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Site Suitability Analysis for Photovoltaic Power Plant Using Geographical Information System

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Abstract: *Among the various renewable energy resources, solar energy potential is vastly and freely available in our country. Solar energy offers a clean, climate-friendly, abundant and inexhaustible energy resource to mankind. The costs of solar energy have been falling rapidly and are entering new areas of competitiveness. Solar Thermal Electricity (STE) and Solar Photo Voltaic Electricity (SPV) are becoming competitive against conventional electricity generation in tropical countries. In conventional methods, site selection based on integrating various performance indicators such as Temperature, DNI, Sunshine hours, Slope, Aspect and Land use are difficult. GIS provides an integrated approach to combine several factors and provides different scenarios for decision making. This paper describes the suitable site selection for installation of photovoltaic power plants using GIS. It involves three stages: the first stage requires the selection of study area based on power crisis in different districts. The second stage includes preparation of the layers such as Direct Normal Irradiance, Temperature, Sun Shine Hours Land use / land cover, Slope and Aspect for study area and at final stage weights for each layer is calculated with the help of Analytical Hierarchy Process and suitable sites for installation of photovoltaic power plants are derived using suitability analysis in GIS environment.*

Keywords: Renewable Energy, Solar Thermal Electricity, Sunshine Hours.

I. Introduction

Solar photovoltaic (SPV) cells are nothing but cells that convert solar radiation (sunlight) into electricity. A solar cell is a semi-conducting device made of Silicon materials, which, when exposed to sunlight, generates electricity. Solar cells are connected in series and parallel combinations to form modules that provide the required power. Tamil Nadu Energy Development Agency (TEDA) is the nodal agency to promote the use of new and renewable sources of energy and to implement renewable projects in Tamil Nadu. Whenever solar radiation is available, solar cells can produce electrical current. Several materials are used to make solar cells; the most common being silicon. The output of the cell is proportional to the light input. Site selection for Grid-connected Photovoltaic Power Plants (GPPPs) can be regulated by means of a carrying capacity model, which combines Multi-Criteria Analysis (MCA) as well as the Analytic Hierarchy Process (AHP) with geographical information systems (GIS) technology. A photovoltaic (PV) system is made up of several photovoltaic solar cells.

Tamil Nadu is expected to have a deficit of around 18%, which was the highest among all the States considered. Availability of power is one of the biggest inputs necessary for the sustained growth of any economy. This becomes even more important for a state like Tamil Nadu, which is one of the most industrialized and urbanized states in India. Power deficits in Tamil Nadu from 2002-03 to 2010-11 is shown in Fig. 1.

Since Tamil Nadu is under severe power crisis, it is necessary to look for an effective alternative source of power to help Agricultural and Industrial activities of the state. Solar power from photovoltaic cells is one such source. By installing solar power panels, tonnes of carbon dioxide emissions every year could be avoided and a huge cut in your carbon footprint could be made. Solar power is a simple, effective and tangible way of making real change by reducing the amount of coal fired electricity needed without any loss of amenity or quality of service.

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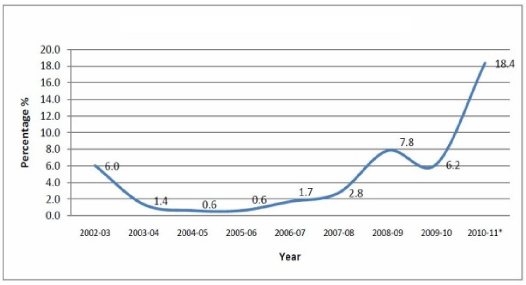

Figure 1: Power deficit in Tamil Nadu (2002-2003 to 2010-11)

The solar panels need almost negligible maintenance and have a life of over 40 years. The aim of this research is to find suitable sites for the establishment of Grid connected Photovoltaic Power Plants (GPPP). The objectives of the research are,

- To select a district of Tamil Nadu as a study area by analyzing power crisis and availability of alternative resources.
- To prepare different thematic layers for the study area from the data collected.
- To assign weightages to different parameters that contributes the performance of photovoltaic power cells using MCA and AHP.
- To suggest suitable sites for installation of photovoltaic power plants via overlay analysis in ArcGIS environment.

