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Greening airports: A methodological framework for site assessment and assessing solar PV potential

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ABSTRACT

Due to energy intensiveness and carbon emissions, the aviation sector is under continuous environmental pressure. In this regard, airports have shown keen interest in solar photovoltaic (PV) technology to decarbonize their energy consumption. Implementing onsite solar projects in the airport is challenging due to various technical and safety aspects. Improper siting of solar PV arrays may adversely affect the safety of the passengers. This paper aims to develop a methodological framework for site assessment and potential estimation of PV projects in airport locations. The developed methodology is applied as a case study to seven Indian airports: Madurai, Goa, Raipur, Ahmedabad, Lucknow, Amritsar, and Dehradun. It was understood that the suitable area for solar PV projects on airport land depends on airspace restrictions, built area, and glare occurrence. On average, 30–40 % of the airport land is observed to be built area; hence, it is unavailable for land-based solar PV systems. Among the studied airports, the highest value of technical potential is observed for Raipur airport (21 MW). These conservative estimates provide baseline information for airport planning and development projects. This study is expected to be a reference material for energy specialists, airport stakeholders, and policymakers.

1. Introduction

Solar Photovoltaic (PV) technologies are widely considered a pathway to decarbonize the energy sector [1]. This can be attributed to the direct conversion of sunlight into electricity in the PV module. Solar energy is environmentally advantageous relative to any other energy source and does not deplete natural resources. It has negligible greenhouse gas emissions. The tool provides site-specific key assessment indicators. Solar PV technology has a wide range of applications due to its versatility and modularity [2]. Over the past few years, solar PV arrays have been deployed in vacant spaces in transport systems, such as airports, railway stations, and highways. In addition to effective land utilization, site-specific key assessment indicators are needed for the safe operation of plants [3]. Unlike other modes of transportation, airports have to decarbonize their energy use without compromising the passenger experience. Airport operators have shown immense interest in the deployment of solar PV systems. However, only a few percent of airports have solar PV installations globally.

1.1. Previous research

The site suitability and potential assessment of solar PV technology in built environments including airport premises are explored in various scientific literature. Kim [4] investigated the relationship between the airport institutional arrangement and solar PV deployment, and it was reported that there is a high chance for solar PV uptake in airports under the special-purpose government category. The three significant hurdles to solar PV deployment in airports are glare from PV modules, interference with the communication signals, and physical intrusion in restricted airspace [5]. Considering airspace constraints, Anurag et al. [5] reported that around 570 acres are suitable for solar farms in an American airport, with a power potential several times higher than energy demand. However, one of the sites is not economically feasible due to the high value of land-related costs. Aviation safety cannot be compromised with the implementation of solar PV projects. Aviation safety is of paramount importance. Improper siting of solar PV arrays can harm passenger safety [6]. Jenan [7] assessed the solar potential on rooftop apartment buildings in Jordan and reported that the energy

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Nomenclature

AIP	Airport Information Publication
ATC	Air Traffic Control
ARP	Airport Reference Point
BTA	Built to Total area
CNS	Communication, Navigation, and Surveillance
FAA	Federal Aviation Administration
F_{LP}	Land to Power Conversion factor
GCPA	Glare Compatible PV Area
GBA	Gross Built Area
PPA	Projected PV Area
PV	Photovoltaic
PTA	PV area to Total area
P_{CS}	Conservative potential
P_{TH}	Theoretical Potential
P_{TE}	Technical Potential
P_{RS}	Resource Potential
TA	Total Area
TGA	Total Glare Area

output could meet 76 %–86 % of their current electricity use and 25 %–29 % over 25 years. In a recent study, Jiang et al. [8] estimated the available rooftop area for solar PV in civil airports in China by using Google Earth software. Emmanuel et al. [9] studied the performance of the 600 kWp grid-tied rooftop photovoltaic system for Strathmore University, Kenya. The plant generated around 735 MWh of electricity with an average performance ratio of 57.4 % and a capacity factor of 13.97 %. The economic analysis revealed the Levelized Cost of Energy (LCOE) and payback period as US$ 0.143/kWh and 9.1 years, respectively. Kim and Song [10] assessed the impact of solar PV plants on glare in selected airports. They concluded that harmful solar reflections could be considerably reduced by facing PV modules away from runways and flight paths. Yildiz et al. [11] conducted a preliminary investigation of rooftop-mounted PV modules at Esenboga Airport, Turkey. They reported that it could fulfill the energy requirement of all ground support equipment (GSEs) for most of the year, thereby mitigating approximately—2000 tons of carbon. In a similar study at UK's Doncaster Sheffield Airport, Sher et al. [12] proposed a 12 MW solar farm by visually identifying vacant space around the airport. Doljak and Stanojevi [13]studied the best locations for land-based solar PV projects in Serbia. They concluded that these sites are spread across the Banat region. Ali et al. [14] identified suitable sites for implementing large-scale solar projects in the Songkhla province of Thailand. It is observed that highly relevant areas (up to 69.51 km^2) are located in the Ranot District with due consideration to physiographic, environmental, and economic factors. Al-Garni and Awasthi [15] reviewed several criteria and factors for assessing suitable locations for solar PV systems. It is reported that the commonly used factors are solar irradiation, ambient temperature, proximity to the electric grid, slope, access to roads, and land use patterns. The site assessment factors chosen by Khan and Rathi [16] were solar resource availability, vacant land areas, access to highways, distance to electric lines, etc. Castillo et al. [17] developed a methodology that combines solar irradiation and geographical variables such as slope, land use, urbanization, population distribution, and closeness to the electricity grid. Considering the effective utilization of rooftop areas, Hong et al. [18] estimate three types of solar potential for the Gangnam district of South Korea. The physical, geographic, and technical potential are observed to be 9287.98 TWh, 4964.12 TWh, and 1130.37 TWh, respectively.

1.2. Research gap and objective of the study

The typical site suitability factors considered for solar PV projects are inadequate in the airport context. There is a need to consider airport-specific constraints for properly siting solar PV arrays in airport locations. Only a few scientific studies focus on solar siting in airport areas. To the best of our knowledge, the research work by Anurag et al. [5] can be considered the earliest study on site selection and design aspects of airport PV systems. Sreenath et al. [19,20] did a detailed analysis of different siting aspects. However, the influence of airport-specific siting factors on solar power potential was not fully explored. To the best of our knowledge, a comprehensive approach to site assessment of solar PV projects has not been formulated yet in the airport context. The absence of a specific site assessment approach might have affected the estimation of solar potential in airports. This scenario could lead to the underutilization of solar potential in several airports. The present study aims to develop a methodological framework for site assessment and potential estimation of PV projects in airport locations. The developed methodology is applied as a case study to seven Indian airports: Madurai, Goa, Raipur, Ahmedabad, Lucknow, Amritsar, and Dehradun.

1.3. Organisation of the manuscript

Firstly, a brief overview of the importance of site selection for Photovoltaics and airport applications is presented. The methodological framework for site assessment and potential estimation of PV projects in airport locations are presented in Section 2. Thirdly, the potential sites based on weather conditions, area assessment, glare-compatible PV area identification, and resource potential are discussed in detail. Lastly, concluding remarks, a summary of key findings, recommendations, and future scope are identified.

