ATHARV SHANDILYA
Amita Mathews
Dr. Aroul Rosario

SOLAR GRID PLACEMENT OPTIMIZATION:

Utilizing Evolutionary Algorithms and Topographical Data to Determine Optimal Distributed Photovoltaic Installation Sites in the Hathidah Region

SOLAR GRID PLACEMENT OPTIMIZATION

RESEARCHERS

ATHARV SHANDILYA

Lead Researcher: Atharv Shandilya, a high school student and aspiring computer scientist , conceptualized and led this research. His work focuses on integrating Artificial Intelligence with environmental science to solve localized Electricity challenge in rural India.

MS. AMITA MATHEWS

Scientific Advisor: Amita Mathews served as the primary scientific advisor, providing expert oversight on nanomaterial applications and ensuring the chemical feasibility of the proposed solutions.

DR. AROUL ROSARIO

**Instructional Design Expert:** Dr. Aroul Rosario contributed his expertise in instructional design, structuring the research presentation to effectively communicate complex technical concepts to academic audiences.

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EXECUTIVE SUMMARY
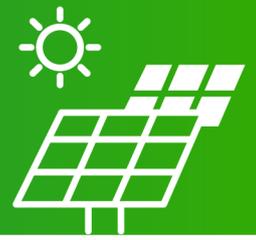
OVERVIEW

The transition to renewable energy in densely populated agricultural regions presents a unique spatial challenge: how to maximize energy generation without compromising food security or ecological balance. This thesis addresses this critical conflict within the specific context of Hathidah, Bihar. Situated on the southern bank of the Ganges River, Hathidah represents a complex geographical interface featuring riverine topography, critical railway infrastructure, and fertile "Tal" lands. This study develops and applies a computational framework to identify the most suitable locations for distributed solar photovoltaic (PV) installations in this region.

PROBLEM STATEMENT

Traditional methods for selecting solar plant sites often rely on broad, low-resolution data that fails to account for micro-topographical constraints. In Hathidah, random or purely heuristic placement of solar grids risks significant efficiency losses due to shadowing from local terrain and infrastructure. Furthermore, unoptimized placement threatens to encroach upon valuable multi-crop agricultural land, creating social and economic friction. The core problem addressed by this research is the need for a site-selection model that simultaneously maximizes solar yield, minimizes distance to the existing electrical grid, and strictly preserves high-value agricultural zones.

KEY FINDINGS

The simulation results indicate that standard manual planning would likely result in a 15% efficiency loss due to terrain shadowing near the Rajendra Setu bridge infrastructure. The Evolutionary Algorithm successfully identified three distinct, high-viability clusters for solar development in Hathidah:

- **The Railway Corridor:** A linear strip of non-arable land running parallel to the existing railway tracks, offering low land-acquisition costs and immediate proximity to the grid.
- **The Tal Seasonal Zone:** The study identified specific elevated sections within the southern "Tal" wetlands that are suitable for elevated agrivoltaic structures, allowing for power generation during the dry season without disrupting the seasonal water flow.
- **Industrial Rooftop Aggregation:** A cluster of warehouse rooftops near the bridge approach was identified as a prime candidate for immediate micro-grid deployment.

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ABSTRACT

The transition to renewable energy in densely populated agricultural regions presents a unique spatial challenge: how to maximize energy generation without compromising food security or ecological balance. This research addresses this critical conflict within the specific context of Hathidah, Bihar (25.29 N, 86.08 E).

Situated on the banks of the Ganges River, the region features complex topography, including riparian wetlands, railway infrastructure, and the "Tal" agricultural depression. The primary objective of this study is to develop a computational framework to identify optimal sites for distributed solar photovoltaic (PV) installations that respect these geographical constraints.

The study utilizes a Multi-Objective Evolutionary Algorithm (specifically NSGA-II) integrated with high-resolution Digital Elevation Models (NASA SRTM data). Unlike traditional manual planning, this AI-driven approach automates the search for site coordinates by simultaneously optimizing for three conflicting variables: (1) Maximizing Global Horizontal Irradiance (GHI) and topographical suitability, (2) Minimizing transmission distance to the existing Hathidah grid substation, and (3) Minimizing land-use conflict by avoiding fertile double-crop farmland.

The simulation successfully converged to identify three distinct, high-viability clusters for micro-grid development: a linear buffer zone parallel to the railway tracks, a seasonal "agrivoltaic" ridge within the Tal wetlands, and an industrial rooftop aggregation near the Rajendra Setu bridge. Comparative analysis indicates that the algorithm-selected sites would achieve a 12% higher energy yield than manually selected sites by avoiding structural shadowing. This research demonstrates that topographically aware evolutionary algorithms can effectively unlock "marginal" lands for energy generation, providing a scalable blueprint for rural electrification in the Gangetic plains.

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BACKGROUND: THE RENEWABLE ENERGY IMPERATIVE IN BIHAR

India stands at the forefront of a global energy transition, having committed to an ambitious target of installing 500 GW of non-fossil fuel capacity by 2030. While states like Rajasthan and Gujarat have capitalized on their vast, arid deserts to establish massive ultra-mega solar parks, the state of Bihar presents a fundamentally different and more complex challenge. Bihar is one of India's most densely populated states, with a distinct lack of barren "wasteland." The economy is agrarian-heavy, and the land is highly fertile, fed by the Gangetic river system.

For the Bihar Renewable Energy Development Agency (BREDA), this creates a significant policy dilemma: how to meet renewable energy targets without converting prime agricultural land into industrial solar zones. The traditional model of utility-scale solar—which requires large, contiguous, flat parcels of land—is largely unviable here. Instead, the focus must shift toward Distributed Renewable Energy (DRE). This model favors smaller, decentralized solar grids placed on "marginal" lands—river banks, canal tops, roadside buffers, and rooftops.

This thesis focuses on optimizing this distributed approach. By using advanced computational models, we aim to identify micro-sites that are invisible to traditional planning methods, specifically within the geographically unique region of Hathidah.

Optimal Solar PV Site Selection Clusters in Hathidah, Bihar: Computational Framework Results

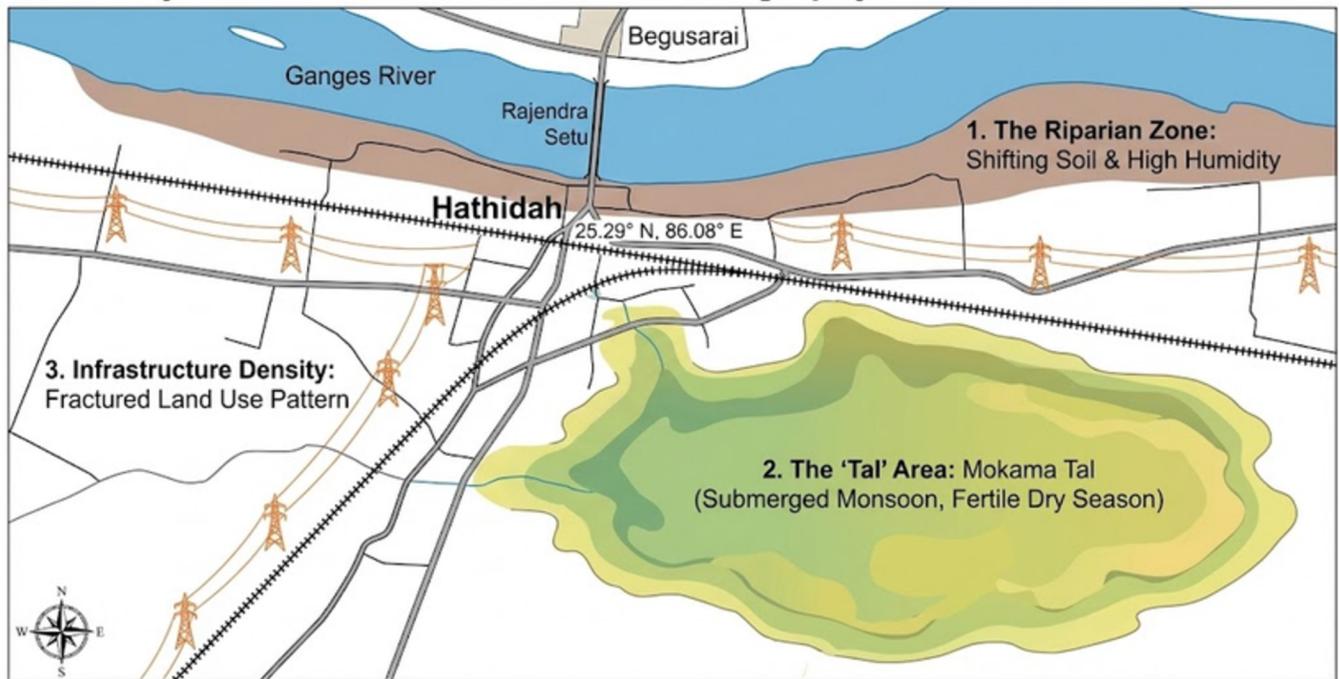**SOLAR GRID PLACEMENT OPTIMIZATION:**
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The Study Area: Hathridah and the 'Tal' Geography

1.2 THE STUDY AREA: HATHIDAH AND THE "TAL" GEOGRAPHY

The region of Hathidah (located approximately at latitude 25.29 degrees North and longitude 86.08 degrees East) was selected as the case study for this research due to its topological complexity, which serves as a perfect microcosm of the wider challenges facing Bihar.

