An-Najah University Journal for Research – A

Natural Sciences

# GIS and Analytical Hierarchy Process (AHP)-Based Solar Energy Suitability Mapping in Palestine

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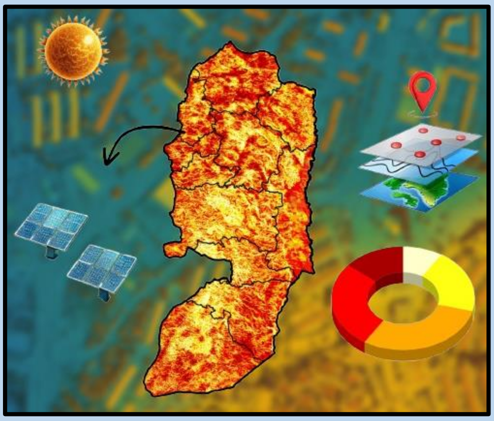
Received 24th Sep. 2024, Accepted 15th Dec, 2024, Published ××××, DOI: https://doi.org/10.xxxx

**Accepted Manuscript, In press**

**Abstract**: This research aims to develop a solar energy suitability (SES) map for the West Bank, Palestine, considering potential driving factors (criteria). This is particularly crucial due to the increasing population and constraints imposed by reliance on Israeli electrical supplies, which amount to approximately 93%. Nine criteria were selected and used including slope, aspect, hillshade, distance from electric connection points, elevation, distance from roads, distance from built-up areas, land uses, and administrative zones. Geographic Information System (GIS) and Analytic Hierarchy Process (AHP) were used to develop the SES map. The study reveals that 41% of the West Bank is highly suitable for solar energy projects (SEPs), while 29% falls into very low to low suitability, and 30% moderately suitable. Notably, Qalqilya and Jenin governorates are highly suitable for SEPs, whereas Ramallah and Jerusalem are the least suitable for SEPs. By intersecting the SES map with the A, B, and C zones of the Oslo Accord, it is evident that approximately 44% of the highly suitable SES areas are located in the A and B zones. This makes expanding SEPs in these areas possible. Additionally, the highly SES areas are mainly located in open space areas, implying that developing SEPs therein is a viable future option. The results of this research will help different stakeholders select potential sites for feasible SEPs in Palestine.



**Keywords**: Solar energy; Geographic information system (GIS); Analytical Hierarchy Process (AHP); Multi-Criteria Decision Analysis (MCDA); Suitability mapping; Palestine.

## Introduction

The main energy sources in the world vary between fossil fuels, nuclear energy, and renewable energy. Fossil fuels are used for heating but contribute to the emission of greenhouse gases (e.g., CO2, CH4, etc.), causing an increase in average temperatures and environmental pollution [1]. On the other hand, the global societal shift towards renewable energy sources is considered the only practical and environmentally friendly solution to replace conventional energy sources for power generation [2,3]. Among these sources, solar energy stands out for its unique ability to provide a local electricity source, especially in rural areas [3]. Additionally, it is a sustainable, cost-effective, and renewable energy source [4].

The energy sector in Palestine encompasses renewable energy (e.g., solar energy, and wind energy), and non-renewable energy (e.g., oil, and natural gas). Palestine heavily relies on importing energy, majorly from the Israeli occupation, constituting about 93% of locally consumed electric power. Additionally, a smaller portion is imported from Egypt and Jordan. In Gaza, a power plant generates approximately 7% of the locally consumed electricity. There is a yearly increase in electricity demand in Palestine by about 7%, due to rapid population growth [5].

In recent years, geographic information system (GIS) has experienced increasing prevalence in site selection and mapping studies, particularly in solar energy suitability (SES) mapping. The literature reflects many GIS-based Multi-Criteria Decision Analysis (MCDA) applications, with a notable focus on SES mapping [6,7]. Driving the transition toward sustainable and resilient energy systems [8]. Due to the diverse criteria influencing the site selection process, the MCDA approach can effectively identify suitable sites for solar energy projects (SEPs) by evaluating multiple criteria [9,10]. This involves the use of GIS supported by the Analytical Hierarchy Process (AHP) approach to develop SES map and enhance decision-making [11,12]. The success of the MCDA approach has been demonstrated in the context of SES mapping [13,14].

Site selection for energy projects is a vital process that greatly affects the efficiency and sustainability of the system. Sites must be carefully selected based on energy production driving factors [15]. Developing the renewable energy sector in Palestine ensures energy source security, potentially reducing reliance on Israeli electrical supplies and neighboring countries, promoting sustainable development, and fostering social and economic development [16,17].

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This research aims to develop the SES map for the entire West Bank using a GIS-based AHP approach. The ultimate objective is to assist stakeholders in identifying and selecting optimal locations for implementing SEPs in Palestine. This in turn will contribute to meeting the sustainable development goals in Palestine, primarily ("SDG 7: Affordable and clean energy" and SDG 13 "Climate action").

