

# Utilizing Image Processing Algorithms and Remote Sensing Technique for Proposing Solar Cell Sites Along the Pilgrimage Route from Baghdad to Karbala

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## Abstract:

Reliance on renewable energy sources, particularly solar energy, is a key component of achieving environmental sustainability, especially in areas with intensive seasonal use, such as the pilgrims' route linking Baghdad and Karbala. This research aims to identify the optimal locations for installing solar cells along this vital route, using remote sensing techniques and image processing algorithms. This ensures maximum energy efficiency while minimizing interference with existing infrastructure and services. The study relied on high-resolution satellite data, along with a digital elevation model (DEM) and solar radiation data, to identify areas with the greatest exposure to sunlight and optimal surface slope. Land cover characteristics were also analyzed using spectral indices such as NDVI and BSI, taking into account topographic factors, shade, and vegetation density, within a Geographic Information Systems (GIS) environment. To weight factors and prioritize impacts, the Analytical Hierarchy Model (AHP) method was applied, producing a final map showing the optimal installation locations. The results showed that approximately 23% of the studied route is highly suitable for solar cell installation. Among the most efficient areas are the outskirts of Yusufiyah, Latifiyah, Sadr al-Yusufiyah, Rustamiyah, al-Radwaniyah, al-Haswa, Khan al-Nas, the outskirts of Alexandria, and al-Hindiyyah Dam, due to their gentle slopes, direct solar exposure, and distance from urban and natural obstacles. This study provides a practical framework for sustainable energy planning in visitor service infrastructure projects. It also opens up future prospects for expanding the model to include similar corridors or integrating it with time-series data to monitor energy performance throughout the year.

**Keywords:** Mass Pilgrimage Crowds – Visitor Services – Arbaeen Pilgrimage – Remote Sensing and Satellite Imagery – Sustainable Development

## Introduction

Recently, international interest has grown in diversifying and renewing renewable energy sources—solar, wind, and hydropower—particularly solar electricity generation. This is in pursuit of a cleaner environment, with the goal of reducing dependence on traditional energy sources and addressing the environmental threats of climate change, particularly the increasing risk of greenhouse gas emissions and global warming. The issue of solar electricity generation has gained attention among relevant international organizations and institutions. This is aimed at reducing the use of non-renewable fossil fuels, which are exposed to massive amounts of pollutants in all their forms, and at obtaining an inexhaustible energy resource that has no negative impact on the environment. The provision of electricity facilitates many services, such as increasing working hours and providing healthcare, in addition to education, industrial, service, and domestic uses, as well as other life activities. Iraq is one of the countries that lacks traditional energy sources for electricity generation, which has prompted it to focus on building and developing the renewable energy sector by increasing investment by 32%, as reported by the Regional Center for Renewable Energy and Energy Efficiency, in accordance with Iraq Vision 2030. Iraq has great potential to benefit from solar energy due to its ideal geographical location and its area of 438,850 km<sup>2</sup>, which has helped to establish many electricity generation projects. Iraq has the geographical potential that qualifies it to invest in solar energy to produce electricity with a very high potential. The geographical location of Iraq has allowed it to receive large amounts of solar radiation ranging between (4908 - 6250) milliwatts/cm<sup>2</sup> and a daily average of up to (12) hours per day, in addition to the low humidity, the short duration of cloud cover and the clear sky, which has helped the solar radiation to reach at a high density, in addition to the presence of vast areas unpopulated and the availability of capital, labor and technical expertise. The surface of Iraq is characterized by several features

resulting from the geological structure of its rocks, which made the distribution of landforms follow the same geological distribution pattern, low elevation, simplicity, regularity and continuity, in addition to the gradual and slow slope from the north to the far south, which represents (1/1000) meters, as it reflects an important geomorphological fact, which is that the variation in elevation is very small for an area estimated at (80)% of the area of Iraq, which allows receiving larger amounts of solar radiation over large areas and air movement without obstacles, in addition to facilitating the installation of solar cells. To increase the efficiency of use, they must be installed in the locations most exposed to solar radiation. Using Geographic Information Systems (GIS) technology, an attempt was made to identify the best locations for collecting solar energy in the study area, which is the pilgrims' road between Baghdad and Karbala (passing through the Jurf al-Sakhar district, extending over a distance of more than 80 km (50 miles). The road starts from the city of Latifiyah, where it connects with Qamishli Street at the Jurf al-Sakhar Bridge in the village of Al-Fadhiliyah, crossing the city of Jurf al-Sakhar lengthwise, passing through the agricultural villages, reaching the Al-Khanafisa and Al-Jamaliyah areas, and then to Karbala Governorate.) Using digital elevation models (DEM) images of the study area, using ArcMap 10.3 tools. This paper focuses on solar energy because the study area enjoys an adequate amount of solar radiation throughout the year. It is a cold area in winter and hot in summer, and therefore there is a great pressure on electricity consumption for heating and cooling purposes, especially in light of the continuous power outages in the region. Therefore, it was necessary to consider using sources other than traditional sources for energy supply. Since the study area is located within the tropical region, it enjoys an adequate amount of solar radiation, being close to the equator. Therefore, the annual sunshine hours exceed 4,000 hours. Therefore, one of the most suitable renewable energy sources used in the study area is solar energy. To make this use successful,

