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Effect of PV material, texturing, orientation and tracking on glare impact: A simulation study from an Indian airport

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ABSTRACT

There is a growing interest in airport-based solar PV systems. At the same time, there is the possibility of glare from the solar PV array, which is a potential aviation safety issue. This paper's main objective is to estimate the technical solar power potential of an airport and assess glare impact for six different scenarios of PV array. These configurations are smooth glass, smooth glass with Anti-Reflective Coating (ARC), light-textured glass with ARC, a variation of tilt & orientation angle, single-axis tracking, and dual-axis tracking. The potential for a land-based solar PV system is assessed based on vacant area and glare impact. The details of the airport site, solar PV array, and the position of observers are provided for software simulation. The occurrence and duration of glare for each scenario are simulated using ForgeSolar software. The impact of glare is assessed based on a standard set by the Federal Aviation Administration (FAA). The technical potential of solar PV in the selected airport is estimated at 9.8 MW. Among the studied scenarios, the safe value of glare is obtained in Scenario 4 (variation of tilt & orientation angle) and Scenario 5 (single-axis tracking). In Scenario 4120 configurations of tilt and orientation angle adhered to FAA's solar glare policy. It is observed that the variation of tilt and orientation angle resulted in zero minutes of glare in several configurations. However, the energy output of the solar PV array was affected. The single-axis tracking solar PV system is expected to generate 35% higher electricity than the fixed-tilt system. Hence, it is concluded that Scenario 5 is the desired arrangement in terms of glare mitigation and energy output. This work will benefit aviation stakeholders for assessing the solar power potential and deciding suitable glare mitigation measures.

1. Introduction

The operation of airports and their occasional construction activities can significantly impact environmental sustainability (Greer et al., 2020). Environmental challenges accompany the benefits of air travel. With passenger growth and associated commercial activities, many airports are transforming into metropolitan regions known as aerotropolis. The carbon emission from the civil aviation sector is about 915 million tCO_2 in 2019 (i.e. 2% of total carbon emissions from human activities) (International Air Transport Association, 2020). The energy consumption of airports significantly contributes to their net carbon footprint. A considerable amount of energy is needed during airport operation, attributed to its round-the-hour operation and heating or cooling requirements. The main consumers of energy in airports are heating, ventilation, and air conditioning (HVAC) systems, lighting (landside and airside), retail facilities (Baxter et al., 2019). Airports seek to implement effective, sustainable energy practices to reduce their environmental burden and improve their operational ability & financial performance. Onsite energy generation is one such initiative that can reduce electrical energy use and its energy bill. Solar PV technology is now a well-known renewable energy source that is versatile, sustainable, and environment friendly (Sreenath et al., 2019). The electricity consumption in airports usually comes from a nearby grid which a local electric utility typically own. This electricity can be substituted with the energy generated from the solar PV system to reduce GHG emissions. The vacant land available in the airport premises can be utilized for solar PV installations. An airport-based solar PV system helps stabilize energy cost, mitigate carbon emissions, meet sustainability targets, and create robust & reliable electricity (Alba and Manana, 2016). Due to the

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Nomenclature

ARC	Anti Reflection Coating
ATC	Air Traffic Control
FAA	Federal Aviation Administration
GHG	Green House Gas
HVAC	Heating, Ventilation, and Air Conditioning
PV	PhotoVoltaic
SGHAT	Solar Glare Hazard Assessment
A_{av}	Available area
A_{PV}	Area of PV sites
A_{PVg}	Area of PV sites with glare
A_b	Built area
A_r	Reference solar area
A_t	Total airport area
P_{TH}	Theoretical power potential
P_{TE}	Technical power potential

continuous pressure to reduce its carbon footprint, there is an increased interest in solar photovoltaic systems among airport operators (Sreenath et al., 2020a).

However, the implementation of solar PV may affect the safe operation of airports (Anurag et al., 2017). reported three main roadblocks to solar PV installation in airports, namely reflectivity & glare from PV array, interference to radar operation, and physical penetration into restricted airspace. Among these, the reflected rays from the solar PV array is a big concern. It may reach the cockpit of the aircraft (landing & take-off) or the window of the ATC tower (Devita and Barrett, 2014). These reflections may cause glint or glare to pilots or airport staff, reducing their visual performance (leading to incorrect decisions, which is a severe aviation issue). Detailed technical guidance on solar PV installations in airports was released by the(Federal Aviation Administration (FAA). In this technical guidance, it is mentioned that the possibility for glare & glint is a new and unforeseen issue from solar energy application in airports (Federal Aviation Administration, 2012). In the interim policy statement, FAA sets forth the standards for glare assessment and its impact (Federal Aviation Administration, 2013). FAA and Sandia National Laboratories developed a glare assessment tool called Solar Glare Hazard Assessment tool (SGHAT). However, this tool is accessible by internal Sandia users or licensed institutions. In the Indian context, there is a lack of guidance, policy, or regulation on assessing the impacts of glare from solar facilities. In 2012, a portion of the solar PV arrays installed in Manchester-Boston airport was covered with wrap temporarily to avoid glare issues raised by ATC tower staff. Later, the PV array was rotated 90° to the east from the current position to mitigate glare problems (Kandt and Romero, 2014). Prior glare assessment helps to mitigate such issues, reduce unnecessary costs on reconstructions, and avoid delays in permission and approval. Although accidents from solar PV glare in airports are rarely reported, glare assessment can be a merit estimation, at least to enhance the confidence of airport operators and other stakeholders. Unlike the glare occurrence from water or snow surfaces, there is a possibility to reduce/mitigate glare from solar PV array through its proper siting and design Sreenath et al. assessed the glare occurrence from a conceptual solar PV array in an airport in Malaysia using ForgeSolar software and reported that the glare is expected to occur for 6776 min on Air Traffic Control (ATC) tower, which do not comply with FAA's solar glare policy (Sreenath et al., 2020b).

