A MULTI-CRITERIA GIS BASED ANALYTICAL HIERARCHICAL APPROACH FOR SOLAR PHOTOVOLTAIC FARM SITE SELECTION IN THE KOLKATA METROPOLITAN AREA, INDIA

R. Bhanja[1], K. Roychowdhury[2 *]

[1] Ph.D. scholar, Department of Geography, Presidency University, Kolkata, West Bengal, India- radhika.rs@presiuniv.ac.in
[2] Department of Geography, Presidency University, Kolkata, West Bengal, India- koel.geog@presiuniv.ac.in

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ABSTRACT:

A smart solar city ensures smart energy resilient future, low emissions and sustainable development of cities through networked infrastructure. This study aims to determine suitable locations for solar farm development in Kolkata Metropolitan Area (KMA), India, which may help the decision makers to plan resource allocation for smart renewable energy development efficiently. Numerous criteria were considered while simulating the model, including solar irradiation, distance from power substation, distance from major roads, land cover distribution, mainly canals, vacant land, urban green zones, and agricultural land. Built-up residential spaces and protected zones were however, no considered. The analysis suggests that wetlands, canals, and a major portion of open vacant land in the outskirts of the KMA are most suitable for investment in solar photovoltaics infrastructure. The present study covers different aspects of solar city planning to determine the suitable locations, which when accompanied by careful onsite investigation and meticulous planning will help decision makers and planners to design an efficient solar energy plan for the deployment of necessary infrastructure and technologies in cities.

1. INTRODUCTION

A smart sustainable city as defined by UNECE (2019) is described as an innovative city that uses information and communication technologies (ICTs) to improve quality of life, efficiency of civic services, and competitiveness, while ensuring that it meets the economic, social, environmental and cultural needs of present and future generations. The city envisions a strong focus on societal benefits, business oriented urban development, and environmental awareness to make judicious use of natural resources, with the help of networked infrastructures (Al-Nasrawi et al., 2015). In order to become energy resilient, smart cities should adopt clean and reliable renewable energy solutions. Solar energy is one of them. Large-scale harvesting of solar energy for smart cities requires well-developed city infrastructure, public services, energy infrastructure with an existing environment for micro-grid connections and a pro-business environment (Zhang et al., 2019). Novel smart solar systems include green components, intelligent tools, and energy management frameworks to attain energy sustainability in smart cities (Caruso et al., 2019; Soyata et al., 2019). Energy harvesting is a serious challenge in metropolitan cities, especially in developing countries, mostly because of unplanned growth and lack of space. If smart energy tools can be implemented in the system, urban organizations can use statistical models and machine learning to predict energy demand at peak hours and propose strategies for energy peak management, thus, converting the threat of excess power generation by solar panels during sunny hours to subsequent opportunities (Ghadami et al., 2021).

India's solar power industry is huge, as it stands fifth among all the countries in terms of installed capacity. As of August 2021, India had already installed 100 GW of solar power, whereas 50 GW was under installation and 27 GW was under tendering (PIB, 2021). The incentives and low-interest rates by the Indian Government have promoted large scale installations of solar rooftops and the construction of solar farms countrywide. In the absence of smart working principles, the effective management of these small and large scale solar farms involves great manpower. The energy generated by green buildings is less compared to the energy generated by utility scale solar farms in the vicinity of metropolitan cities. Therefore, this study takes the opportunity, with the Kolkata Metropolitan region as an example, to understand the functioning of a city to allow the dissemination of solar technologies on a large scale.

Location allocation for solar photovoltaic mapping using the Geographic Information System (GIS) has gained much importance in the recent times owing to the ease of mapping and accurate solution provided by the system for effective planning (Asakereh et al., 2017; Doorga et al., 2019; Nguyen et al., 2021). The planning of solar farms, irrespective of their spatial extent, is dependent on numerous factors pertaining to climatological factors (Son and Jung, 2020), capital investments, and financial security in solar infrastructure (Obeng et al., 2020; Yendaluru et al., 2020), environment sustainability(Sreenath et al., 2022), and society's willingness to pay (Gao et al., 2020). This study tries to determine optimal locations for establishing solar farms within one of the biggest urban agglomerations of India with the help of expert opinion and provide an overview of the feasibility of solar planning in the region using both GIS and Multiple Criteria Decision Making (MCDM) approach. The paper is organized as follows: Section 2 describes the Study area, datasets, and methods used in the study in a detailed manner. Section 3 explains the findings of the analysis and discusses the feasibility of the solar farm planning in KMA, and the benefits and limitations of the research, finally section 4 concludes the work.