1.1 Study Area

Karur district is bounded by Namakkal district in the north, Dindigul district in the south, Tiruchirapalli district on the east and Erode district on the west. Karur is located between 10°35‶N to 11°7‶N of latitude and 77°28'E to 78°50'E of longitude as shown in Fig 4.1. It has an average elevation of 122 metres (400 feet). The highest temperature is obtained in early May to early June usually about 34 °C (93.2 °F).Average daily temperature in Karur during January is around 23 °C (73.4 °F). The average annual rainfall is about 775 mm (30.5 in). Karur is famous for its home textiles. It also includes the industries like ginning and spinning mills, dyeing factories, weaving etc., that employ around 450,000 people in and around Karur.

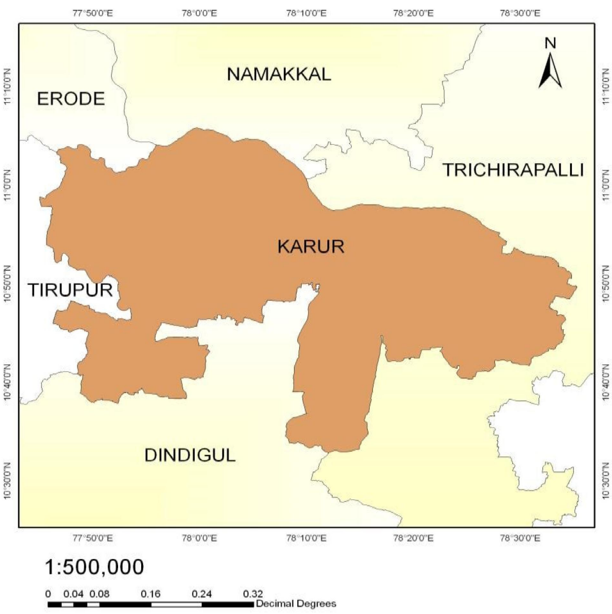

Figure 2: Study area –Karur District

II. METHODOLOGY

The step by step procedures involved in methodology. A point layer is created in ArcCatalog. The locations of temperature observation stations in five districts (Karur, Erode, Trichy, Dindigul and Namakkal) are digitized using their latitude and longitude in ArcMap. The attributes such as latitude, longitude and average temperature are populated. Inverse Distance Weighted (IDW) method is used for interpolation. IDW is an advanced nearest neighbour approach that allows including more observations than only the nearest points. The value at a certain grid cell is obtained from a linear combination of the surrounding locations. The weight of each observation is determined by the distance, the distance function is non-linear. IDW is an exact interpolator. From that interpolated layer, Temperature layer of Karur district is clipped. The same procedure mentioned above is followed for sunshine hours layer also. The spread sheet containing the information such as latitude, longitude and Annual DNI of Karur district is added to ArcGIS. It is exported as a point layer using export data option. An interpolated layer is prepared using IDW method from that which represents Annual Direct Normal Irradiance of Karurdistrict.Land use / Land cover layer, road network data and reserved areas layer are added to ArcMap. 1 km buffer is created in road network data using BUFFER function and it is removed from land use layer using ERASE function. Reserved areas also removed from the resulting layer using the same ERASE operation.

The original elevation dataset has a spatial resolution of about 90m. This can be resampled to higher resolution of 30m. This is done to obtain even more greater details. A study reveals that 30m DEM is 10 times more detailed than a 90m DEM. Hence it is resampled to 30m.

Formula used in the raster calculator is,

Resample ([elevationimage_name],0.000278,bilinear)

Using the above formula the elevation raster is converted to a calculation layer. This resulting calculation layer gives the elevation data with a spatial resolution of 30m. The calculation layer formed is used to find the slope layer. This is given as the input for creating slope. Slope option in the spatial analyst tool is used for this purpose. To create this we need the following

The cell size corresponding to 30m elevation data.

The proper Z factor.

The cell size is *0.000278*and the Z factor corresponds to the Latitude value of our study area and the value was found to be *0.00000912*.

Aspect is derived from a raster surface. Aspect identifies the downslope direction of the maximum rate of change in value from each cell to its neighbours. Aspect can be thought of as the slope direction. The values of the output raster will be the compass direction of the aspect.