Solar PV modules form an integral part of the solar PV system. The top layer of the PV module is usually made of glass material. A smooth glass is the most elementary type of PV module's top cover. A part of sunlight falling on the PV surface reflects different directions (Paolini et al., 2020). An anti-reflective coating (ARC) on the solar PV module reduces reflection from its surface. AR coating improves the transmission of sunlight for each angle of incidence over a wide range of wavelengths. This improved absorption of sunlight is beneficial in the efficiency improvement of solar PV modules. Traditionally, the coatings of AR layers on silicon solar cells are made of SiO_2 and TiO_2, or Si_3N_4. This faced some practical problems such as optical match, surface passivation, or angle-dependent anti-reflection. The double-layer ARC is observed to be suitable for preventing two-tier reflection in solar PV modules (Raut et al., 2011). The reduction in reflection using rough surface and anti-reflection materials has been researched widely. The need for omnidirectional AR property led to the development of surface-topography based ARC such as porous, photonic nanostructures, textured glass, anti-reflection grating (ARG). The use of these PV materials not only reduces reflective energy losses but also improves conversion efficiency (Tällberg et al., 2019). The front glass cover of the solar PV module can be altered optically to minimize glare and maximize light absorption (Fig. 1). Another technique to reduce reflection is the texturing of the PV's module, which is based on light trapping and multiple internal reflections. Some examples of texturing structures on the top surface are the pyramid, inverted pyramid, and honeycomb. The spacing between structures and their depth is varied to obtain the required level of texture (lightly to deeply). In the monocrystalline silicon cell, it is reported that the surface texturing causes a reduction of 10% (approximately) in reflectance (Raut et al., 2011). In a fixed-tilt mechanism, PV modules are installed at a particular position throughout the year. The PV array receives maximum sunlight when the sun's ray falls perpendicular to it. The orientation of the PV module and the position of the sun decides the amount of electricity generation. In a fixed-tilt solar PV system, two separate angles, namely tilt and azimuth angle, define the PV array's orientation (Shukla et al., 2016). The azimuth angle refers to the direction in which the top surface of the PV module is facing. Solar PV systems in the northern hemisphere are faced in the south direction and vice versa. The angle at which the PV module is tilted from the horizontal is the tilt angle. The main factor that determines the tilt angle is the latitude of the location. Typically, the tilt of PV modules at an angle equal to its latitude maximizes the collection of sunlight (Banda et al., 2019). Since solar energy is dilute in nature, the energy density of the fixed tilt solar photovoltaic (PV) system is comparatively low (Shukla et al., 2017). This problem can be solved to some extent through tracking the sun by the PV array (from sunrise to sunset). Solar PV array rotates in one axis of movement (usually aligned with north and south) in a single-axis tracking solar PV system. In a dual-axis tracking technique, the solar PV array follows the sun's movement in two axes (elevation and azimuth). In the sun-tracking solar PV system, the reflective surface of the solar module is rotated to follow the movement of the sun (Tudorache et al., 2012). compared the performance of fixed tilt and tracker solar PV system (prototype) and reported that tracking solar PV generated more energy than the standing solar PV array (Fazlizan et al., 2019). assessed the energy output for 12 peak kilowatt (kW) dual-axis solar tracking systems in a tropical climate and reported that the energy generation from the tracking system is 49% more than a similar fixed-tilt PV system for a gloomy day.

(Ghasemi et al., 2019) investigated the energy generation potential of a solar PV power plant in two provinces of Southeast Iran and estimated that the technical potential in the specified location was 8758 TWh/annum (Choudhary et al., 2020). proposed a grid-connected solar PV power plant for three Indian airports located at Udaipur (2.43 MW), Raipur (3.20 MW), and Aurangabad (2.08 MW) and predicted that the annual energy generation as 4238.3 MWh, 5012 MWh, 3425.5 MWh, respectively (Hong et al., 2017). investigated the solar potential in building rooftops of Gangnam district, South Korea, and reported the physical, geographic, and technical potential as 9287.98 GWh, 4964.11 GWh, and 1130.37 MWh, respectively (Singh, 2020). estimated the power potential for rooftop solar PV for 13 Indian cities and reported a cumulative technical rooftop PV potential of 17.8 GWp for these studied cities (Ali et al., 2018). investigated the total rooftop area and solar PV

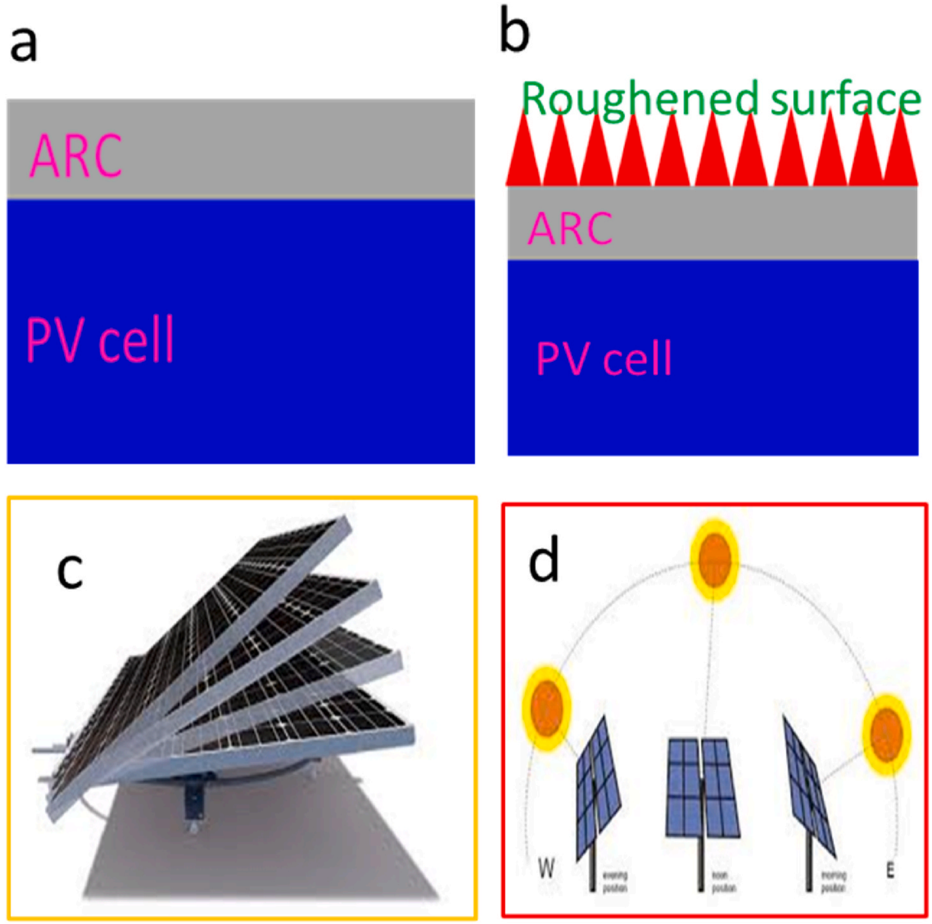

Fig. 1. Top glass material and orientation aspects of solar PV module a. Anti-Glare Coating b. Surface texture c. Varying tilt angle d. Solar tracking.

potential for an Island in the Maldives. The approximate rooftop area was estimated using Google Earth Pro software. The energy generation potential of 4.8 GWh and 8.0 GWh is obtained for 30% and 50% of the useable area of the rooftop. Some authors reported the energy performance of fixed-tilt solar PV systems located in airport premises (Banda et al., 2019). investigated the performance of 830 kW solar PV power plant in Kamuzu airport, Malawi and reported an overall system efficiency of 14.6%, a capacity factor of 17.7% and a performance ratio of 79.5%.In a study by (Mpholo et al., 2015), it was concluded that the 281 kW solar photovoltaic power plant in Moshoeshoe I airport had operated satisfactorily with a performance ratio of 70% (Sukumaran and Sudhakar, 2017). Investigated the performance of a 12 MW solar PV power plant installed in Cochin airport, India and observed a high value of performance ratio (86.56%), capacity utilization factor (20.12%) with a final yield of 1984.1 MWh/MW. Araki et al. assessed the annual energy generation of 30 kWp bifacial solar PV system in the premise of Aichi airport, Japan, and reported that the solar plant generated 30,506 kWh (measured) and 30,628 kWh (calculated) based on one-year operational data (Araki et al., 2009).