## Materials and Methods

### Study Area

The West Bank, Palestine is located in the Middle East, west of the Jordan River, between the latitudes of 31.34 and 32.55 N, and the longitudes of 34.96 and 35.56 E. It has a surface area of about 5,624 km2. In the West Bank, surface elevations changed from 410 m below mean sea level near the east (in Jericho) to 1,022 m above mean sea level in the south (in Hebron) [18]. Governmentally, the West Bank is split up into 11 governorates, as shown in Figure 1, where the projected population for mid of the year 2023 is about 3.25 million people [19].

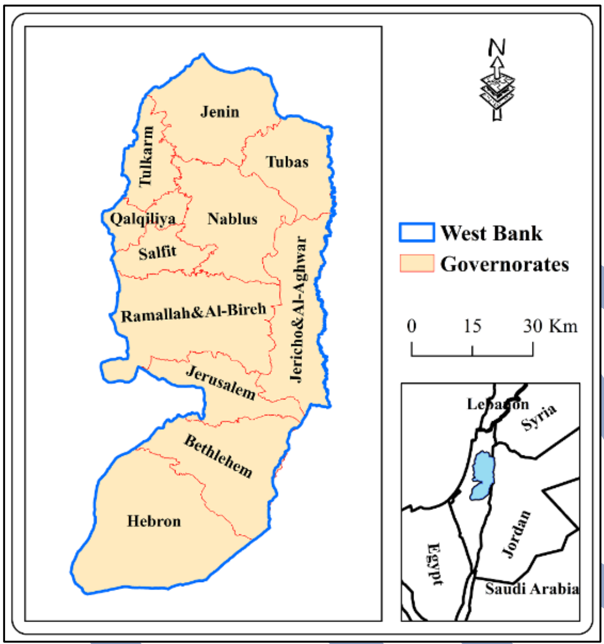


**Figure (1):** General map of the study area.

Climate in the West Bank is predominantly Mediterranean, characterized by significant seasonal differences between summer (dry and hot) and winter (wet and cold) [20]. The West Bank is characterized by over 300 sunny days yearly, averaging 8 hours of daily sunshine. With a daily average solar radiation of approximately 5.4 kW/m2, equivalent to 1950 kWh of energy. These conditions make the West Bank one of the best areas for solar energy investment [21].

### Methodology

A GIS-based MCDA approach was employed to develop the SES map for the West Bank. The overall methodological framework can be depicted in Figure 2. Nine influencing factors (criteria) of solar energy in the West Bank were identified based on the best available national-level datasets from the Geomolg (2023) [22]. Moreover, the data on electric connection points was acquired from Palestinian Electricity Transmission Ltd (PETL).

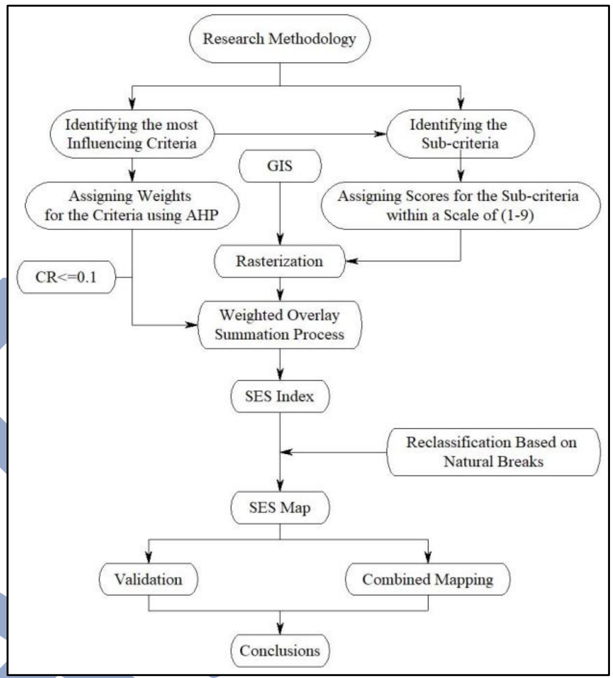


**Figure (2):** General conceptual flowchart methodology.

A GIS-based database was created to facilitate the development of the West Bank SES map. The factors are slope (S), aspect (A), hillshade (HS), distance from electric connection points (CP), DEM, distance from road network (RD), distance from built-up areas (BU), land uses (LU), and administrative zones (ABC).

The AHP pairwise comparison matrix approach is one of the inclusive approaches in MCDA. The hierarchical manner of complex problems is made easier with this approach. By the AHP, favorable weights for the selected SES mapping criteria are given in Table 1 [13].

