Assessment of Damage and Design Modification of Solar Plant Affected by Cyclone Amphan: A Case Study in Jadavpur University, Kolkata

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CERTIFICATE FOR RECOMMENDATION

This is to certify that the thesis Entitled **Assessment of Damage and Design Modification of Solar Plant Affected by Cyclone Amphan: A Case Study in Jadavpur University, Kolkata,** which is being submitted by Saikat Halder in partial fulfillment of the requirements for the award of degree of Master of Technology at the School of Energy Studies and Application, Jadavpur University, Kolkata 700032, during the academic year 2022-2024, is the record of the student's own work carried out by him under our supervision.

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CERTIFICATE FOR APPROVAL

The foregoing thesis entitled **Assessment of Damage and Design Modification of Solar Plant Affected by Cyclone Amphan: A Case Study in Jadavpur University, Kolkata,** is hereby approved as a creditable study of an Engineering subject carried out and presented in a satisfactory manner to warrant its acceptance as a prerequisite for the degree of **Master of Energy Studies** at the School of Energy Studies and Application, Jadavpur University, Kolkata 700032, for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed, or conclusion drawn there in but approve the thesis only for the purpose for which it is submitted.

COMMITTEE ON FINAL EXAMINATION

FOR EVALUATION OF THESIS

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DELARATION OF ORIGINALITY & COMPLIANCE OF ACADEMIC ETHICS

It is hereby declared that the thesis entitled **Assessment of Damage and Design Modification of Solar Plant Affected by Cyclone Amphan: A Case Study in Jadavpur University, Kolkata,** contains literature survey and original research work by the undersigned candidate, as part of his degree of **Master of Energy Studies** at the School of Energy Studies and Application, Jadavpur University, Kolkata 700032.

All the information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

It is also declared that all materials and results, not original to this work have been fully cited and referred throughout this thesis, according to rules of ethical conduct.

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Dedicated

to

My

Parents

and

Teachers

ABSTRACT

This thesis examines the damage inflicted on the solar power plant at Jadavpur University, Kolkata, by Cyclone Amphan, which struck in May 2020, and proposes a series of design modifications aimed at enhancing the plant's resilience against future cyclonic events. Cyclone Amphan was one of the most powerful storms to hit the Bay of Bengal in over two decades, causing extensive destruction across West Bengal, including significant impacts on renewable energy infrastructures. The solar plant at Jadavpur University, a crucial component of the university's commitment to sustainable energy, experienced notable damage, highlighting the need for a detailed assessment and subsequent fortification against such extreme weather events.

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Chapter 1

Introduction

1.1 Background and Context:

Renewable energy, particularly solar power, has become a pivotal element in the global effort to achieve sustainable development and mitigate the impacts of climate change. India, endowed with abundant solar resources, has been at the forefront of this movement, rapidly expanding its solar power capacity. The solar power plant at Jadavpur University, Kolkata, is part of this national initiative to harness renewable energy and reduce dependence on fossil fuels.

In May 2020, Cyclone Amphan, one of the most powerful storms to strike the Bay of Bengal in over two decades, made landfall in West Bengal. The cyclone caused widespread destruction, affecting millions of people and severely damaging infrastructure across Kolkata. Among the affected structures was the solar power plant at Jadavpur University, which sustained significant damage, disrupting its operations and highlighting vulnerabilities in its design and construction.

1.2 Objectives of the Study:

This thesis aims to provide a comprehensive assessment of the damage caused to the solar plant by Cyclone Amphan and to develop design modifications to enhance its resilience against future cyclonic events. The specific objectives of the study are:

- To assess the extent and nature of the damage sustained by the solar plant at Jadavpur University due to Cyclone Amphan.
- To identify the primary factors that contributed to the plant's vulnerability to the cyclone.
- To propose design modifications that can improve the plant's structural and operational resilience to similar extreme weather events in the future.

1.3 Significance of Study:

- **Resilience of Renewable Energy Infrastructure**: The findings will contribute to the broader understanding of how renewable energy infrastructures, particularly solar plants, can be made more resilient to extreme weather events, which are becoming increasingly frequent and severe due to climate change.
- **Policy Implications**: The recommendations derived from this study can inform policymakers and planners in the renewable energy sector, leading to the development of more robust standards and guidelines for the design and construction of solar plants in cyclone-prone regions.
- **Academic Contribution**: The thesis adds to the academic literature on disaster resilience and renewable energy, providing a detailed case study that can be used as a reference for future research.
- **Practical Solutions**: By proposing actionable design modifications and testing their effectiveness, the study offers practical solutions that can be implemented not only at Jadavpur University but also at other similar installations across the region and beyond.

1.4 Structure of the Thesis:

The thesis is structured as follows:

- **Chapter 2: Literature Review**: This chapter reviews existing literature on solar power generation, the impact of cyclones on infrastructure, and case studies of cyclone-resilient solar plants.
- **Chapter 3: Methodology**: This chapter outlines the methods used for damage assessment, data collection, and the development of design modifications.