The calculation layer formed is used to find the aspect layer. This is given as the input for creating aspect. Aspect option in the surface analysis of spatial analyst toolused for this purpose. This only requires the cell size value which is *0.000278***.** In many situations it may not be possible to assign weights to different criteria involved in making a decision. Therefore it is necessary to adopt a technique that allows an estimation of the weights. One such technique is the Analytical Hierarchy Process (AHP) and involves a pair wise comparison between the various criteria. The step wise procedure is given below:

Step 1: Define the focus

The focus is the pinnacle of the decision hierarchy which will be constructed in step 3 and is the ultimate outcome that is desired from the AHP.

Step 2: Identify the criteria to be used in the AHP

The criteria to be used in the AHP is limited only by the data at hand related to the decision making process. All data can be used and the AHP does not intrinsically discriminate according to accuracy or quality of data.

Step 3: Creation of Value Tree (Decision Hierarchy)

The decision hierarchy is structured with the focus at the top and with each lower level of the tree more detail. Criteria at lower levels of the hierarchy should be grouped into clusters with common characteristics. The hierarchy allows for the assessment of the contribution of individual criterion at lower levels to higher levels of the hierarchy.

The hierarchy is iterated in that it can be reviewed and magnified.

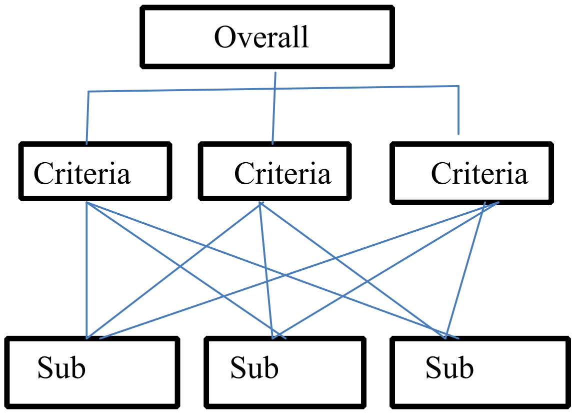

Figure 3: Decision Hierarchy

Step 4: Pair wise Comparison (Weighting of the Criteria)

A set of questions is posed between pairs of criteria within clusters at each level of the hierarchy to establish relative importance between criteria. The principle of the AHP relies on the pair wise comparison and is carried out using a scale from 1 to 9 as follows:

1. Equally preferred
2. Equally or moderately preferred
3. Moderately preferred
4. Moderately to strongly preferred
5. Strongly preferred
6. Strongly to Very Strongly preferred
7. Very Strongly preferred
8. Very Strongly to Extremely Strongly preferred
9. Extremely preferred

This process, carried out with the aid of a matrix (Table 1), allows for weightings of criteria to be estimated. Weightings within each cluster or at each level of the hierarchies are then standardized and sum to 1.

Table 1: Template for Pair Wise Comparison Matrix

	Criteria 1	**Criteria 2**	**Criteria 3**	**Criteria 4**
Criteria 1	1	C12	C13	C14
Criteria 2	1/C12	1	C24	C25
Criteria 3	1/C13	1/C24	1	C45
Criteria 4	1/C14	1/C25	1/C45	1

Step 5: Check Consistency of Evaluation

For each cluster in the hierarchy it is necessary to know whether the pair wise comparison has been consistent in order to accept the results of the process. The parameter that is used to check this is called the Consistency Ratio. The Consistency ratio is a measure of how much variation is allowed and must be less than 10%.

Consistency Ratio=CI/RI

where, CI- Consistency index = ($\lambda max - N$) / (N-1)

N- Order of matrix

RI- Random Index for given matrix λmax - largest eigen value of matrix

Recommended Consistency ratio<=0.1

Random index for corresponding order of matrix is shown in Table 2 is given below

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Table II: Table for Random Index

SL NO	N (order of matrix)	RI (Random index for given matrix)
1	2	0
2	3	0.58
3	4	0.9
4	5	1.12
5	6	1.24
6	7	1.32
7	8	1.41
8	9	1.45
9	10	1.49

2.1 Overlay Analysis

All the layers are overlayed in ArcGIS using UNION operation. In the resulting layer three fields are added namely Area_Acre, CSI (Cumulative Suitability Index) and Suit.

Acre is calculated using the formula,

Area in acre = area in m^2 / 4046.85

CSI is calculated as follows,

CSI =∑Wi*Rj

where, Wi - Weightage of criterion

Rj - Rating of sub criteria in the corresponding i^{th} criterion

Then the statistics of CSI such as Mean (μ) and Standard Deviation (σ) are found. Using these details ranges for different suitability areas are calculated. The Suit field in union layer is populated

2.2 Extraction of Suitable Sites

Summary statistics of field Area_Acre is calculated from the union layer by selecting Suit field as the case field in Summary statistics dialog box. From this the area of the four suitability classes can be extracted.