it was important to study the amount of solar radiation in the area using geographic information systems (GIS) technology, as well as its ability to achieve the principle of sustainability for the development of renewable energy sources (Al-ramahi, Shnain, & Ali, 2022). GIS is one of the important technologies in developing renewable energy applications on a sound basis. (Al-ramahi, Shnain, & Ali, 2022) Many studies have resorted to using spatial analysis tools to manage renewable energy sources. For example, there is a study that examined the possibility of generating energy in an Egyptian governorate through spatial analysis of solar radiation. This study was able to identify the best locations to start using solar energy. Many other studies aimed to identify the most suitable locations for using renewable energies such as solar and wind energy through spatial analysis, resulting in identifying the most suitable locations. In this regard, Germany issued a law to prevent changes resulting from the use of old energy sources and limit their use as primary sources of energy generation in 2000. This law is known as the Renewable Energy Law (Alsajjad, Mohammed, & Jasim, 2023). In addition, the economic cost of using these traditional sources is very high. Renewable and clean energies are the ideal alternative to meet daily energy needs (Allouche, Tsoar, & Kadmon, 2006). These renewable sources are worthy of study to learn more about them and to encourage their use and make them one of the most important sources of electricity and thermal energy production, especially in light of the pollution caused by energy sources. There are many renewable energy sources, including hydropower, wind energy, energy resulting from wave movement, some types of agricultural crops, solar energy, and many others. However, the aim of this study will focus on solar energy, the possibility of installing solar energy collection stations, and identifying the best locations for their installation along the visitor route. It has been noted for quite some time that it is necessary to take advantage of the latent energy in solar radiation, as it is a renewable energy that does not run out when used con-

tinuously (McCann, Repasky, Morin, Lawrence, & Powell, 2017). Solar energy has also proven its effectiveness and positivity in generating electrical and thermal energy to a large extent in many countries such as Germany and Morocco. Egypt has also turned to clean energy sources in many areas as a quick solution to provide the necessary energy. Egypt is not an oil-producing country and relies primarily on fossil fuels for energy production. Therefore, it has turned to renewable energies for energy production, as its production reached 574 megawatts in 2014 from solar energy (Khanjer, Hassan, Ismael, & Gazal, 2020). Algeria also launched a solar power plant using photovoltaic panels. Trade in renewable energy, particularly solar energy, has recently increased among Arab countries, known as energy export. Countries with high solar radiation supply countries that do not receive adequate solar radiation, such as the northern Mediterranean countries, with the energy needed to generate electricity (Liu, Liang, Xiao, & Fang, 2014) (Liu, Qi, Li, & Yeh, 2019). This study represents a pivotal step in identifying the optimal locations for establishing solar power plants, using GIS techniques and precise spatial analysis. A digital elevation model (DEM) was used to evaluate surface slopes and orientations, which contributes to identifying areas with the highest potential for solar radiation. Solar radiation data were also used to accurately determine the spatial distribution of direct sunlight. In addition, land cover characteristics were analyzed using spectral indices such as the Normalized Vegetation Index (NDVI) and the Urban Building Index (NDBI), taking into account topographic factors, terrain shade, and vegetation density. These analyses were conducted within a Geographic Information Systems (GIS) environment, enabling the integration of spatial and environmental data to provide an accurate picture of the most suitable locations in terms of production efficiency and spatial suitability for solar power plants, especially along the pilgrims' route between Baghdad and Karbala.