- **Chapter 4: Damage Assessment**: This chapter presents the findings from the damage assessment, detailing the extent and nature of the damage and identifying factors contributing to the plant's vulnerability.
- **Chapter 5: Design Modifications**: This chapter proposes specific design modifications to enhance the resilience of the solar plant and discusses the rationale behind these recommendations.
- **Chapter 6: Discussion:** This section discusses the implications of these findings, the challenges faced, and the broader impact on the university's energy strategy and sustainability goals.
- **Chapter 7: Conclusion and Recommendations**: This chapter summarizes the key findings, offers recommendations for future work, and reflects on the broader implications of the study for sustainable energy development.
- **Finally, Chapter 8** lists the references cited throughout the thesis.

By following this structure, the thesis aims to provide a thorough and systematic analysis of the damage caused by Cyclone Amphan to the solar plant at Jadavpur University and to offer practical solutions for enhancing the resilience of similar installations in the future.

Chapter 2

Literature Review

2.1 Literature Review

Advanced modeling and simulation techniques play a crucial role in assessing and redesigning the resilience of infrastructure to cyclonic events. Chowdhury et al. (2018) utilized finite element analysis (FEA) simulations to evaluate the structural performance of buildings and bridges under cyclonic wind loads, identifying critical failure modes and opportunities for improvement. Dhonde et al. (2019) explored the use of fiber-reinforced composites and aerodynamic design principles to enhance the resilience of infrastructure, demonstrating the potential benefits of innovative materials and structural configurations. These methods offer valuable tools for engineers and designers to optimize the performance of infrastructure in cyclone-prone regions.

The nature of the load induced on a structure by the wind depends, largely on the characteristics of the wind such as its direction, speed, exposure conditions and the shape of the structure. Ground mounted PV modules, which are the subject of this study, are typically low-rise structures. They are therefore immersed within the lowest region of the atmospheric boundary layer (ABL) where the flow of the wind is highly unpredictable due to the intense turbulence actions [13]. The mean velocity profile of the wind in this region is largely influenced by the ground roughness. Although in nature, for any particular terrain,

roughness cannot be accurately determined owing to variations in the size, shape, distribution and density of the roughness elements (trees, grasses, buildings, etc.) [14]. In wind experiments, a power law is commonly used to characterize the mean wind velocity profile and turbulence characteristics [15]. The exponent of the power law is dependent on the terrain (roughness) and provided in various codes such as the National Building Code of Canada (NBCC) [16] and its American counterpart from the ASCE [17].

By reviewing the literature on cyclone characteristics, vulnerabilities of solar mounting structures, previous studies on infrastructure resilience, and methods for assessing and redesigning structural resilience, this review provides a comprehensive understanding of the challenges and opportunities for enhancing the resilience of infrastructure in cyclone-prone regions. These insights inform the subsequent chapters of the thesis, guiding the assessment and redesign of solar mounting structures affected by Cyclone Amphan in Kolkata.

The wind loads on various types of solar modules had been measured in the wind tunnels and reported in the literature. Early examples include the wind load experimental tests on arrays of flat plate PV panels, commissioned for testing by the US Department of Energy [18]. The results of the test show that upstream flow sheltering elements such as barriers and fences can be used to reduce the wind loads on PV arrays while end plates were found most suitable in reducing the large load measured on the panels at the corners of the array. Radu et al. [19] tested an array of solar panel models, mounted on the roof of a scaled five storeybuilding model in a boundary layer wind tunnel. Their tests were performed on three different building models with flat roof. Each building had different kind of attics. The results showed that the front row panels had higher pressure and force coefficients. These front row panels shelter the panels behind them from the wind action. In subsequent studies, the lift forces on the support structures of these panels were also investigated [20]. They concluded that using appropriate building attics could reduce wind loads on PV modules installed on building rooftops. Wood et al. [21] also tested PV modules mounted on the flat rooftops of a scaled building model in a wind tunnel. The pressure on the scaled building roof was simultaneously measured which agreed well with the full-scale results of the Texas Tech experimental building. In the test, they varied both the clearance height between the rooftop and the panel and the lateral spacing between the panels. Except at the leading edge where slight variation was recorded, their results showed no significant changes in the overall pressure on the modules from the variation of the clearance height and panel spacing.

An array of six parallel slender solar modules were tested by Kopp et al. [22] in the wind tunnel at a Reynolds number of 7.6 x 104 and wind speed of 15m/s. They determined the location of the highest system torque on the modules as well as the critical loading angle of the approach wind. A linearized model to predict the peak system torque of these modules was subsequently presented. Full-scale outdoor experiments were carried out on roofmounted PV modules by Geurts et al. [23] to investigate lift forces on the panels. The PV modules were mounted parallel to a pitched roof. The wind speed and wind direction were measured using a cup anemometer and directional vane position at a height of 10m above the ground. The pressure difference at the top and underside of the panel were measured to determine the wind load. The maximum lift force on the solar panel, which is dependent on wind direction, corresponded with a pressure coefficient,value Cp of -0.55. A differential pressure coefficient, ΔCp value of -0.3 for the upward and 0.2 for the downward acting force was recommended for a single solar panel on such rooftops.