* Corresponding author

2. DATASETS AND METHODS

2.1 Study Area

Located on the left bank of river Hooghly, Kolkata Metropolitan Area is the third largest urban agglomeration of India extending over 1851.41 km^2 area, consisting of Kolkata district and partially covering the districts of Haora, Hooghly, Nadia, North 24 Parganas and South 24 Parganas. The location extends from 22°19′N to 22°00′N and 88°4′E to 88°33′E (figure 1). KMA consists of three Municipal Corporation, mainly Kolkata Municipal Corporation (KMC), Howrah Municipal Corporation (HMC) and Chandannagar Municipal Corporation (CMC), along with 38 municipalities – 18 from North 24 Parganas, 11 from Hooghly district, 6 from South 24 Parganas, 2 from Nadia and one belonging to Haora district of West Bengal. Further, the urban agglomeration comprises 77 census towns and 16 outgrowths, emerging as the new hotspots of development in the economic sector. There are around 445 villages under the administration of KMA with ample vacant and agricultural land to house new settlements and allow developments within its confines (Census of India, 2011; Rahaman et al., 2019). The metropolitan area has spread linearly along the river Hooghly at a height of 6 m above the mean sea level on a flat terrain characterized by higher slopes in the fringes of the study area. KMA is influenced by the tropical climate conditions, with an annual mean monthly temperature of 27°C and average rainfall varying from 1400 mm/year to 1600 mm/year. Inhabited by a population of 14.03 million people, with a population density of 7950 persons per km^2.

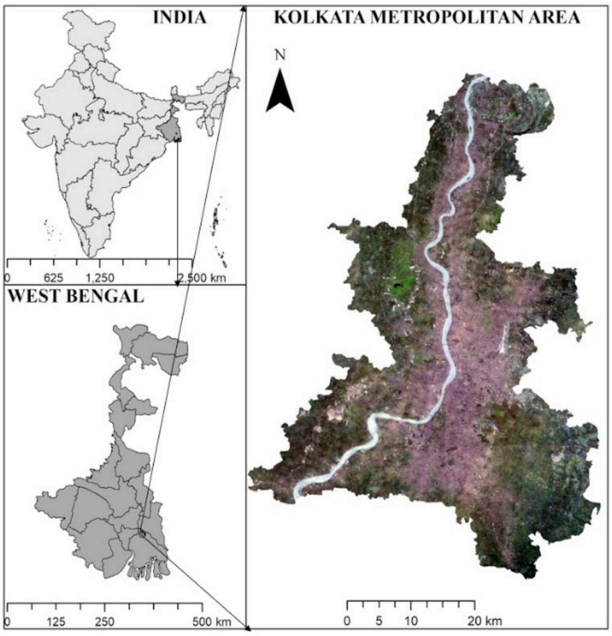

Figure 1. Location map of KMA

2.2 Datasets

The datasets used in this study include meteorological indicators, land use, and topographical and energy-related variables as input parameters for the utility scale site suitability analysis. The datasets used in this study are Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) data from the National Aeronautics and Space Administration (NASA) "The Power Project", solar irradiation at pixel level was calculated using the Solar radiation tool from ArcGIS 10.5, Land Surface Temperature as derived from Landsat 8 OLI/TIRS, Land use land cover mapping from Sentinel 2B satellite image (captured on 05.11.2021) as per CORINE, Digital Elevation Model was derived from SRTM DEM 1 Arc second data, the road network map was accessed from Open Source Map, and the power distribution map was accessed from WBSEDCL Power Utility Map.