2. Methodology

The site assessment methodology for airport solar PV projects consists of three main steps. At first, the non-suitable locations, such as built areas, safety zones, and vegetation areas, were identified using Google Earth. The potential sites for deploying solar PV systems are identified in the second step. Based on the analysis using ForgeSolar software, glare-compactible sites are finally chosen. The area parameters are assessed by resource, theoretical, and technical power potential estimation. An overview of the methodology for site assessment and potential estimation of solar PV systems in airport locations is shown in Fig. 1.

2.1. Selection of airports

The airports are selected mainly on Trewartha's climate classification [21]. An airport is chosen from each climate zone. Since seven climatic zones constitute Trewartha's classification, this case study contains only seven airports. A three-step selection process is followed since many airports are in the same zone. At first, the metro airports are excluded because of their existing sustainability activities. Also, these airports have already installed PV systems on their premises. The metro airports in India are located in Delhi, Mumbai, Chennai, and Kolkata. Secondly, all non-metro airports with international flights from each zone are clustered together. These airports have considerable carbon emissions and are often neglected in sustainability case studies. Thirdly, a non-metro airport is selected from each zone depending on the availability of Airport Information Publication [22]. The information on selected airports in India is shown in Fig. 2 and Table 1.

2.2. Framework for site assessment of solar PV systems in airport locations

2.2.1. General criteria for site assessment

The standard selection factors for solar PV power plants include solar

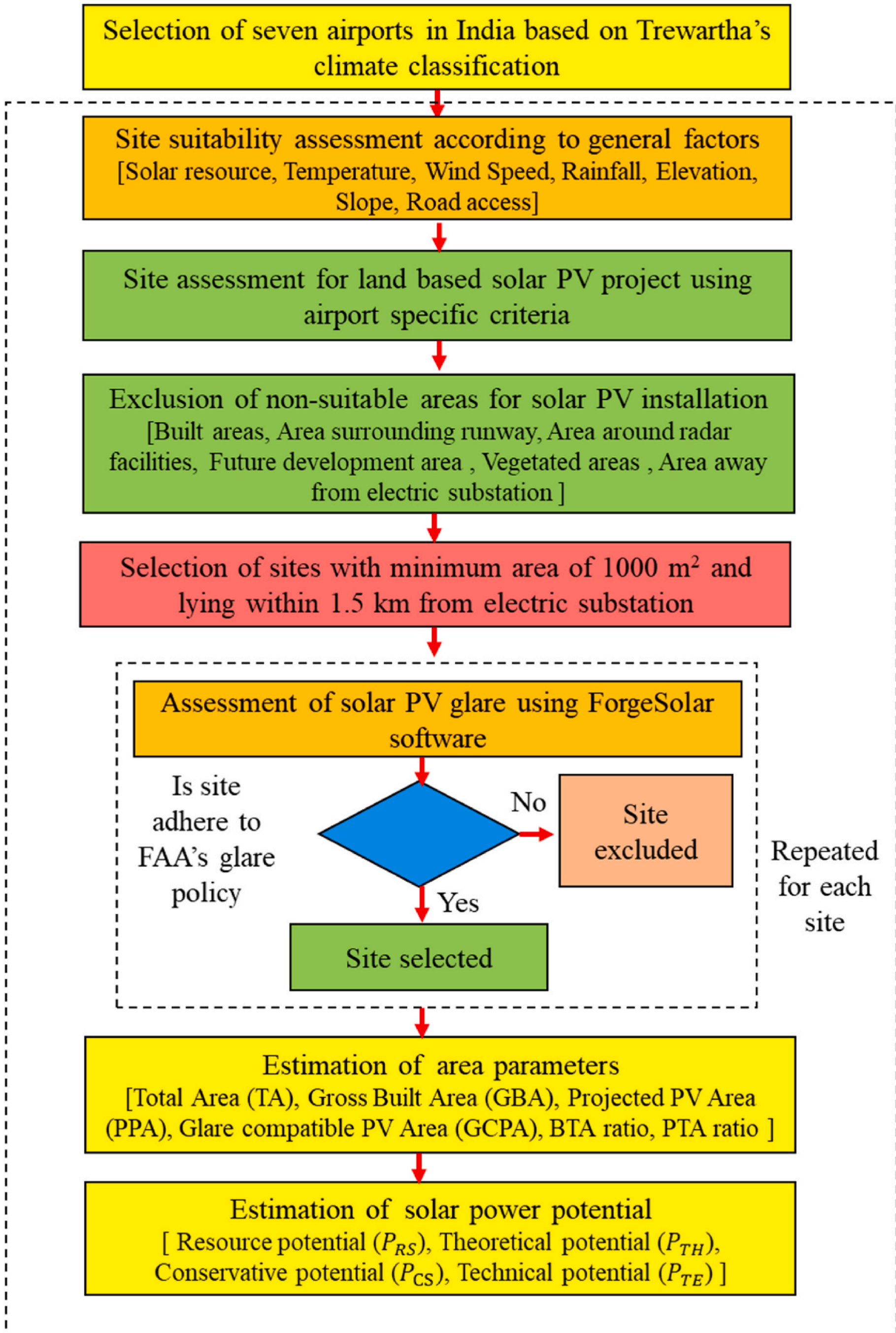

Fig. 1. Methodology for site assessment and potential estimation of solar PV systems in the airport.

irradiation, local climate, shading, soiling conditions, topography, accessibility, etc. [14]. The values of qualitative factors such as solar irradiation and climatic conditions are collected from the meteorological database. In this regard, the coordinates of the airport reference point (ARP) are identified for each airport [22,23]. It is reasonable to assume that these values do not vary much with any sites within the airport boundary. Some factors are assessed qualitatively. Frequent occurrences of drastic events such as flooding and earthquakes are unsuitable for the proper functioning of the solar PV power plant. Also, the site must not receive heavy snowfall during winter. The site must have little or no shading from nearby hills and buildings. Loose soil texture is unfavorable because it results in the soiling of PV arrays. A summary of general factors for assessing the site suitability of PV projects is provided in Table 2. The meteorological database provided by RETScreen software is utilized to obtain the weather conditions of each airport.

2.2.2. Airport specific criteria for site assessment

The unsuitable sites for land-based solar PV systems are excluded based on three main factors. These are airport-built areas, aviation safety regulations, vegetation and electrical infrastructure.