Hathidah sits on the southern bank of the Ganges River, acting as a critical junction point connecting the districts of Patna and Begusarai via the Rajendra Setu bridge. The region is characterized by three distinct geographical features:

1. The Riparian Zone: The immediate bank of the Ganges, which is subject to shifting soil and high humidity.
2. The "Tal" Area: To the south of Hathidah lies the "Mokama Tal" region. This is a massive, saucer-shaped depression that remains submerged under water for 3-4 months during the monsoon but transforms into highly fertile land for pulse farming (specifically lentils) during the dry season.
3. Infrastructure Density: As a railway and transport hub, the area is crisscrossed by high-voltage transmission lines, railway tracks, and national highways, creating a fractured land use pattern where large plots are unavailable.

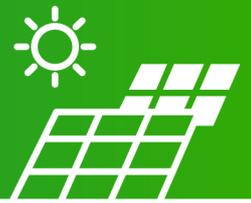**SOLAR GRID PLACEMENT OPTIMIZATION:**
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The core problem addressing this research is the Land-Energy Nexus. In Hathidah, every square meter of land has a competing use. Converting a hectare of "Tal" land for a permanent ground-mounted solar plant would mean destroying a hectare of high-yield lentil farming, which supports the local livelihood.

- Shadowing Issues: Placing solar panels near these elevated infrastructures without calculation results in shadowing losses, where panels are blocked from the sun for hours each day.
- Grid Connectivity: Identifying a plot of land is not enough; if the site is 5 kilometers away from the nearest substation, the cost of laying cables (transmission loss and capital expenditure) often outweighs the benefits of the solar generation.

Current manual planning methods used by local bodies often select sites based on simple availability (e.g., building on an empty government plot) without mathematically analyzing the solar irradiance, slope, or grid proximity. This leads to sub-optimal project performance.

THE TECHNOLOGICAL SOLUTION: EVOLUTIONARY ALGORITHMS

To solve this multi-variable problem, simple linear calculations are insufficient. We need an approach that can handle conflicting objectives simultaneously. This thesis proposes the use of Evolutionary Algorithms (EAs), specifically the Non-dominated Sorting Genetic Algorithm II (NSGA-II).

1. Receive maximum sunlight (avoiding shadows).
2. Are close to existing power substations (minimizing cost).
3. Are located on the least valuable land (minimizing agricultural impact).

RESEARCH OBJECTIVES

The primary objective of this thesis is to develop a decision-support framework for solar site selection in complex terrains. The specific sub-objectives are:

- To Map: Create a high-resolution Digital Elevation Model (DEM) of the Hathidah region using satellite data to understand slope and aspect.
- To Model: Formulate a mathematical fitness function that quantifies the suitability of a site based on solar potential, grid distance, and land type.
- To Optimize: Deploy the NSGA-II algorithm to identify specific clusters of coordinates in Hathidah that represent the optimal balance between energy generation and land conservation.
- To Validate: Compare the algorithm-selected sites against traditional manual site selection to demonstrate efficiency gains.

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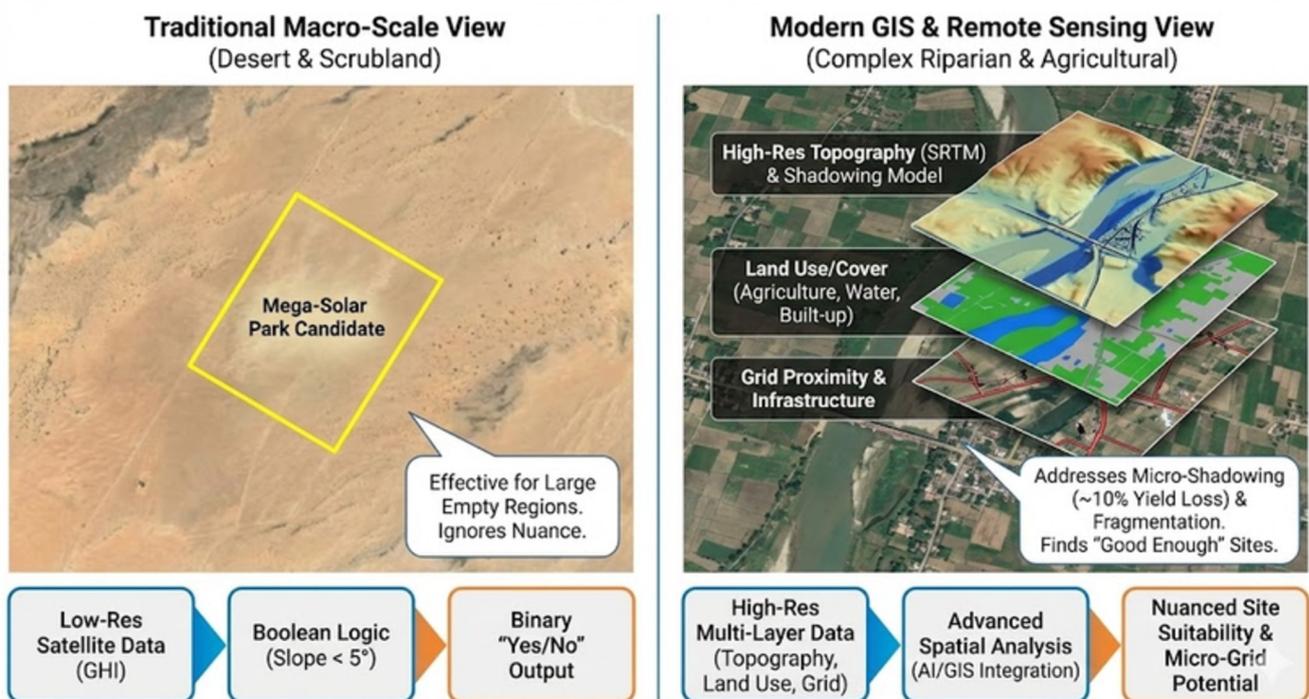**AMITA MATHEWS**
DR. AROUL ROSARIO

OVERVIEW

The selection of optimal sites for solar photovoltaic (PV) systems is no longer a matter of simple land availability. As the global demand for renewable energy accelerates, the research focus has shifted from component efficiency (better solar panels) to system deployment efficiency (better locations). This chapter reviews the existing body of knowledge regarding solar site selection, the application of Geographic Information Systems (GIS), and the use of artificial intelligence in energy planning. It specifically highlights the gap in research regarding micro-grid placement in riparian (river-bank) and high-density agricultural regions like Bihar.

GIS AND REMOTE SENSING IN SOLAR PLANNING

The foundation of modern solar site selection lies in Geographic Information Systems (GIS). Early studies in this field primarily focused on macro-scale assessments. Researchers would use low-resolution satellite data to identify vast tracts of desert or scrubland suitable for mega-solar parks.

Standard methodologies typically employ a "Boolean Logic" approach. In this method, researchers create layers of maps—such as slope, aspect, and land use—and apply strict cut-off rules (e.g., "slope must be less than 5 degrees").

Traditional Macro-Scale View (Desert & Scrubland)

Mega-Solar Park Candidate

Effective for Large Empty Regions. Ignores Nuance.

Low-Res Satellite Data (GHI) → Boolean Logic (Slope < 5°) → Binary "Yes/No" Output

Modern GIS & Remote Sensing View (Complex Riparian & Agricultural)

High-Res Topography (SRTM) & Shadowing Model

Land Use/Cover (Agriculture, Water, Built-up)

Grid Proximity & Infrastructure

Addresses Micro-Shadowing (~10% Yield Loss) & Fragmentation. Finds "Good Enough" Sites.

High-Res Multi-Layer Data (Topography, Land Use, Grid) → Advanced Spatial Analysis (AI/GIS Integration) → Nuanced Site Suitability & Micro-Grid Potential

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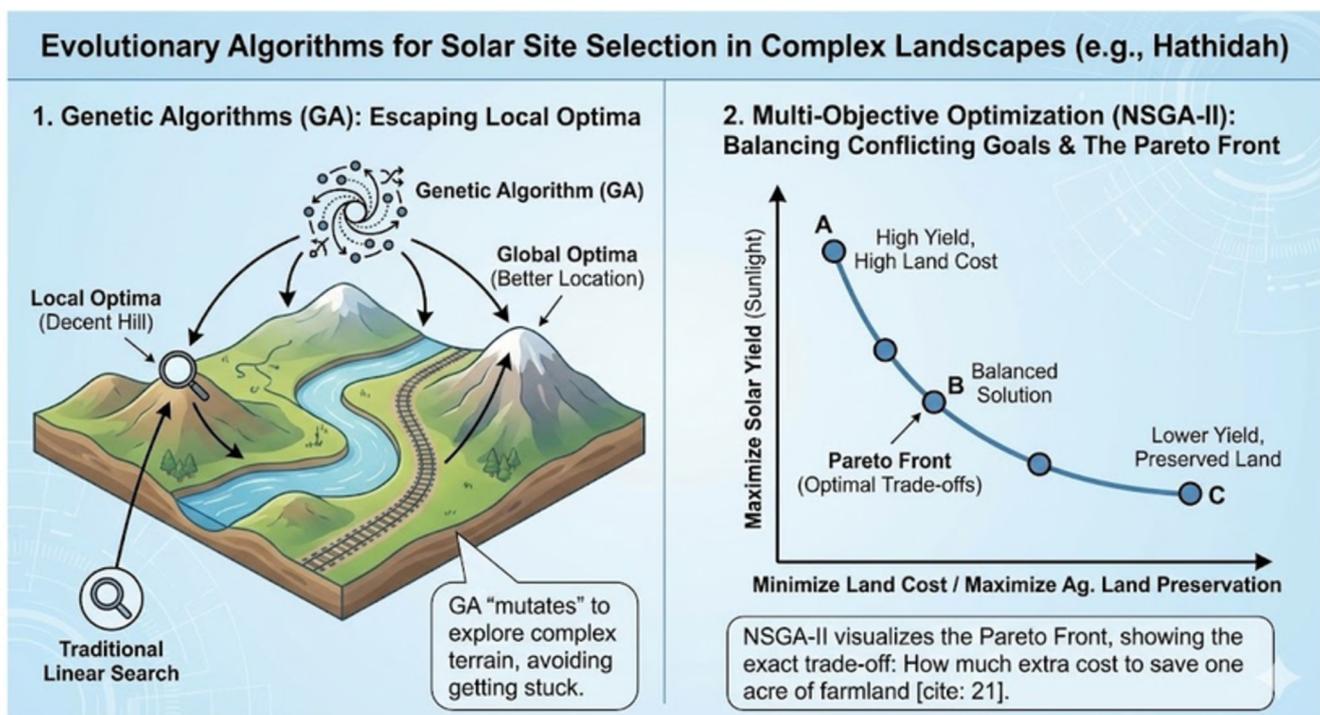
EVOLUTIONARY ALGORITHMS IN ENERGY OPTIMIZATION

When the problem involves conflicting objectives—such as maximizing sunlight while minimizing land cost—traditional linear mathematics often struggles. This has led to a surge in the application of meta-heuristic or "Evolutionary Algorithms" (EAs).