## Spatial Suitability of Solar Energy in a GIS Framework

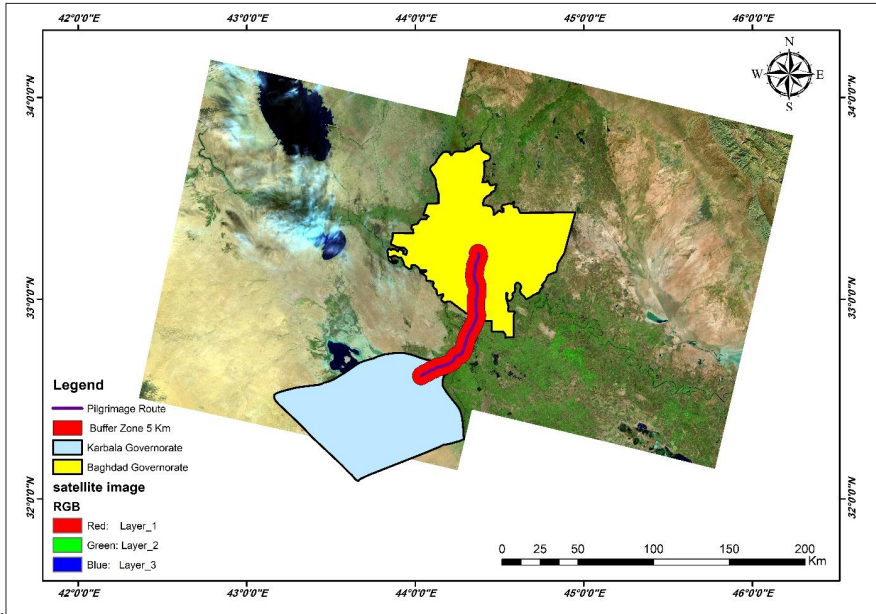
Location is one of the most important topics of interest to service researchers and planners, as the geographic location of a service plays a significant role in influencing its attractiveness, effectiveness, and accessibility to the population. This influences usage, which creates new patterns of service demand. It is an important part of the geographer's interest in the influence of location on behavior. It helps the geographer discover connections, track service trends, and identify new locations where services will be needed in the future. This focuses on the geographer's interest in studying services before they are established. This is an effective factor in planning them, which develops a future vision for them based on their location, size, characteristics, and other attributes that must be consistent with the population size that will benefit from them. Using their geographical knowledge, the geographer contributes effectively to the process of spatially identifying the service, selecting the ideal location, and planning it using technologies such as geographic information systems (GIS) and remote sensing. These technologies have proven effective in constructing a spatial model based on the concept of spatial suitability (Suitability Model), which relies on modeling and simulation. These models have demonstrated their ability to predict phenomenon behavior and select suitable locations based on spatial proposals and the application of service planning criteria to select the optimal future location within the city. Therefore, the use of GIS and multi-criteria spatial analysis models based on them is an important means of identifying optimal locations for various services. Therefore, the use of model-based spatial analysis (Model Builder) and its linkage with GIS is an important tool for building a spatial decision support system for decision-makers related to site selection more efficiently. Thus, the study seeks to determine the spatial suitability

model for establishing solar power plants from technical, economic, and environmental perspectives. In this context, the Geographic Information Systems (GIS) environment enables the integration and analysis of various spatial layers, including the Digital Elevation Model (DEM) to assess slope and surface orientation, solar radiation data to determine the amount of energy available, as well as spectral indices such as NDVI to measure vegetation density, and NDBI to identify urban or built-up areas. Limiting factors such as the site's distance from roads and electricity grids, and residential or protected areas are also taken into account, supporting data-driven decision-making and enhancing investment efficiency in this vital sector. This analysis is particularly important in areas experiencing contrasting climatic or topographic conditions, such as the vital corridor of the pilgrims' route between Baghdad and Karbala.

### The Study Area

The study area included the Baghdad-Karbala Road, passing through the Jurf al-Sakhar district, which extends over 80 kilometers (50 miles). The road begins in the city of Latifiyah, where it connects with Qamishli Street at the Jurf al-Sakhar Bridge in the village of Al-Fadhiliyah. It crosses the city of Jurf al-Sakhar lengthwise, passing through agricultural villages, reaching the areas of Al-Khanafisa and Al-Jamaliyah, and then on to Karbala Governorate Fig.1. The region falls within a desert climate characterized by very hot summers and moderate to cold winters. Summers are long and dry, with temperatures rising to over 40 degrees Celsius during the day, while they drop at night but remain high. Winters are relatively short, with little rain, and temperatures sometimes drop below zero at night on the coldest days. Monsoon winds are common and can stir up dust and sand, affecting visibility and agricultural activities. The road holds

significant geostrategic and economic importance as it connects Baghdad and Karbala, making it a major hub for commercial and religious traffic, especially during the Hajj season and the large religious pilgrimages that Karbala witnesses. The city witnesses religious pilgrimages throughout the year, and perhaps the most important pilgrimage is the Arabian pilgrimage, a religious, social, and humanitarian occasion and ritual practiced on the twentieth of Safar each year according to the Islamic calendar. Millions of pilgrim's flocks to the city. In this study, the Buffer tool was used within a Geographic Information Systems (GIS) environment to create a buffer zone 5 kilometers deep on both sides of the pilgrims' road linking Baghdad and Karbala. This aim was to define the scope of the proposed spatial analysis for the construction of solar power plants. This distance was adopted based on spatial planning criteria that take into account the availability of infrastructure on the one hand, and avoid overlapping with residential or protected areas on the other. This procedure helped confine the study to an effective spatial belt surrounding the main road, facilitating the process of evaluating the environmental, topographical, and radiation factors affecting the identification of optimal locations for the construction of solar plants within this vital corridor, which witnesses high seasonal population density during religious occasions.



1. Satellite Image from Landsat 8 Illustrating the Spatial Distribution of the Pilgrimage Route between Baghdad and Karbala Governorates with a 5 km Buffer Zone for Solar Site Suitability Analysis”

A 5-kilometer buffer zone was adopted on both sides of the pilgrims’ road linking Baghdad and Karbala for spatial analysis and site selection, based on multiple technical and planning justifications. This depth is sufficient to achieve a balance between proximity to the main road to facilitate construction and maintenance operations and appropriate distance to avoid interference with large crowds during religious occasions, enhancing the security and operational aspects of the proposed projects. This area also covers open and semi-utilized lands, providing good opportunities in terms of the availability of suitable space. Furthermore, the 5-kilometer zone often falls within the coverage area of secondary road networks and power lines, reducing the cost of connecting to infrastructure. From an analytical perspective, this depth provides a suitable spatial scope for applying GIS tools such as regression analysis, solar radiation, and spatial suitability, without being affected by interfering urban or topographical factors, consistent with previous similar studies in this field.