III. Results and Discussions

Several thematic layers are prepared in GIS environment from the data collected from different sources. They are,

3.1 Land Use

The land use layer consists several land use types such as Agriculture, Forest, Built-up, Waterbodies, Wetland and Wasteland. The layer from which the 1 km road buffer and reserved areas are eliminated.

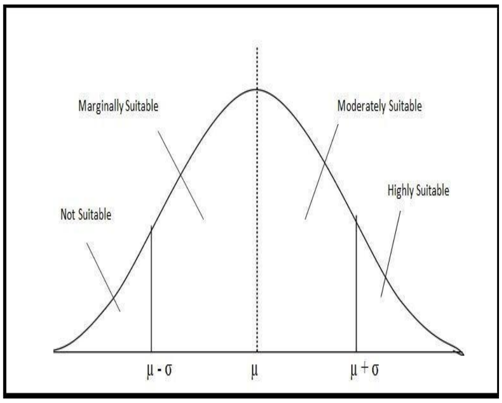

Figure 4: Suitability Classes

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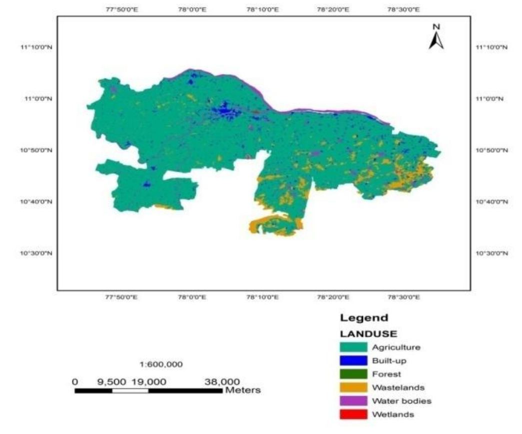

Figure 5: Land use / Land cover map of Karur District

3.2 Slope

The slope layer is prepared using the following dialog box in ArcGIS and the slope layer shown in Fig 6. Most of the areas are flat in the study area.

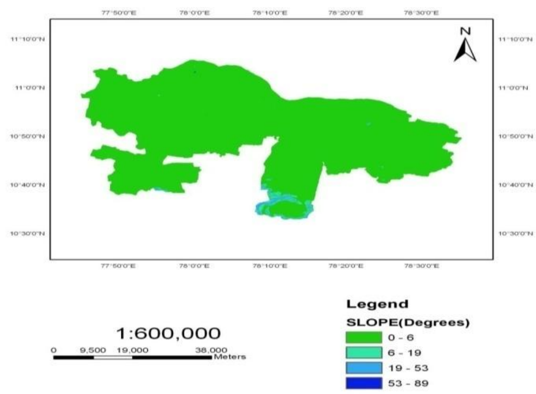

Figure 6: Slope map of Karur District

3.3 Aspect

Aspect shows the direction of slope. The Aspect map is prepared in ArcGIS and tha Aspect is shown in Fig 7.

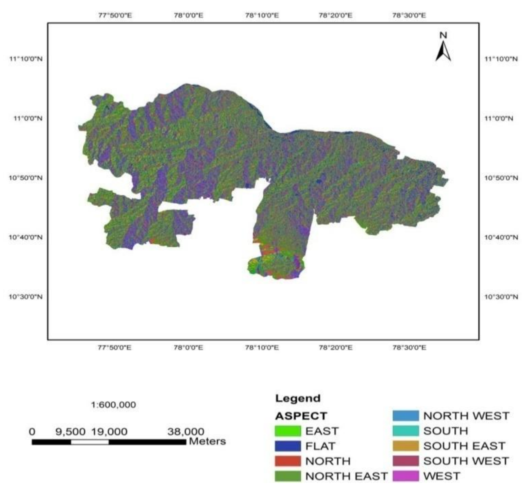

Figure 7: Aspect Map of Karur District

3.4 DNI

The Direct Normal Irradiance of Karur district varies from 5.23 -5.57 KW/m^2 as shown in Fig 8 which is suitable for high power output.