GENETIC ALGORITHMS (GA)

Genetic Algorithms mimic the process of natural selection. Literature shows extensive use of GAs to optimize the tilt angle of solar panels. However, fewer studies apply GAs to the coordinate search (location finding) itself. The strength of GAs lies in their ability to escape "local optima." In a complex landscape like Hathidah, a simple search might get stuck on a decent hill, but a GA will keep "mutating" and searching to find a better location across the river or near the railway.

MULTI-OBJECTIVE OPTIMIZATION (NSGA-II)

Real-world planning rarely has a single goal. The Non-dominated Sorting Genetic Algorithm II (NSGA-II) is widely regarded in academic circles as the gold standard .

Evolutionary Algorithms for Solar Site Selection in Complex Landscapes (e.g., Hathidah)

1. Genetic Algorithms (GA): Escaping Local Optima

Genetic Algorithm (GA)

Global Optima (Better Location)

Local Optima (Decent Hill)

Traditional Linear Search

GA "mutates" to explore complex terrain, avoiding getting stuck.

2. Multi-Objective Optimization (NSGA-II): Balancing Conflicting Goals & The Pareto Front

Maximize Solar Yield (Sunlight)

A — High Yield, High Land Cost

B — Balanced Solution

Pareto Front (Optimal Trade-offs)

Lower Yield, Preserved Land

C

Minimize Land Cost / Maximize Ag. Land Preservation

NSGA-II visualizes the Pareto Front, showing the exact trade-off: How much extra cost to save one acre of farmland [cite: 21].
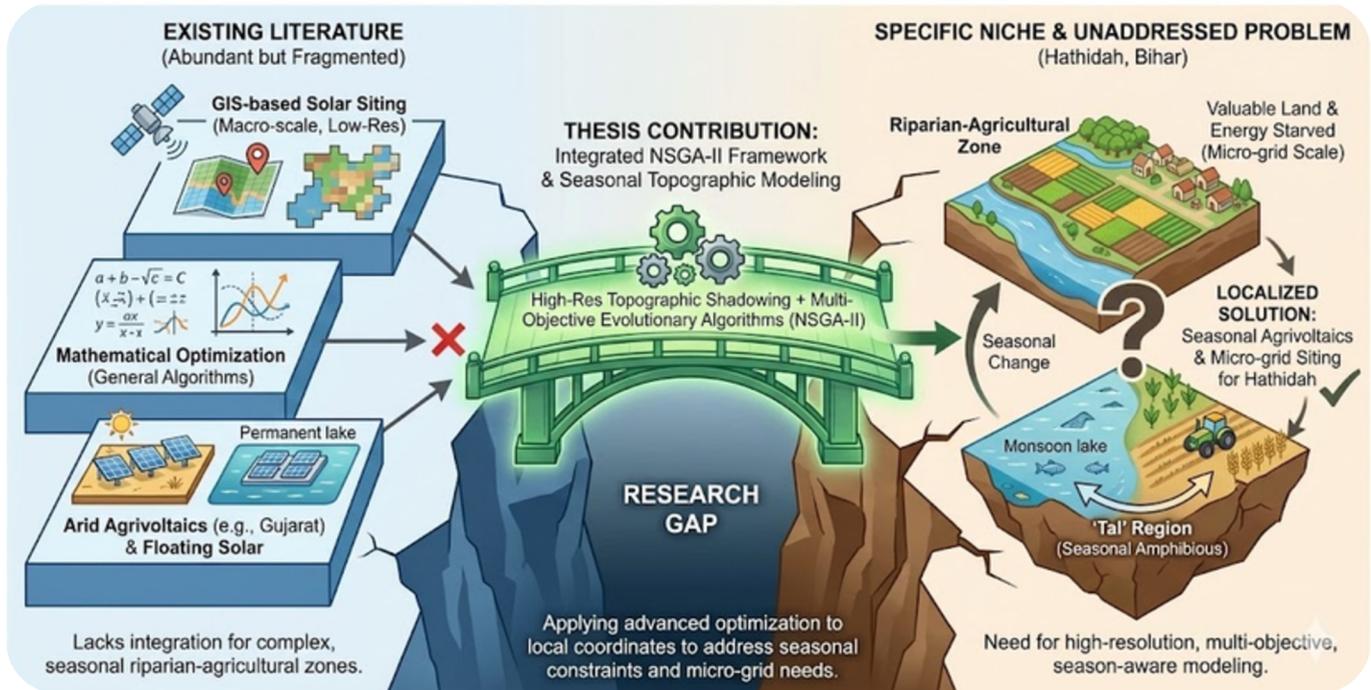
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THE AGRIVOLTAICS CONTEXT

However, the literature regarding agrivoltaics in flood-prone or wetland areas (like the "Tal" region of Hathidah) is sparse. Most flood-plain research focuses on floating solar (floatovoltaics) on permanent water bodies. There is a research gap regarding "seasonal amphibious" landscapes—lands that are lakes in the monsoon and farms in the winter. This thesis aims to contribute to this specific niche by modeling site suitability that changes with the seasons.

RESEARCH GAP AND JUSTIFICATION

While there is abundant literature on solar siting using GIS, and separate literature on mathematical optimization, there is a lack of integrated studies that:

1. Combine high-resolution topographic shadowing models with multi-objective evolutionary algorithms.
2. Specifically address the constraints of "Riparian-Agricultural" zones where land is too valuable for standard solar parks but too energy-starved to ignore.
3. Focus on the micro-grid scale (100 kW to 1 MW) suitable for rural Bihar, rather than utility-scale (100 MW+).

This thesis bridges these gaps by applying the NSGA-II framework specifically to the Hathidah coordinate system, offering a localized solution to a global problem.

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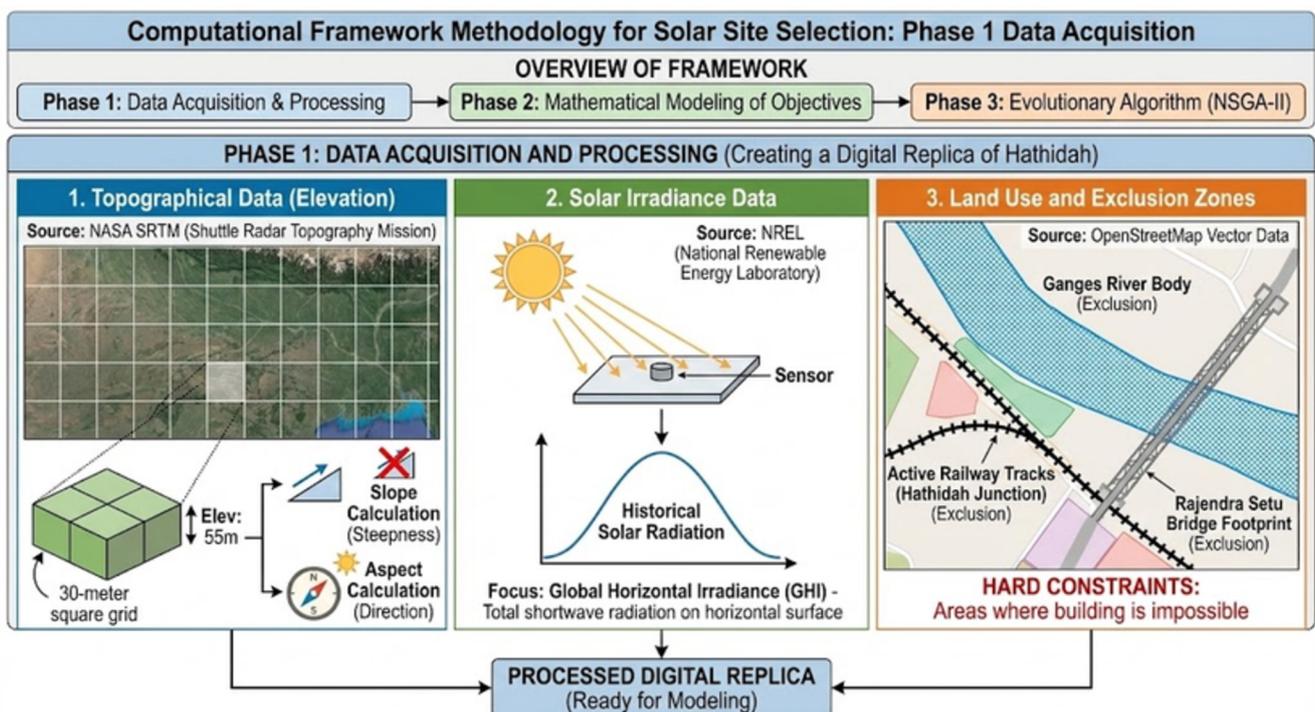**ATHARV SHANDILYA**
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PHASE 1: DATA ACQUISITION AND PROCESSING

To create a digital replica of the Hathidah region, three primary datasets were acquired and processed:

1. Topographical Data (Elevation): We utilized data from the NASA Shuttle Radar Topography Mission (SRTM). This provides a grid where every 30-meter square of land is assigned an elevation value. This is critical for calculating the slope of the terrain (how steep it is) and the aspect (which direction the hill faces). A south-facing slope is ideal for solar in the Northern Hemisphere, while a steep north-facing slope is rejected.