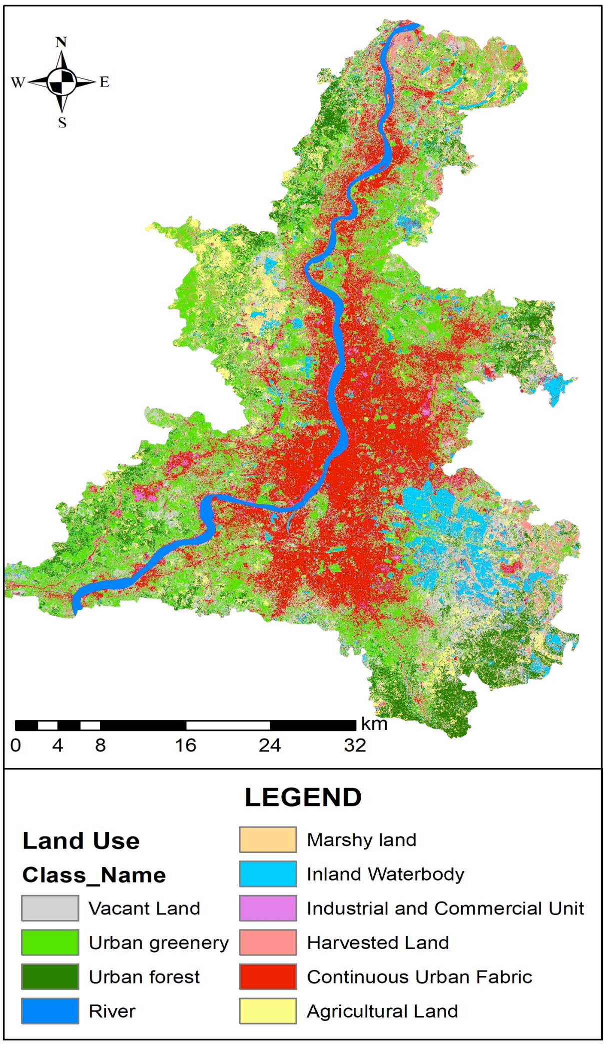

Figure 2. Land use map of KMA

A total of six main criteria and three sub-criteria were considered for mapping the suitable sites of solar farms in the vicinity of the study area. The land cover map was developed using supervised classification using the Support Vector Mechanism (SVM) technique, and an accuracy assessment was conducted using 100 points. The landcover was verified from Google earth images and more than 95% user's accuracy was obtained. The slope of the terrain was derived from SRTM data with a 30 m resolution. Figure 2 represents the land use map of the KMA region. Regions with a slope of more than 3% were excluded. Further, the Solar radiation tool from ArcGIS 10.5 was used to calculate the monthly average of the total amount of insolation received in different parts of the Kolkata Metropolitan Area (KMA). After obtaining the road layer and electricity grid-substation layer, the variables were mapped for visualization purposes.

2.3 Criteria mapping

The criteria along with their suitability scale, as per different literature (Makkiabadi et al., 2021; Nguyen et al., 2021; Uyan, 2013), are mentioned in table 1. This method of solar farm suitability planning has been applied in many regions; however, this approach is being applied for the first time in an urban agglomeration. With respect to solar irradiation falling over the city, the minimum criteria of GHI values being more than 4.0 kWh/m^2/day and DNI values of more than 5.47 kWh/m^2/day are met. The areas with solar irradiation less than 4 kWh/m^2 are excluded from the analysis as the concentration of solar radiation falling on the solar panels will be insufficient to generate electricity. The most suitable sites are regions with a gentle slope, preferably a flat surface, oriented towards the south, thus, the best suitable locations considered are areas with less than 3% terrain slope and as it increases by 1%, the weightage of the criterion decreases. The presence of an existing transmission line in the vicinity of the solar farms will reduce the cost of constructing new power lines and energy losses (Alzyoud et al., 2021). Thus, the shorter the distance from the substations and transmission lines, the higher the potential for developing solar power farms with minimum energy losses. This impact of the distance from road criterion is similar to the one on distance from the substation. With respect to land use criterion, open space and agricultural lands are most preferred for the construction of solar farms. As per expert opinion, canals are suitable for the deployment of solar arrays on canals for efficient use of land space and electricity generation.