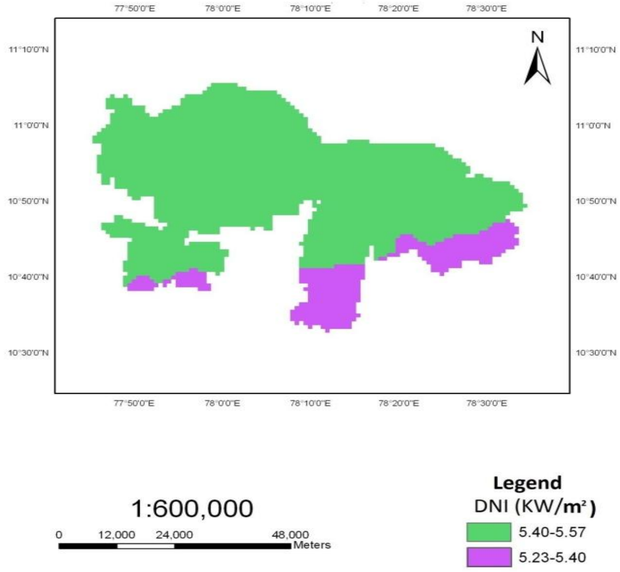

Figure 8: Direct Normal Irradiance map of Karur District

3.5 Temperature

The temperature of the district varies from 32.33°C to 35.7°C as shown in Fig 9. This helpful for efficient power production.

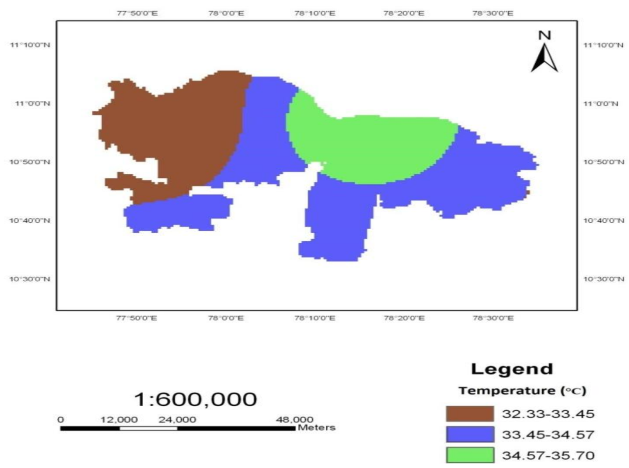

Figure 9: Temperature map of Karur district

3.6 Sun Shine Hours

The average sun shine hours of the district varies from 6.80 hrs/day to 7.10 hrs/day as shown in Fig 10. Since it is more than 5hrs/day, it will improve the power production.

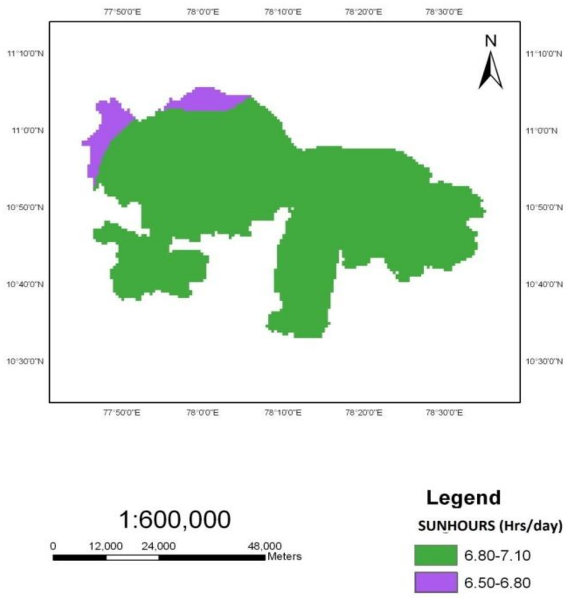

Figure 10: Sun shine hours map of Karur district

3.7 Ranks and Weights

Ranks for each individual subfactors of all the layers are collected from various experts of solar energy. The ranks are assigned to the sub factors as are shown in Tables

Table III: Rank for Different Slopes(in Degrees)

SL NO	SLOPE (In Degrees)	RANK
1	8 – 13	1
2	0 – 7 and 14 – 20	2
3	21 – 25	3
4	>26	4

Table IV: Rank for Different DNI

SL NO	DNI	RANK
1	5.40 – 5.57	1
2	5.23 -5.40	2

The Pairwise importance for all the layers is collected from different experts. The questionnaire used for that purpose is attached in Appendix.