2.2.2.1. Airport built areas. Since land-based solar PV is considered in this study, regions built within airport boundaries, such as runways, terminal buildings, vehicle parking zones, and other concrete structures, are excluded during the site selection. These surface details of an airport are collected from airport information publication (AIP) released by the concerned airport authority. These areas are marked with the help of Google Earth Pro software (hereafter called Google Earth), a non-

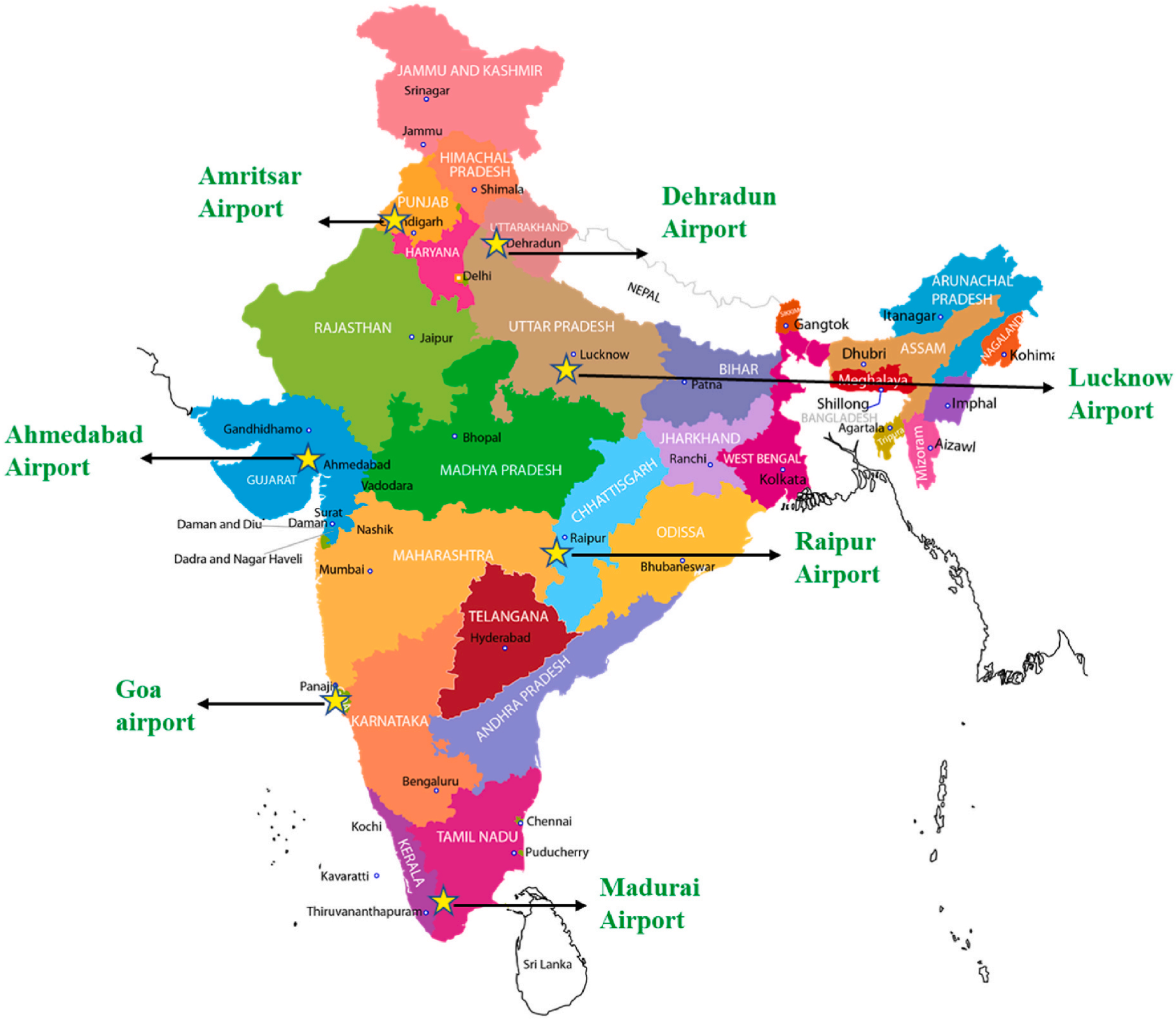

Fig. 2. Selected airports of India.

Table 1
List of selected airports in India.

Airport Name	Latitude & Longitude	Place	Climatic Classification
Madurai Airport	09°50′01″N 78°05′22″E	Madurai, TamilNadu	Tropical semi-arid steppe
Goa Airport	15°22′51″N 73°49′53″E	Dabolim, Goa	Tropical monsoon
Swami Vivekananda Airport	21°10′52″N 81°44′18.5″E	Raipur, Chhattisgarh	Tropical savanna
Sardar Vallabhbhai Patel Airport	23°04′38″N 72°38′05″E	Ahmedabad, Gujarat	Tropical & subtropical steppe
Chaudhary Charan Singh Airport	26°45′43″N 80°53′00″E	Lucknow, Uttar Pradesh	Humid subtropical climate & dry winter
Sri Guru Ram Dass Jee airport	31°42′28″N 74°47′57″E	Amritsar, Punjab	Tropical desert
Dehradun Airport	30°11′23″N 78°10′49″E	Dehradun, Himachal Pradesh	Mountain or Highland (H)

commercial software. Google Earth was chosen because it provides good-quality images without any subscription charges. Buildings, trees, roads, etc., are visible in actual colors on the maps provided by Google Earth. This enables proper differentiation of built areas and vacant spaces in an airport. The area of each building is estimated using Google Earth's built-in tools. At first, the airport's boundary is marked, followed by the built area. Then, the total land and built area within the airport boundary are estimated. The built area is not considered for the site selection process of the land-based solar PV power plants. The area between the runway and taxiway and the area from the apron to the taxiway are excluded from prospectus PV sites (high possibility of violating aviation regulations). The main areas built in an airport and the corresponding color code used in the Google Earth drawing (categorized as airside and landside area) are summarised in Table A1.

Table 2
General factors considered for site assessment of PV systems.

General criteria	Suitable value	References
Solar resource	>3.5 kWh/m^2/day	[24]
Ambient temperature	Less than 40 °C	[13]
Wind Speed	More than 1 m/s	[25]
Avg. rainfall	More than 500 mm	[25]
Overall elevation	Less than 2000 m	[26]
Overall slope	Less than 5 %	[1]
Access to road	Less than 10 km	[24]

2.2.2.2. Aviation safety regulations. Three safety-related exclusion criteria are identified based on the review of journal articles, manuals, and relevant reports. Based on these criteria, unsuitable areas are marked on the airport map on Google Earth. Solar PV deployment in these locations impedes the airport's safe operation and future development. Hence, these areas are eliminated.

Exclusion criteria based on obstacle limitation surfaces: According to an aviation document [27], any object other than navigational aids in the airside is considered an obstacle. In this regard, ICAO defines obstacle limitation surfaces as follows: The obstacle assessment depends on the object's height and location concerning the obstacle limitation surfaces. This study's object is the solar PV array with a maximum height of 3 m. Hence, the land area covering the entire runway strip and a portion of the approach surface, departure surface, and transitional surface are avoided for siting solar PV. The information about the runway and its strip from AIP is utilized. The dimensions provided in the ICAO document for code number 4 runway with precision approach category II or III are considered for the other unsuitable surfaces. These surfaces are marked on the airport land using Google Earth tools and excluded. However, the runway end area, clearway, and stopway are not considered separately because of the overlapping nature of these surfaces with the runway strip.

Exclusion criteria based on communication, navigation and surveillance (CNS) facilities: Using the information on AIP and related reports, the location of CNS facilities is marked on the airport map. If this information is unavailable, the approximate location of CNS facilities is considered based on a visual inspection of the airport map. To safeguard CNS facilities from possible interference of the PV array, a radial distance buffer is provided from each system. A 1500-foot setback is kept from surveillance radars such as primary surveillance radar. A 1000-foot buffer distance is provided for a very high-frequency omnirange station. For other CNS facilities, a radial distance of 250 feet is maintained [28]. In this regard, a circular area is marked on the airport map for each CNS system, and these encircled areas are excluded.

