \times 8760 \times \text{CF},$$

where W_{power} is the annual energy generation by a wind turbine (kWh), ρ is the air density (~ 1.225 kg/m³); A_{rotor} is the swept area of the wind turbine rotor (m²), V^3 is the cube of the average wind speed (m/s), and C_p is the power coefficient of the wind turbine (~ 0.4 – 0.5).

Equation (2) was used only for preliminary screening. Final wind generation was calculated as $E_{\text{wind}} = N \times P_{\text{rated}} \times 8760 \times \text{CF}$, with CF derived from the turbine power curve and site wind distribution.

The proposed configuration combines 4 onshore and 8 nearshore/offshore turbines (Table 1).

T a b l e 1

Proposed onshore and offshore wind farm configuration and generation estimates

Parameter	Onshore	Offshore	Total
Number of turbines	4	8	12
Installed capacity	13.8 MW	27.6 MW	41.4 MW
CF	0.30	0.35	0.333 (weighted)
Annual generation (gross)	36.3 GWh	84.6 GWh	120.9 GWh
Annual production (net, with 5.5% loss)	34.3 GWh	80.0 GWh	114.3 GWh

PV losses are: inverter 2.5%, cabling 1.5%, transformer 1.0%, soiling/temperature 4.0%, grid/auxiliary 2.0%. Wind losses are: availability 3.0%, electrical/transformer 2.5%. These loss factors were applied separately and sequentially to the corresponding gross generation. Because wake effects were not modelled, no wake loss was applied in the base case. The net hybrid energy is therefore:

$$(3) \quad W_{\text{hybrid}} = W_{\text{solar,net}} + W_{\text{wind,net}},$$

where

$$\begin{aligned} W_{\text{solar,net}} &= W_{\text{solar,gross}}(1 - 0.025)(1 - 0.015)(1 - 0.010)(1 - 0.040)(1 - 0.020) \\ &\approx 0.8945W_{\text{solar,gross}} \\ W_{\text{wind,net}} &= W_{\text{wind,gross}}(1 - 0.030)(1 - 0.025) \approx 0.9458W_{\text{wind,gross}}. \end{aligned}$$

For the base case, solar PV gross generation is 158.0 GWh/year, giving $W_{\text{solar,net}} \approx 141.3$ GWh/year. Wind gross generation is 120.9 GWh/year,

giving $W_{\text{wind,net}} \approx 114.3$ GWh/year. Total net hybrid generation is therefore 255.6 GWh/year. The overall effective loss is about 8.3% of gross hybrid generation. A conservative sensitivity case using a blanket 14% loss on the combined gross generation yields 239.9 GWh/year; this is reported only as a lower-bound sensitivity scenario.

For the Vestas V90 (80 m hub height), a conservative wind speed of 7.0 m/s was adopted, lower than the 7.7–7.9 m/s power-law extrapolation from coastal GWA values, to account for inland surface roughness.

Results and discussion. Solar energy. Analysis of climatic factors affecting PV efficiency shows total annual solar radiation of 1580 kWh/m² (national data) and 1526 kWh/m² (GSA data). These results align with SURI et al. [12], confirming Azerbaijan’s moderate-to-high solar resource classification. The region receives ~ 2400 annual sunshine hours across 280–300 clear days (80% of the year), yielding daily GHI and DNI values of 4.04 kWh/m² and 3.82 kWh/m², respectively (Fig. 2). Radiation peaks between April and September (60%; 960 kWh/m²), with higher concentration in the southern zone, identifying it as optimal for photovoltaic deployment.

