Spatio-Temporal Modelling of Solar Photovoltaic Potential across Sylhet District: A GIS-Based Multi-Criteria Approach for Sustainable Energy Planning

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***Abstract*—Sylhet District in northeastern Bangladesh possesses substantial yet underutilized solar photovoltaic (PV) potential, hindered by its complex topography and monsoon-influenced climate. This study bridges critical knowledge gaps by quantifying monthly capacity factors amid seasonal variability, assessing economically viable storage solutions for grid stability, and evaluating deployment strategies for sustainable energy planning. The research employs a high-resolution spatiotemporal model integrating Geographic Information System (GIS) with Multi-Criteria Decision Making (MCDM) and the Analytical Hierarchy Process (AHP). Key inputs include daily meteorological data (solar irradiation, rainfall, humidity, and wind speed), Digital Elevation Models for terrain analysis, and historical extreme weather records. The model identifies the top 5% of land areas by monthly suitability for solar PV deployment, focusing on three archetypes: rooftop, floating, and degraded-land ground installations. Monthly capacity factors and levelized cost of electricity (LCOE) are estimated, accounting for monsoon-induced soiling and operational costs. Sensitivity analysis of AHP weights ($\pm$20% perturbation) ensures robustness in suitability assessments. Findings highlight high-potential zones in low-population regions with favorable topography, minimizing social displacement risks. The study delivers monthly capacity factor distributions, LCOE comparisons across deployment types, and optimized storage scenarios to achieve 80% grid firming. Additionally, lifecycle waste projections per MW and local recycling pathways are evaluated to address environmental sustainability. This work provides actionable insights for policymakers, aligning with Bangladesh's renewable energy goals and offering a replicable framework for tropical regions facing similar seasonal challenges. You can access the repository here:**

***Index Terms*—Solar PV Potential, Spatiotemporal Modeling, GIS-MCDM, Analytical Hierarchy Process (AHP), Monsoon Climate, Energy Storage, Sustainable Deployment, LCOE.**

I. Introduction

BANGLADESH faces mounting energy challenges driven by rapid urbanization, population growth, and industrial expansion. The nation's electricity demand is projected to reach 34,000 MW by 2030, while current installed capacity remains insufficient [1]. Sylhet District, located in northeastern Bangladesh (24.6°N–25.3°N, 91.6°E–92.3°E), encompasses approximately 3,452 km² and presents unique opportunities for renewable energy development despite its complex monsoon-influenced climate and varied topography [2].

A. Motivation and Challenges

Solar photovoltaic (PV) technology offers a promising solution to Bangladesh's energy security concerns. However, the deployment of solar PV in Sylhet faces several critical challenges:

1) **Seasonal Variability:** Monsoon seasons (June–September) significantly reduce solar irradiation and increase soiling losses, affecting annual capacity factors by 15–25% [3].
2) **Complex Topography:** Elevation ranges from 5m to 100m create microclimatic variations affecting site suitability and infrastructure accessibility [4].
3) **Grid Integration:** Limited transmission infrastructure and distance to substations (0.1–15 km) necessitate optimized storage solutions for grid stability [5].
4) **Economic Viability:** LCOE estimations must account for deployment-specific costs, with rooftop, floating, and ground-mounted systems exhibiting distinct economic profiles [6].

B. Research Gaps

Existing studies on solar potential in Bangladesh have primarily focused on national-level assessments or specific technologies in isolation. Critical gaps include:

- Limited spatiotemporal modeling at district-level resolution
- Insufficient integration of meteorological variability with GIS-based suitability analysis
- Lack of deployment-specific economic and technical comparisons
- Absence of comprehensive storage requirement analysis for monsoon climates
- Inadequate consideration of lifecycle environmental impacts

C. Research Objectives

This study addresses these gaps through the following objectives:

1) Develop a high-resolution (200×200 grid) spatiotemporal model integrating meteorological data, terrain analysis, and infrastructure constraints
2) Quantify monthly capacity factors for three deployment archetypes across seasonal variations
3) Conduct comprehensive economic analysis comparing LCOE, NPV, IRR, and payback periods
4) Optimize energy storage configurations for 80% grid firming capability
5) Assess environmental impacts including 25-year lifecycle waste projections
6) Identify priority deployment zones through robust MCDM-AHP methodology

D. Novel Contributions

The key contributions of this research include:

- **Integrated Framework:** First comprehensive GIS-MCDM model specifically calibrated for monsoon-influenced tropical regions
- **Temporal Granularity:** Monthly capacity factor analysis revealing seasonal optimization opportunities
- **Multi-Archetype Comparison:** Systematic evaluation of rooftop, floating, and ground-mounted systems under identical constraints
- **Storage Optimization:** Technology-specific storage requirements for lithium-ion, flow battery, and pumped hydro solutions
- **Sustainability Assessment:** Complete lifecycle analysis including material recycling pathways achieving 85.1% recovery rate

The remainder of this paper is organized as follows: Section II reviews relevant literature, Section III details the methodology including data sources and analytical framework, Section IV presents comprehensive results, Section V discusses implications and limitations, and Section VI concludes with policy recommendations.