## Research Methodology

### 1- Cartographic Method:

The cartographic research method is used to study the spatial distribution, interconnectedness, and evolution of phenomena. It is based on the preparation and purposeful use of cartographic works in scientific and practical activities. This method involves preparing maps for methods for deriving digital elevation models.

### 2- Statistical Research Method:

The field of statistics includes methods for describing and analyzing data, and for making decisions or inferences about the phenomena represented by the data. Descriptive and inferential statistics help researchers develop appropriate interpretations of the relationships between variables that express complex social phenomena. Statistics generally provides the tools necessary for analyzing, representing, and interpreting these relationships. The statistical method was used in various stages of research, as all methods rely on pre-prepared statistical mathematical models. This also applies to interpreting the results obtained with the aim of forming complete, statistically based perceptions of the research topic.

### 3- Descriptive Research Method:

The descriptive method was used to explain the methods for creating digital elevation models.

### 4- Experimental Research Method:

The experimental method was used by applying four methods to create the digital model, conduct appropriate analyses, and evaluate the results.

## Data Used

This study used a carefully selected set of data to meet the requirements of spatial and environmental analysis for determining optimal locations for solar power plants. Spectral data included satellite images from the Landsat 8 OLI satellite for the most recent period (2023–2024), which were used to extract spectral indices such as the Normalized Vegetation Index (NDVI), the Built-Up Area Index (NDBI), and the Bare Soil Index (BSI). Annual solar radiation data, obtained from global climate data platforms such as Global Solar Atlas or NASA POWER, were also used to assess the distribution of solar energy across the Earth’s surface. Additionally, a 30-meter-resolution Digital Elevation Model (DEM) was used to determine the slope and orientation characteristics of the surface, which are critical factors in the design of solar power plants. Spatial data also included road networks and power lines, obtained from national infrastructure databases or the OpenStreetMap platform, to assess spatial proximity to vital services. Finally, land use and land cover maps were analyzed to identify areas that were excluded or unsuitable from an environmental or legal perspective, such as residential areas, nature reserves, and active agricultural land. This data was integrated into a geographic information systems (GIS) environment to conduct spatial analysis and generate the final suitability map for solar power plant sites.

## Data Processing

The first step in data processing was to identify a set of criteria required for the most suitable locations for solar energy collection projects. In this context, a number of international studies and research papers related to the same topic were compiled, and the criteria applied in each study were examined to determine the most accurate criteria for the efficiency of these locations in establishing solar energy collection projects. The value of solar radiation reaching the Earth's surface is the primary criterion for solar energy collection, followed by the slope of the Earth's surface, which affects the equipment and installation of the necessary equipment for these projects. Distance from the electricity distribution network is also an important factor. The greater the distance, the greater the amount of energy lost during transmission, and the greater the cost of energy transfer. From an environmental perspective, distance from major cities, airports, roads, and beaches are also important factors in selecting the most suitable locations for solar energy projects. Accordingly, seven technical and economic criteria were selected (Table No. (1)) to be met in the most suitable locations for solar energy projects, in addition to two restrictions to avoid establishing these projects within urban areas or on agricultural land.

Table 1. Spatial Suitability Criteria for Solar Power Plant Site Selection

Criterion	Description	Recommended Values
Slope	Preferably low slope to ease solar panel installation	$\leq 5\text{--}10$ degrees
Aspect	South-facing slope in the Northern Hemisphere	South direction ( $180^\circ \pm 45^\circ$ )
Solar Irradiance	Required level of solar radiation to ensure good productivity	$\geq 5$ kWh/m <sup>2</sup> /day
NDVI (Vegetation Index)	Low values indicate sparsely vegetated or bare land	$< 0.1$
BSI (Bare Soil Index)	High values indicate suitable barren land	High (e.g., $> 0.3$ )

### Global Standards for Selecting Optimal Sites for Solar Power Plants

Selecting optimal sites for solar power plants requires the integration of several spatial and environmental criteria analyzed within a Geographic Information Systems (GIS) environment. These criteria begin with topographic characteristics. It is preferable for areas with a gentle slope not exceeding 5–10 degrees to facilitate the installation of solar panels and ensure efficient performance and structural stability. It is also preferable for the slope to be oriented southward in areas located in the Northern Hemisphere to increase exposure to solar radiation. Annual solar radiation rates are also among the most important indicators, with solar radiation values preferably exceeding 5 kWh/m<sup>2</sup>/day to ensure high energy yield. Environmentally, areas with dense vegetation are excluded based on NDVI values exceeding (+0.3), while preference is given to areas with negative or low NDVI values (<0.1). Built-up areas are also monitored using the NDBI, which indicates high urban activity when values are positive (>0). It is also important to avoid agricultural lands or areas with active economic

use, focusing on barren lands that exhibit high BSIs. Furthermore, climatic criteria are taken into account, such as moderate temperatures (25–35°C) that support panel efficiency, and wind speeds not exceeding 7–8 m/s to ensure structural safety. Regarding infrastructure, proximity to electrical grids ( $\leq 5$  km) and paved roads ( $\leq 3$  km) are essential factors to reduce construction and connection costs. Sites within 1–2 km of residential areas or environmental reserves should also be avoided to maintain social and environmental balance. When these criteria are integrated within a GIS environment using spatial analysis techniques and multi-criteria decision-making models (such as AHP or Weighted Overlay), accurate spatial suitability maps can be produced to help inform planning decisions that achieve the sustainability and economic efficiency of solar power plants.