The glare aspects of solar PV in airports are underserved in the literature. Only a few studies are carried out on the glare assessment of solar PV arrays in the airport environment. Some authors carried out the glare assessment of solar PV array in airports for a particular PV configuration. However, the glare analysis of solar PV array for different scenarios of PV material, tilt angle, and tracking has not been explored yet. The objective of this paper is to estimate the theoretical and technical power potential of solar PV technology in an airport and investigate the glare occurrence from solar PV array under six different scenarios. In addition, the best scenario for solar PV array in terms of glare impact and energy generation in the selected site of the airport is also assessed. The results reported in the present study have thrown light on different technology alternatives capable of reducing the glare impact from solar PV arrays. A promising approach to assess the theoretical and technical potential of solar PV power in the airport is provided. This research work can be a reference material to staff considering solar projects in their airport. It is expected that this work will influence solar PV glare related decision making and policies that are in the revision or development phase. These results will strengthen the theoretical support on the application of solar PV in the airport area. Although this analysis is carried out for the Indian airport, the technical concepts and methodology framework reported in this work can be applied to other airport locations worldwide.

2. Methodology

In this study, an Indian airport is chosen as a case study. Based on area availability, the theoretical power potential of the selected airport is estimated. Then the technical solar power potential is assessed with due consideration to glare impact. Finally, a specific site within the airport is chosen to analyze the occurrence and duration of glare from solar PV array in six different scenarios.

2.1. Site selection

An Indian airport is selected for the case study in this research work. Ahmedabad airport is an international airport which is located in the western part of India. It is the seventh busiest airport in India (Airports Authority of India, 2020). The solar irradiation received in this region lies between 5.2 kWh/m^2 and 5.6 kWh/m^2, which is suitable for solar PV installation (Solargis, 2019). A 700 kWp solar PV system is already installed on the rooftop of the airport building (PIB Ahmedabad, 2017). The topographic details of the selected airport (terminal buildings, car parking zones, runways, etc.) are analyzed using Google Earth software. The total area of Ahmedabad airport is estimated to be 37,72,570 m^2. The built zones inside the airport boundary are identified, and their areas are measured (Table 1). Then the sites suitable for the land based solar PV system in airport's boundary are chosen. The area of each selected site for solar PV array is given in Table 2. All the selected sites lie within the airport boundary. It is assumed that the chosen site is not reserved for the airport's future development activities. The energy generated from the hypothetical solar PV plant is supposed to meet the airport's captive energy consumption. The surplus energy will be fed to the electric grid under the net-metering scheme. The position of the built area, selected solar PV sites, and observation points (for glare analysis) are shown in Fig. 2. These areas are roughly drawn in Google Earth based on visual inspection, reasonable assumptions and limited open-source information.

2.2. Theoretical and technical solar power potential

Theoretical power potential (P_{TH}): It can be defined as the total capacity of the solar PV system (in kW) that can be installed in the defined region based on area availability. Built areas such as terminal buildings, apron, taxiway, runway, car parking zone, there is no possibility of installing a land-based solar PV system (Lee and Roberts, 2018). In this study, the region within the airport boundary (A_t) and outside of the built area (A_b) is considered for the theoretical estimation of solar power. Hence built areas are subtracted from the total area to obtain the available area (A_{av}). The theoretical solar potential is estimated using equation (2). The reference area (A_r) is taken as 3.5 acres or 14,164 m^2 which is the land area needed to install a 1 MW solar PV system (Sreenath et al., 2020c).

$$A_{av} = A_t - A_b \tag{1}$$

$$P_{TH} = \frac{(A_t - A_b)}{A_r} \tag{2}$$

Technical power potential (P_{TE}): This assessment involves the preliminary identification of solar PV sites due to possible technical issues from the development of solar PV systems. Different sites within the airport boundary are chosen to estimate the technical solar power potential. For simplicity, a limit is kept where the total area of PV sites (A_{PV}) equals 10% of the available area (A_{av}). It is reasonable to assume that all the selected sites have access to roads and electric infrastructure (due to airport operations). However, the effect of site conditions such as slope, elevation, soil condition & shading on the implementation of the solar project is neglected. Ten sites are selected from the available area based on visual inspection of the Airport's Google Earth image. Then glare analysis is conducted for each of these sites using ForgeSolar software. It is assumed that the solar PV modules in the selected sites do not physically penetrate restricted airspace and do not interfere with the operation of the Communication, Navigational, and Surveillance (CNS) facilities of the airport. The theoretical solar power potential is estimated using equation (3). The cumulative area of PV sites that cause glare and violate FAA's glare policy is represented by A_{PVg}. In addition, the possibility of glare mitigation through remedial measures are not considered in this potential assessment.

$$P_{TE} = \frac{A_{PV} - A_{PVg}}{A_r} \tag{3}$$

2.3. Scenario analysis

Six different scenarios are framed to study the effect of AR coating, texturing, tilt & orientation, and tracking of PV array on glare impact (Fig. 3). Out of the ten sites identified, site one with the largest area is chosen for scenario analysis. This is because it lies to close observation points (ATC tower & flight path). The characteristics of the six scenarios considered in this study are shown in Table 3. For each scenario, the occurrence and duration of glare are assessed using ForgeSolar software. In addition, the impact of glare on aviation safety is evaluated based on the solar glare policy of the Federal Aviation Administration (FAA). Scenario 1 and Scenario 2 are formulated because the reflectance of PV array surface reduces with AR coating and surface texturing. The optimum tilt angle for a fixed-tilt PV array in the northern hemisphere equals the site's latitude.Similarly, the theoretical maximum of energy output is obtained when the PV array faces the south direction. The first-generation technologies have the maximum share in commercial production. They are expected to be in the top position for the coming decade (Fraunhofer Institute for Solar Energy Systems, 2020). Mono-crystalline and Poly-crystalline silicon PV technology (distinguished based on crystal structure) belongs to first-generation solar cells. The poly-crystalline silicon solar PV modules have a higher production rate, comparatively low cost, and highly standardized production process (Ahmadi et al., 2018). In the present study, 23° and 180° are the optimum tilt and orientation angle values. The glare strike on observation receptors is dependent on the tilt and orientation of the PV array. In Scenario 4, the tilt angle is varied from 0° to 90° in the step of 10°, and the orientation angle is varied from 0° to 180° in the step of 10°. This facilitates the selection of the best configuration in terms of glare impact and energy generation. A lightly textured glass-covered and anti-reflective (AR) coated solar PV module is considered for tracking scenarios. For a single-axis tracking PV system, the range of tracking angle varies from 0° to 120° with a maximum tracking angle of 60° (east or west) in one direction. A typical tracking system in the northern hemisphere has a tracking axis at an orientation of 180°. Dual-axis module tracking systems are assumed to track the sun at all times. Hence a limit on the angle of rotation is not provided. Besides, the annual energy generation for each scenario is also recorded.