**Table (1):** Pairwise comparison matrix for the criteria and their weight.

| Criteria | S | A | HS | CP | DEM | DR | BU | LU | ABC | Weight |
|---|---|---|---|---|---|---|---|---|---|---|
| **S** | 1.0 | 2.0 | 2.0 | 0.3 | 3.0 | 2.0 | 2.0 | 2.0 | 2.0 | 0.16 |
| **A** | 0.5 | 1.0 | 2.0 | 0.3 | 2.0 | 2.0 | 2.0 | 3.0 | 3.0 | 0.15 |
| **HS** | 0.5 | 0.5 | 1.0 | 0.5 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 0.12 |
| **CP** | 3.0 | 3.0 | 2.0 | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 | 3.0 | 0.19 |
| **DEM** | 0.3 | 0.5 | 0.5 | 0.5 | 1.0 | 2.0 | 0.5 | 0.5 | 0.5 | 0.06 |
| **RD** | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 1.0 | 0.5 | 0.5 | 0.5 | 0.05 |
| **BU** | 0.5 | 0.5 | 0.5 | 0.5 | 2.0 | 2.0 | 1.0 | 0.5 | 0.5 | 0.08 |
| **LU** | 0.5 | 0.3 | 0.5 | 0.5 | 2.0 | 2.0 | 2.0 | 1.0 | 2.0 | 0.10 |
| **ABC** | 0.5 | 0.3 | 0.5 | 0.3 | 2.0 | 2.0 | 2.0 | 0.5 | 1.0 | 0.09 |

Consistency Ratio (CR) is computed to assess the consistency of the pairwise comparison matrix using the following equations:

$$CR = \frac{CI}{RI} \quad (1)$$

$$CI = \frac{\lambda - n}{n - 1} \quad (2)$$

Where CI is the consistency index, RI is the random index, λ is the normalized principal eigenvector, and n is the number of factors (criteria). For n = 9, λ = 9.76, and RI = 1.45, the CR in this study is calculated as 0.07.

The requirement that the CR value be less than or equal to 0.1 suggests that the matrix is consistent. Conversely, if the CR is greater than 0.1 it means that pairwise comparison has inadequate consistency [23]. It is worth mentioning that the values presented in Table 1 were assigned in consultation with five solar energy experts based on their subjective opinion as shown in Table 2.

**Table (2):** Experts' provided criteria weights (%) of SES mapping and their mean.

| Criteria | Expert 1 | Expert 2 | Expert 3 | Expert 4 | Expert 5 | Mean |
|---|---|---|---|---|---|---|
| **S** | 20 | 10 | 10 | 10 | 14 | 13 |
| **A** | 20 | 10 | 5 | 10 | 13 | 12 |
| **HS** | 10 | 11 | 10 | 15 | 13 | 12 |
| **CP** | 20 | 14 | 26 | 10 | 11 | 16 |
| **DEM** | 5 | 8 | 5 | 15 | 7 | 8 |
| **RD** | 5 | 11 | 5 | 10 | 8 | 8 |
| **BU** | 5 | 10 | 5 | 15 | 8 | 9 |
| **LU** | 5 | 13 | 17 | 10 | 13 | 11 |
| **ABC** | 10 | 13 | 17 | 5 | 13 | 11 |

For each factor used in the development of the SES map, several classes scored from 1 to 9 were produced, as shown in Table 3. The highest suitability is indicated by scores close to 9, whereas scores close to 1, indicate lowest suitability.

The SES map factors were rasterized and classified with proper GIS tools, as shown in Figure 3. SES index was computed using the weighted overlay summation process, which combined the weighted cell values of different SES factors. Model builder is a built-in tool GIS, which was used to automate the development procedure of the SES map as shown in Figure 4.

**Table (3):** Scoring of the SES mapping sub-criteria classes.

| # | Criteria | Sub-criteria | Suitability value | Unit |
|---|---|---|---|---|
| 1 | S | ≥ 20 | 1 | ° |
| | | 15-20 | 3 | |
| | | 10-15 | 5 | |
| | | 5-10 | 7 | |
| | | < 5 | 9 | |
| 2 | A | North | 1 | - |
| | | Northeast, Northwest | 3 | |
| | | East, West | 5 | |
| | | Southeast, Southwest | 7 | |
| | | South, Flat | 9 | |
| 3 | HS | 1-50 | 1 | - |
| | | 50-100 | 3 | |
| | | 100-150 | 5 | |
| | | 150-200 | 7 | |
| | | 200-254 | 9 | |
| 4 | CP | ≥ 1500 | 3 | m |
| | | 1000-1500 | 5 | |
| | | 500-1000 | 7 | |
| | | < 500 | 9 | |
| 5 | DEM | -375-0 | 3 | m |
| | | 0-250 | 8 | |
| | | 250-500 | 9 | |
| | | 500-750 | 7 | |
| | | > 750 | 5 | |
| 6 | RD | ≥ 1500 | 2 | m |
| | | 1000-1500 | 5 | |
| | | 500-1000 | 7 | |
| | | < 500 | 9 | |
| 7 | BU | ≥ 1500 | 9 | m |
| | | 1000-1500 | 7 | |
| | | 500-1000 | 5 | |
| | | < 500 | 1 | |
| 8 | LU | Built-up | 1 | - |
| | | Woodland/Forest | 2 | |
| | | Trees | 3 | |
| | | Irrigated farming | 6 | |
| | | Arable Land | 8 | |
| | | Open Spaces | 9 | |
| 9 | ABC | C | 3 | - |
| | | B | 6 | |
| | | A | 8 | |