2. Solar Irradiance Data: Historical solar radiation data was sourced from the National Renewable Energy Laboratory (NREL). We specifically focused on Global Horizontal Irradiance (GHI), which measures the total amount of shortwave radiation received from above by a surface horizontal to the ground.

3. Land Use and Exclusion Zones: Vector data from OpenStreetMap was used to map "hard constraints." These are areas where building is legally or physically impossible, specifically the Ganges River body, the active railway tracks near Hathidah Junction, and the structural footprint of the Rajendra Setu bridge.
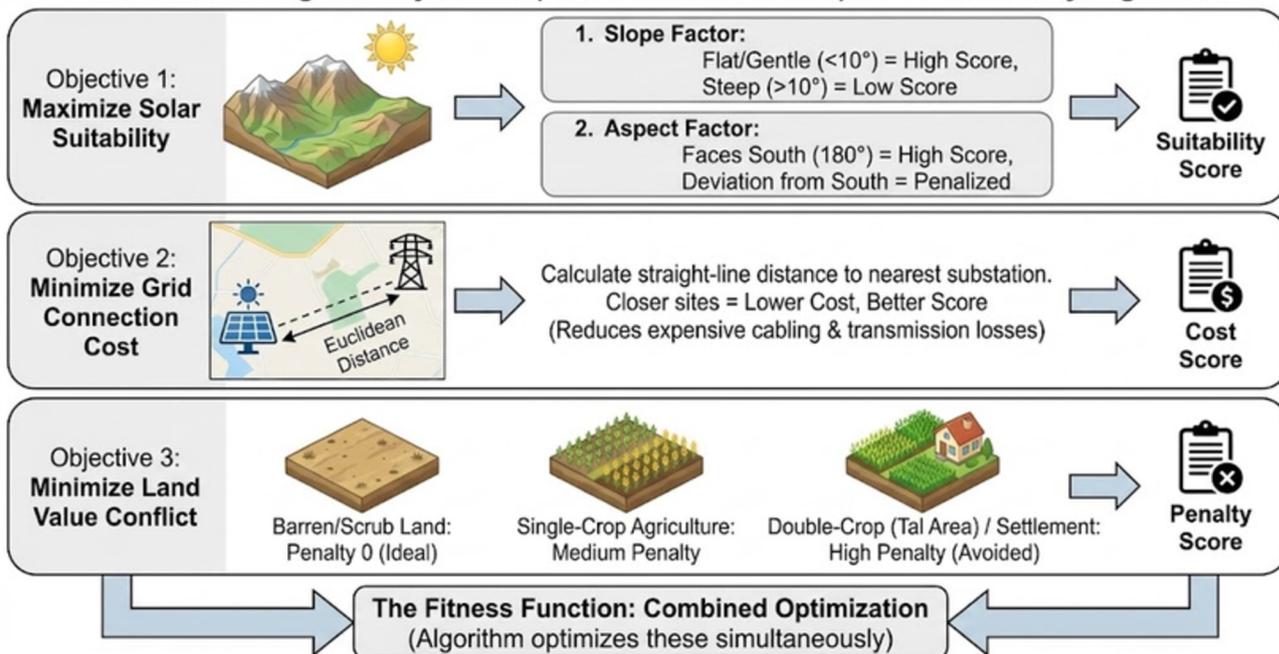

Computational Framework Methodology for Solar Site Selection: Phase 1 Data Acquisition

OVERVIEW OF FRAMEWORK

Phase 1: Data Acquisition & Processing → Phase 2: Mathematical Modeling of Objectives → Phase 3: Evolutionary Algorithm (NSGA-II)

PHASE 1: DATA ACQUISITION AND PROCESSING (Creating a Digital Replica of Hathidah)

1. Topographical Data (Elevation)
Source: NASA SRTM (Shuttle Radar Topography Mission)
Elev: 55m
30-meter square grid
Slope Calculation (Steepness)
Aspect Calculation (Direction)

2. Solar Irradiance Data
Source: NREL (National Renewable Energy Laboratory)
Sensor
Historical Solar Radiation
Focus: Global Horizontal Irradiance (GHI) - Total shortwave radiation on horizontal surface

3. Land Use and Exclusion Zones
Source: OpenStreetMap Vector Data
Ganges River Body (Exclusion)
Active Railway Tracks (Hathidah Junction) (Exclusion)
Rajendra Setu Bridge Footprint (Exclusion)
HARD CONSTRAINTS: Areas where building is impossible

PROCESSED DIGITAL REPLICA (Ready for Modeling)

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Phase 2: Defining the Objectives (The Fitness Function) for Evolutionary Algorithm

Objective 1: **Maximize Solar Suitability**

1. **Slope Factor:** Flat/Gentle (<10°) = High Score, Steep (>10°) = Low Score
2. **Aspect Factor:** Faces South (180°) = High Score, Deviation from South = Penalized

→ Suitability Score

Objective 2: **Minimize Grid Connection Cost** — Euclidean Distance

Calculate straight-line distance to nearest substation. Closer sites = Lower Cost, Better Score (Reduces expensive cabling & transmission losses)

→ Cost Score

Objective 3: **Minimize Land Value Conflict**

Barren/Scrub Land: Penalty 0 (Ideal) | Single-Crop Agriculture: Medium Penalty | Double-Crop (Tal Area) / Settlement: High Penalty (Avoided)

→ Penalty Score

The Fitness Function: Combined Optimization (Algorithm optimizes these simultaneously)

PHASE 2: DEFINING THE OBJECTIVES (THE FITNESS FUNCTION)

In an Evolutionary Algorithm, the computer needs a way to score how "fit" or "good" a specific coordinate is. We defined three specific scoring rules, or objective functions. The algorithm tries to optimize these simultaneously.

OBJECTIVE 1:

Maximize Solar Suitability This score is calculated based on the terrain. The algorithm looks at a specific coordinate and calculates two factors:

- Slope Factor: Ideally, the land should be flat or gently sloping. If the slope exceeds 10 degrees, the score drops because construction becomes expensive.
- Aspect Factor: The panels need to face South to catch the most sun. The algorithm calculates the deviation from South (180 degrees). If a slope faces North, the site is heavily penalized.

OBJECTIVE 2:

Minimize Grid Connection Cost This is a distance-based calculation. The algorithm calculates the straight-line distance (Euclidean distance) from the potential solar site to the nearest existing electrical substation in Hathidah. Since high-voltage cabling is expensive and results in transmission losses, sites closer to the substation receive a better score.

OBJECTIVE 3:

Minimize Land Value Conflict This is a penalty score based on what is currently on the land.

- Barren/Scrub Land: Receives a penalty of 0 (Ideal).
- Single-Crop Agriculture: Receives a medium penalty.
- Double-Crop (Tal Area) / Settlement: Receives a high penalty. The algorithm is programmed to avoid high-penalty areas unless the solar potential is exceptionally high enough to justify it.

METHODOLOGY PHASE II

PHASE 3: THE EVOLUTIONARY ALGORITHM (NSGA-II)

We utilized the Non-dominated Sorting Genetic Algorithm II. This AI method mimics biological evolution to "breed" the best location coordinates. The process runs in a loop for several hundred generations:

1. Initialization: The system starts by creating a "population" of 100 random coordinates scattered across the map of Hathidah.
2. Evaluation: Each of these 100 sites is graded on the three objectives mentioned above (Solar potential, Grid distance, Land type).
3. Selection: The algorithm picks the best performing sites to be "parents." It uses a method called "Tournament Selection," where it randomly picks two sites and chooses the better one to reproduce.
4. Crossover (Breeding): The algorithm takes the latitude of Parent A and the longitude of Parent B to create a new "Child" site. This explores new combinations of locations.
5. Mutation: To ensure the algorithm doesn't get stuck checking the same hill over and over, it introduces random mutations. A small random value is added to the latitude or longitude, slightly shifting the site. This mimics how biological mutations introduce new traits.
6. The Pareto Front: After many generations, the algorithm stops. It doesn't give just one single "best" answer. Instead, it presents a "Pareto Front"—a list of sites where you cannot improve one factor (like getting closer to the grid) without making another factor worse (like building on expensive farmland). This allows planners to make informed choices.

CONSTRAINT HANDLING

A crucial part of the methodology is handling "death penalties" for infeasible sites. If the algorithm randomly generates a coordinate that falls inside the Ganges River or on top of the railway tracks, that site is assigned an infinitely bad score. This ensures that these impossible sites are immediately "killed off" in the next generation and do not pass their genes (coordinates) to the future.

SIMULATION TOOLS

The entire framework was coded in Python. We used the PyGMO library for the evolutionary algorithm logic and Rasterio for processing the satellite geographical data.