### Digital Elevation Model and Spectral Indices

A digital elevation model (DEM) is a point data representation of a continuous surface, usually referring to the Earth's surface. The accuracy of this data is determined primarily by the resolution (the distance between sampled points). Other factors affecting accuracy are the type of data (integer or floating point) and the actual surface sampling when the original DEM was created. Errors in DEMs are usually classified as either estuaries or crests. An estuary is an area surrounded by higher elevation values and is also referred to as a depression or chamber. This is an internal drainage area. Some may be natural, especially in glacial or karst regions (Mark 1988), although many estuaries are defects in a DEM. Similarly, a rise or crest is an area surrounded by cells of lower values. These are more common natural features and less detrimental to flow direction calculations. Such errors, especially estuaries, must be removed before any surface information can be derived. Estuaries, as internal drainage areas, prevent water flow from being directed downslope. According to the equations below.

**1.Slope Calculation from DEM:**

Slope is calculated using the change in elevation in the x and y directions from the DEM data. The formula is given by:

$$Slope = \tan^{-1} \left( \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \right) \dots\dots\dots (1)$$

where  $\left(\frac{dz}{dx}\right)$  is Change in elevation in the east-west direction. And is Change in elevation in the north-south direction. The result is typically expressed in degrees or percent.

**2.Aspect Calculation from DEM:**

Aspect defines the compass direction that a slope faces. It is calculated as:

$$Aspect = \tan^{-1} \left( \frac{\frac{dz}{dy}}{-\frac{dz}{dx}} \right) \dots\dots\dots (2)$$

The result is expressed in degrees: 0° for North, 90° for East, 180° for South, etc.

**3.Normalized Difference Vegetation Index (NDVI):**

The Normalized Difference Vegetation Index (NDVI) is probably the most widely used index that combines near-infrared data with data in the red spectral region. It is normalized and values are calculated between -1 (no vegetation) and 1 (abundant vegetation). Variations in illumination and the influence of land surface can be compensated for:

NDVI is related to many vegetation characteristics. For example, it is used to determine plant health, to visualize cyclical biological changes, to estimate green biomass and crop yield, and for many other applications.

#### 4. Bare Soil Index (BSI):

The Bare Soil Index (BSI) is the most effective method for determining the properties of bare soil because it is a numerical measurement that relates to blue, red, and infrared (IR) wavelengths. Short and red wavelengths are used to predict soil mineral composition, while short and blue wavelengths are used to detect vegetation. The BSI is calculated based on the Landsat satellite imagery equation, wet and dry seasons, and is classified into three categories, as shown in the following equation:

### Results and discussion

The results of satellite image analysis and digital processing techniques based on remote sensing data demonstrated high effectiveness in identifying optimal locations for solar cell installations along the Hajj route from Baghdad to Karbala. Spectral classification algorithms and environmental criteria analysis were used to identify areas with the highest potential in terms of solar radiation availability, low slope, and suitable geographical orientation (south and southwest), taking into account proximity to major roads and infrastructure networks.

The results of the spatial analysis, combined with the use of remote sensing techniques and GIS algorithms, demonstrated the effectiveness of proposing strategic locations for solar power plants. The study demonstrated the importance of integrating topographic and spectral indicators in arriving at informed and realistic spatial decisions. The results of the topographic analysis using slope and aspect data showed that large sections of the road linking Baghdad and Karbala have suitable spatial characteristics for the construction of solar power plants. As Fig.2. A show, most of the areas within the study area fall within a slope range of  $3.1^{\circ}$  to  $5.1^{\circ}$ , which is within the optimal range for installing solar panels as recommended ( $<10^{\circ}$ ). These areas were concentrated, particularly in the cen-

ter and south of the studied sector, close to the visitor trail marked in red. The Aspect map shown in Fig.2. B shows that a large proportion of the land is southward ( $155^{\circ}$ – $175^{\circ}$ ), particularly in the central and southern parts of the trail, which enhances the efficiency of solar radiation reception throughout the day in the Northern Hemisphere. The areas classified in light colors (yellow and beige) indicate that these areas represent the optimal orientations for solar panels. The combination of a low slope and a southern orientation at several points along the trail are critical factors that increase the feasibility of the proposed sites, as these characteristics provide ideal conditions in terms of efficiency and ease of installing solar systems. The most suitable sites were concentrated in the areas south of the Mahmoudiyah district, the outskirts of the Yusufiyah district, and the southern part of Yusufiyah, up to the outskirts of Latifiyah. These areas combine optimal slope and orientation characteristics, making them strategic locations for establishing permanent, long-term solar power plants along the service route of the visitor trail.