II. Literature Review

A. Solar PV Potential Assessment Methods

Solar resource assessment has evolved from simple irradiation mapping to sophisticated multi-criteria frameworks. Ramachandra et al. [7] pioneered GIS-based solar potential mapping in India, demonstrating the utility of spatial analysis for renewable energy planning. More recent work by Gueymard and Yang [8] emphasized the importance of high-temporal-resolution data for accurate capacity factor estimation.

In the Bangladesh context, Mondal and Islam [9] conducted national-level solar resource assessment, identifying annual average irradiation of 4.5–5.5 kWh/m²/day. However, their study lacked district-level granularity and seasonal variability analysis. Alam et al. [10] improved upon this by incorporating cloud cover and aerosol data, achieving 12% better prediction accuracy.

B. Multi-Criteria Decision Making in Energy Planning

The Analytical Hierarchy Process (AHP) has become a standard tool for renewable energy site selection. Saaty [11] established the theoretical foundation, while Noorollahi et al. [12] demonstrated its application to solar farm siting in Iran. More recently, Al Garni and Awasthi [13] combined AHP with GIS for large-scale solar project evaluation in Saudi Arabia.

For tropical climates specifically, Doorga et al. [14] developed a climate-adapted MCDM framework for Mauritius, incorporating cyclone risk and humidity factors. Their methodology influenced our approach to monsoon risk assessment in Sylhet District.

C. Floating Solar PV Technologies

Floating photovoltaic (FPV) systems represent an emerging deployment paradigm particularly relevant to water-rich regions like Sylhet. Sahu et al. [15] demonstrated 10–15% efficiency gains from evaporative cooling in Indian reservoirs. More comprehensive techno-economic analysis by Choi [16] in South Korea showed LCOE competitiveness with ground-mounted systems when water body availability exceeds 5 hectares.

Cazzaniga et al. [17] provided critical insights on anchoring systems and wave resistance, directly applicable to Sylhet's monsoon-affected water bodies. Our FPV suitability criteria build upon their structural resilience framework.

D. Energy Storage Integration

Grid integration of variable renewable energy requires sophisticated storage solutions. Zakeri and Syri [18] conducted comparative LCOS (Levelized Cost of Storage) analysis across battery technologies, demonstrating lithium-ion dominance for 2–4 hour discharge durations. For longer-duration storage, Zakeri et al. [19] advocated flow batteries and pumped hydro.

Bangladesh-specific studies remain limited. Rahman et al. [20] assessed battery storage for off-grid rural electrification but did not address grid-scale applications. Our work fills this gap by optimizing storage configurations for 80% grid firming in a monsoon context.

E. Economic and Environmental Sustainability

LCOE remains the primary metric for economic viability assessment. Branker et al. [21] established standard methodologies, later refined by Fu et al. [22] to account for regional cost variations. Their framework informs our deployment-specific cost modeling.

Environmental sustainability increasingly demands lifecycle assessment. Fthenakis and Kim [23] pioneered PV module recycling analysis, projecting 85–90% material recovery potential. Xu et al. [24] extended this to end-of-life waste projections, methodology we adapt for 25-year Sylhet projections.

F. Research Positioning

Our study uniquely integrates these disparate research streams—GIS-based siting, MCDM optimization, deployment-specific technical analysis, storage integration, and lifecycle sustainability—into a cohesive framework calibrated for monsoon climates. This holistic approach addresses the multi-dimensional challenges of solar PV deployment in tropical developing regions.

III. Methodology

A. Study Area Characteristics

Sylhet District (24.6°N–25.3°N, 91.6°E–92.3°E) encompasses 3,452 km² in northeastern Bangladesh, characterized by:

- **Climate:** Humid subtropical with distinct seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November)
- **Topography:** Rolling hills (5–100m elevation) interspersed with haor wetlands
- **Population:** Approximately 3.5 million inhabitants with density varying from 50 to 2,937 people/km²
- **Infrastructure:** Grid substations concentrated near Sylhet City with transmission gaps in rural areas

B. Data Acquisition and Preprocessing

1) Meteorological Data: Daily time-series data (2020–2023) were compiled from three sources:

1) **NASA POWER:** Global horizontal irradiation (GHI), temperature, humidity (0.5° resolution)
2) **PVGIS Database:** Direct normal irradiation (DNI), diffuse irradiation
3) **Bangladesh Meteorological Department:** Ground station validation data (3 stations)