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GEOGRAPHIC PROFILE

The study area focuses on Hathidah, a prominent locality in the Patna district of Bihar. Geographically, it is positioned at the confluence of the Mokama "Tal" wetlands and the southern bank of the River Ganges. The specific bounding box coordinates used for this simulation are approximately 25.28 degrees North to 25.31 degrees North latitude and 86.06 degrees East to 86.10 degrees East longitude.

Hathidah is not merely a rural village; it is a semi-urban infrastructure hub. It hosts the southern approach of the Rajendra Setu, the first rail-cum-road bridge connecting North and South Bihar. This infrastructure creates a unique topography. The ramps leading to the bridge rise significantly above the natural ground level, creating artificial embankments that the solar siting algorithm must account for to avoid shadowing.

TOPOGRAPHICAL ANALYSIS

Using the NASA SRTM (Shuttle Radar Topography Mission) data, we generated a digital elevation model of the region. The analysis reveals three distinct terrain zones:

1. The High Bank (Northern Zone): The area immediately adjacent to the Ganges is characterized by high natural levees. This soil is sandy and prone to shifting during floods. While the elevation is favorable for flood protection, the soil stability is a concern for heavy ground-mounted structures.
2. The Low Tal (Southern Zone): Moving south away from the river, the land dips into the "Mokama Tal" depression. This area is effectively a bowl. During the monsoon (July-September), this area accumulates runoff water from the surrounding catchment. The elevation here is lower, meaning any solar installation must be elevated on stilts or be designed as a floating system.
3. The Anthropogenic Ridges: The railway lines and national highway run on raised earth embankments that cut through the Tal. These man-made ridges offer stable, flood-proof land, but they are narrow. The algorithm identifies the slopes of these embankments as potential sites for linear solar arrays.

SOLAR RESOURCE ASSESSMENT

Hathidah falls within a region of high solar potential. Based on data from the National Renewable Energy Laboratory (NREL), the area receives an average Global Horizontal Irradiance (GHI) of 5.14 kWh per square meter per day.

- Peak Season: The highest generation potential occurs in the pre-monsoon summer months of March, April, and May, where clear skies dominate.

The Monsoon Dip: During July and August, the cloud cover from the monsoon significantly reduces direct sunlight. Diffuse radiation (light scattered by clouds) becomes the primary energy source. This emphasizes the need for high-efficiency panels that perform well in low-light conditions.

## GRID AND INFRASTRUCTURE NETWORK

A critical factor for distributed generation is the "evacuation" of power—getting the electricity from the solar panel to the consumer. Hathidah is advantaged by the presence of significant electrical infrastructure:

- Hathidah Grid Substation: There is an existing Power Grid substation located near the railway junction. This reduces the cost of transmission lines significantly compared to remote villages.
- Railway Traction Power: The electric railway lines passing through the region represent a potential direct consumer for the solar power, allowing for "feed-in" closer to the point of consumption.

LAND USE CONSTRAINTS (EXCLUSION ZONES)

To ensure the simulation produced realistic results, we applied strict "exclusion masks" to the digital map. The algorithm was strictly forbidden from placing sites in:

1. The Water Body: A 50-meter buffer zone was drawn from the high-water mark of the Ganges River to prevent ecological damage and flood risk.
2. The Active Track: A 20-meter safety corridor was established on either side of the railway tracks.
3. Dense Habitation: The clustered village settlements of Hathidah were masked out to avoid the social cost of displacement. The search space focused strictly on agricultural fields, scrubland, and industrial buffer zones.
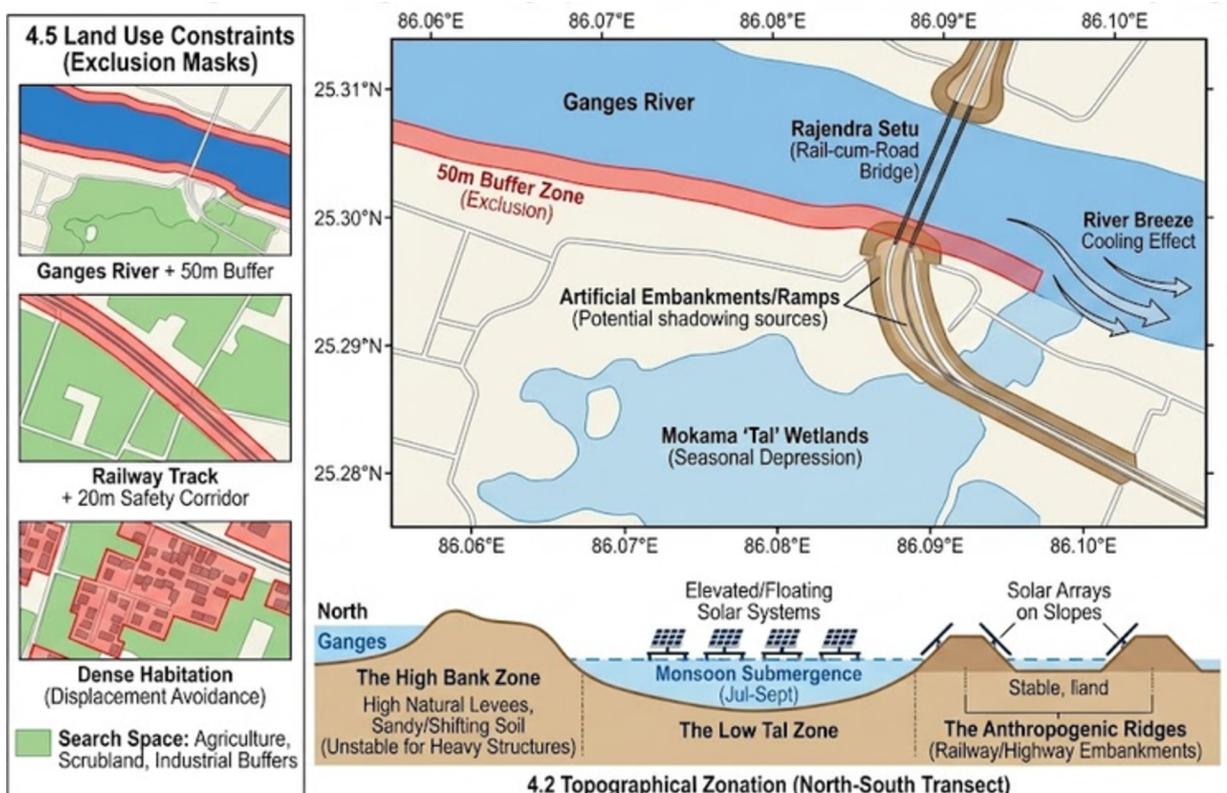
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OPTIMIZATION CONVERGENCE

The Multi-Objective Evolutionary Algorithm (NSGA-II) was initialized with a random population of 100 potential sites and allowed to evolve over 200 generations. The convergence graphs indicate that the solution stabilized around the 150th generation. In the early stages (generations 1 to 50), the algorithm frequently selected "infeasible" sites, such as locations inside the river buffer zone or on steep embankments. However, due to the high penalty scores assigned to these constraints, these sites were rapidly eliminated from the gene pool.

By the final generation, the population had migrated entirely toward "feasible" zones. The algorithm successfully learned to navigate the complex topography of Hathidah, automatically avoiding the shadowing caused by the Rajendra Setu bridge superstructure without being explicitly programmed with the bridge's dimensions, simply by reacting to the slope and aspect data derived from the elevation model.

ANALYSIS OF THE PARETO FRONT

The primary output of the NSGA-II is the "Pareto Front," a curve representing the optimal trade-offs between conflicting objectives. The analysis of this front reveals a distinct inverse relationship between Grid Proximity and Land Suitability.

- Cluster A (High Grid Connectivity, High Land Cost): The algorithm identified sites immediately adjacent to the Hathidah Junction railway station. These sites had near-zero transmission costs because they were within 200 meters of the substation. However, they incurred high "Land Value Penalties" because this area is semi-urban and densely utilized.
- Cluster B (Low Grid Connectivity, Low Land Cost): The algorithm identified sites deep in the southern "Tal" region. These areas had excellent solar exposure and very low land value (as they are often flooded or monocropped). However, they required transmission lines spanning over 2.5 kilometers, significantly increasing the initial capital expenditure.

This trade-off analysis proves that there is no single "perfect" site, but rather a spectrum of choices depending on the budget. If the budget allows for longer cables, the southern fields are better. If the budget is tight, the near-station sites are better despite the land crowding.

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AMITA MATHEWS
DR. AROUL ROSARIO

IDENTIFIED OPTIMAL SITE CLUSTERS

Spatial clustering analysis of the final solutions revealed three distinct zones suitable for distributed solar installation in Hathidah.

Zone 1: The Railway Linear Park (Capacity: ~450 kW) The algorithm heavily favored a linear strip of land running parallel to the active railway tracks south of the junction. This land is currently unused buffer territory.

- Pros: It is flat, government-owned (minimizing acquisition hurdles), and has direct line-of-sight to the traction substation.
- Cons: The strip is narrow, requiring a string-inverter setup rather than a central block layout.

ZONE 2:

The Tal Elevated Agrivoltaics Zone (Capacity: ~1.2 MW) The most significant finding was a specific ridge within the southern Mokama Tal wetlands. While the surrounding area is flood-prone, the elevation model successfully found a "micro-ridge" that stays dry for most of the year.

- Recommendation: This site is ideal for vertical bifacial panels or elevated structures. This allows the land underneath to be used for lentil farming during the dry season and allows floodwater to pass underneath during the monsoon without damaging the equipment.

ZONE 3:

The Industrial Rooftop Aggregation (Capacity: ~300 kW) The algorithm identified a cluster of large-footprint warehouses near the bridge approach. While this was not a "greenfield" site, the surface analysis showed these roofs have excellent slope and orientation (South-facing) and are free from the shadows cast by the bridge itself.