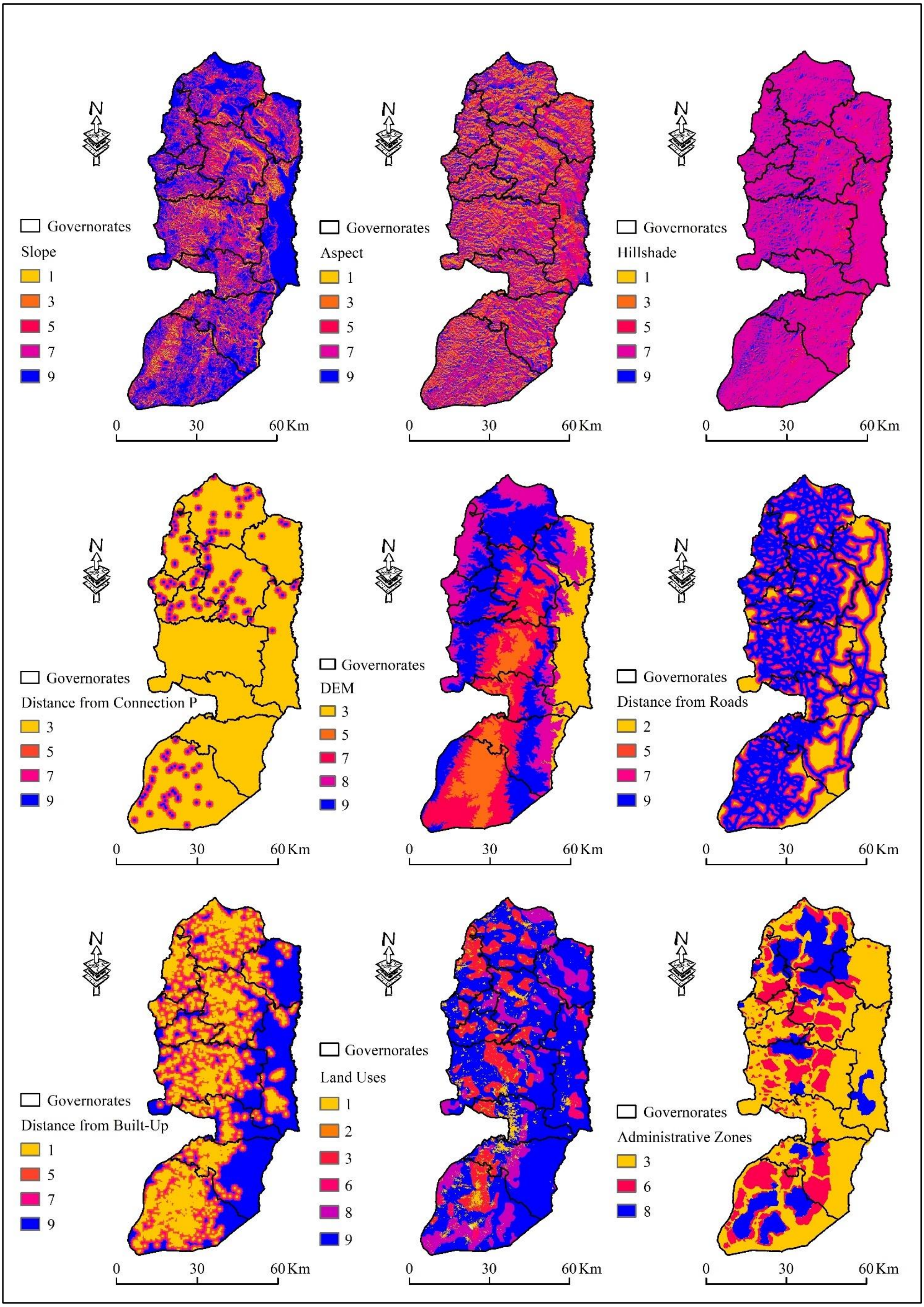


**Figure (3):** Classified criteria maps for SES mapping.

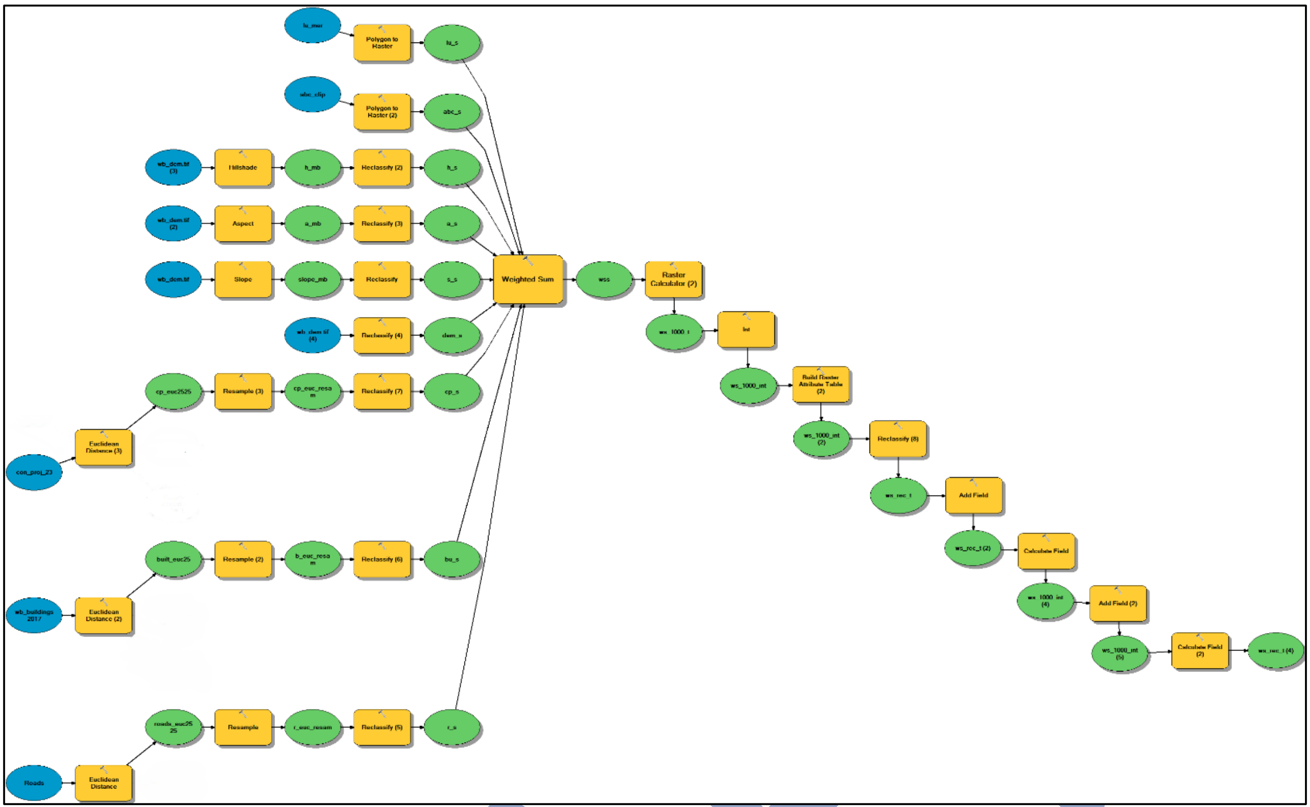


**Figure (4):** Model builder for SES map.

Input rasters were multiplied by their weights to compute the SES index as follows:

$$SES_i = \sum_{i=1}^{n} W_i \times S_{ij} \qquad (3)$$

Where $SES_i$ is the total cell index, $W_i$ is a factor weight ($\sum W_i = 1$), $S_{ij}$ is the suitability value of the ith cell for the jth factor, and n is the number of cells in each jth factor [24]. The final SES map for the entire West Bank was obtained by reclassifying of $SES_i$ map by natural breaks (Jenks). The obtained SES map was validated based on the existing SEPs located at different governorates. Finally, intersection mapping between (1) the SES map and governorates (2) the SES map and administrative zones (3) the SES map and land uses were accomplished to locate proper sites for future investment in SEPs in the West Bank.

## Results and Discussion

### SES Map

The obtained SES map for the entire West Bank was categorized into five categories of suitability: very low, low, moderate, high, and very high, as shown in Figure 5. The West Bank SES map indicates that areas with high to very high suitability are predominantly located in the northern and southern parts. Conversely, areas with very low to low suitability are mainly located in the central governorates. This pattern can be assigned to the spatial distribution of electric connection points in the West Bank, which is almost non-existent in Jerusalem due to the political situation where Palestinians have no hands on the development of electric projects. The percentage distribution of the five SES categories in the West Bank is detailed in Table 4.