Exclusion criteria based on future development activities: The airport's ongoing projects and expansion plans (such as extending runways/aprons) are also considered during the site selection. This information is obtained through AIP, visual inspection (Google Maps), and the airport website. In addition, the master plan and layout plan of the airport can be reviewed, if available. The area earmarked for aeronautical use and future development is identified in the airport map. This ensures that the proposed solar PV project remains consistent with future construction activities. In the absence of the data mentioned earlier, PV array proposed at a site can be reallocated for future development activities.

2.2.2.3. Vegetation and electrical infrastructure. The vegetation and electrical infrastructure information is collected through desktop-based searches, especially technical reports or Airport Information Publication.

Exclusion of vegetated areas: These environmental resources include shrubs, trees, and wetlands. First, the vegetated area is marked on Google Earth based on the information collected. In addition, the green patches within the airport boundary are identified using visual inspection of the airport's image. Those vegetated land parcels or green patches with an area of more than 1000 m^2 are excluded. This can be attributed to two main reasons. Firstly, removing vegetation to execute solar projects is absurd from an environmental aspect. Secondly, the presence of vegetation may trigger the need for an environmental impact assessment study, which involves delays in the project and extra costs. However, sparsely vegetated areas are not considered from an ecological perspective.

Distance from electrical infrastructure: The suitability of the electrical connection between the solar PV system and the electricity network is to be assessed. In this regard, the information about the existing electric substation (location and capacity) is checked on AIP or technical reports [22,23]. It is suggested that this information be authorized while preparing a detailed project report. Suppose the location and capacity of the electric substation are unavailable; it is reasonably assumed that the terminal building has an electric feed-in point with a minimum capacity of 11 kV. The land area located more than 1.5 km from the electric feed-in point substation is excluded. This exclusion helps to minimize power loss in cables and reduce the cost of laying cables. The circle tool of Google Earth is used to identify and mark the excluded areas.

2.2.3. Criteria for site selection

Considering the excluded areas of an airport, different area polygons (solar PV sites) are drawn in the Google Earth imagery. The minimum area for a polygon is taken as 1416.4 m^2. This area can accommodate approximately 100 kW_p fixed-tilt solar PV system. The rationale behind the minimum area criterion is that the system cost reduces with an increase in the capacity of the solar PV system. Also, the area polygon is drawn with a minimum edge-to-edge distance of 50 m. A clear distance is provided from the airport boundary wall and buildings in the wake of possible near-shading. The possibility of inter-row shading is addressed through the proper design of the plant layout. If the total area of the PV site is more than 42,492 m^2, it is subdivided into smaller and non-contiguous land areas. From a glare assessment perspective, this limitation in the maximum area of the solar PV site is beneficial.

2.2.4. Glare assessment of the selected site

The glare assessment methodology and glare impact safety criteria defined in the FAA's interim policy on glare (78 FR 63276) have been adopted [29]. According to FAA's safety criteria on solar PV glare, the solar PV array proposed in the airport should not possess any potential for an after-image on the ATC tower's cab (green or yellow glare) as well as high potential for an after-image pilot during the final approach path (yellow glare). ForgeSolar software follows the glare assessment methodology and glare impact safety criteria the FAA sets [30]. The glare analysis is carried out for each selected site of the airports using ForgeSolar software. Those sites that comply with FAA's glare policy have finally been chosen for the proposed solar PV project. The following steps are carried out for each site.

1. The proposed PV array layout is initially provided in ForgeSolar software using the interactive map feature.
2. The details of the solar PV array, such as type of tracking, tilt angle, orientation angle, and characteristics of PV module (top layer material), are given.
3. Then, the location of the observation point (ATC tower cab) and path (final approach) are provided on the map. The default values provided by the software are taken for different parameters.

The software estimates the glare occurrence and duration based on the user inputs. The possible results of glare assessment are shown in Table 3.

2.3. Area parameters

A procedure to select sites for a solar PV project in an airport is presented in Section 3.2.3. This site selection procedure is employed as a case study of India's airports. For each airport, the following area parameters are estimated using the drawing tools of Google Earth software.

The total Area (TA) corresponds to the entire area occupied by the airport. Gross Built Area (GBA) is the cumulative area within the airport boundary with permanent structures (as shown in Table 3). These areas are not suitable for land-based solar PV systems. However, these areas can be considered if rooftop solar PV systems are proposed.

The projected PV Area (PPA) is the cumulative area of all the sites that can install land solar PV in the airport. It depends on the different area polygons (solar PV sites) drawn in the Google Earth image with due consideration to the exclusion criteria. Glare-compatible PV Area (GCPA) corresponds to the cumulative PV-active land area compatible with the FAA's glare policy. The total area omitted due to glare concerns

Table 3
Possible results from ForgeSolar software and its interpretation.

Is glare found	Color	Significance	Remarks	Adherence to FAA's glare policy
No	Nil	No	No glare occurrence	Yes. No glare is observed for both ATC and flight path
Yes	Yellow	Moderate	Potential to cause an after-image	No. Yellow glare on ATC/flight path violates FAA's policy.
	Green	Low	Low potential to cause an after-image	Adhered only if green glare is found on the flight path. At the same time, ATC must be free from both yellow and green glare.

is the Total Glare Area (TGA).

The BTA ratio is the ratio between the gross built area (GBA) and the airport's total area (TA). The PTA ratio represents the portion of the airport area suitable for land solar PV projects. It depends on the (a) built area of the airport, (b) airport-specific criteria such as restricted airspace, (c) the presence of vegetation (d) the location of an electrical substation.

2.4. Solar power potential estimation

Solar power potential is dependent mainly on area constraints and land-to-power conversion factors. PV's resource, theoretical, and technical power potential are assessed in this study (Fig. 3). Land to Power conversion factor (F_{LP}) is taken as 14,161 m^2 (or 3.5 acres), which is equivalent to the land area needed for the installation of a 1 MW solar PV system [31]. The technical specifications of PV modules have a low influence on the abovementioned factors.

Resource potential (P_{RS}): Also called solar PV power resource potential. It is estimated based on the assumption that the total airport area is available. Hence, the total airport area (*TA*) is divided by the conversion factor to obtain the resource potential.

$$P_{RS} = \frac{TA}{F_{LP}} \quad (1)$$

Theoretical potential (P_{TH}): It is defined as the capacity of the solar PV system (in MW) that can be implemented in an airport based on its non-built area. The ground-mounted solar PV system cannot be proposed in the built areas of the airport. Hence, these areas are deducted from the TA [32], and the available area is estimated. The theoretical solar potential is calculated using Equation (3).

$$NBA = TA - GBA \quad (2)$$

$$P_{TH} = \frac{(TA - GBA)}{F_{LP}} \quad (3)$$

Conservative potential (P_{CS}): Also called conservative solar PV power potential. It is estimated based on solar sites selected in an airport. The constraints considered in this site selection process are built area, obstacle limitation surfaces, CNS facilities, future development areas, vegetation/wetland area, and electrical infrastructure. The potential for glare occurrence is not considered in this estimation.

$$P_{CS} = \frac{PPA}{F_{LP}} \quad (4)$$

Technical potential (P_{TE}): In this scenario, the sites with glare occurrences are identified. Hence, only the sites that comply with the glare policy will be considered. The theoretical solar potential is estimated using Equation (5).

$$P_{TE} = \frac{GCPA}{F_{LP}} \quad (5)$$

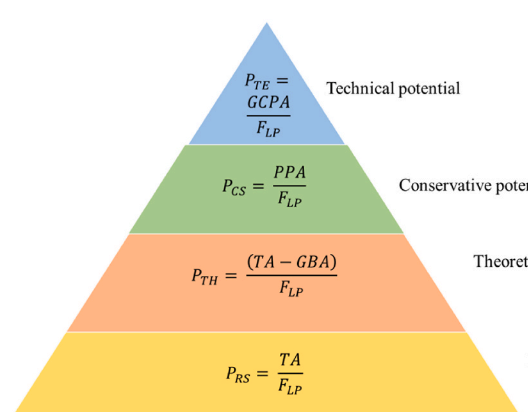

Fig. 3. Hierarchical representation of various solar potential.