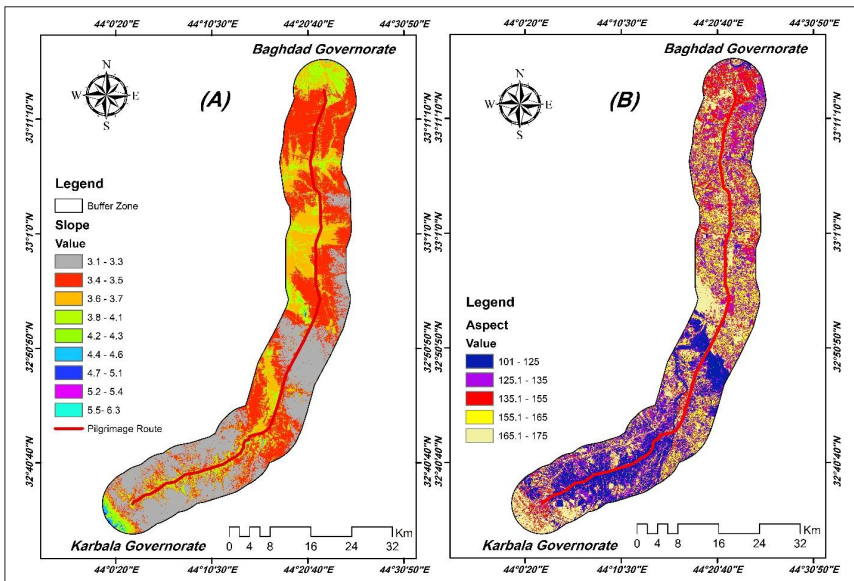


Fig.2. Topographic Analysis for Solar Site Suitability Along the Pilgrimage Route from Baghdad to Karbala (A) Slope Distribution – (B) Aspect Classification

The results of spectral analysis using the bare soil index (BSI) and the normalized vegetation index (NDVI) revealed the clear suitability of several areas along the pilgrims' route from Baghdad to Karbala for the construction of solar power plants. The BSI Fig.3.A showed that areas with high values (up to 0.89) were concentrated in the southern and central parts of the route, particularly around Sadr al-Yusufiyah, Latifiyah, and the outskirts of al-Zaidan, indicating the presence of suitable exposed soil with little interference with agricultural or environmental uses. In contrast, the NDVI Fig.3.B showed very low values (less than 0.1 and extending to -0.89) in areas such as al-Radwaniyah, south of Baghdad, and the northern entrance to Karbala Governorate. This reflects the low vegetation density and enhances the feasibility of exploiting these lands for energy production without harming ecosystems.

When these results are combined with the favorable topographical characteristics (low slope and southern orientation), it becomes clear that the best proposed locations include the areas of: South Mahmoudiyah, Latifiyah, Sadr Al-Yusufiyah, Al-Zaidan, Al-Radwaniyah, and North Karbala, making them strong candidates for the establishment of medium to large-scale solar power plants within a sustainable vision that supports infrastructure and visitor paths.

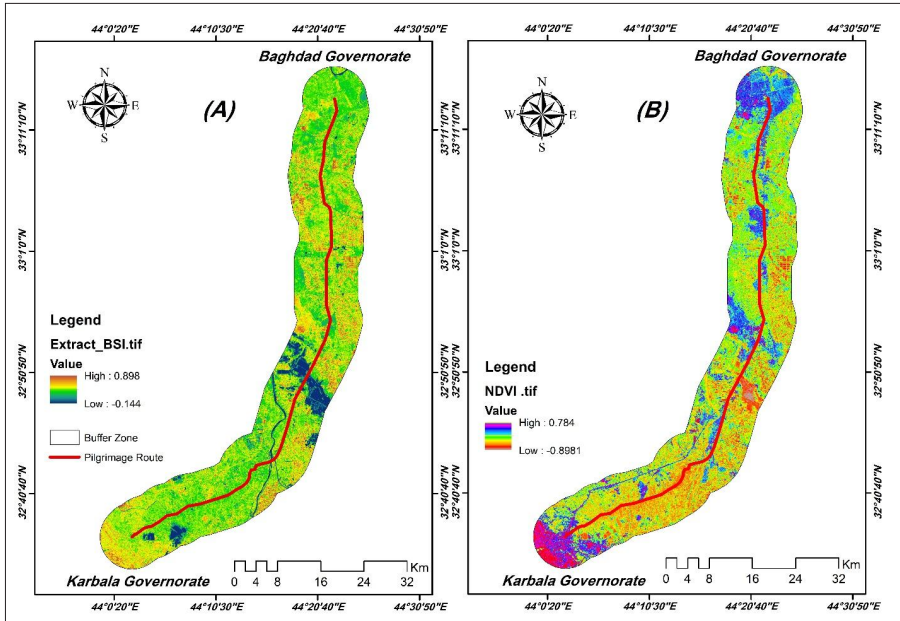


Fig.2. Spectral Analysis of Land Cover Suitability for Solar Energy Deployment Along the Pilgrimage Route from Baghdad to Karbala (A) Bare Soil Index (BSI) – (B) Normalized Difference Vegetation Index (NDVI)