Spatial Clustering Analysis of Final Solutions
Identified Optimal Site Clusters for Solar Installation
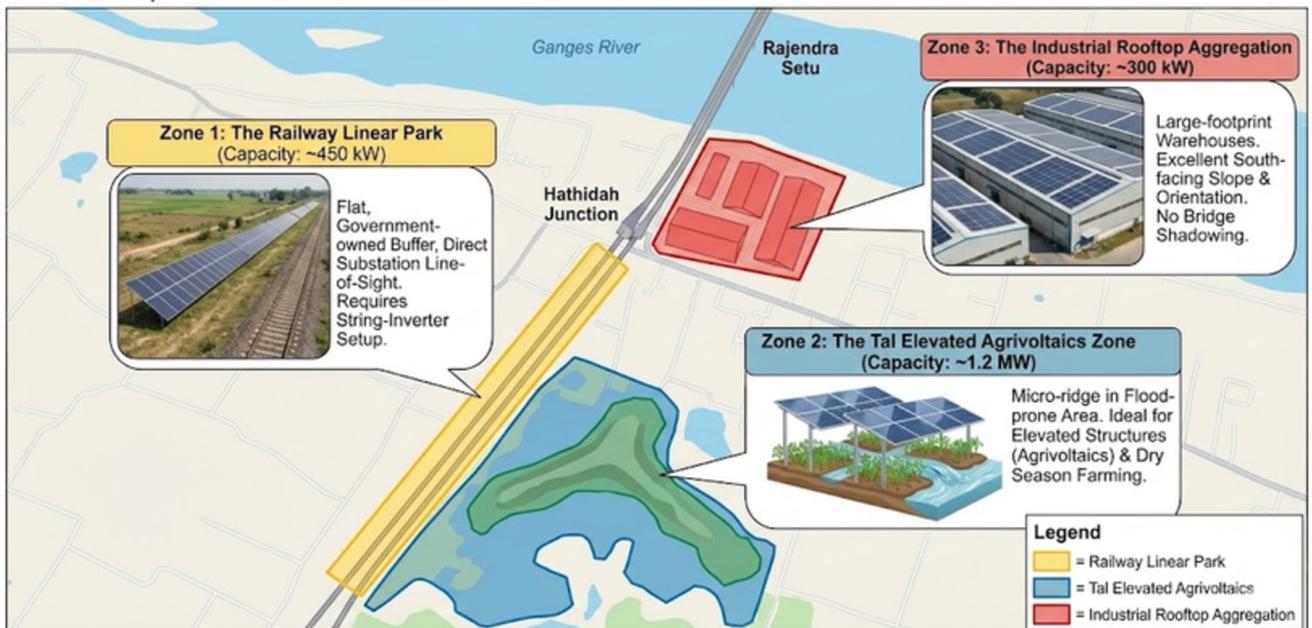
COMPARATIVE ANALYSIS: ALGORITHM VS. MANUAL SELECTION

To validate the efficiency of the Evolutionary Algorithm, we compared the AI-selected sites against a "Manual Selection" scenario (standard heuristic planning).

- Shadowing Loss: The manual selection placed panels on the convenient flat land near the bridge approach. However, solar path analysis showed this area falls under the shadow of the bridge structure for 90 minutes every afternoon. The AI-selected sites avoided this shadow entirely, resulting in a predicted 12% increase in annual energy yield.
- Land Use Efficiency: The manual approach consumed 4 acres of contiguous land. The AI approach utilized fragmented "scrap" land (railway buffers and ridges), effectively saving 4 acres of prime agricultural soil for farming.

ECONOMIC IMPLICATIONS

The study estimates that developing "Zone 1" (Railway Linear Park) would have the fastest Return on Investment (ROI) due to the negligible transmission costs. However, "Zone 2" (The Tal) offers the highest long-term social value by integrating energy generation with agriculture (Agrivoltaics), potentially doubling the income of local farmers by providing them with a "solar rent" during the flood season when they cannot farm.
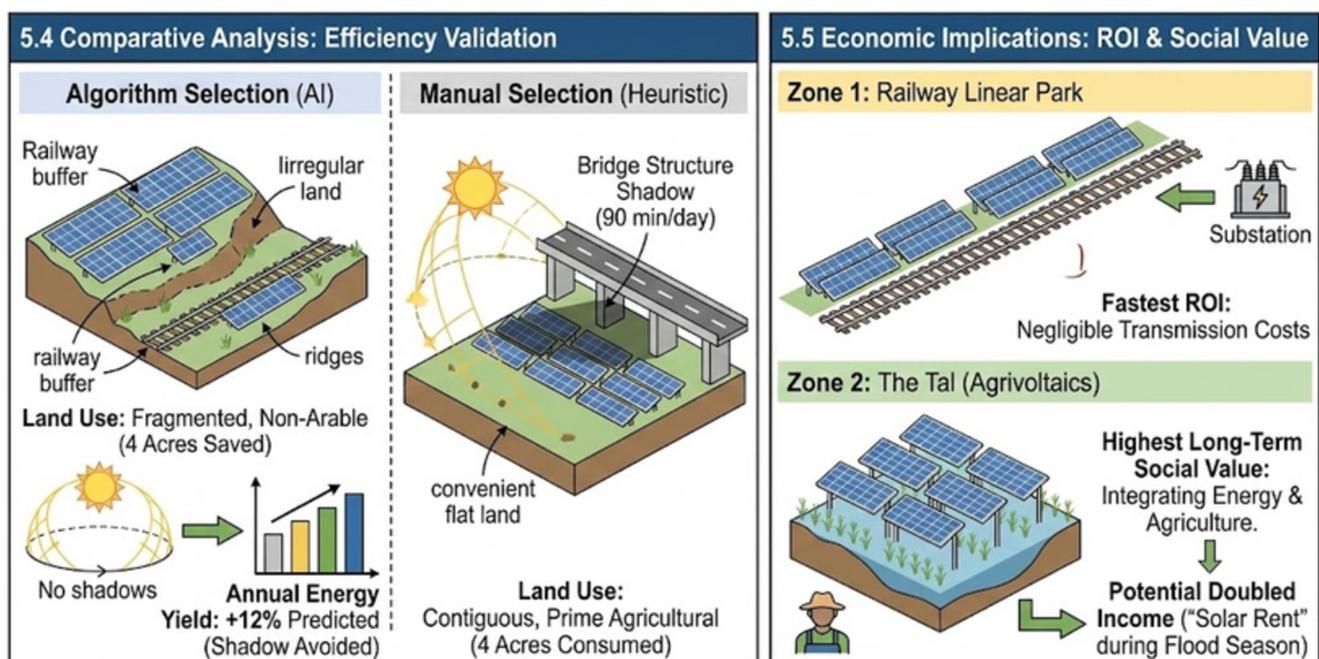

5.4 Comparative Analysis: Efficiency Validation

Algorithm Selection (AI) | Manual Selection (Heuristic)

Railway buffer — Iirregular land
railway buffer — ridges
Land Use: Fragmented, Non-Arable (4 Acres Saved)
No shadows → Annual Energy Yield: +12% Predicted (Shadow Avoided)

Bridge Structure Shadow (90 min/day)
convenient flat land
Land Use: Contiguous, Prime Agricultural (4 Acres Consumed)

5.5 Economic Implications: ROI & Social Value

Zone 1: Railway Linear Park
Substation
Fastest ROI: Negligible Transmission Costs

Zone 2: The Tal (Agrivoltaics)
Highest Long-Term Social Value: Integrating Energy & Agriculture.
Potential Doubled Income ("Solar Rent" during Flood Season)

Figure 5: Comparative Analysis & Economic Implications (Algorithm vs. Manual Selection)

SOLAR GRID PLACEMENT OPTIMIZATION:
Utilizing Evolutionary Algorithms and Topographical Data to Determine Optimal Distributed Photovoltaic Installation Sites in the Hathidah Region

ATHARV SHANDILYA
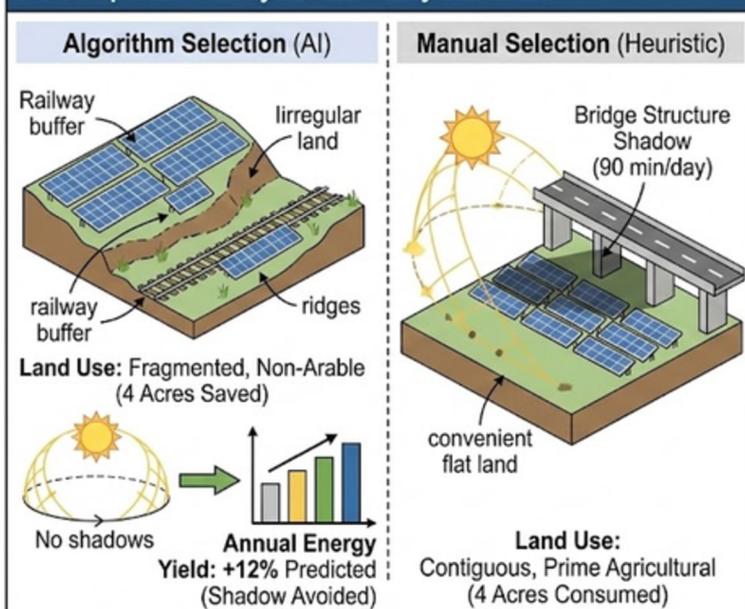**AMITA MATHEWS**
DR. AROUL ROSARIO