Land covers that are excluded from the site suitability analysis include residential and other built-up regions, protected land, airports, and historical and tourism sites. Residential and commercial buildings are more suitable for rooftop solar planning where SPVs can be installed on the rooftop to electrify the building and sell excess power to the distribution company through on-grid connections.

Criteria	Most suitable	Suitable	Moderately suitable	Less suitable	Least suitable
Solar irradiation (kWh/m2)	>12	10-12	10-8	6-8	4-6
Slope (in %)	<1	1-2	2-3	3-4	>4
Distance from power transmission lines (m)	100	100-500	500-1000	1000-1500	>1500
Distance from roads (m)	100-500	500-1000	1000-1500	1500-2000	>2000
Land Use	Open spaces, Canal	Agricultural land	-	Urban greenery	

Table 1. Datasets used in this study and their description

2.4 GIS-based Multiple Criteria Based Decision Making Analysis

Analytical Hierarchical Process (AHP), designed by Saaty (1980) was used to determine the most important criteria that contribute to identifying suitable locations for solar farm establishment in KMA. Here, higher weights indicate higher significance of the criterion. In AHP, pairwise comparison between indicators is performed in the form of matrices, based on comparison results. Here, a 9-point scale of comparison was used to allot the significance of the indicator, with respect to the other indicators. The next process is to define a square matrix Am (m is the number of indicators) based on the comparison matrix divided by the sum of the values of each column. Finally, the relative weight of each criterion was obtained by deducing the average values of each row in matrix Am. To ascertain the accuracy of the weights, the consistency ratio (CR) was calculated. First, the comparison matrix and weight matrix were multiplied and the maximum value from the column matrix was identified and termed as λ_{max}. The Consistency Index was calculated as:

$$\mathrm{CI} = \frac{\lambda_{\max} - \mathrm{m}}{\mathrm{m} - 1}, \qquad (1)$$

while CR is CI/ RI. RI is random CI results, for which the value depends on the number of criteria chosen for the study, it is derived from Saaty (1980). The CR value should be less than or equal to 0.1, else the pairwise comparison must be revised. Expert opinions from six experts involved in the solar city planning of the cities were consulted to determine the weights of the indicators. The experts are engineers and consultants associated with Kolkata Municipal Development Authority, Haora Municipal Corporation, and New Town Kolkata Development Authority (NKDA). The formulas used to derive the weights were referred from Saaty (1980). The method followed is etched in Figure 3.

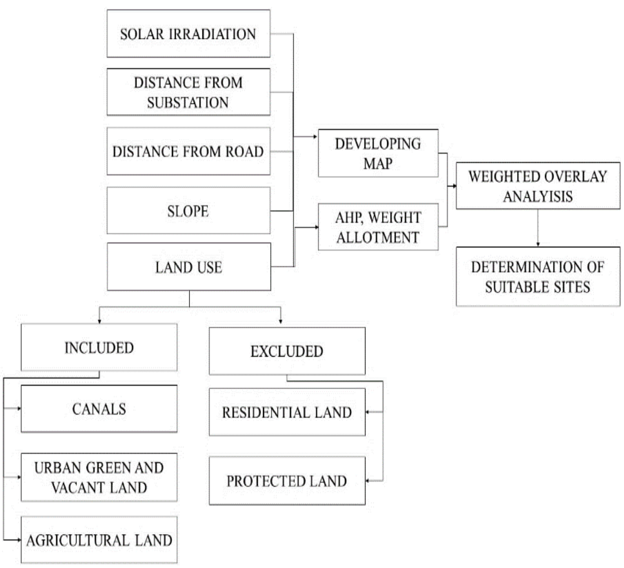

Figure 3. Description of method used

3. RESULTS AND DISCUSSIONS

3.1 RESULTS

3.1.1 Criteria distribution analysis

The described method was applied to KMA to delineate potential solar farm sites in the region. The solar irradiation values, as obtained from secondary sources and calculated in ArcGIS software, indicate that the region qualifies for harnessing solar energy successfully. The annual GHI of KMA is 5.7 kW/m^2/day. The monthly GHI range of KMA makes it feasible for solar power harnessing on both rooftops. On the other hand, the annual average of DNI values across KMA is 4.8 kW/m^2/day. This mean value is feasible for generating solar powered electricity from utility scale CSPs in and around KMA. The flat terrain of the urban agglomeration also makes it suitable for constructing solar farms in the vicinity. The northern and north-eastern fringes of the city have more suitable terrain than the other parts of the city (Figure 4 (b)). The nearness to power distribution and transmission zone and major roadways have been mapped according to the suitability scale and the former can be seen in Figure 4 (c).