3. Results

The suitable sites for solar PV systems in some airports of India are determined based on the developed site assessment approach. The unsuitable sites are marked on Google Earth maps for each airport based on qualitative and quantitative criteria. The potential sites for hypothetical solar PV systems are identified, followed by a glare assessment of solar PV sites. A pictorial representation of the site assessment for solar PV plants is provided in Appendix B. Different types of solar power potential are estimated for India's airports. Resource potential was the highest for all the studied airports, followed by theoretical and technical potential.

3.1. General site conditions in selected airports

Favorable general conditions for the solar PV power plant are observed in India's selected airport locations. As shown in Fig. 4, solar irradiation's minimum and maximum values are 4.68 kWh/m^2/day (Amritsar Airport) and 5.19 kWh/m^2/day (Lucknow Airport). Also, the ambient temperature is shown in Fig. 5, which is the lowest (19.8 °C) in Dehradun airport. The wind speed and rainfall are shown in Figs. 6 and 7, respectively. Madurai Airport has the highest wind speed value (3.5 m/s). Also, All the airport locations have a wind speed above two m/s, which is more than the threshold value of 1 m/s. Reasonably satisfactory

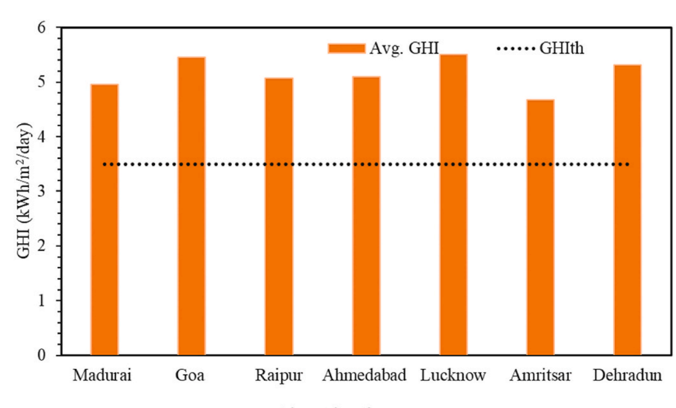

Fig. 4. Comparison of solar irradiation (Avg. GHI) and threshold value (GHIth) in the context of selected airports in India.

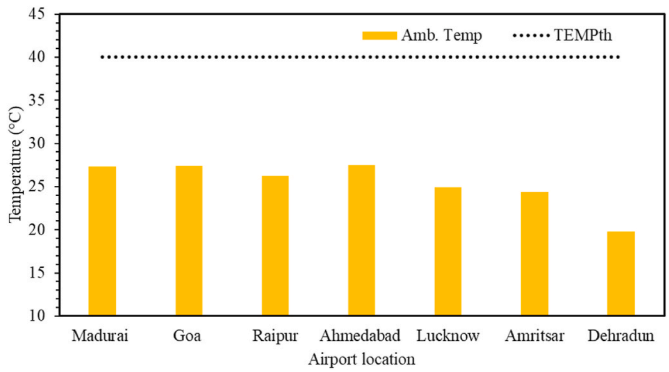

Fig. 5. Comparison of ambient temperature (Amb. Temp) and threshold value (TEMPth) for the selected airports of India.

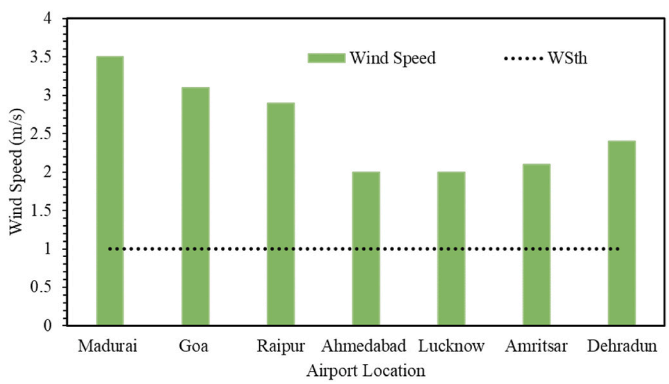

Fig. 6. Comparison of wind speed and threshold value (WSth) in the selected airports of India.

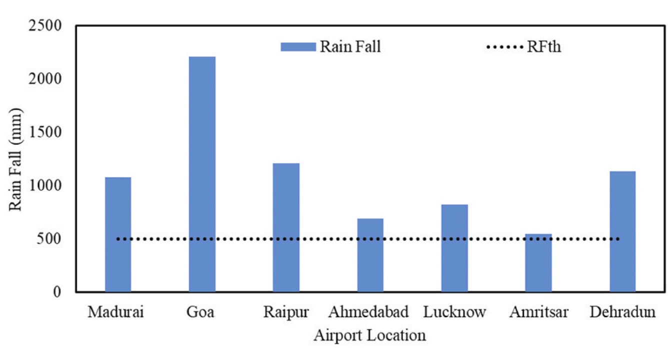

Fig. 7. Comparison of rainfall and its threshold value in the selected airports of India.

rainfall (above 500 mm) is observed in all the airport locations. The minimum rainfall value in Amritsar airport can be attributed to the closeness to the desert climate. Also, there is a rare possibility for abrupt slope topography in airport locations. The solar PV sites in the selected locations have good access to road facilities.

3.2. Assessment of site and area parameters

The area assessment in selected airports of India is shown in Figs. 8 and 9. Among the studied airports of India, the most significant and smallest areas are observed for Amritsar Airport (1366 acres) and Dehradun Airport (307 acres), respectively. The high total area (TA) can be attributed to non-aviation facilities and vast vacant areas. The gross built area (GBA) is observed to be higher for airports that house non-aviation facilities such as residential colonies naval/airbase facilities. This condition is observed for the Amritsar airport, which has a GBA of 573 acres. The BTA ratio is highest for Amritsar airport (42 %) and lowest for Raipur airport (19 %). Based on the selection criteria described in section 3, the solar PV sites are chosen for each airport in India. The percentage of the total area suitable for solar PV installation is observed to be low. As shown in Fig. 9, the lowest and highest values of the PTA ratio are 3.6 % (Lucknow airport) and 21 % (Madurai airport), respectively. A considerable variation in the BTA ratio is not observed for the selected airports. However, the PTA ratio varied widely based on the airport conditions, such as the orientation of runways, distribution of vacant areas etc.