2.4. Glare analysis software: ForgeSolar

ForgeSolar is a glare prediction software that assesses solar PV array glare potential exclusively in airport areas. This software is a licensed version of the Solar Glare Hazard Assessment Tool (SGHAT). It provides two glare assessment tools to users. The GlareGauge of ForgeSolar software is used to predict the occurrence of glare. While and GlareReduce tool is used to optimize the PV design for glare mitigation. The glare assessment methodology and glare impact analysis follow FAA's standards (78 FR 63276). As per FAA's solar glare policy, a proposed solar PV array must not possess an after-image on ATC tower (green or yellow glare) and a low potential for an after-image on the final approach path of flight (yellow glare). The glare prediction does not account for the obstructions between the solar PV array and the observers. This software assumes unobstructed visibility of the solar PV array from the observation point, which may be true in many cases. Therefore, any results can be considered to be conservative.

Table 1
Description of built regions in the selected airport and its area in m^2.

Name of built areas	Runway	Apron	Terminal buildings	Car park	Taxiway	Other built areas	Total
Area (m^2)	3,75,288	3,33,955	80,677	45,855	1,58,651	3,90,284	13,84,710

Table 2
Area of sites selected for solar PV array in the airport.

Name of PV sites	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site10
Area (m^2)	30,419	26,303	28,217	17,869	17,181	15,880	28,782	22,585	28,624	20,933

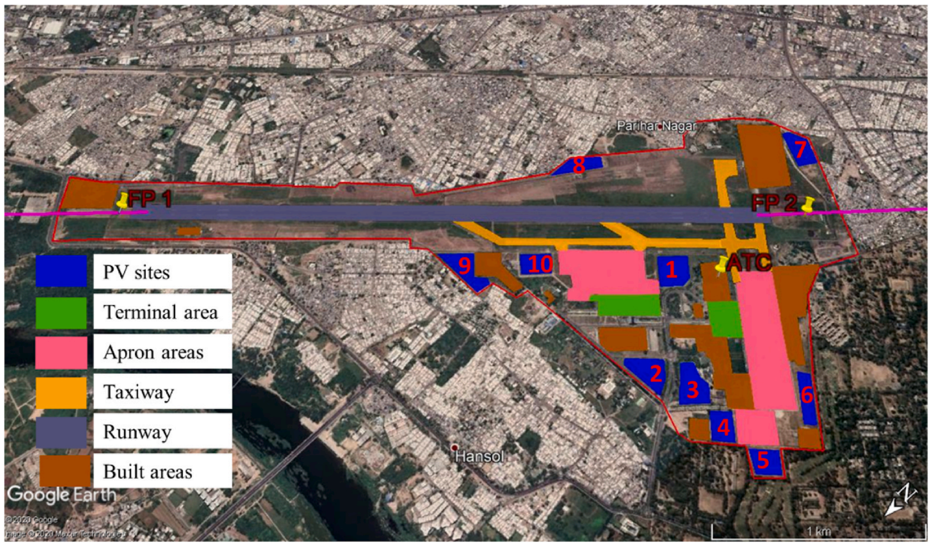

Fig. 2. Location of the proposed solar PV sites in the airport premises and observation points for glare analysis.

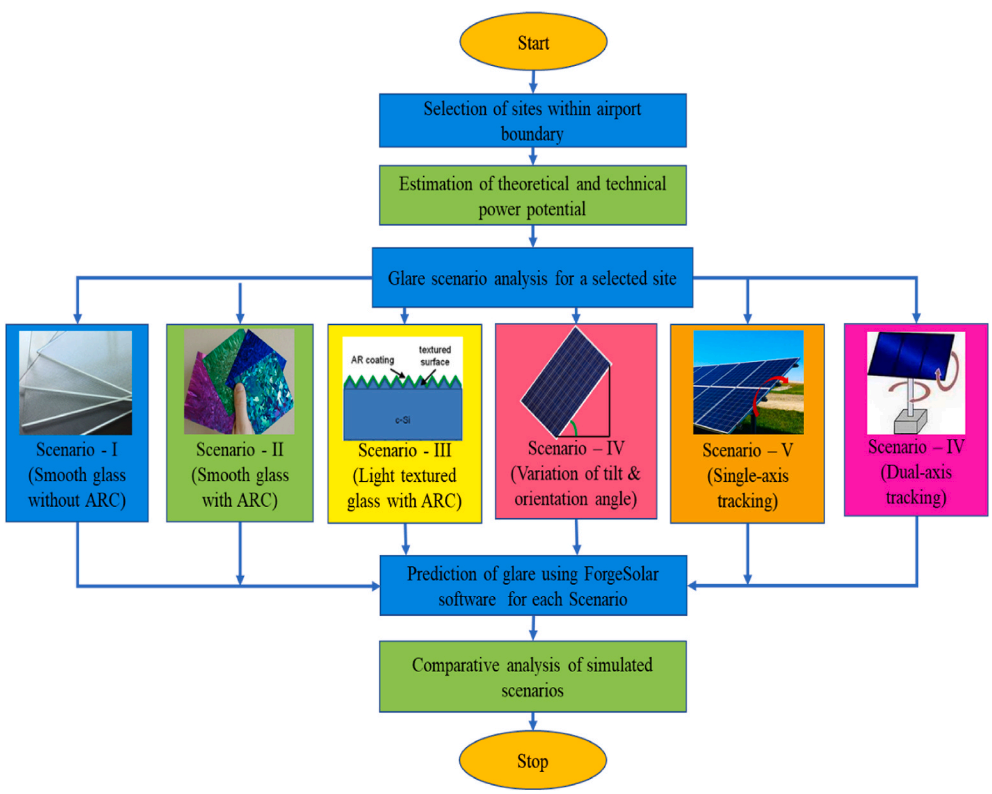

Fig. 3. Flowchart representation of the potential and glare assessment carried out in the study.