The land cover classification was first conducted to classify the region and further demarcate the suitable and unsuitable zones for solar farm planning in KMA. The urban built-up area comprising residential and commercial buildings is unsuitable for planning, along with the East Kolkata wetlands which fall under the protected land category and are accordingly categorized into the excluded criteria list. Therefore, the open spaces and agricultural lands are highly suitable for planning the solar farm feasibility. Figure 4 (d) highlights the least to more suitable land use zone in the study area. The vacant land and agricultural land are most suitable for conversion to small solar farms, especially in the periphery of the urban agglomeration.

In this research, expert opinions were required to compare the relative importance among different indicators. Their valuable inputs regarding choices gave insights into the planning process of solar farm suitability planning in urban and suburban areas. As opted by the experts, the large stretches of uncultivable lands or vacant land under the development area serve as a primary option to construct small scale solar farms. Further, setting up floating solar plants in the small ponds or mounted solar plants above the canals is a secondary option that can be considered for space allocation for solar farm construction than converting urban green space near the residential zones to solar farms.

3.1.2 Suitability distribution mapping

According to the AHP calculation, the Consistency Ratio of the AHP analysis was 0.038, which describes that the expert opinions and weights derived are consistent. The weights of the different criteria for solar farm suitability planning can be summarized in table 2. The weighted overlay analysis was performed to derive suitable locations for solar infrastructure deployment in the form of solar photovoltaics in KMA. The suitable zones, ranging from the worst to the best, can be observed in Figure 5. The distribution of suitable regions is evenly balanced. The core of the region is densely packed with residential and commercial buildings, composed of several Municipalities and Municipal Corporations with more than 10 lakh populations each. India's third largest metropolitan city – Kolkata Municipal Corporation lies on the left bank of the river Ganga, which divides the study area into almost two equal parts. These zones, along with the protected areas of East Kolkata wetlands, airports, heritage, and tourism spots have been declared unsuitable in the suitability analysis. 30% of the area falls under this category.

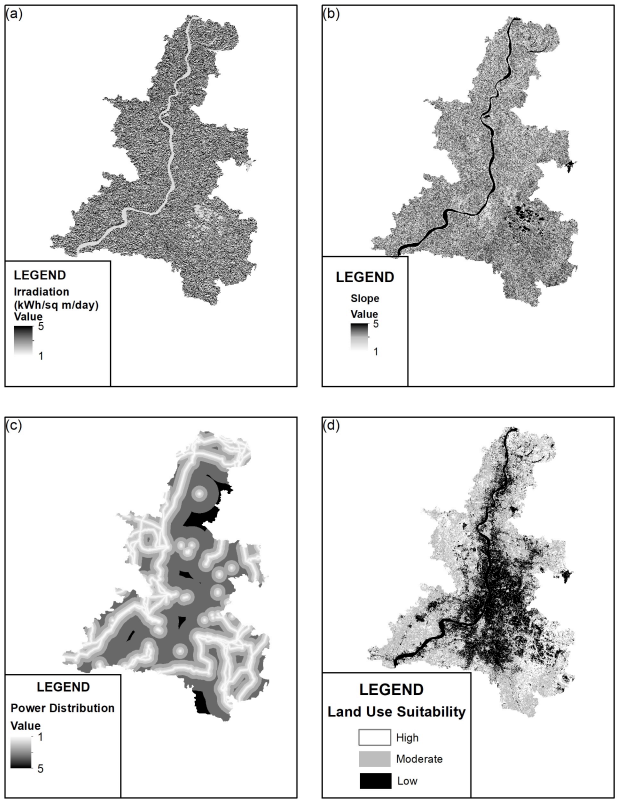

Figure 4. Criteria selected for determining suitable zones for solar farm planning in KMA