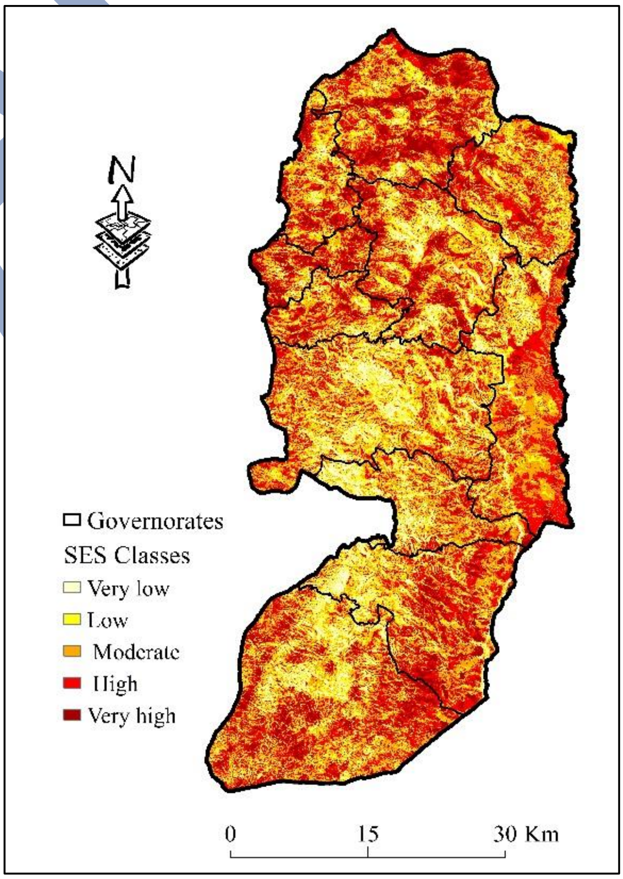


**Figure (5):** Developed SES map for the West Bank.

**Table 4:** Percentage distribution of the five SES categories in the West Bank.

| SES category | Very low | Low | Moderate | High | Very high |
|---|---|---|---|---|---|
| **Area (%)** | 9 | 20 | 30 | 27 | 14 |

According to Table 4, approximately 41% of the total West Bank area is under high to very high suitability for SEPs. This can be attributed to the location of Palestine within the sun-belt between latitudes 40 degrees north and 40 degrees south and has more than 300 sunny days annually [21,25]. Areas with very low to low suitability form 29% of the West Bank area, while 30% of the West Bank falls under the moderate suitability class. Additionally, for the various governorates, area percentages of the five suitability categories are presented in Figure 6.

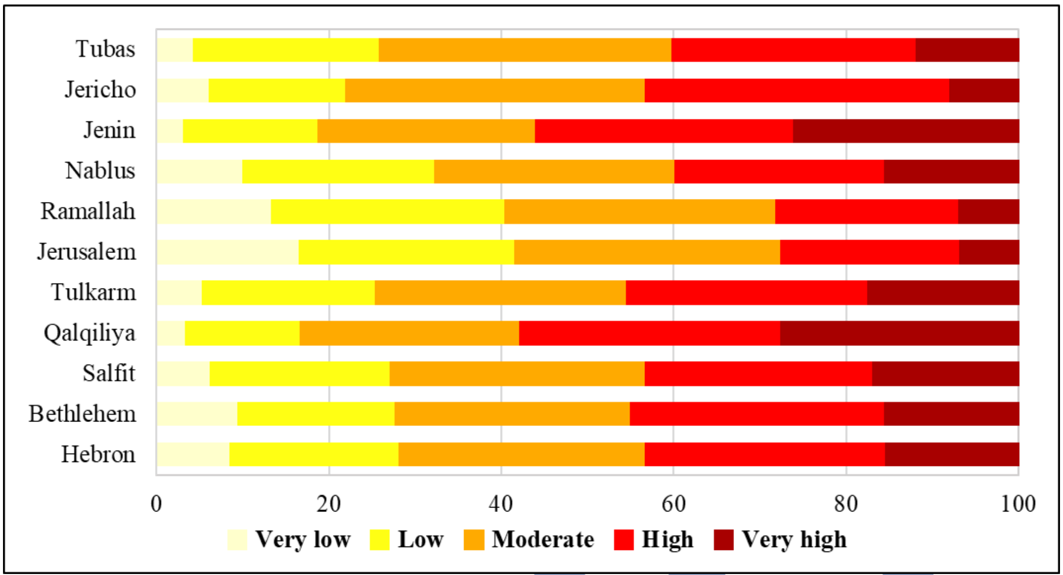


**Figure (6):** Area percentages of the five SES suitability categories in the various governorates.

Figure 6 illustrates that over 55% of the land areas in Qalqiliya and Jenin governorates fall within high to very high SES classes. This suggests significant potential for expanding SEPs in these governorates to enhance solar energy supplies in Palestine. Conversely, Jerusalem and Ramallah are identified as the least suitable governorates for SEPs, with very low to low suitable areas occupying 42% and 41%, respectively, of the total governorate area, because of a lack of electric connection points, due to the Israeli political restrictions. The obtained results will inspire energy planners to verify the feasibility of the existing SEPs in the different governorates. This, in turn, can improve the overall planning process for investing new SEPs in the West Bank.