Wind energy. Pirallahi Island is influenced by northerly ‘Khazri’ winds (with maximum gusts of 25–30 m/s), southerly ‘Gilavar’, and coastal ‘Meltem’

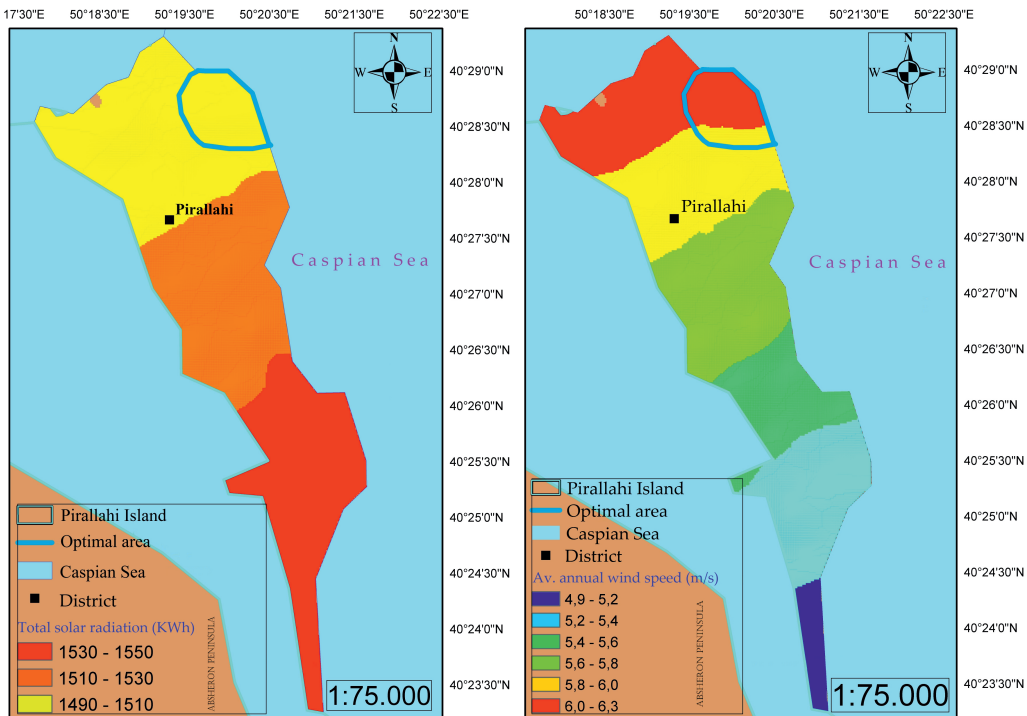


Fig. 2. Global horizontal irradiation and average annual wind speeds on Pirallahi Island

breezes. Long-term MERRA-2 data indicate a mean wind speed of 4.94 m/s at 10 m. Using a power-law exponent of 0.20, this corresponds to approximately 6.8–7.0 m/s at 80–100 m. GWA reports a mean annual speed of 6.17 m/s at 50 m, with seasonal autumn–winter values reaching 7.27 m/s at 50 m and 7.98 m/s at 100 m in exposed coastal areas. For the generic IEC Class turbine, a conservative hub-height wind speed of 7.5 m/s at 100 m was adopted; the 8.5 m/s value was used only as an upper-bound sensitivity case (Fig. 2). The cubic relationship ($P \propto v^3$) means doubling speed increases power 8-fold, highlighting the importance of accurate wind assessment.

Long-term stability is inferred from the 1981–2022 MERRA-2 record. Comparison of data sources: regional station – 5.9 m/s; on-site – 5.7 m/s; MERRA-2 – 4.94 m/s (10 m height); GWA – 6.17 m/s (50 m height) [9, 11]. MERRA-2 was used for long-term temporal analysis because it provides a consistent 1981–2022 record; GWA and short-term measurements were used for spatial and hub-height adjustments.

Geospatial optimization identified 5.6 km² for wind turbine deployment (4 onshore + 8 offshore = 12 units) and 3.2 km² for PV (100.2 MW capacity). Layout planning used SketchUp software to minimize environmental impact and maximize efficiency (Fig. 3).