Initially, the user draws a PV array in the selected site using the interactive map feature provided by the software. The details of the solar PV array, such as type of tracking, tilt angle, orientation angle, characteristics of PV top layer, are given in a separate tab. Then the location of observers whose visual performance is to be assessed is provided in the map. The observer's considered in the present study are staff in the ATC tower and pilots in the approach path (2-mile flight path). The default values are considered for parameters such as viewing angle of observer, eye characteristics of observer, etc. (Table 4). Based on these input values, the Glaregauge tool estimates the occurrence and duration

Table 3
Details of different scenarios considered for glare analysis.

Name	Is PV module textured	Is ARC present	Type of tracking	Tilt angle (degree)	Orientation angle (degree)	Remarks
Scenario 1	×	×	Fixed tilt	23	180 (south)	Optimum tilt and orientation angle
Scenario 2	×	✓	Fixed tilt	23	180(south)	Optimum tilt and orientation angle
Scenario 3	✓	✓	Fixed tilt	23	180(south)	Optimum tilt and orientation angle
Scenario 4	✓	✓	Fixed tilt	NA	NA	Different sets of tilt and orientation angles
Scenario 5	✓	✓	Single-axis	NA	180 (south)	Rotates from 0° to 120°
Scenario 6	✓	✓	Dual-axis	NA	NA	Tracks the movement of the sun

Table 4
List of assumptions and inputs for glare prediction tool.

Feature	Parameter	Values	Remarks
Project	Unit of height	Metre/Feet	User's choice
	Time zone	UTC +5	Depends on the location of the airport
Site configuration	Peak DNI (daily)	1000 W/m^2	Typical value at solar noon on a clear sunny day
	Interval between analysis	1 min	As per FAA's solar glare policy
	Ocular transmission coefficient	0.5	Typical value
	Pupil diameter (approx.)	0.002 m	Typical value
	Eye focal length (approx.)	0.017 m	Typical value
	Sun's subtended angle	9.3 mrad	Typical value
PV array	Tracking	As per design	Refer to Table 3
	Tilt angle	As per design	
	Orientation	As per design	
ATC	Height	40 m	It usually varies between 25 m and 75 m
	Location	Location dependent	Visual inspection/technical reports
Flight Path	Threshold crossing height	15.24 m	As per FAA's solar glare policy
	Glideslope	3°	As per FAA's solar glare policy
	Max downward viewing angle	30°	Default visibility constraints
	Azimuthal viewing angle	50°	Default visibility constraints

of glare (monthly variation). All the inputs needed for the simulation, such as the flight path location, height of the Air Traffic Control (ATC) tower, are obtained through publicly available sources. It is assumed that reflectivity varies with incidence angle, and slope error is correlated with PV module surface. This software is capable of performing glare prediction for different PV module scenarios and tracking systems. Using the GlareReduce tool, the glare occurrence for different tilt and orientation of solar PV array (Scenario 4) is estimated.

3. Results

The theoretical and technical potential of solar power in an Indian

Table 5
Duration of glare and solar power potential in selected sites.

PV site	Annual Green Glare (min)	Annual Yellow Glare (min)	Is it acceptable as per FAA's policy	Solar power potential (kW)
Site 1	514	7,408	×	2,147.63
Site 2	0	0	✓	1,857.03
Site 3	0	0	✓	1,992.16
Site 4	0	0	✓	1,261.58
Site 5	0	0	✓	1,213.00
Site 6	1,623	731	×	1,121.15
Site 7	669	1,555	×	2,032.05
Site 8	1,049	168	×	1,594.53
Site 9	0	0	✓	2,020.90
Site10	0	0	✓	1,477.90
Solar power potential without consideration of glare			**16,718 kW (rounded off)**	
Solar power potential with consideration of glare			**9,823 kW (rounded off)**	

airport is estimated. The occurrence and duration of glare from solar PV array in six different scenarios are also assessed.

3.1. Theoretical and technical power potential

The theoretical solar power potential of the selected airport is estimated to be 169 MW. This theoretical capacity is possible only when the entire non-built space in the airport is utilized to deploy solar PV system. The estimated value of theoretical power potential is idealistic and is always higher than the technical power potential. The technical solar power potential is assessed with due consideration to solar PV glare. The technical power potential in the selected airport is around 9.8 MW which is spread across six sites. Out of the ten possible chosen sites for solar PV, the six sites adhered to FAA's solar glare policy. It is observed that Site 2, Site 3, Site 4, Site 5, Site 9, and Site 10 have zero minutes of glare duration. This can be attributed to the far distance of these sites from the ATC and flight path (Table 5). The longest duration of glare among the selected sites is observed in Site 1 (7922 min). It can be attributed to its close position with respect to ATC and Flightpath 2.

3.2. Glare scenario analysis

The results of multiple glare analysis that are carried out to study the effect of AR coating, texture, orientation, and tracking (single axis & dual axis) on glare occurrence is described in this section.

3.2.1. Effect of PV material on glare

In scenario 1, glare analysis is carried out for PV array with smooth glass and without AR coating. The considerable duration of glare is predicted from the proposed solar PV array (Table 6). While the flight path is free from glare strike, the ATC tower receives 7922 min of glare (yellow and green). Hence, the visibility of pilots ascending/descending along the 2-mile flight path will not be affected. However, the visibility of airport staff in ATC will be affected by the glare. As per FAA guidelines, the glare occurrence from the proposed solar PV array does not comply with FAA's glare policy. The null value of glare for flight path 1 and flight path 2 can be attributed to the relative position between the flight path and solar PV array. The predicted glare on ATC occurs between 6 a.m., and 9 a.m. during the middle of March to the end of October. The longest duration of glare is observed in June for about 55 min. The glare impact on the ATC tower is mainly yellow glare, which is more intense (Fig. 4). The energy output predicted in this scenario is 5190 MWh.

Solar PV array with smooth glass and coated with AR material is considered in Scenario 2. Since glare is predicted at the ATC tower from the proposed solar PV array, the visibility of airport staff in ATC can be affected by the glare. The glare impact and duration do not adhere to FAA's policy (Table 7). The annual duration of glare for flight path 1 and flight path 2 is zero mins, similar to Scenario 1 (Fig. 5). It is observed that the duration of yellow glare reduced by 161 min in Scenario 2. When smooth glass with AR coated PV module is considered, the intensity of reflections is reduced, which in turn caused an increase in the duration of green glare (less intense). The occurrence and duration of glare for the ATC tower remained almost similar to Scenario 1 (Fig. 5). The area of green glare in the daily glare duration graph increased to a broader area in Scenario 2 when compared with Scenario 2. The energy generation expected in scenario 2 is 5190 MWh which is the same as in scenario 1.