Table V: Pairwise Comparison List Matrix

	DNI	Temperature	Sunhour	Slope	Aspect	Landuse
DNI	1	3	1	3	3	5
Temperature	0.33	1	0.2	5	7	1
Sunhour	1	5	1	5	1	5
Slope	0.33	0.2	0.2	1	5	7
Aspect	0.33	0.14	1	0.2	1	3
Landuse	0.2	1	0.2	0.14	0.33	1

Order of the matrix is 6 (N=6). The pairwise comparison matrix is given as input to AHP method and weightage for each individual layer is calculated.
Then it is checked for consistency.

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From the weights calculated in AHP method,

CI - 0.123675255

RI - 1.24

CR - 0.099738109

Since the CR is less than 0.1, the weights calculated are consistent.

Therefore there is no need for further iterations.

The sum of the weights equals to 1. The DNI and Sun shine hours layers get more weightage whereas aspect and landuse layer get less weightage.

3.8 Suitability Analysis

After calculating the ranks and weights, the UNION operation is performed. The resulting layer is named as Suitability map. Then CSI field in that layer is populated by using the following formula in Field calculator,

[CSI] =([DNI]*0.28) + ([Temperature]*0.18) + ([Sun Hours]* 0.25) + ([Slope]*0.14) + ([Aspect]*0.10) + ([Landuse]*0.05)

Statistics of CSI are as follows,

Mean 2.0802

Standard Deviation 0.221907601

Using the graph in Fig 4.7 the ranges for different suitability classes are calculated from mean and standard deviation. The ranges for different suitability classes are shown in Table 6.

Table VI: Suitability Ranges

SL NO	RANGE OF [CSI]	SUITABILITY
1	[CSI] > 1.88	High
2	[CSI] > 1.698 and [CSI] <= 1.88	Moderate
3	[CSI] > 1.507 and [CSI] <= 1.698	Marginal
4	[CSI] <= 1.507	Poor

The Area_Acre field is populated using the formula mentioned earlier. Summary statistics of the area is calculated. The graph comparing areas under different suitability classes

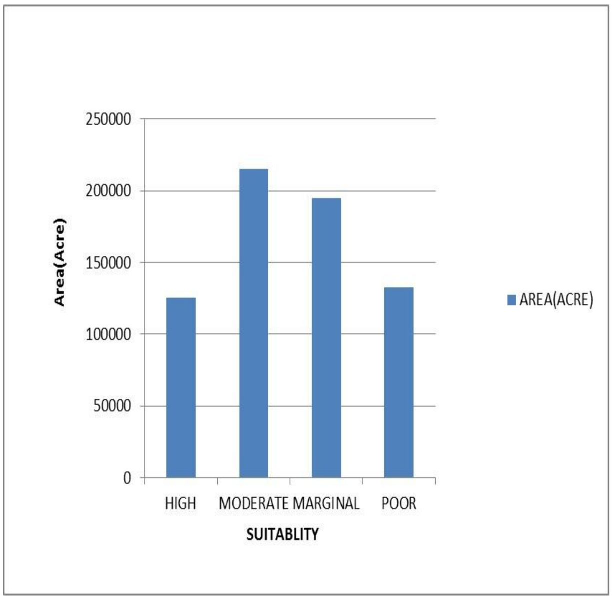

Figure 11: Area under different suitability classes

The suitability map that shows different suitability classes for installation of photovoltaic power plants is shown in Fig 11.

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IV. Conclusion

Several climatic and spatial factors influencing the performance of photovoltaic power plants are considered in the study. The analysis on those factors reveals that the study area is mostly flat and its climatic conditions are suitable for the enhanced performance of photovoltaic panels. Inverse Distance Weighted (IDW) method has been used for the interpolation of climatic factors such as Temperature, Sunshine hours and DNI. Weightages derived from Importance levels of different factors collected from different experts shows that DNI has more importance than all other factors. The result of the study suggests the suitable areas for the installation of Photovoltaic Power Plants. Minimum of about 132 acres and Maximum of approximately 16195 acres of most suitable lands are obtained. Placing the photovoltaic plants sites in these areas would provide us with the best output required to meet the power demand of our study area to a considerable amount. Previous installations prove that about six acres of land provides 1 MW of output power. Therefore installation in the resulted areas would prove to be fruitful along with the other factors.

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