Data preprocessing involved:

- Quality control: removal of outliers ($>3\sigma$ from mean)
- Gap filling: cubic spline interpolation for missing values ($<2\%$)
- Spatial interpolation: Inverse Distance Weighting (IDW) to 200×200 grid
- Temporal aggregation: daily to monthly averages and standard deviations

TABLE I: Geospatial Data Sources and Specifications

Dataset	Source	Resolution
Digital Elevation Model	SRTM 30m	30m
Land Use/Land Cover	Sentinel-2	10m
Road Network	OpenStreetMap	Vector
Grid Infrastructure	BPDB	Vector
Water Bodies	Global Surface Water	30m
Population Density	WorldPop	100m
Administrative Boundaries	GADM	Vector

2) Geospatial Data:

3) Economic and Technical Parameters: Deployment-specific parameters were compiled from manufacturer datasheets, market surveys, and literature:

TABLE II: Key Technical and Economic Parameters

Parameter	Rooftop	Floating	Ground
CAPEX (USD/kW)	1,200	1,450	1,100
OPEX (% CAPEX/year)	1.5	2.0	1.8
System Lifetime (years)	25	25	25
Panel Efficiency (%)	20.5	21.0	20.0
Performance Ratio	0.80	0.85	0.78
Soiling Loss (dry/monsoon)	2%/8%	1%/5%	3%/10%

C. GIS-MCDM Framework

1) Criteria Selection and Scoring: Five primary criteria were identified through expert consultation and literature review:

1) **Solar Resource (SR):** Weighted by monthly irradiation and seasonal variability

$$SR = \frac{\sum_{m=1}^{12}(GHI_m \times w_m)}{GHI_{Bangladesh}} \tag{1}$$

where w_m = monsoon adjustment weights

2) **Terrain Suitability (TS):** Function of slope and elevation

$$TS = e^{-(\alpha \cdot slope + \beta \cdot |elev - elev_{opt}|)} \tag{2}$$

with $\alpha = 0.15$, $\beta = 0.02$, $elev_{opt} = 35m$

3) **Infrastructure Accessibility (IA):** Inverse distance to roads and grid

$$IA = w_r \cdot e^{-d_{road}/\lambda_r} + w_g \cdot e^{-d_{grid}/\lambda_g} \tag{3}$$

where $\lambda_r = 2$ km, $\lambda_g = 5$ km

4) **Grid Proximity (GP):** Weighted by available substation capacity

$$GP = \frac{C_{available}}{d_{grid}^{1.5}} \tag{4}$$

5) **Social Impact (SI):** Minimizing displacement, maximizing benefit

$$SI = (1 - \rho_{norm}) \times (1 + E_{benefit}) \tag{5}$$

where ρ_{norm} = normalized population density, $E_{benefit}$ = employment potential

2) Analytical Hierarchy Process: AHP weights were determined through pairwise comparison matrices validated by Consistency Ratio (CR < 0.10):

TABLE III: AHP Criterion Weights

Criterion	Weight	Sensitivity ($\pm 20\%$)
Solar Resource	0.35	0.28–0.42
Terrain Suitability	0.25	0.20–0.30
Infrastructure Accessibility	0.20	0.16–0.24
Grid Proximity	0.12	0.10–0.14
Social Impact	0.08	0.06–0.10
CR	0.087	–

Overall suitability scores were computed as:

$$S_{overall} = \sum_{i=1}^{5} w_i \cdot C_i \tag{6}$$

where w_i = AHP weights, C_i = normalized criterion scores (0–100 scale).

D. Spatial Hotspot Analysis

Getis-Ord G_i^* statistic identified statistically significant spatial clustering:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j - \bar{X} \sum_{j=1}^{n} w_{ij}}{S \sqrt{\frac{n \sum_{j=1}^{n} w_{ij}^2 - (\sum_{j=1}^{n} w_{ij})^2}{n-1}}} \tag{7}$$

where w_{ij} = spatial weight matrix (inverse distance), x_j = suitability score, $\bar{X}$ = mean suitability, S = standard deviation.

Sites with $G_i^* > 1.96$ ($p < 0.05$) were classified as "hot spots", indicating high-potential clustering.

E. Capacity Factor Modeling

Monthly capacity factors accounted for:

- Temperature effects: $\eta(T) = \eta_{STC}[1 - \gamma(T_{cell} - 25)]$
- Soiling losses: deployment and season-specific
- Shading: horizon profiling for rooftop systems
- Aging: linear degradation rate (0.5%/year)

$$CF_m = \frac{GHI_m \times PR \times \eta(T_m) \times (1 - L_{soil,m})}{1000 \times 24 \times days_m} \tag{8}$$

where PR = performance ratio, L_{soil} = soiling loss factor.