Table 6
Duration of green and yellow glare at flight path and observation receptors for scenario 1.

Receptor	Annual Green Glare (min)	Annual Yellow Glare (min)	Is it acceptable as per FAA's policy
Flight Path 1	0	0	✓
Flight Path 2	0	0	✓
ATC tower	514	7408	×

In Scenario 3, glare assessment is carried out for solar PV array with textured surface (lightly) and AR coating. A considerable duration of glare is predicted from the proposed solar PV array in this scenario (Table 8). The visibility of airport staff in ATC will be affected by the glare. The annual duration of glare for flight path 1 and flight path 2 remained at zero mins (similar to Scenario 1 and Scenario 2). The duration of yellow glare on the ATC tower was reduced to 7080 min as compared to 7352 in Scenario 1. It can be attributed to the reduction in the intensity of reflections from the chosen solar PV module, which is less reflective. At the same time, the duration of green glare (ATC) increased from 1896 min in Scenario 2 to 2465 min in Scenario 2. It accounts for the increased presence of low intense reflections (Fig. 6). The effect of AR coating and texturing on energy output is observed to be negligible. The energy generation for these 3 scenarios is predicted to be 5190 MWh.

3.2.2. Effect of tilt and orientation angle on glare

In this scenario, the glare prediction for different sets of tilt and orientation angles of the PV array is carried out. The material of the PV module top layer is chosen as lightly textured glass with ARC. Out of 190 configurations, 120 sets of tilt and orientation angle adherence to FAA's solar policy. Among the configurations that adhere to FAA's policy, PV array tilted at 20° and oriented at 120° have the highest percentage (95.2%) of theoretical maximum energy output (4941 MWh). It is observed that the glare impact reduces with the increase in the tilt angle. With the increase in orientation angle, glare impact becomes hazardous. In Fig. 7, the blue colour corresponds to those sets of angles to which FAA's glare policy has adhered. The red colour points to the failure of the FAA's glare policy. The percentages denote energy output from the proposed solar PV array relative to the theoretical maximum at a 23-degree tilt angle and oriented south (180°).

3.2.3. Effect of solar PV tracking on glare

For the glare assessment carried out for single-axis tracking solar PV array, it is observed that the duration of glare is zero minutes for both flight path and ATC (Table 6). This can be attributed to the fact that the angle of incidence (angle between the incoming sunlight and the photovoltaic module) is minimized due to the sun tracking of the PV module. Hence PV array with single-axis tracking is safe for deployment in the selected site as per FAA's solar glare policy. The expected energy generation from a single-axis tracking scenario is 6963 MWh. It is supposed that the east to west movement of the solar PV array in tracking mode mitigated the glare occurrence on the observation points. In Scenario 6, glare prediction is carried out for dual-axis tracking solar PV array located in the selected airport area. The results show that there would be glare occurrence for the ATC observation point (Table 9). Since yellow glare and green are forecasted for ATC observers, the dual-axis solar PV array poses a risk to aviation safety as per FAA's solar glare policy. The proposed PV array is expected to produce 8005 min of "green" and 1658 min of "yellow" glare on ATC (Table 9). The proposed PV array is expected to produce glare for receptors at sunset (between 4 p.m. and 6 p.m.) from January to April and from mid-September to December (Fig. 8). Hence it is evident the time and direction of glare occurrence are correlated with the sun's path. Considering the glare duration and its impact (green and yellow), the dual-axis tracking technique can only be implemented in airport areas with utmost care and precautions. In Scenario 6, the dual-axis tracked solar PV array is expected to generate 7203 MWh electrical energy (see Table 10).

3.3. Discussions

The tilt and orientation angle of the PV array is constant for the first four scenarios. However, the top layer material of the PV module surface

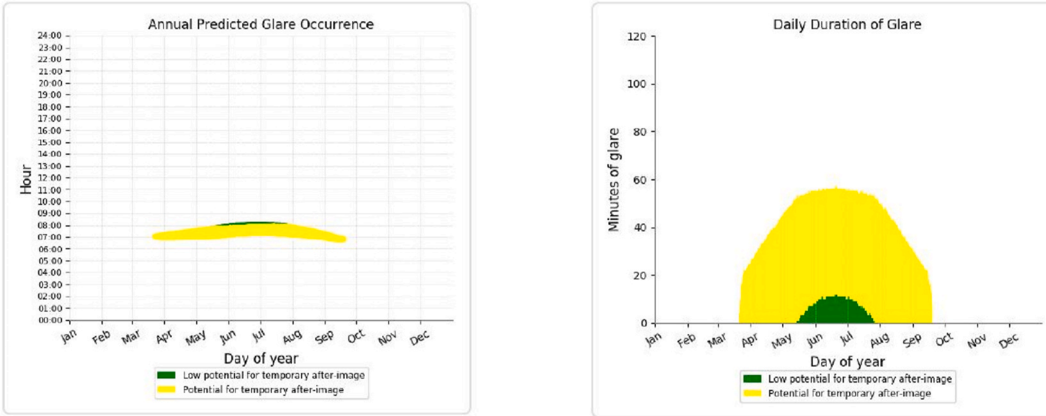

Fig. 4. Variation glare occurrence and duration at ATC for Scenario 1.

Table 7
Duration of yellow and green glare at flight path and observation receptors for Scenario 2.

Receptor	Annual Green Glare (min)	Annual Yellow Glare (min)	Is it acceptable as per FAA's policy
Flight Path 1	0	0	✓
Flight Path 2	0	0	✓
ATC tower	1896	7191	×

is different. In Scenario 3 and Scenario 4, the top layer of the PV module is made of lightly textured glass with ARC. Solar PV modules customized with the anti-glare coating are available in the solar market suitable for projects near the airport or similar site with strict policies on glare occurrence (LG Solar, 2020) (Vikram solar, 2019). The ARC helps reduce the reflectivity of solar PV surface, which leads to better absorption of sunlight. However, the durability of AR coating is limited as it degrades from natural corrosion and module cleaning. The increased energy output due to AR coating or texturing is not significant and hence not considered in the simulation software. The energy generated from the solar PV array as per Scenario 1, Scenario 2, Scenario 3 is predicted as equal. A reduction in glare duration and its intensity is observed from Scenario 1 to Scenario 3. The duration of yellow glare is longer for smooth glass without ARC (Scenario1) than for the light-textured PV module. However, the reduction in glare duration occurred for a shorter duration and did not adhere to FAA's glare policy. Glare duration and its visual impact from dual-axis PV array are much higher than the other scenarios considered in the study. In addition, the initial investment and maintenance cost is comparatively high for such systems. So, the implementation of dual-axis tracking solar PV systems in the airport area is trivial. The local conditions such as temperature, soiling effect, wind speed, clearness index experienced by the PV array remains nearly constant for the six scenarios. A slight variation in soiling loss and module temperature is expected when the PV array is in tracking mode. In actual condition, the area required for tracking solar PV is more than a fixed-tilt system. However, this variation in the area has not been accounted for in the present case study.