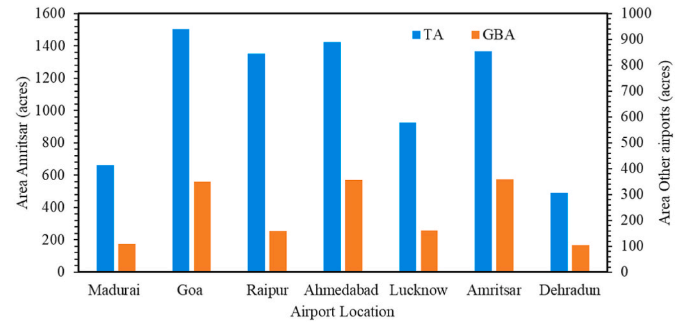

Fig. 8. Variation of total area (TA) and gross built area (GBA) in airports of India.

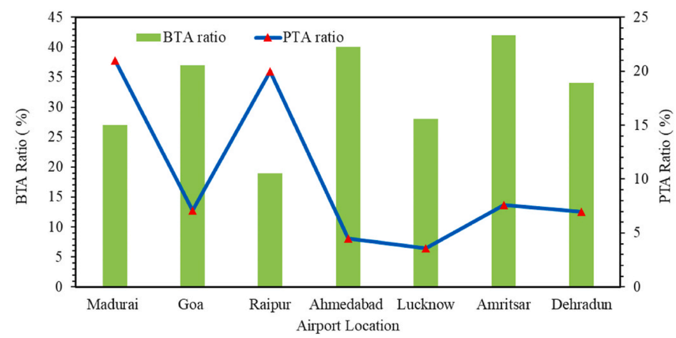

Fig. 9. Variation of built-to-total area (BTA) ratio and PV area-to-total area (PTA) ratio in selected airports of India.

The most possible PV sites are observed at Amritsar Airport (26) and Raipur Airport (22) (See Fig. 10). This can be attributed to the distribution of vacant areas and their radial distance from the electrical substation. Glare assessment is carried out for all solar PV sites according to the steps provided in the Methodology. It is observed that Amritsar Airport has the highest number of sites (15 sites), which

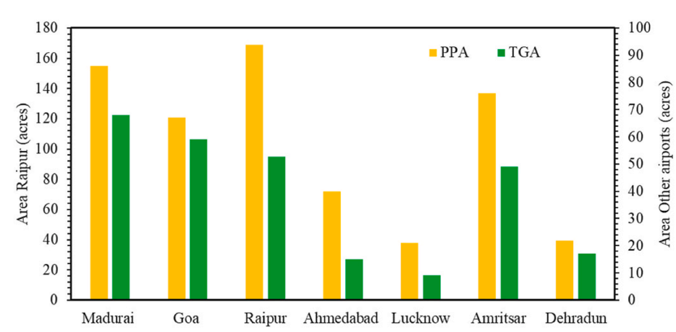

Fig. 10. Variation of projected PV area (PPA) and total glare area (TGA) in the selected airports of India.

adheres to the FAA's glare policy. However, nearly 50 % of the projected sites in Amritsar airport are omitted because of glare hazards. This can be mainly attributed to the closeness of these sites to the flight path/ATC tower. In addition, the sun's movement might have influenced the occurrence of glare. The glare area for airports in India is shown in Table 4.

3.3. Assessment of solar potential

The values of resource potential and the theoretical potential for selected airports in India are shown in Fig. 11. The highest value of resource potential is observed for Amritsar Airport, followed by Goa Airport and Ahmedabad Airport. The lowest value of resource potential is observed for Dehradun Airport. This variation in resource potential can be correlated with the airport's total area. For instance, the resource potential of Amritsar Airport (1366 acres) is more than Dehradun Airport's (307 acres). The low value of theoretical potential is observed for Madurai Airport (86.01 MW) and Dehradun Airport (58.14 MW). This can be attributed to its low total area value (less than 500 acres).

The conservative and technical solar potential for selected airports in India is shown in Fig. 12. It is observed that the actual potential (technical) for solar PV deployment is significantly less compared to the theoretical potential. The majority of the vacant area is observed to be unsuitable for solar PV systems due to the possibility of glare hazards and consideration of airport-specific constraints. The highest conservative potential value is observed in Raipur airport (48 MW). This can be attributed to 169 acres of suitable vacant area in this airport, around 20 % of the total area. The low value of technical potential is observed in Dehradun airport (1 MW), followed by Goa airport (2.23 MW) and Lucknow airport (3 MW). This reduction in potential can be correlated with glare occurrence. Raipur airport is found to have the highest technical potential. However, 95.5 acres of projected solar PV sites are excluded due to the risk of glare strikes.

4. Discussions

Based on the review of topographical details of different airport sites, it is understood that a considerable amount of vacant area exists in the airport. It is reported that about 3306 km^2 of grasslands are available in selected airports in the United States [33]. Similar to an approach by Ali et al. [7], the developed methodology could be applied to any airport. However, the PV-compatible area and solar potential depend on unique values such as the gross built area, total vacant area, and the sun's movement for the individual airport. The use of optimization algorithms for site selection is one of the future scopes of the study. Such algorithms are widely employed in the feasibility assessment of hybrid energy systems in built environments such as universities, airports etc [34,35].

Table 4
Results of glare analysis and glare-compatible PV area in airports of India.

Name of airport	No: of possible PV sites	Number of PV sites with glare policy adherence	Number of omitted PV sites	Glare-compatible PV area (acres)
Madurai Airport	20	6	14	18.6
Goa Airport	20	7	13	7.82
Raipur Airport	22	10	12	74.07
Ahmedabad Airport	9	6	9	24.67
Lucknow Airport	3	2	1	11.89
Amritsar Airport	26	15	11	26.61
Dehradun Airport	7	2	5	4.78

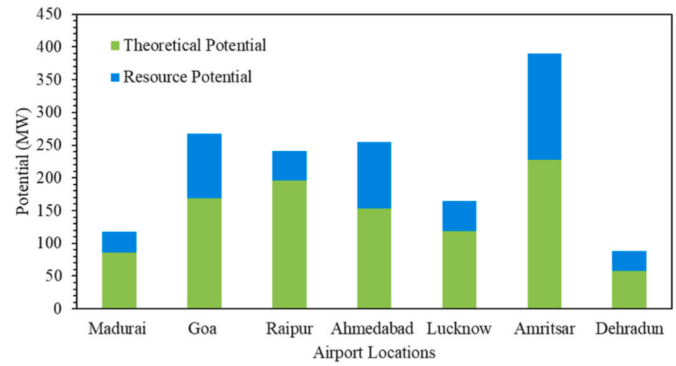

Fig. 11. Variation of resource and theoretical potential in airports of India.

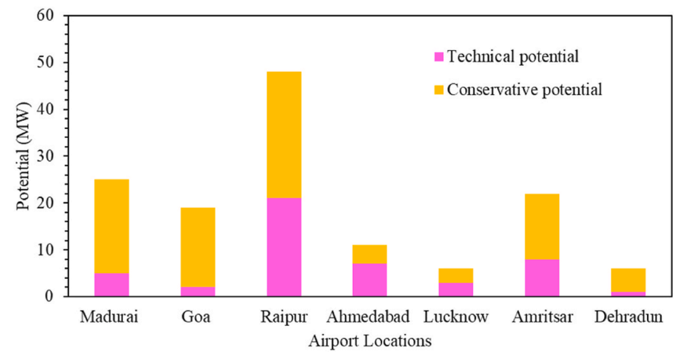

Fig. 12. Variation of conservative and technical potential in airports of India.