The attached map illustrates two complementary spatial analyses of the pilgrims’ route from Baghdad to Karbala. Fig.3. (A) shows a composite (RGB) satellite image illustrating the general distribution of land cover, including agricultural areas (green), urban areas (grey and beige), and wet or shaded areas (dark), which facilitates visual verification of the results of other spectral indices. Fig.3. (B) displays a digital elevation model (DEM), showing the elevation gradient between 30 and 73 meters above sea level. The lowlands are visible north of the route (green), while elevations gradually increase southward, reaching their highest levels near Karbala (purple). This model reflects the importance of topographic considerations in selecting solar power plant sites, as areas with moderate and stable elevations are preferred to minimize topographic impacts and improve structural stability.

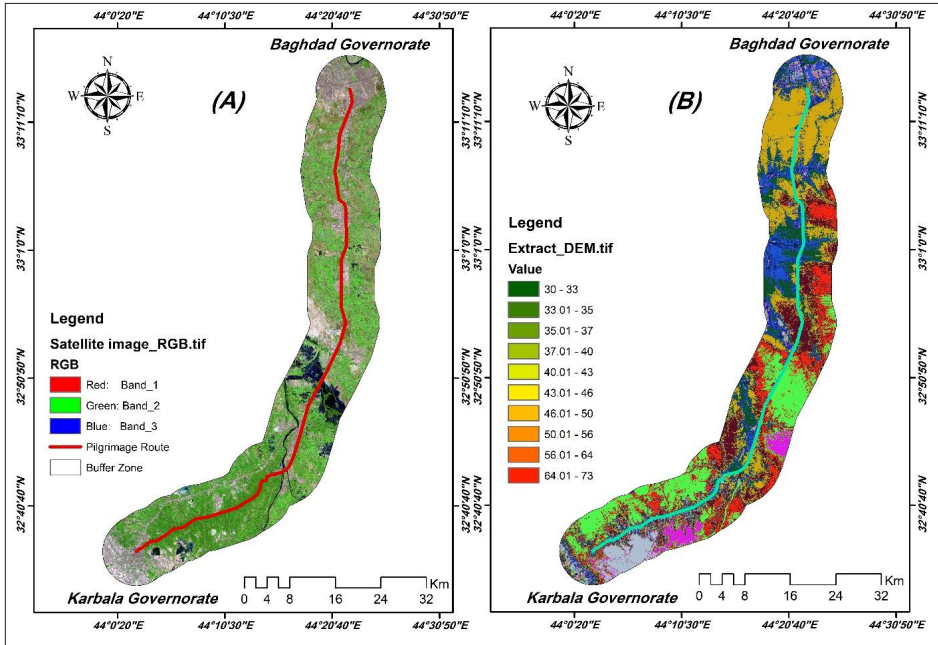


Fig.3. Visual and Topographic Characterization of the Pilgrimage Route from Baghdad to Karbala (A) Satellite RGB Image – (B) Digital Elevation Model (DEM)

The final spatial suitability map resulting from this analysis is a synthesis of the integration of environmental, topographic, spectral, and climatic data to identify the optimal locations for solar power plants along the pilgrims' route from Baghdad to Karbala. This map Fig.4. was constructed by combining several key spatial layers: slope map, aspect map, NDVI (Natural Vegetation Index), bare soil index (BSI), digital elevation model (DEM), and solar irradiance map. Each layer was classified into levels representing varying degrees of suitability and then combined within a weighted overlay model within a geographic information system (GIS) environment to produce a single map that illustrates the spatial distribution of suitability levels from "very high" to "unsuitable." The left part of the Fig.4. (A) shows a colored solar radiation map ranging from gray to red. The lowest values (4.32 – 4.5 kWh/m<sup>2</sup>/day) are represented

by gray and purple, while the highest values (5.66 – 5.89 kWh/m<sup>2</sup>/day) are represented by warm colors such as red and orange. From this map, it can be seen that areas of high solar radiation are clearly concentrated in the southern part of the studied corridor, especially as the road approaches the outskirts of Karbala Governorate, with other radiation pockets in parts of the central corridor, specifically south of Yusufiyah. These high values represent the optimal climate for electricity production using solar cells, as they ensure a high and stable daily production rate. The right Fig.4. (B) is the combined spatial suitability map, reflecting the final result of the analysis of all criteria combined. The color gradient is shown from green (high suitability) to black (unsuitable), passing through blue, purple, and pink, representing medium to limited levels. Comparing this map with the solar radiation map, it is clear that the areas with very high suitability largely correspond to areas with high solar radiation, especially around Sadr al-Yusufiyah, the outskirts of the Latifiyah district, south of Mahmoudiyah, and the western sector leading to the entrance to Karbala. These areas appear clearly on the map in intense blue and green. These sites also feature low slopes (less than 5 degrees), a suitable southerly orientation (155°–175°), and low NDVI values (<0.1) and high BSI values (>0.3), indicating that they are environmentally suitable arid areas that do not require vegetation removal or complex terrain modification. On the other hand, some areas in the northern part of the route, particularly within the boundaries of Baghdad Governorate, appear less suitable due to low solar radiation, increased topographic slope, or high relative vegetation density. Furthermore, some urban and built-up areas along the route—such as al-Radwaniyah and al-Yusufiyah Center—were classified as “unsuitable” due to their overlap with existing land uses that do not permit the establishment of large-scale solar energy systems. This final map