In terms of energy generation, tracking solar PV system produces more energy than fixed tilt system. However, the dual-axis tracking system in the selected site does not comply with FAA's solar glare policy. At the same time, zero minutes of glare is predicted for the proposed single-axis tracking solar PV system in the present study. The complexity in design and installation is least for a fixed-tilt solar PV system than a tracking system. However, the fixed-tilt solar PV in Scenario 1, Scenario 2, and Scenario 3 is expected to cause glare considerably. There is a significant increase in initial investment and O&M cost of tracking solar

Table 8
Duration of yellow and green glare at the flight path and observation receptors for Scenario 3.

Receptor	Annual Green Glare (min)	Annual Yellow Glare (min)	Is it acceptable as per FAA's policy
Flight Path 1	0	0	✓
Flight Path 2	0	0	✓
ATC tower	2465	7080	×

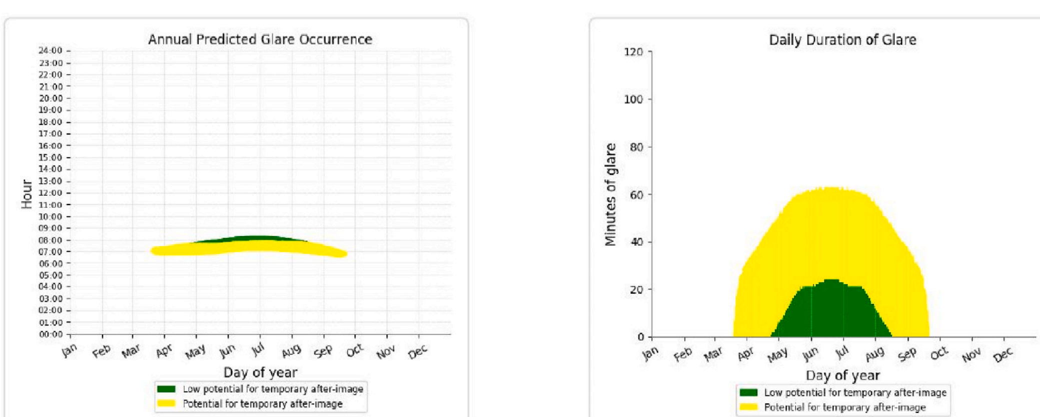

Fig. 5. Variation in glare occurrence and duration at ATC for Scenario 2.

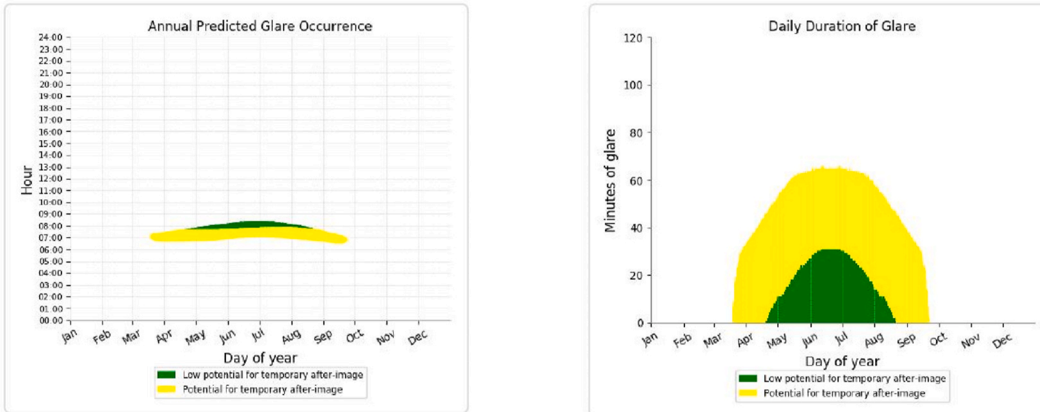

Fig. 6. Variation in glare occurrence and duration at ATC for Scenario 3.

Tilt → Orient ↓	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
0°	93.1%	85.5%	75.5%	63.4%	50.1%	38.0%	27.6%	18.6%	11.0%	5.6%
10°	93.1%	85.6%	75.7%	63.9%	50.8%	38.6%	28.3%	19.3%	11.8%	6.6%
20°	93.1%	86.0%	76.5%	65.2%	52.9%	40.7%	30.4%	21.5%	14.3%	9.7%
30°	93.1%	86.5%	77.7%	67.3%	55.9%	44.7%	34.4%	25.8%	19.1%	14.1%
40°	93.1%	87.2%	79.3%	69.9%	59.7%	49.5%	40.0%	31.8%	24.9%	19.3%
50°	93.1%	88.1%	81.1%	72.9%	63.9%	54.8%	46.0%	38.0%	31.0%	24.8%
60°	93.1%	89.0%	83.2%	76.1%	68.3%	60.1%	52.0%	44.2%	36.9%	30.2%
70°	93.1%	90.1%	85.4%	79.4%	72.6%	65.2%	57.6%	49.9%	42.4%	35.2%
80°	93.1%	91.1%	87.6%	82.7%	76.7%	69.9%	62.7%	55.0%	47.3%	39.6%
90°	93.1%	92.2%	89.7%	85.7%	80.5%	74.2%	67.1%	59.4%	51.4%	43.2%
100°	93.1%	93.3%	91.7%	88.5%	83.8%	77.9%	70.8%	63.0%	54.6%	45.9%
110°	93.1%	94.3%	93.6%	91.0%	86.7%	80.9%	73.8%	65.6%	56.8%	47.6%
120°	93.1%	95.2%	95.2%	93.2%	89.2%	83.4%	76.0%	67.5%	58.1%	48.2%
130°	93.1%	96.1%	96.7%	95.0%	91.2%	85.3%	77.6%	68.5%	58.5%	48.0%
140°	93.1%	96.7%	97.9%	96.5%	92.7%	86.6%	78.6%	68.9%	58.2%	46.9%
150°	93.1%	97.3%	98.8%	97.6%	93.8%	87.6%	79.1%	68.9%	57.4%	45.3%
160°	93.1%	97.7%	99.5%	98.4%	94.6%	88.2%	79.4%	68.6%	56.3%	43.5%
170°	93.1%	97.9%	99.9%	98.9%	95.1%	88.5%	79.4%	68.2%	55.4%	42.0%
180°	93.1%	98.0%	100.0%	99.1%	95.2%	88.5%	79.4%	68.0%	55.0%	41.5%

Fig. 7. Screenshot of optimisation table generated by the glare prediction software for Scenario 4.