F. Economic Analysis

1) Levelized Cost of Electricity: LCOE calculated using standard formula with Bangladesh-specific parameters:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{9}$$

with discount rate $r = 8\%$, project lifetime $n = 25$ years.

2) Financial Metrics:

- **Net Present Value:** $NPV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+r)^t} - I_0$
- **Internal Rate of Return:** Solving $NPV = 0$ for r
- **Payback Period:** t where $\sum_{i=1}^{t} CF_i = I_0$

Electricity tariff assumed at 0.12 USD/kWh (industrial rate).

G. Energy Storage Optimization

Three storage technologies evaluated: lithium-ion (Li-ion), vanadium redox flow battery (VRFB), and pumped hydro storage (PHS).

Grid firming capability defined as:

$$GF = \frac{E_{firm}}{E_{total}} \times 100\% \tag{10}$$

Target: 80% grid firming with optimized storage capacity using linear programming:

Minimize: $LCOS = \frac{C_{storage} + \sum_{t=1}^{n} O\&M_t/(1+r)^t}{\sum_{t=1}^{n} E_{cycled,t}/(1+r)^t}$

Subject to: $GF \geq 80\%$, storage constraints

H. Environmental Impact Assessment

1) Lifecycle Waste Projection: 25-year waste estimates based on panel composition:

- Glass: 74% (90% recyclable)
- Aluminum: 10% (95% recyclable)
- Silicon: 5% (85% recyclable)
- Copper: 1% (99% recyclable)
- Inverters & BOS: 10%

Total waste intensity: 18–22 tonnes/MW.

2) Carbon Offset Calculation:

$$CO_{2offset} = E_{annual} \times EF_{grid} \times n \tag{11}$$

where $EF_{grid} = 0.7$ tCO/MWh (Bangladesh grid emission factor).

I. Sensitivity and Uncertainty Analysis

Monte Carlo simulation (10,000 iterations) assessed parameter uncertainty:

- GHI: $\pm$10% variation
- CAPEX: $\pm$15% variation
- Discount rate: 6–10% range
- Panel degradation: 0.4–0.7%/year

AHP sensitivity tested criterion weights with $\pm$20% perturbation.

IV. Results

A. Spatial Suitability Assessment

1) Overall Suitability Distribution: Analysis of 400 candidate sites revealed mean overall suitability of 68.2 $\pm$ 12.5. The distribution exhibits right skewness (skewness = 0.32), indicating concentration in medium-high suitability range.

TABLE IV: Suitability Score Statistics

Metric	**All Sites**	**Top 5%**	**Top 10%**
Mean Score	68.2	91.5	88.3
Std. Deviation	12.5	2.1	3.4
Min Score	46.1	90.8	86.4
Max Score	97.3	97.3	96.1
25th Percentile	59.4	90.2	86.9
75th Percentile	76.8	92.8	90.5

Top 5% sites (n=20, threshold score $\geq$ 90.8) demonstrate remarkable consistency (CV = 2.3%), validating robust identification of high-potential zones.

2) Deployment Type Distribution: Among the 400 analyzed sites:

- Ground-mounted (degraded land): 48.5% (194 sites)
- Rooftop: 31.8% (127 sites)
- Floating PV: 19.8% (79 sites)

Top 5% sites show balanced distribution: Ground (50%), Rooftop (30%), Floating (20%), indicating diverse deployment opportunities.

3) Geographic Distribution: High-suitability sites cluster in three primary zones:

TABLE V: Geographic Clustering of Priority Sites

Zone	Location	Sites	Avg. Score	Area (km²)
Northern Uplands	25.1–25.3°N	8	92.8	245
Central Corridor	24.8–25.0°N	7	91.2	312
Southern Basin	24.6–24.7°N	5	90.9	198

4) Hotspot Analysis Results: Getis-Ord G_i^* analysis identified 68 hot spots (17% of sites) and 43 cold spots (10.8%).

Key findings:

- Hot spots predominantly in low-population density areas (avg: 89 people/km² vs. district avg: 1,015 people/km²)
- Strong correlation with grid proximity ($r = 0.67$, $p < 0.001$)
- Clustering coefficient: 0.58 (moderate spatial autocorrelation)

B. Temporal Analysis: Seasonal Patterns

1) Monthly Solar Resource Variability: Solar irradiation exhibits pronounced seasonal variation:

TABLE VI: Monthly Solar Irradiation Statistics (kWh/m²/day)

Season	Mean	Std. Dev.	Range
Winter (Dec–Feb)	4.82	0.35	4.2–5.4
Pre-Monsoon (Mar–May)	5.67	0.42	4.9–6.5
Monsoon (Jun–Sep)	4.15	0.58	2.8–5.1
Post-Monsoon (Oct–Nov)	4.94	0.31	4.3–5.6
Annual Average	4.89	0.68	2.8–6.5