With the rising distance from the core, the suitability for location allocation for solar farm construction increases. The suitable zone lies adjacent to the least suitable zones or in the sparse vacant land between the concrete fabrics of the city. This zone is followed by the moderately suitable zones, which determine second best optimum sites for investors to participate in capital and resource allocation for solar technologies at utility scale in the KMA region. This zone occupies around 557 km^2 and consists of mainly urban green land use, allotted for recreation purposes, or vacant lands currently covered by grasses and not used for cultivation. Similarly, some areas consisting of agricultural land and vacant lands, especially in the peripheral zone, fall under the moderately suitable zones of the suitability distribution analysis.

Criteria	Solar irradiation	Slope	Distance from power transmission lines	Distance from roads
Weights	0.24	0.14	0.19	0.19
Criteria	Land Use			
	Canal	Vacant land	Agricultural land and urban green zones	
Weights	0.12	0.07	0.05	

Table 2. Weights derived from AHP analysis

Finally, the highly recommended sites for location allocation of utility scale CSPs at KMA belong to areas that are near the power substations, transmission and distribution lines, and highways. These are constructed across vacant lands and therefore, establishment of a solar farm at the vicinity of parameters are beneficial for both investors, utility companies, power distribution companies (DISCOMs) and other stakeholders.

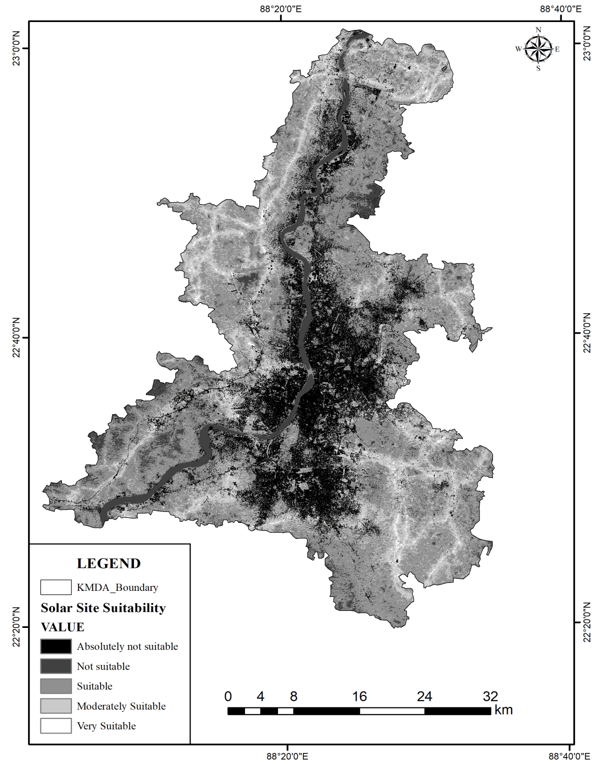

Figure 5. Delineation of suitable zones for solar farm establishment in Kolkata Metropolitan Area, India

3.2 DISCUSSIONS

As cities grow and aspire to become smart and energy-efficient, renewable energy technologies play a significant role in achieving these ambitious goals in the foreseeable future. The deployment of Solar Photovoltaics (SPVs) in rooftops is difficult to achieve at a large scale in cities, as factors related to the reception of SPVs by the citizens, and their willingness to pay hinders the growth of such technologies. Thus, the establishment of utility scale solar farms on unused lands for a brief period, on a contractual basis, gives an insight to understand if such solar plants are feasible to power a large number of buildings in cities. In this case, an urban agglomeration with three Municipal Corporations, 38 Municipalities, one established smart city, and three designated solar cities by the Ministry of New and Renewable Energy (MNRE) India was considered as a case study to determine how much land can be utilized to deploy solar infrastructure within its premises. KMA urban agglomeration encompasses Kolkata Municipal Corporation and New Town Kolkata Development Authority (NKDA), which is both a solar and a smart city. Haora Municipal Corporation and Madhyamgram Municipality are solar cities designated by the MNRE and funds have been allocated to these cities for developing Master Plans for investment in solar technologies to electrify the city. In 2016, KMA approved the Green Cities Mission proposed by the Urban Development and Municipal Affairs Department of the Government of West Bengal (Government of West Bengal, 2016). In this mission, city governments should design approaches with schemes to increase green areas, conserve water bodies, beautify public spaces, and build energy positive city. Energy positive city can be achieved through the installation of solar panels at government buildings, replacing sodium bulbs with LEDs in streetlights and public spaces, and introducing incentives for green building.