Table 9
Duration of glare occurrence on observation points for single-axis tracking solar PV array.

Receptor	Annual Green Glare (min)	Annual Yellow Glare (min)	Is it acceptable as per FAA's policy
Flight Path 1	0	0	✓
Flight Path 2	0	0	✓
ATC tower	0	0	✓

Table 10
Duration of glare occurrence on observation points for single-axis tracking solar PV array.

Receptor	Annual Green Glare (min)	Annual Yellow Glare (min)	Is it acceptable as per FAA's policy
Flight Path 1	0	0	✓
Flight Path 2	0	0	✓
ATC tower	8005	1658	✓

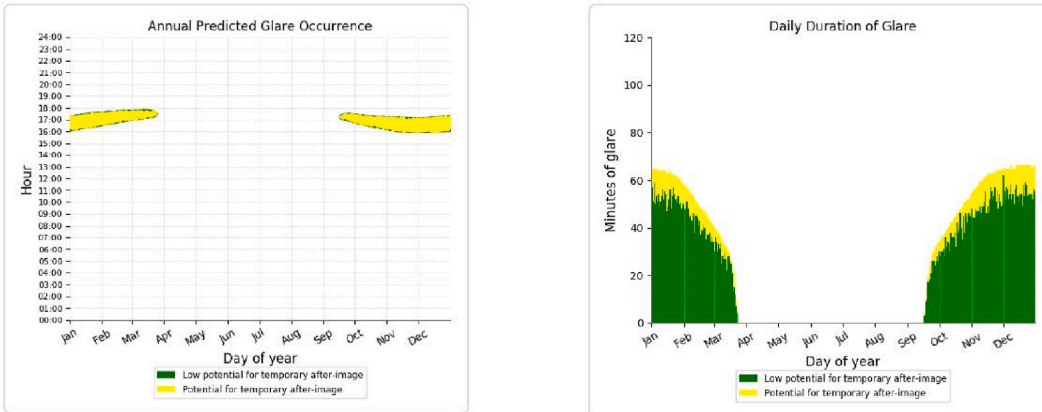

Fig. 8. Variation in glare occurrence and duration at ATC for Scenario 6.

PV system than the fixed-tilt system. There is the possibility for a slight increase in PV module price within the first four Scenarios due to the application of AR coated (Scenario 2) or textured (Scenario 3) or both (Scenario 3 & Scenario 4). Since the PV technology and mounting structure is the same for these scenarios, additional cost from AR coating or texturing or both is expected to be negligible and can be neglected. It is observed that adherence to FAA's solar glare policy is compiled in Scenario 4 and Scenario 5. With the consideration of energy generation, a single-axis tracker solar PV array is a suitable scenario. A single tracking solar PV system is expected to generate a high amount of electricity than a fixed-tilt system (Table 11). However, single tracking systems are more complex than fixed-tilt systems in site preparations, shading analysis, and cabling design. Hence the initial cost is higher. These systems also contain a more complex structure, control mechanism and require regular maintenance due to motors and rotating parts. It is expected that the reliability and accountability of tracking solar PV systems will be further improved by the use of artificial neural network-based tracking algorithms. The fixed-tilt solar PV systems can accommodate harder topographical conditions and requires the least maintenance. The glare occurrence in fixed-tilt solar PV can be avoided by selecting appropriate tilt and orientation angles. Though energy output is comparatively low, fixed-tilt solar PV is highly suitable for cost-effective and less complex solar PV projects in the airport. Though the work is carried out for a specific location in India, the approach and analysis can be applied to any airport across the world.

Table 11
Comparison of glare analysis and energy generation for the studied scenarios.

Scenario Name	Is it adhering to FAA's Glare policy	Energy Generation (MWh)	Remarks
Scenario 1	×	5190	Theoretical maximum energy generation & do not comply with FAA's policy
Scenario 2	×	5190	Theoretical maximum energy generation & do not comply with FAA's policy
Scenario 3	×	5190	Theoretical maximum energy generation & do not comply with FAA's policy
Scenario 4	✓	4941	95.2% of theoretical maximum energy generation & comply with FAA's policy
Scenario 5	✓	6963	35% more energy generation than fixed-tilt & comply with FAA's policy
Scenario 6	×	7203	39% more energy generation than fixed-tilt & do not comply with FAA's policy

4. Conclusions

In this study, the theoretical and technical power potential of solar PV in the airport is estimated. The glare impact for different scenarios of PV array in the airport location is carried out using glare prediction software. The following conclusions are drawn.

- The theoretical solar power potential for the selected airport is estimated to be 169 MW. However, the technical power potential is expected as a 9.8 MW solar PV system (spread across six sites). Therefore, the theoretical power potential is higher than the technical power potential.
- Among the studied scenarios, the safe value of glare is obtained in Scenario 4 (variation tilt & orientation angle) and Scenario 5 (single-axis tracking) for Site 1. Besides, the single-axis tracking solar PV system generated 35% higher electricity than the fixed-tilt system. Hence, it is concluded that single-axis tracking is the best scenario for glare mitigation and energy generation.
- In Scenario 4, 120 configurations of tilt and orientation angle adhered to FAA's glare policy. However, the tilt angle of 20° and the orientation angle of 120° is desirable because this configuration is expected to generate 95.2% of the theoretical maximum energy output for a solar PV system.
- The yellow glare duration on ATC was reduced in the descending order of Scenario 1 (7,922min), Scenario 2 (7191 min), and Scenario 3 (7080 min). It can be attributed to the reduction in reflectivity from the PV module surface. However, these mitigation measures (AR coating and surface texturing) were insufficient to adhere to FAA's glare policy.
- The variation of tilt or orientation angle (Scenario 4) provides vast possibilities of glare mitigation compared to remedial measures such as glass texturing and AR coating in PV modules (Scenario 1, Scenario 2 and Scenario 3).
- The limitation of this study was that only silicon-based PV technology could be considered for glare assessment of the selected site in the airport. The future work includes a detailed analysis of the economic implication of the different scenarios considered in this work. Based on this, the implementation potential of solar PV can also be estimated.
- The findings of this study can be a valuable reference to airport operators and solar developers who are concerned about glare impact from a proposed solar PV project. If a significant amount of glare is predicted by the software, suitable mitigation measures can be adopted, as evident in the present study.

Data availability

The data in this research study cannot be shared publicly due to the presence of sensitive information.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in the submitted manuscript. The opinion, facts, insights and discussions in manuscript are solely of the authors and do not necessarily reflect the opinion of the any organization involved directly or indirectly. The assumptions and case studies reported within this article are based on limited open-source information. Hence these informations are to be considered as an example. The authors are not responsible for any consequences thereof with the use of information presented in this work.

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