Fig. 3. Scheme of the location of the planned renewable energy facilities on Pirallahi Island

The PV system (3.2 km²) provides 100.2 MW installed capacity with a CF of 0.18, generating 158.0 GWh/year gross. The wind farm (5.6 km²) provides 41.4 MW with a weighted CF of 0.333 (onshore 0.30; offshore 0.35), producing 120.9 GWh/year gross. Total gross theoretical generation is 158.0 + 120.9 = 278.9 GWh/year. After separate PV and wind losses, net hybrid generation is 141.3 GWh/year (solar) + 114.3 GWh/year (wind) = 255.6 GWh/year. This exceeds the estimated local demand of 26–35 GWh/year by approximately 7.3–9.8 times. Under the conservative blanket 14% loss sensitivity case, net generation

is 239.9 GWh/year, still exceeding local demand by 6.9–9.2 times. Actual export capacity depends on hourly generation–load matching, grid connection capacity, curtailment, storage, voltage stability, and load-flow analyses.

At the lower wind-speed range (4.5–6.5 m/s), a single 3.45 MW turbine operates well below rated capacity, with instantaneous output of approximately 570 kW. Over the long-term wind distribution, however, the average output per turbine is about 1035 kW onshore and about 1208 kW offshore, corresponding to approximately 9.1 and 10.6 GWh/year, respectively; these yield 120.9 GWh/year for 12 turbines at a weighted CF of 0.333. The practical power coefficient (C_p) ranges from 0.35 to 0.45, below the Betz limit (59.3%). Typical capacity factors are 27–35% for onshore and 32–40% for offshore turbines.

Wind speed analysis for 1981–2022 indicates an average of 4.94 m/s, varying mainly between 4.7 and 5.2 m/s [9,13]. The maximum annual average (5.24 m/s) occurred in 1997, and the minimum (4.61 m/s) in 1984. The standard deviation was 0.16 m/s and the variance was approximately 0.026 (m/s)^2 , indicating low interannual variability. Winter winds (5.5–6.0 m/s) are stronger than summer winds (3.5–4.5 m/s), while April–June records the lowest speeds (3.0–4.0 m/s). Annual and winter mean wind speeds exceed the 4.5 m/s economic threshold, while summer months fall below it, and coastal aerodynamic effects further enhance the region’s wind energy potential [11].

During the 1981–2022 period, the mean wind speed was 4.94 m/s, with a maximum of 5.24 m/s in 1997 and a minimum of 4.61 m/s in 1984 [13].

Conclusions. The proposed Pirallahi hybrid solar-wind system has the theoretical potential to generate 255.6 GWh/year after separate PV and wind losses (239.9 GWh/year under a conservative 14% blanket-loss sensitivity case), substantially exceeding the estimated local demand of 26–35 GWh/year. This indicates a large annual energy surplus that could support export to the Absheron grid, provided that hourly matching, interconnection capacity, curtailment, storage, and grid-stability requirements are satisfied in future studies.

Multi-source datasets confirm the island’s strong renewable energy potential. MERRA-2 data (1981–2022) indicate stable average annual wind speeds of 4.8–5.2 m/s (minimum 4.61 m/s in 1984; maximum 5.24 m/s in 1997), with dominant northerly and northeasterly (Khazri) winds [9]. Annual solar radiation reaches 1526 kWh/m^2 , with an optimal PV tilt of 29° . Suitable development areas are 3.2 km^2 for PV and 5.6 km^2 for wind energy.