There is difficulty in finding suitable sites for solar PV systems due to aviation safety and regulations. Hence, the site selection procedure developed in this study is focused on the suitability of land area for solar PV deployment in airport boundaries. The location of the rooftop and carpark is not considered for the area estimation and potential assessment. Though there is rising interest in solar power, the uptake of solar in airports is happening at a snail's pace. Airport operators are often concerned with safety breaches when installing solar PV systems [36].

Due to area constraints and site restrictions, solar power potential in Goa and Dehradun airports was observed to be low. Highly efficient solar PV modules (for example, bifacial) are suitable for airports with low solar potential values.

However, the extent of utilization of vacant areas for non-aeronautical purposes depends on aviation rules and regulations. A round-table discussion among airport stakeholders is beneficial to maximize the deployment of solar PV systems in vacant places. Prior space allocation for solar PV systems in the airport master plan will positively affect solar PV power potential. To promote airport solar projects and establish relevant policies, it is important to assess the solar PV potential in the best possible way. New airports can be planned so that effective utilization of vacant spaces is viable for solar PV projects.

In the wake of difficulty in collecting airport technical data (electrical and civil), the site selection approach is developed based on publicly available data. Hence, a manual selection method was employed to identify suitable areas. The proposed approach is based on Google Earth Software, which is beneficial in terms of inexpensive tools, freely available data, and minimal computational know-how. However, this method becomes time-intensive and cumbersome, especially when the study involves large airports (e.g., more than 1000 acres). This shortcoming was realized at the time of site selection for Kuala Lumpur Airport, which is spread over 6188 acres. In the present study, the site selection approach was aimed to provide a workable estimate rather than a precise prediction. Approximate estimates of solar PV potential are good enough for the initial planning and feasibility study in airports

[9]. A data-intensive and precise methodology may be needed during the detailed project report phase. Before finalizing solar PV implementation, a field survey is suggested to collect actual site details, load demand, and other data.

5. Conclusion

In this paper, a unique approach for site assessment and potential evaluation was developed for the airport solar PV system. The developed framework was applied to different airports in India as a case study. Based on the site assessment of Indian airports, it was concluded that the suitable site for airport solar PV systems depends predominantly on airspace restrictions, gross built area, and glare occurrence. Also, it observed that around 40 % of the total area in an airport is covered by buildings; hence, these sites are not available for land-based solar PV projects. The solar power potential of the airport varied with its geographical characteristics and land-use pattern. The highest value of technical potential is observed for Raipur Airport (21 MW) among airports in India. These conservative estimates are good enough for planning and developing airport solar projects.

The developed unique approach for site assessment can be applied to any airport worldwide. This approach was established with due consideration of the general sitting factors and airport-specific factors. The robustness and inclusiveness of this framework are established based on a study of different airports in India. The site selection and assessment procedure for solar tracking PV projects can be explored as future work. The effect of prevailing solar policies can also be included. Therefore, the present study can be extended to assess the implementation potential of solar PV in airports.

CRediT authorship contribution statement

S. Sreenath: Writing – original draft, Dr. **K. Sudhakar:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **A.F. Yusop:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sudhakar Kumarasamy reports financial support was provided by University of Malaysia Pahang Al-Sultan Abdullah. "The corresponding author, Sudhakar Kumarasamy, discloses membership on the Editorial Board of Heliyon Journal If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Color code for built areas in the airport

Table A.1
Description of built areas in the airport and associated color code

Location	Built areas	Colour code
Airside	Runway	Black
	Taxiway	Brown
	Apron	Grey
	Other built area	Grape
Landside	Terminal built	Pink
	Vehicle parking	Light blue
	Access roads (width> 10 m)	Reddish orange
	Other built area	Grape
Remarks	Any concrete structures with an area of more than 1000 m^2 are considered as the built area. Areas are marked roughly to get a workable estimate. A buffer distance of 150 feet is provided for the cooling pit and fire pit. Land parcels collocated with vegetation (gardens), buildings, and open space (hybrid areas) are also considered among other built areas. The runway area includes a runway, isolation bay, runway shoulders Taxiway area includes the taxiway and its shoulders. The apron area includes aprons, hangars, a maintenance unit, and more. Other built areas include a meteorological station, general aviation buildings, fire and rescue buildings, helicopter stand, fuel depot, commercial buildings, cargo buildings.	

Appendix B. Site assessment for solar PV plant in selected airports of India (based on Google Earth imagery)

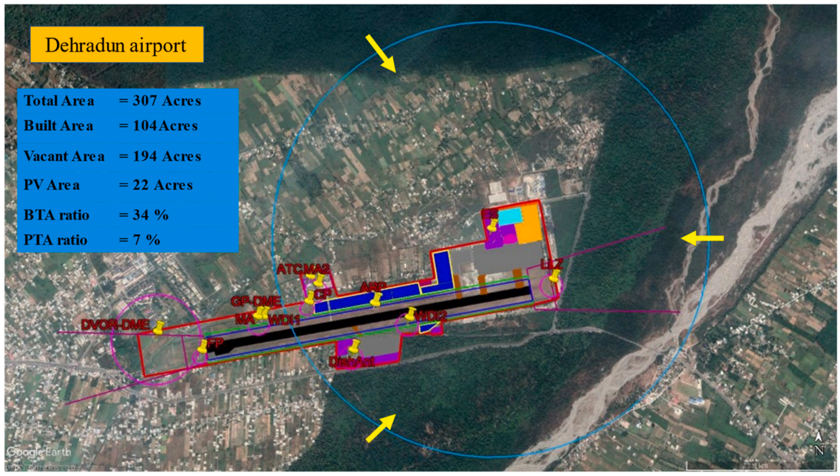

Fig. B.1. Site assessment for solar PV plant in Dehradun airport.

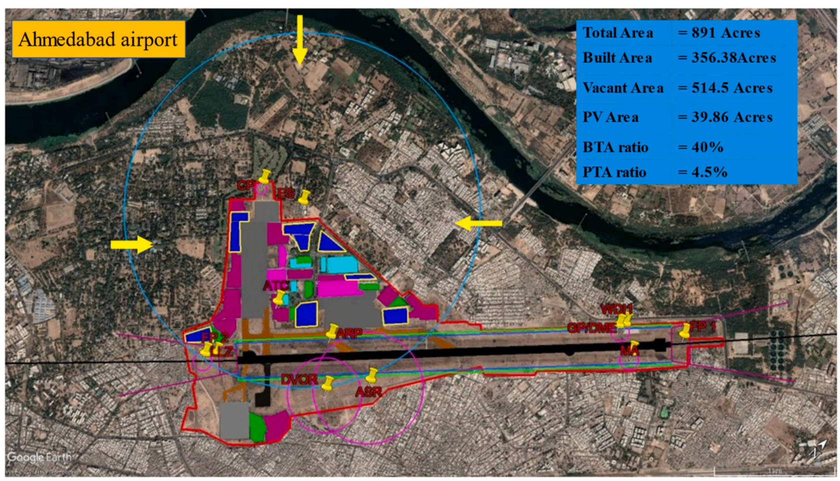

Fig. B.2. Site assessment for solar PV plant in Ahmedabad airport.