## SES Map Validation

To assess the accuracy of the obtained SES map, the locations of 35 existing SEPs in various governorates of the West Bank were identified and compared with the five SES categories, as shown in Figure 7. Results indicate that 60% of the existing SEPs are located in high to very high solar energy-suitable areas. Overall, it can be concluded that investment in SEPs in the different governorates to enhance energy supplies and meet the increasing electricity demand is possible. However, a feasibility analysis is required to realize such an investment. Furthermore, this general alignment between existing SEPs and highly SES areas (60%) suggests that the utilized approach is valid for developing the SES map in the West Bank, Palestine. Although Qalqiliya is the governorate with the highest suitability for SEPs, it is the only one without any SEPs due to the land used for farming. Therefore, proper SEPs should be developed in Qalqiliya without altering agricultural activities.

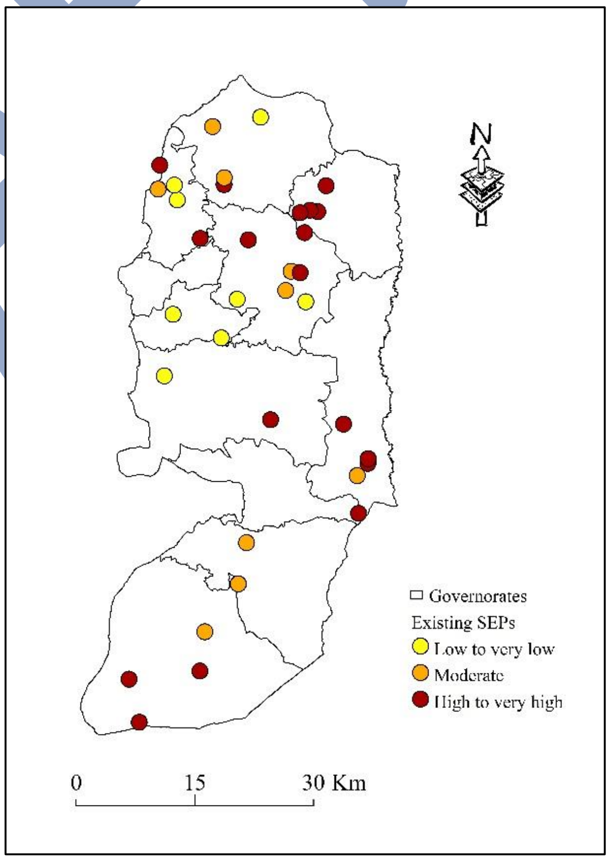


**Figure (7):** Existing SEPs in the West Bank governorates.

## SES-Administrative Zones Intersection Map

A detailed analysis was conducted to evaluate the distribution of potential SEPs based on the administrative zones in the West Bank. According to the Oslo Accords, the West Bank is divided into A, B, and C zones each with different levels of Palestinian and Israeli control [22]. Understanding the SES distribution in these areas is crucial for identifying suitable locations for SEPs, particularly in areas A and B where the Palestinian Authority has certain administrative and security control. The intersection mapping of the developed SES map and the administrative zones has been conducted. Results are presented in Figure 8.

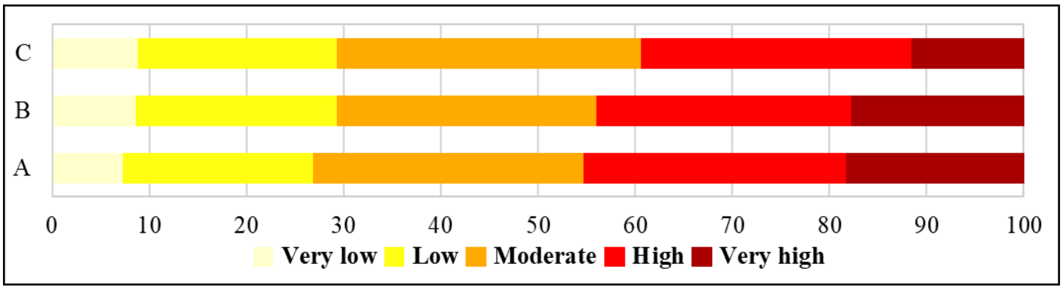


**Figure (8):** Percentage of area for the five SES suitability categories in administrative zones.

Figure 8 shows that 44% of the highly SES areas are within A and B zones. Future investment in SEPs in these areas is feasible and would enhance electricity supplies in Palestine. Conversely, the investment in SEPs in the C zone is at risk and requires permits from the Israeli authorities. This will influence the achievement of electrical supplies self-sufficiency and increase reliance on imported Israeli electricity in this zone. Furthermore, the obtained results can assist policymakers in strategic planning for future investments in SEPs in A, B, and C zones across the West Bank.