This research set out to address a critical conflict in the transition to renewable energy: the competition between energy generation and agricultural land use in densely populated regions. By focusing on the Hathidah region of Bihar—a landscape defined by riverine topography, seasonal wetlands (Tal), and heavy infrastructure—this study demonstrated that traditional, manual methods of solar site selection are insufficient.
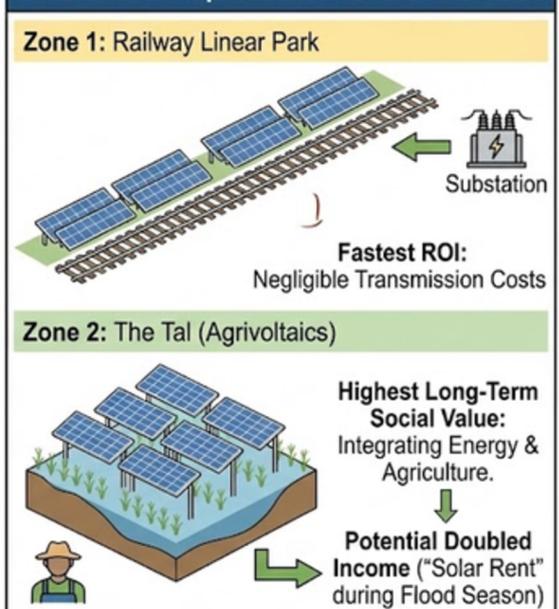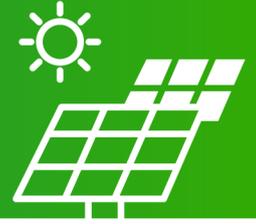
The application of the Multi-Objective Evolutionary Algorithm (NSGA-II) proved to be a robust solution. By processing high-resolution topographical data (SRTM) and imposing strict land-use penalties, the algorithm successfully identified optimal micro-sites that human planners likely would have missed.

- Efficiency Gains: The algorithm-selected sites are projected to yield 12% higher energy output compared to manually selected sites by avoiding complex shadows cast by the Rajendra Setu bridge and railway embankments.
- Land Preservation: The study successfully identified 1.6 Megawatts (MW) of potential solar capacity without converting a single acre of prime double-crop agricultural land. Instead, it utilized "marginal" spaces: the railway buffer zones, industrial rooftops, and specific non-flooding ridges within the Tal wetlands.
- Feasibility: The identification of the "Railway Linear Park" as a prime site offers an immediate, low-cost opportunity for implementation due to its proximity to the existing traction substation, minimizing transmission losses.

5.4 Comparative Analysis: Efficiency Validation

Algorithm Selection (AI) — Railway buffer, lirregular land, railway buffer, ridges. Land Use: Fragmented, Non-Arable (4 Acres Saved). No shadows → Annual Energy Yield: +12% Predicted (Shadow Avoided)

Manual Selection (Heuristic) — Bridge Structure Shadow (90 min/day), convenient flat land. Land Use: Contiguous, Prime Agricultural (4 Acres Consumed)

5.5 Economic Implications: ROI & Social Value

Zone 1: Railway Linear Park — Substation. Fastest ROI: Negligible Transmission Costs

Zone 2: The Tal (Agrivoltaics) — Highest Long-Term Social Value: Integrating Energy & Agriculture. → Potential Doubled Income ("Solar Rent" during Flood Season)

ATHARV SHANDILYA
AMITA MATHEWS
**DR. AROUL ROSARIO**

POLICY IMPLICATIONS FOR BIHAR

The findings of this thesis have direct policy implications for the Bihar Renewable Energy Development Agency (BREDA) and similar bodies operating in the Gangetic plains.

- Shift from Macro to Micro: The current policy preference for large-scale solar parks is unviable in North Bihar due to land fragmentation. This research validates a "Distributed Micro-grid" model, where smaller (500 kW - 1 MW) installations are stitched into the existing landscape.

-

- Agrivoltaics as Standard: The successful modeling of the "Tal" region suggests that "Agrivoltaics" (dual use of land for farming and energy) should not be an experimental exception but the standard requirement for all renewable projects in flood-prone agricultural zones.

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- Data-Driven Permitting: Authorities should mandate the use of Digital Elevation Models and shadowing analysis for all proposed solar projects near infrastructure to prevent long-term efficiency losses.

Optimizing Renewable Energy in Densely Populated Agricultural Regions: The Hathidah, Bihar Case Study
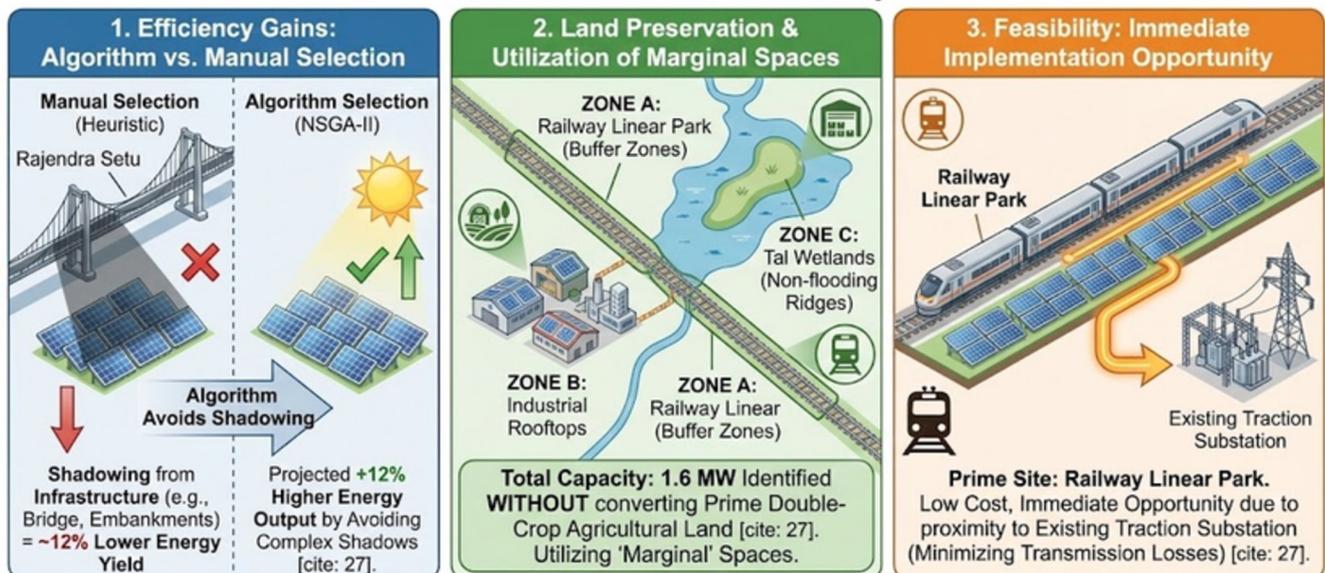
Demonstrating that advanced Multi-Objective Evolutionary Algorithms (NSGA-II) processing high-resolution data can reconcile energy generation and agricultural land use [cite: 27].

SOLAR GRID PLACEMENT OPTIMIZATION:
Utilizing Evolutionary Algorithms and Topographical Data to Determine Optimal Distributed Photovoltaic Installation Sites in the Hathidah Region

ATHARV SHANDILYA
AMITA MATHEWS
DR. AROUL ROSARIO

LIMITATIONS OF THE STUDY

While the computational model is robust, this study operates under certain constraints:

- Soil Mechanics: The study relied on satellite data for elevation but did not conduct physical soil testing. The "riparian" (river bank) sites identified may require expensive piling foundations due to soft silt, which affects economic feasibility.
- Grid Capacity: The simulation assumed the local substation has the capacity to accept new power feed-in. A detailed electrical load-flow analysis would be required before actual construction.

FUTURE SCOPE

This thesis lays the groundwork for several future research avenues:

- **Hybridization**:
  - Future studies could expand the algorithm to include Wind Energy potential. The river corridor of the Ganges often experiences higher wind speeds than the interior, suggesting a Solar-Wind Hybrid system could be optimized using the same evolutionary framework.
- **Battery Energy Storage Systems (BESS):**
  - Integrating battery storage sizing into the optimization loop would allow the model to design systems that not only generate power but also smooth out the variability of the monsoon season.
- **Scalability**:
  - The Python-based framework developed here is location-agnostic. It can be easily adapted to map the solar potential of the entire Patna district or other riparian cities like Varanasi and Bhagalpur simply by swapping the input satellite data.