Peak month: April (5.89 kWh/m²/day)
Lowest month: July (3.92 kWh/m²/day)
Seasonal variability: 33.5%

2) Monthly Capacity Factor Analysis: Deployment-type specific capacity factors:

TABLE VII: Average Monthly Capacity Factors by Deployment Type

Month	Rooftop	Floating	Ground	Avg.
January	0.162	0.178	0.155	0.165
February	0.175	0.192	0.168	0.178
March	0.198	0.215	0.189	0.201
April	0.212	0.231	0.203	0.215
May	0.201	0.219	0.192	0.204
June	0.142	0.165	0.131	0.146
July	0.128	0.152	0.118	0.133
August	0.135	0.159	0.125	0.140
September	0.151	0.172	0.142	0.155
October	0.168	0.185	0.159	0.171
November	0.171	0.188	0.163	0.174
December	0.158	0.174	0.151	0.161
Annual Avg.	**0.167**	**0.186**	**0.158**	**0.170**

Key observations:

- Floating PV achieves 11.4% higher annual CF due to evaporative cooling
- Monsoon season (Jun–Sep) reduces CF by 28–35% across all types
- Ground systems suffer most from soiling (10% loss vs. 5% for floating)
- Pre-monsoon season (Mar–May) optimal for maintenance scheduling

C. Economic Viability Assessment

1) LCOE Analysis: Comprehensive LCOE analysis across 50 economically assessed sites:

TABLE VIII: LCOE Statistics by Deployment Type (USD/kWh)

Metric	Rooftop	Floating	Ground
Mean	0.0853	0.0834	0.0869
Median	0.0842	0.0826	0.0862
Std. Dev.	0.0089	0.0095	0.0103
Min	0.0731	0.0744	0.0729
Max	0.1014	0.1055	0.1128
95% CI	0.083–0.088	0.080–0.087	0.084–0.090

Floating systems demonstrate lowest mean LCOE (USD 0.0834/kWh) due to superior capacity factors offsetting higher CAPEX. All deployment types remain below Bangladesh's industrial tariff (USD 0.12/kWh), confirming economic viability.

TABLE IX: Comprehensive Financial Analysis

Metric	Rooftop	Floating	Ground	Overall
NPV (Million USD)	2.18	2.45	1.96	2.20
IRR (%)	14.8	15.9	13.7	14.8
Payback (years)	7.4	6.9	7.9	7.4
Capacity (MW)	1.8	2.1	1.6	1.8
Ann. Gen. (MWh)	2,650	3,420	2,280	2,780

2) Financial Performance Metrics:

3) Aggregate Deployment Potential: Analysis of top 50 sites reveals:

- **Total capacity:** 89.2 MW
- **Required investment:** USD 109.4 million
- **Annual generation:** 138,950 MWh
- **CO offset:** 97,265 tonnes/year
- **Weighted average LCOE:** USD 0.0852/kWh
- **Average payback:** 7.4 years
- **Average IRR:** 14.8%

Economic viability classification:

- High viability (LCOE < 0.08): 28% of sites
- Medium viability (0.08–0.09): 54% of sites
- Low viability (LCOE > 0.09): 18% of sites

D. Energy Storage Requirements

1) Storage Technology Comparison:

TABLE X: Storage Technology Performance Metrics

Technology	Li-ion	VRFB	PHS
CAPEX (USD/kWh)	285	412	178
Round-trip Eff. (%)	89.5	72.8	81.2
Cycle Life (cycles)	5,000	12,000	20,000
Grid Firming (%)	78.3	82.1	85.6
LCOS (USD/kWh)	0.142	0.168	0.095
Combined LCOE	0.095	0.101	0.091

2) Optimal Storage Configuration: To achieve 80% grid firming:

- **Li-ion:** 4.2 hours storage duration, 374 MWh capacity
- **VRFB:** 6.8 hours storage duration, 606 MWh capacity
- **PHS:** 8.5 hours storage duration, 758 MWh capacity

Recommended solution: Hybrid Li-ion (60%) + VRFB (40%) configuration:

- Leverages Li-ion for high-frequency cycling
- VRFB handles longer-duration monsoon deficits
- Combined LCOS: USD 0.151/kWh
- Grid firming capability: 81.4%
- Total storage investment: USD 148.2 million

E. Environmental Impact Assessment

1) Lifecycle Waste Projections: 25-year deployment scenario (89.2 MW):

TABLE XI: Lifecycle Waste Generation and Recovery

Material	Waste (tonnes)	Recovery Rate	Recycled (tonnes)
Glass	1,328	90%	1,195
Aluminum	179	95%	170
Silicon	90	85%	77
Copper	18	99%	18
Inverter/BOS	179	60%	107
Total	**1,794**	**–**	**1,567**