represents not only the result of a numerical analysis, but also serves as a strategic planning tool that can guide government or private investment decisions in renewable energy projects, particularly those aimed at supplying service stations, visitor filling stations, or street lighting with clean energy. It can also be used as a scientific basis for preparing a detailed feasibility study for specific sites on the ground.

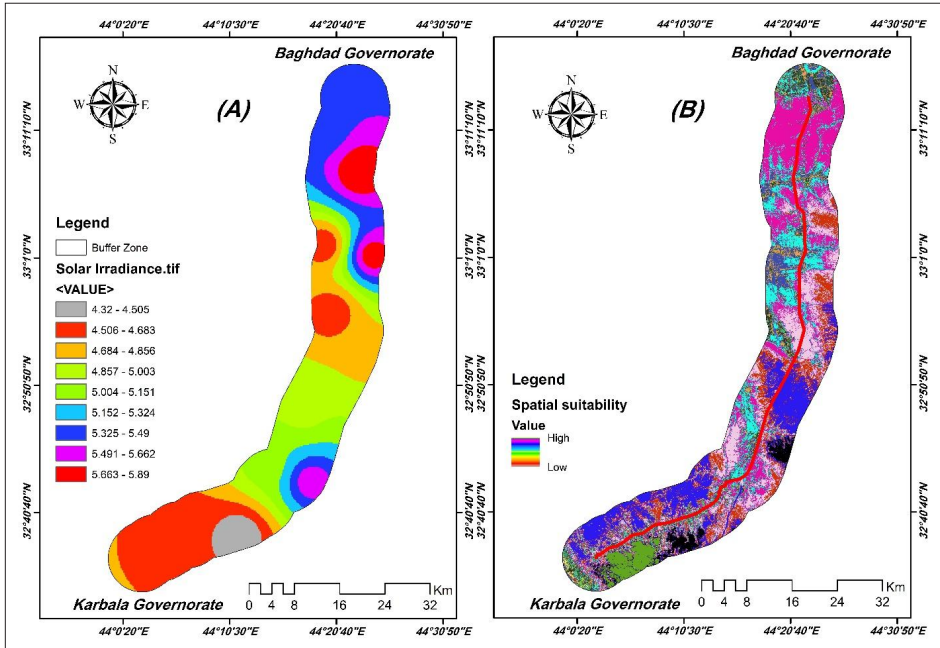


Fig.4. Integrated Spatial Suitability and Solar Irradiance Map for Optimal Solar Power Plant Site Selection Along the Pilgrimage Route from Baghdad to Karbala (A) Solar Irradiance Distribution – (B) Final Spatial Suitability Classification

## Conclusions

1. The results of the spatial analysis demonstrate the effectiveness of using remote sensing techniques and GIS algorithms in proposing strategic locations for solar power plants along the Hajj route from Baghdad to Karbala. The study demonstrated the importance of integrating topographic and spectral indicators in arriving at informed and realistic spatial decisions.
2. First, the slope index proved its crucial role in identifying sites with low construction costs. It was found that more than 70% of the studied area lies within a slope of no more than 5 degrees, reflecting the feasibility of installation without the need for extensive leveling. This is an important economic factor in solar energy projects, especially for temporary or mobile infrastructure that can serve pilgrims during the pilgrimage season.
3. Second, the topographic orientation (aspect) is a factor that directly affects the efficiency of solar radiation absorption. The results showed that a large portion of the land is oriented south or southwest, which is consistent with global standards for solar panel installation in the Northern Hemisphere. This natural orientation reduces the need for expensive mechanical rotation structures to optimize solar incidence angles.
4. Third, spectral analysis using the NDVI and BSI indices enabled a precise environmental assessment of the land. Areas with low NDVI and high BSI represent vegetation-poor environments rich in exposed soil, indicating that implementing solar projects in these locations will not cause the removal of vegetation cover or the destruction of sensitive natural ecosystems. This supports the concept of environmental sustainability in the spatial planning of energy projects.
5. The results of the digital elevation model (DEM) contributed to understanding the general topography and demonstrated the stability of the

land at moderate elevations, which is structurally suitable and has little impact on wind flow or shade from the surrounding terrain.

6. Overall, these results confirm that using multiple, spatially overlapping criteria—rather than relying on a single index—is a more accurate approach to selecting optimal solar energy sites. They also indicate that the areas south of Mahmoudiya and Latifiya are among the most promising sites, both topographically and environmentally.
7. However, it is worth noting some potential challenges, such as the availability of energy transmission infrastructure, the security situation in some areas, and the need to update solar radiation data monthly to ensure the accuracy of production estimates.

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