### SES-Land Uses Intersection Map

The obtained SES map intersected with the land uses map. Figure 9 shows the percentages of the five SES categories for different land uses. Utilizing these lands for solar energy initiatives is crucial for maximizing the efficient use of available resources.

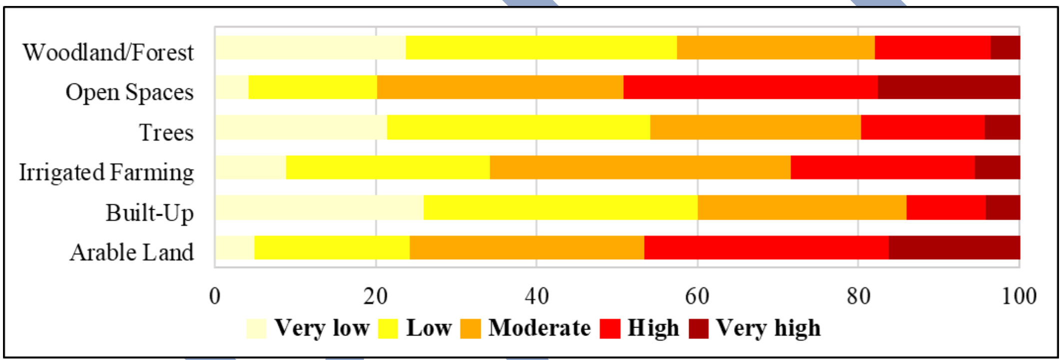


**Figure (9):** Percentage of area for the five SES categories in different land uses.

According to the results in Figure 9, open spaces areas, which make up 62% of the West Bank, are predominantly covered by highly SES-suitable areas (49%). This highlights a potential investment in SEPs in these areas to enhance electricity supplies. Transforming the land use of these open spaces for SEPs not only supports sustainable development but also ensures energy security and economic growth for the region.

## Conclusion

In this research, optimal locations for large-scale SEPs in the West Bank, Palestine, were identified. The study considered a variety of influential factors, including slope, aspect, hillshade, distance from electric connection points, DEM, distance from road network, distance from built-up areas, land uses, and administrative zones. The AHP approach was employed to determine the relative weights of these decision criteria. By integrating these weights with GIS data, the study identified the most suitable areas for the implementation of SEPs in the West Bank. This success of the developed SES map underscores the efficacy of GIS-MCDA in site selection for renewable energy. Quantitatively, the general conclusions are summarized as follows:

- The SES map developed for the West Bank delineates five classes of suitability for SEPs: very low (9%), low (20%), moderate (30%), high (27%), and very high (14%).
- The combined mapping of the SES map with the A, B, and C areas reveals that approximately 44% of the total highly SES regions are located within areas A and B.
- By implementing existing SEPs based on the suitability map, it was found that 60% of existing SEPs are located within areas categorized as high to very high suitability for solar energy.
- Depending on the developed SES map, the increasing energy supply-demand gap in the West Bank can be effectively bridged by proper investment in SEPs in highly suitable areas where possible.
- Targeting highly suitable areas, identified in the northern and southern parts of the West Bank, can maximize the efficiency and production of SEPs therein.

## List of abbreviations

**List of abbreviations**

- A — Aspect
- ABC — Administrative Zones
- ahp — Analytical Hierarchy Process
- BU — Distance from Built-Up areas
- CP — Distance from Electric Connection Points
- CR — Consistency Ratio

- dem Digital Elevation Model
- DR Distance from Road Network
- gis Geographic Information System
- HS Hillshade
- LU Land Uses
- mcda Multi-Criteria Decision Analysis
- PETL Palestinian Electric Transmission Ltd
- S Slope
- SEPs Solar Energy Projects
- ses Solar Energy Suitability

## DISCLOSURE STATEMENT

- Ethics approval and consent to participate: Not applicable
- Consent for publication: Not applicable
- Availability of data and materials: The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.
- Author's contribution: The authors confirm their contribution to the paper as follows: Razan Hijazi and Sondos were involved in the study conception, GIS calculations and modeling, data analysis, and results validation. Razan Hijazi drafted the manuscript. Sameer Shadeed was involved in the formulation of the general idea of the research, supervising the entire work, manuscript editing, and proofreading. All authors reviewed the results and approved the final version of the manuscript.

- Funding: Not applicable

- Conflicts of interest: The authors declare that there is no conflict of interest regarding the publication of this article

- Acknowledgments: The authors would like to express their gratitude to everyone who helped bring this article to completion. Also, the authors are interested in conveying thanks to reviewers of the An-Najah University Journal for Research, A: Natural Sciences, for their helpful comments, which enhanced the paper's value.


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