Overall recovery rate: 87.4%
Landfill waste: 227 tonnes (12.6%)

2) Carbon Footprint Analysis:

- **Manufacturing emissions:** 42 gCOeq/kWh
- **Lifecycle emissions:** 48 gCOeq/kWh
- **Grid displacement:** 700 gCO/kWh
- **Net carbon offset:** 652 gCO/kWh
- **Energy payback time:** 2.1 years
- **25-year cumulative offset:** 2.43 million tonnes CO

F. Risk Assessment

1) Monsoon Risk Classification: Sites categorized by integrated risk score:

TABLE XII: Monsoon Risk Distribution

Risk Category	Sites (%)	Avg. Flood Score	Avg. Cyclone Exp.
Low Risk	42.5	0.18	0.22
Medium Risk	40.0	0.35	0.38
High Risk	17.5	0.62	0.51

High-risk sites primarily in southern haor basin. Risk mitigation strategies:

- Elevated mounting structures (+1.5m)
- Enhanced anchoring systems (cyclone-rated)
- Quarterly inspection during monsoon season
- Insurance coverage (estimated 2.5% of CAPEX annually)

2) Extreme Weather Impact: Historical analysis (15-year record):

- 24 significant weather events
- Average PV damage: 3.2% per event
- Generation loss: 1,250 MWh/year (0.9% of total)
- Most vulnerable: Ground systems in flood zones

G. Sensitivity Analysis

1) AHP Weight Perturbation: ±20% variation in criterion weights:

TABLE XIII: Sensitivity Index by Criterion

Criterion	Sensitivity Index	Rank Stability
Solar Resource	1.82	94%
Terrain Suitability	1.15	97%
Infrastructure	0.98	98%
Grid Proximity	1.67	95%
Social Impact	0.74	99%
Average	**1.27**	**96.6%**

Model demonstrates **HIGH robustness** (avg. sensitivity $<$ 2.0). Top 10 sites maintain rank in 96.6% of perturbation scenarios.

2) Economic Parameter Uncertainty: Monte Carlo simulation (10,000 iterations):

TABLE XIV: LCOE Uncertainty Analysis (USD/kWh)

Percentile	Rooftop	Floating	Ground
5th	0.0725	0.0698	0.0742
25th	0.0798	0.0771	0.0815
50th (Median)	0.0853	0.0834	0.0869
75th	0.0911	0.0902	0.0928
95th	0.0998	0.1012	0.1045
Probability LCOE $<$ 0.10	92%	94%	89%

High confidence in economic viability: 89–94% probability of LCOE remaining below 0.10 USD/kWh threshold.

H. Comparative Benchmarking

1) Regional Comparison: Sylhet District performance vs. other South Asian regions:

Sylhet's monsoon climate reduces performance 8–12% compared to drier regions but remains economically competitive through optimized deployment strategies.

V. Discussion

A. Key Findings and Implications

1) Spatial Deployment Strategy: The identification of 20 top-tier sites (suitability $\geq$ 90.8) with 89.2 MW aggregate

TABLE XV: Regional Solar PV Benchmarking

Region	Avg. GHI	Capacity Factor	LCOE
Sylhet, Bangladesh	4.89	0.170	0.085
Rajshahi, Bangladesh	5.21	0.182	0.079
Kerala, India	5.15	0.178	0.082
Tamil Nadu, India	5.68	0.195	0.074
Punjab, Pakistan	5.92	0.203	0.071

capacity provides actionable deployment roadmap. Geographic clustering in three zones facilitates:

- **Economies of scale:** Shared infrastructure and O&M services
- **Grid integration:** Concentrated generation reduces transmission losses
- **Risk diversification:** Geographic spread mitigates localized weather impacts

Priority deployment sequence: Northern Uplands (highest suitability) $\rightarrow$ Central Corridor (best grid access) $\rightarrow$ Southern Basin (lowest population density).

2) Temporal Optimization Opportunities: Monthly capacity factor analysis reveals critical insights:

1) **Seasonal load matching:** Pre-monsoon peak (April: CF=0.215) aligns with agricultural irrigation demand
2) **Storage sizing:** Monsoon deficit (Jul–Sep: avg CF=0.143) drives 6–8 hour storage requirement
3) **Maintenance scheduling:** Post-monsoon period (Oct–Nov) optimal for system servicing
4) **Soiling mitigation:** Enhanced cleaning protocols during dry season can improve annual CF by 3–5%

3) Technology-Specific Advantages: Floating PV emerges as optimal technology for Sylhet:

Advantages:

- 11.4% higher CF (evaporative cooling effect)
- Reduced land acquisition costs (utilize existing water bodies)
- Lower soiling losses (5% vs. 10% for ground systems)
- Potential for aquaculture integration

Challenges:

- 32% higher CAPEX (anchoring and flotation systems)
- Monsoon-season operational constraints
- Limited suitable water body inventory (79 sites identified)

Recommendation: 20–30% floating deployment in mixed portfolio.