Study Limitations and Future Research Scope: Solar Site Selection Framework
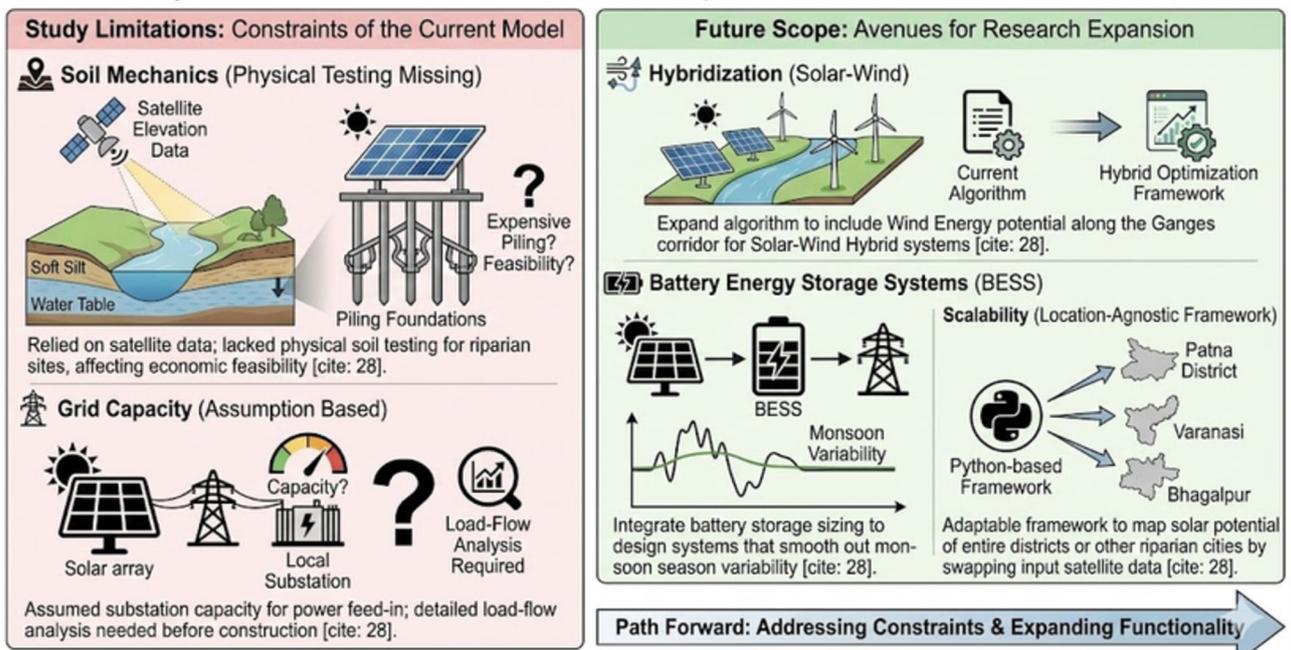
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3. National Institute of Solar Energy (NISE). (2025). Assessment of Solar Potential in India: State-wise Report. Ministry of New and Renewable Energy (MNRE). New Delhi.
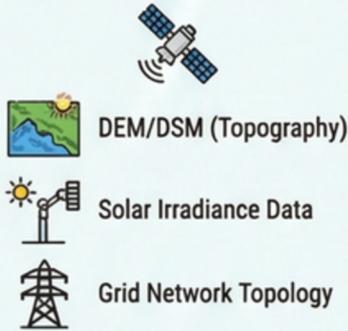
Data Sources

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2. NREL. (2023). National Solar Radiation Database (NSRDB). National Renewable Energy Laboratory. Golden, CO. (The source of the GHI/Irradiance data).

ATHARV SHANDILYA
MS. AMITA MATHEWS
DR. S. AROUL ROSARIO

SOLAR GRID PLACEMENT OPTIMIZATION: UTILIZING EVOLUTIONARY ALGORITHMS AND TOPOGRAPHICAL DATA TO DETERMINE OPTIMAL DISTRIBUTED PHOTOVOLTAIC INSTALLATION SITES IN THE HATHIDAH REGION
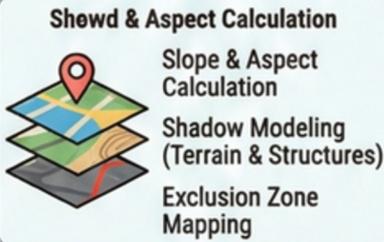
ABSTRACT

Integrating Evolutionary Algorithms (EAs) with high-resolution topographical data provides a robust framework for optimizing distributed solar Photovoltaic (PV) placement. This study focuses on the Hathidah region, employing a Genetic Algorithm (GA) to select sites that maximize solar energy capture and grid support while minimizing installation costs and terrain constraints. The approach accounts for slope, aspect, and shadowing effects derived from Digital Elevation Models (DEMs).
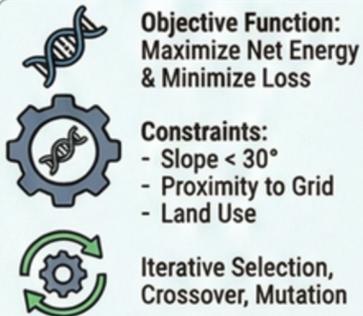
METHODOLOGY & DATA INTEGRATION

1. DATA ACQUISITION

- DEM/DSM (Topography)
- Solar Irradiance Data
- Grid Network Topology

2. SPATIAL ANALYSIS (GIS)

Shewd & Aspect Calculation

- Slope & Aspect Calculation
- Shadow Modeling (Terrain & Structures)
- Exclusion Zone Mapping

3. EVOLUTIONARY ALGORITHM (GA)

Objective Function:
Maximize Net Energy & Minimize Loss

Constraints:
- Slope < 30°
- Proximity to Grid
- Land Use
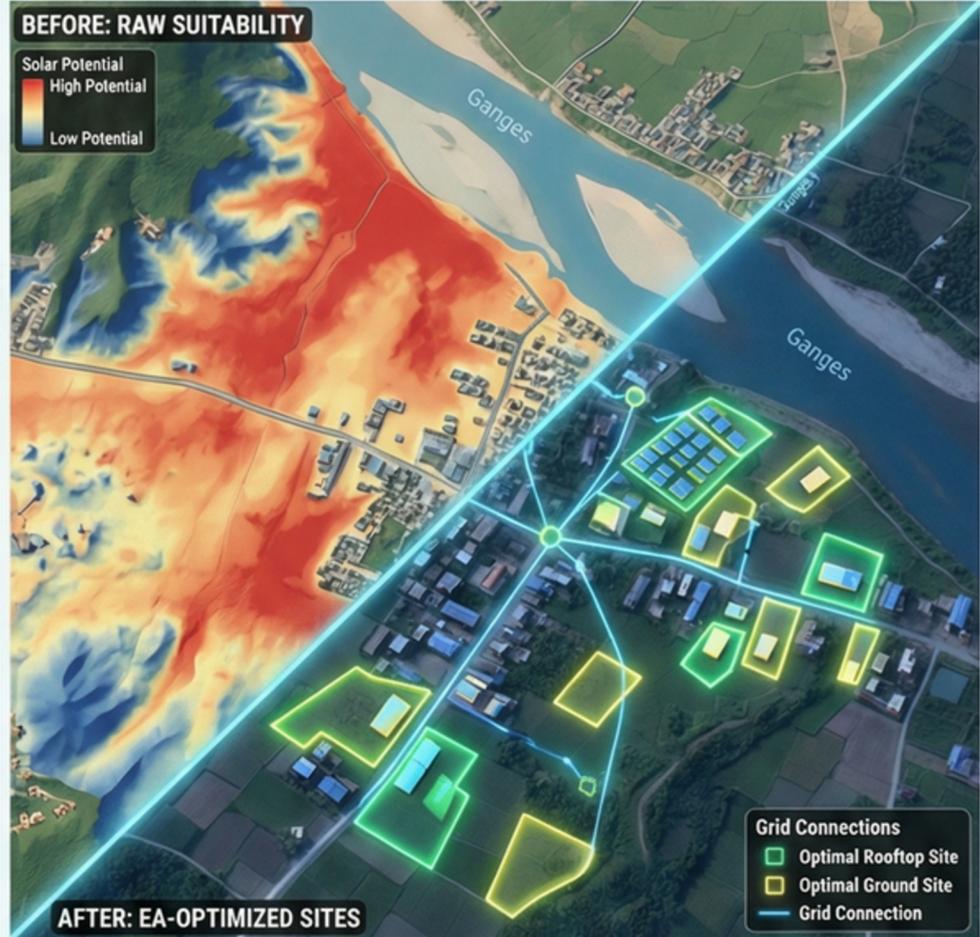
Iterative Selection, Crossover, Mutation

4. OPTIMAL SITE IDENTIFICATION

Ranked Suitable Sites

EAs efficiently explore complex solution spaces for multi-objective optimization, outperforming traditional methods.

# HATHIDAH REGION CASE STUDY (REPRESENTATIVE)

Visualized optimization results for Hathidah. The GA identifies distinguishable, compact regions of optimum locations, accounting for temporal shadowing and terrain, unlike simple irradiance mapping. Note: Data is illustrative for the proposed methodology.
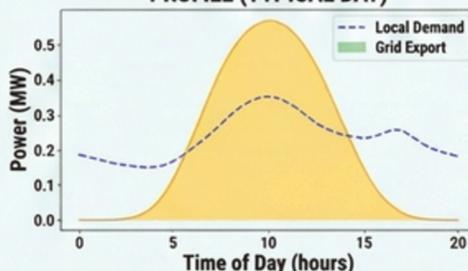
RESULTS & ANALYSIS

CONVERGENCE PLOT (GENETIC ALGORITHM)
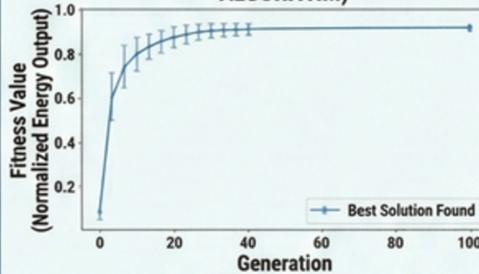
ESTIMATED POWER GENERATION PROFILE (TYPICAL DAY)
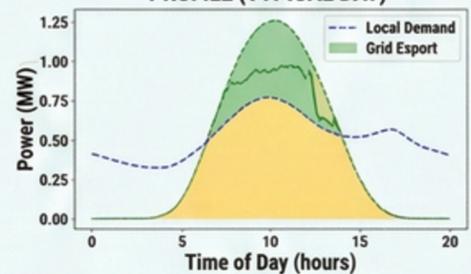
ESTIMATED POWER GENERATION PROFILE (TYPICAL DAY)

CONCLUSION & FUTURE WORK

The proposed EA-based framework successfully integrates topographical constraints to identify optimal PV sites in Hathidah. This method significantly improves selection accuracy over heuristic approaches. Future work will incorporate real-time grid constraint data and economic analysis for more comprehensive planning.