The total annual gross energy generation of the proposed hybrid system with an installed capacity of 141.6 MW (100.2 MW Solar PV and 41.4 MW Wind – 12 turbines) is estimated at 278.9 GWh/year (Solar PV: 158.0 GWh/year; Wind: 120.9 GWh/year). Accounting for separate PV and wind losses, the net energy delivered to the grid is calculated as 255.6 GWh/year (Solar PV: 141.3 GWh/year; Wind: 114.3 GWh/year). Under a conservative 14% blanket-loss sensitivity case, net generation is 239.9 GWh/year (Solar PV: 135.9 GWh/year; Wind:

104.0 GWh/year). Against a local annual energy demand of 26–35 GWh, the projected base-case net generation exceeds local demand by approximately 7.3–9.8 times (6.9–9.2 times in the conservative case), indicating a large theoretical annual energy surplus that could support export to the Absheron grid, provided that hourly matching, interconnection capacity, curtailment, storage, and grid-stability requirements are satisfied in future studies.

Limitations include the lack of long-term wind measurements above 50 m and the exclusion of energy storage and dynamic load modelling. A 40–60 MWh battery system would improve daily balancing, while economic indicators such as LCOE and payback period remain subjects for future research.

Overall, the proposed GIS-based framework provides a reproducible approach for regional renewable energy assessment and supports future smart-grid integration, energy storage planning, and economic optimization.

REFERENCES

- [1] IMAMVERDIYEV N. (2026) Assessing wind energy potential in Azerbaijan (case of Shorabad settlement, Khizi district), *Ukr. Geogr. J.*, **2026**(1), 28–40.
- [2] OZGUR M. A. (2008) Review of Turkey’s renewable energy potential, *Renew. Energy*, **33**(11), 2345–2356.
- [3] ILKILIC C. (2012) Wind energy and assessment of wind energy potential in Turkey, *Renew. Sustain. Energy Rev.*, **16**(2), 1165–1173.
- [4] BANDOC G., R. PRAVALIE, C. PATRICHE et al. (2018) Spatial assessment of wind power potential at global scale: A geographical approach, *J. Clean. Prod.*, **196**, 1065–1086.
- [5] OKEDU K. E., B. OYINNA, I. COLAK et al. (2024) GIS-based assessment of various renewable energy potentials in Nigeria, *Energy Rep.*, **11**, 1147–1160.
- [6] KARIPOGLU F., S. OZTURK, B. EFE (2023) A GIS-based FAHP and FEDAS analysis framework for suitable site selection of a hybrid offshore wind and solar power plant, *Energy Sustain. Dev.*, **77**(3), 101349.
- [7] ROY D., H. TAGHAVIFAR, K. V. SHIVAPRASAD et al. (2025) Multi-criteria decision-making and uncertainty analyses of off-grid hybrid renewable energy systems for an island community, *Energy Convers. Manag.*, **343**, 120120.
- [8] NASA Langley Research Center (2024) POWER Project Data Sets. Retrieved March 11, 2024, from <https://power.larc.nasa.gov/>.
- [9] GELARO R., W. MCCARTY, M. J. SUAREZ et al. (2017) The modern-era retrospective analysis for research and applications, Version 2 (MERRA-2), *J. Clim.*, **30**(14), 5419–5454.
- [10] World Bank Group (2026) Global Solar Atlas 3.0. Retrieved March 11, 2026, from <https://globalsolaratlas.info>.
- [11] Technical University of Denmark (DTU) (2024) Global Wind Atlas 3.0. Retrieved March 11, 2024, from <https://globalwindatlas.info>.
- [12] SURI M., J. BETAK, K. ROSINA et al. (2020) Global Photovoltaic Power Potential by Country, World Bank.

- [13] GARDASHOV E., R. GARDASHOV (2024) On the derivation of an analytical expression for wind power probability distribution function and capacity factor of turbine, Int. J. Sustain. Energy, **43**(1), 2390447.

Institute of Geography, Ministry of Science and Education of the Republic of Azerbaijan, AZ1073, Baku, Azerbaijan

e-mails:

nicat.imamverdiyev@geo.edu.az (<https://orcid.org/0000-0002-5573-0209>)

gunes.agakisiyeva@geo.edu.az (<https://orcid.org/0000-0002-8200-7278>)

natiq_@20mail.ru (<https://orcid.org/0009-0009-5497-9203>)