B. Economic and Policy Considerations

1) Financial Viability: All analyzed deployment types demonstrate strong economics:

- IRR (13.7–15.9%) exceeds Bangladesh's infrastructure project hurdle rate (12%)
- Payback periods (6.9–7.9 years) within acceptable investor timelines
- LCOE (USD 0.083–0.087) below grid parity threshold

Financing mechanisms to accelerate deployment:

1) Feed-in tariffs: Guaranteed USD 0.095/kWh for 15 years
2) Concessional loans: IDA/ADB financing at 3–5% interest
3) Tax incentives: 5-year exemption on equipment imports
4) Green bonds: Municipal-level renewable energy financing

2) Grid Integration Roadmap: Current grid infrastructure constraints require phased approach:

Phase 1 (0–2 years): 25 MW deployment near existing substations

- Sites within 2 km of grid (high accessibility)
- Minimal transmission upgrades required
- Li-ion storage (2–4 hour duration)

Phase 2 (2–5 years): 35 MW expansion with transmission enhancement

- Medium accessibility sites (2–5 km from grid)
- 33 kV line extensions
- Hybrid Li-ion/VRFB storage

Phase 3 (5–10 years): 29 MW completion with advanced integration

- Remote sites with high solar potential
- Smart grid infrastructure
- Potential pumped hydro storage (hillside reservoirs)

C. Environmental and Social Co-Benefits

1) Carbon Mitigation Impact: 89.2 MW deployment yields substantial emissions reductions:

- Annual offset: 97,265 tonnes CO
- 25-year cumulative: 2.43 million tonnes CO
- Equivalent to removing 52,000 cars from roads
- Supports Bangladesh's NDC commitment (40% renewable energy by 2041)

2) Circular Economy Opportunities: High material recovery rate (87.4%) creates local economic opportunities:

Recommended ecosystem:

- Establish regional PV recycling facility in Sylhet City
- Partner with cement manufacturers for glass recovery
- Export high-value materials (silicon, copper) to specialized processors
- Create 50–75 green jobs in recycling sector

3) Social Equity Considerations: Prioritizing low-population-density sites (avg. 89 vs. 1,015 people/km²) minimizes displacement. Additional social benefits:

- Rural electrification: Off-grid communities gain reliable power
- Agricultural productivity: Irrigation pump electrification
- Healthcare access: Refrigerated vaccine storage in rural clinics
- Education: School electrification enabling digital learning

D. Challenges and Mitigation Strategies

1) Monsoon Risk Management: High-risk sites (17.5%) require enhanced resilience measures:

Recommended approach: Combine structural measures (13% CAPEX premium) with insurance for optimal risk-return profile.

TABLE XVI: Risk Mitigation Cost-Benefit Analysis

Mitigation Strategy	Cost (% CAPEX)	Risk Reduction	ROI
Elevated structures	8%	65%	4.2:1
Enhanced anchoring	5%	45%	5.8:1
Flood barriers	12%	80%	3.1:1
Insurance coverage	2.5%/yr	100%	N/A

2) Technical Skill Gap: Bangladesh faces shortage of specialized O&M personnel. Capacity building initiatives:

- Establish PV technician training program at Sylhet Engineering College
- Partner with international manufacturers for knowledge transfer
- Develop local supply chain for spare parts and consumables
- Create certification framework for solar installers

3) Land Tenure Complexity: Degraded land deployment faces regulatory hurdles. Policy recommendations:

1) Streamline land lease procedures for renewable projects
2) Develop standard PPP (Public-Private Partnership) frameworks
3) Provide land tax incentives for solar-compatible use
4) Fast-track environmental clearances for low-impact sites

E. Limitations and Future Research

1) Study Limitations:

1) **Spatial resolution:** 200×200 grid may miss micro-scale variations
2) **Climate data:** Reliance on modeled data (POWER, PVGIS) rather than dense ground station network
3) **Economic assumptions:** Fixed discount rate (8%) and equipment costs; actual values may vary
4) **Grid constraints:** Simplified transmission modeling; detailed power flow analysis needed
5) **Social factors:** Limited primary stakeholder engagement; community acceptance not quantified

2) Future Research Directions:

1) **High-resolution validation:** Deploy ground-based monitoring at top 10 sites for model validation
2) **Dynamic grid modeling:** Integrate with Bangladesh Power Development Board's grid simulation tools
3) **Hybrid systems analysis:** Assess solar-wind complementarity and hybrid plant optimization
4) **Agrivoltaics potential:** Evaluate dual land-use opportunities for food-energy nexus
5) **Climate change scenarios:** Project impacts of RCP 4.5 and 8.5 pathways on solar resource
6) **Real-time forecasting:** Develop ML-based day-ahead generation prediction models
7) **Community-scale projects:** Design and pilot community-owned solar cooperatives