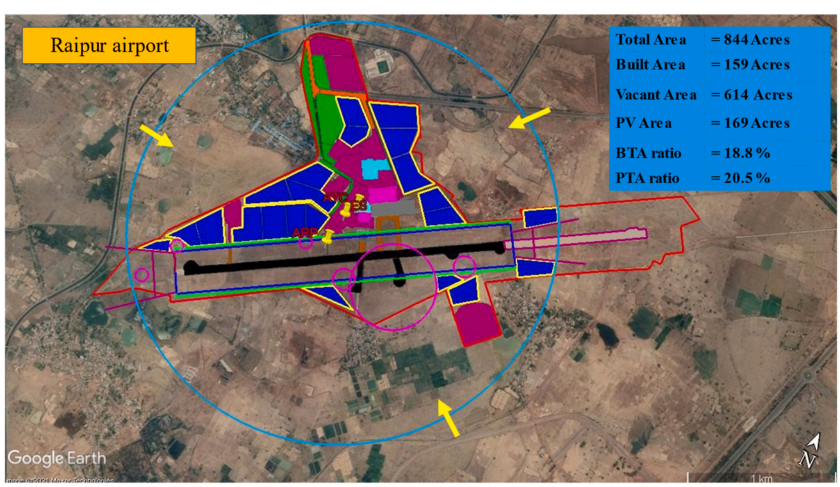

Fig. B.3. Site assessment for solar PV plant in Raipur airport.

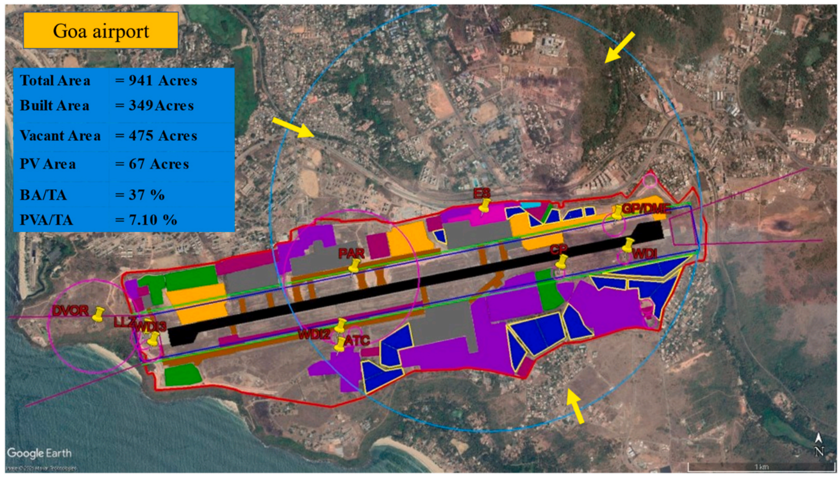

Fig. B.4. Site assessment for solar PV plant in Goa airport.

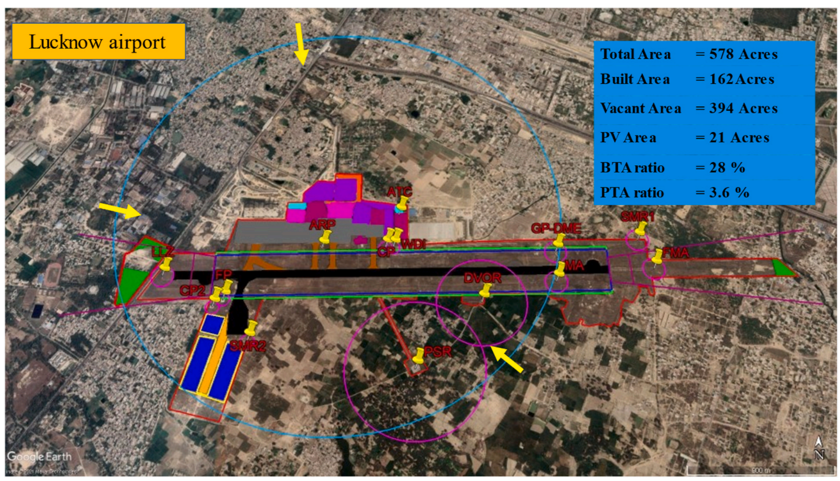

Fig. B.5. Site assessment for solar PV plant in Lucknow airport.

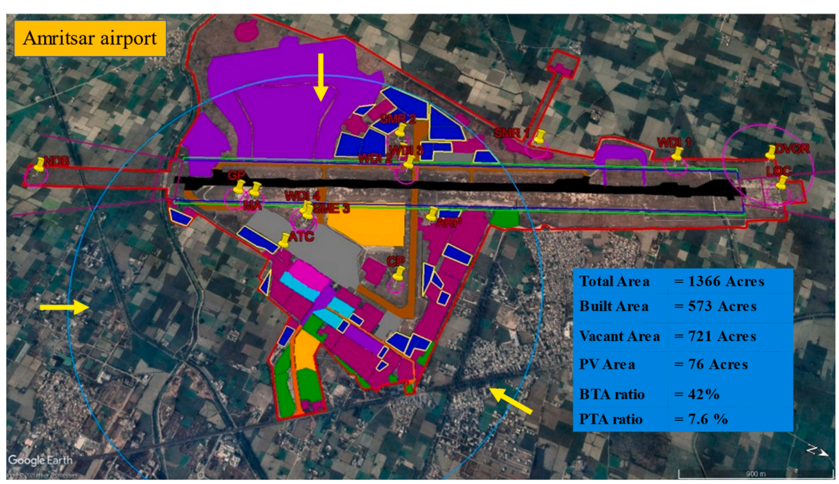

Fig. B.6. Site assessment for solar PV plant in Amritsar airport.

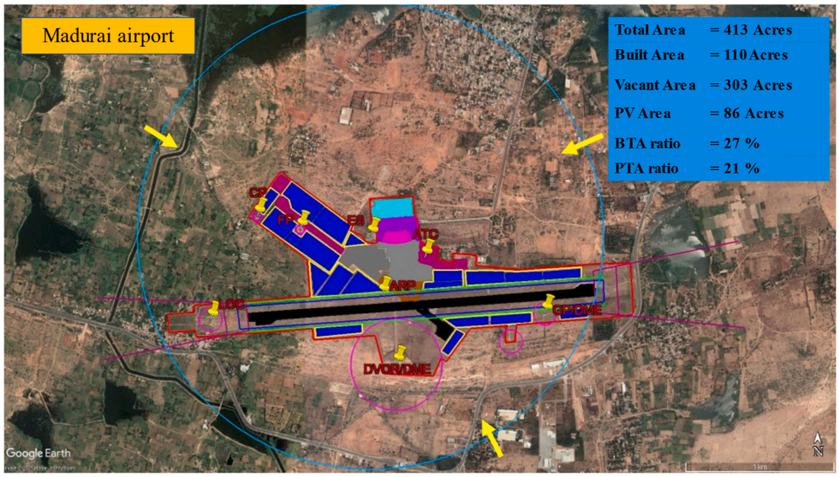

Fig. B.7. Site assessment for solar PV plant in Madurai airport.

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