The Kolkata Municipal Development Authority overviews the functioning of the civic services in KMA, and the electricity is supplied by the Calcutta Electric Supply Corporation Limited (CESC) and the West Bengal State Electricity Distribution Company Limited (WBSEDCL). CESC installed its first microgrid plant in 2022 with a 100kW floating solar system and 218kWh battery storage in an inland pond adjacent to the existing smart city under KMA (CESC, 2022). Similarly, solar panels have been already installed on different Government buildings, streetlights, traffic signals, and small canals in the solar cities of KMA (WDSEDCL, 2022). These sites fall under the suitable to moderately suitable sites as depicted in Figure 5. As per expert opinion survey, the decision to utilize land for solar panel set-up is determined on availability of land and its investment cost. The unsuitable zones are strictly avoided for solar farm planning, however, conversion of existing buildings to green buildings and installation of rooftop panels are encouraged by the authorities in the residential and commercial buildings of the metropolitan region for smart energy harnessing. The area demarcated under the very suitable zones is highly recommended for utility scale solar planning in KMA and decision makers can consider these sites for future energy planning purposes. For a complete transformation of a fossil fuel driven city to a green city, Artificial Intelligence (AI) driven PV technologies at a utility scale are a much-needed solution for energy-efficient smart city development.

IoT applications in solar farms are commonly used in the form of sensors to monitor processes related to the production, transmission, and distribution of solar energy to the system. The ability to remotely track the operations of the solar energy systems by the solar investors and commercial customers in real time from one central control panel is a major catalyst for solar adoption. Some smart solar systems use wired sensor devices connecting arrays of solar panels, where the direct current (DC) power produced by the panels is converted to alternating current (AC) using the solar inverter, which is later used to power the installation site or building. Intelligent platforms allow stakeholders to proactively manage outages, faulty wires, and defective panels in a timely manner, ensuring efficient performance. Robust platforms using big data and online monitoring systems are necessary to supervise utility scale solar plants in smart cities for cost-efficiency.

To include such ambitious projects in establishing smart solar farms, allocation of space and resources needs to be conducted judiciously to avoid future investor losses. The vacant land that has been identified in the very suitable category is owned by both private institutions and the Government. The area of land under the Municipality can be utilized as solar farms till new construction activity begins. Solar infrastructure can be shifted to other locations at a minimal cost and therefore, the longevity of the technology is more. However, certain hindrances should be considered while planning the solar city. Firstly, the distance between electricity substations and solar power distribution lines should not be far, and secondly, it is cheaper to invest in agricultural land by is cheaper than to pay rent to the local Government to install solar technologies in private energy enterprises. These options should be given importance while planning suitable sites for CSPs in cities.

4. CONCLUSION

This study developed a site suitability model for solar farm development in KMA to help the decision makers to plan resource allocation for renewable energy development efficiently. Numerous criteria were considered while simulating the model, which ranged from solar irradiation, distance from power substation, distance from major roads, land cover distribution, mainly canals, vacant land, urban green zones, and agricultural land, while built-up residential spaces and protected zones were obliterated. The analysis was done using AHP technique to assign weights to the criteria and accordingly overlay weightage analysis was performed to delineate the different suitability zones in the KMA region for solar farm planning. The analysis suggests that canals and a major portion of open vacant land in the outskirts of the study area are most suitable for investment in solar photovoltaics infrastructure. The zones can be used by the authorities in charge of solar planning to attract investors, planning bodies, and other stakeholders to exploit the unutilized land for energy development and management purpose to design green energy markets and infrastructure for the upcoming generations to experience a smart sustainable future.

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