F. Replicability and Scalability

The developed framework demonstrates strong replicability potential for similar tropical/subtropical regions facing monsoon variability:

Transferable methodologies:

- GIS-MCDM-AHP integration approach
- Seasonal capacity factor modeling with climate-specific corrections
- Deployment-type comparative assessment framework
- Storage optimization for variable renewable integration

Adaptation requirements for other regions:

- Recalibrate AHP weights through local expert elicitation
- Adjust soiling loss factors based on local aerosol conditions
- Update economic parameters using regional cost data
- Modify risk assessment for region-specific hazards (e.g., typhoons, dust storms)

VI. Conclusions

This study presents a comprehensive spatiotemporal assessment of solar PV potential in Sylhet District, Bangladesh, integrating GIS-based suitability analysis, seasonal performance modeling, economic evaluation, and environmental impact assessment.The code and everything available at https://github.com/near-ingenious/GIS-based-Spatio-Temporal-Model
Key conclusions:

A. Technical Findings

1) **Viable deployment potential:** 89.2 MW identified across 50 high-suitability sites with mean overall suitability score of 91.5 (top 5%)
2) **Performance characteristics:** Annual capacity factors range from 0.158 (ground) to 0.186 (floating), with pronounced seasonal variation (28–35% reduction during monsoon)
3) **Spatial clustering:** Three priority deployment zones identified with 96.6% rank stability under sensitivity analysis, demonstrating robust site selection
4) **Technology differentiation:** Floating PV demonstrates 11.4% performance advantage, offsetting 32% higher CAPEX for net LCOE competitiveness

B. Economic Outcomes

1) **Financial viability:** All deployment types achieve LCOE (USD 0.083–0.087/kWh) below grid parity, with IRR of 13.7–15.9% and payback periods of 6.9–7.9 years
2) **Investment requirement:** Total CAPEX of USD 109.4 million for 89.2 MW, yielding 138,950 MWh annual generation
3) **Storage integration:** Hybrid Li-ion/VRFB configuration (USD 148.2 million) achieves 81.4% grid firming at combined LCOS of USD 0.151/kWh

C. Environmental and Social Impact

1) **Carbon mitigation:** 97,265 tonnes CO offset annually (2.43 million tonnes over 25 years), supporting Bangladesh's NDC targets
2) **Circular economy:** 87.4% material recovery rate through proposed regional recycling infrastructure, creating 50–75 green jobs
3) **Social equity:** Site prioritization in low-density areas (89 vs. 1,015 people/km² district average) minimizes displacement while enabling rural electrification

D. Policy Recommendations

Immediate actions (0–2 years):

- Implement feed-in tariff of USD 0.095/kWh for 15 years
- Fast-track environmental clearances for identified priority sites
- Establish regional PV technician training program
- Deploy 25 MW near existing grid infrastructure

Medium-term initiatives (2–5 years):

- Upgrade transmission infrastructure to accommodate 60 MW total
- Launch municipal green bond program for distributed generation
- Develop standard PPP frameworks for degraded land utilization
- Pilot community-owned solar cooperative models

Long-term strategy (5–10 years):

- Complete 89.2 MW deployment with advanced storage integration
- Establish Southeast Asia's first comprehensive PV recycling facility
- Integrate smart grid technologies for real-time optimization
- Expand framework to remaining Bangladesh districts

E. Broader Implications

This research demonstrates that despite monsoon climate challenges, Sylhet District possesses significant economically viable solar PV potential. The integrated GIS-MCDM-AHP framework provides a replicable methodology for similar tropical regions, addressing the critical need for climate-adapted renewable energy planning tools.

By quantifying seasonal variability, optimizing storage solutions, and addressing lifecycle sustainability, this study bridges the gap between theoretical potential and practical deployment strategy. The findings directly support Bangladesh's renewable energy targets while providing a template for sustainable energy transitions in monsoon-influenced developing regions globally.

Final perspective: Solar PV development in Sylhet District represents not merely an energy infrastructure project, but a pathway toward climate resilience, economic development, and social equity. Successful implementation of the proposed roadmap could establish Sylhet as a model for sustainable energy planning in challenging tropical climates, demonstrating that environmental constraints can be transformed into opportunities through rigorous analysis and strategic deployment.

Acknowledgments

The authors acknowledge the Bangladesh Meteorological Department for providing ground validation data, the Bangladesh Power Development Board for grid infrastructure information, and the anonymous reviewers for their constructive feedback. This research was supported by Metropolitan University, Sylhet.

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