Shademan [27] carried out wind load investigations on standalone and array PV modules using CFD. Six configurations of the standalone solar panel were tested. Their results were validated with the experimental results of a flat plate [29]. The results showed that as the inclination angle of the standalone panel increased, the drag force induced by wind load also increased. The tests were conducted at three wind angles of 30o, 60o and 90o. In all of the cases, maximum drag was produced at wind angle of 90o and on the panels at the bottom row of a standalone system. Panels at the front row of arrays shelter other panels from the wind, therefore reducing the drag force experienced by the sheltered panels. However, Shademan [27] identified the critical spacing between the panels, beyond which the drag force reduction on the downstream panels was not significant. Meroney [12] used different turbulence models to simulate the flow around PV modules. The study estimated the drag, lift and overturning moments on the solar panel support systems. Static pressure results on the panels at 0o and 180owind angles showed higher pressures at the front rows of panels, consistent with the experimental observations of Radu et al. [19] and Shademan [27]. Wu et al. [30] investigated the effect of the gaps between panels on the surface of a heliostat was investigated through CFD and experimental tests. Heliostats have similar geometrical configurations as PV panels. A 1⁄10 scaled model of the heliostat was used for the wind tunnel experiments, similar to the length scale of this current study. The computational model of the CFD test was greatly simplified due to the huge cost of modeling the flow near the gap. Both the experimental and numerical results showed that the overall wind load slightly increased with an increase in the gap size. The CFD results showed that this increase was due to the flow acceleration through the gap, which caused a decrease in the static pressure at the gap's outlet. Therefore the overall drag force increased due to the resultant decrease in the leeward pressure coefficient. This present study was experimentally conducted in a boundary layer wind tunnel. The aim is measure the wind load on the PV module, and to determine the effect of varying parameters such as wind exposure and inclination. A comparison between the load on the model and its flat plate equivalent (without the gaps between individual panels) will also be presented.

Chih-Kuang Lin et al. [39] used FEA approach to find the effects of self-weight and wind loads on structural deformation and misalignment of solar radiation. They contemplate distribution of stress and deformation with wind speed seven and twelve with varied processing directions as well as gravity. The result shows that this CAE technique is applicable for coming up with a reliable and economical trailing electrical phenomenon system. Highly stressed regions are settled at bushing and needle bearing von-mises criterion there's no structural failure for given electrical phenomenon system. AlyMousaadAly et al. [40] built testing models of large civil engineering structures at geometric scale 1:500 to 1:100. They were manufacturing Associate in Nursing mechanics model of solar battery subjected to wind load and mounted on ground. Testing can be carried out experimentally (in boundary layer wind tunnel) and numerically (by computational fluid dynamics) at different geometric scale. The result shows that for very small size solar panels are having different mean loads as they are located very close to ground. Alex Mathew et. al. [41] Worked on style and stability analysis of solar battery support structure created out from soft-cast steel. They conducted this work as a vicinity of project of Mahindra Reva Ltd. Named as "solar 2 car". The result shows that the solar panel support structure can able to sustain a wind load with velocity 55 km/hr. They calculated required amount of weight to withstand wind load for different wind zones without any holding arrangements and then after optimization can be done for easy assembly, dismantle and transportation Georgeta Vasies et al. [42] given Numerical simulations for analysis of wind action on star panels settled on flat roofs with and while not parapets. Numerical simulations are performed in ANSYS CFX, for an incidence wind angle of 45°.they are watching that Oblique direction of wind generating high intensity of uplift forces in the corner areas of the flat roof, forces which bring an additional load on support systems of solar panels. Presence of the parapet facilitate mitigate the wind hundreds, and average pressure is up to 18.6% lower that for solar panels placed on flat roof without parapet.

Girma T. Bitsuamlaka et al. [43] presented the aerodynamic features of ground-mounted solar panels under atmospheric boundary layer. They did four different test cases to determine the wind effects on stand –alone ground mounted solar panels differing from one another by wind angle of attack and number of panels. They verified that there is reduction in wind loads on the adjacent solar panel when they are arranged in tandem. After that they were conclude that „the solar panels experienced the highest overall wind loads for wind angle of attac k.

Chapter 3

Methodology and Calculation

3.1 Site Description

3.1.1 Overview of the Solar Plant

The solar power plant at Jadavpur University, Kolkata, is an on-campus installation designed to contribute to the university's energy needs and promote sustainable practices. The plant comprises:

- **Photovoltaic Panels**: A no of series and parallel combination of polycrystalline panels totaling a capacity of 50 kW.
- **Mounting Structures**: Fixed-tilt ($\theta = 11.3^{o}$) mounting systems designed to optimize sunlight capture.
- **Site Layout**: The panels are distributed across rooftop of building.

3.2 Damage Assessment Procedure

3.2.1 Initial Inspection and Data Collection

The damage assessment began with a detailed site inspection following Cyclone Amphan. The procedure included:

- **Visual Inspection**: Identifying visible damage to panels, mounting structures, and electrical components.
- **Photographic Documentation**: Capturing images of damaged areas for detailed analysis.

Fig. 3.1: Damaged areas of the Solar Plant.

- **Data Collection**: Evaluating the integrity of mounting structures and their ability to withstand the wind loads experienced during the cyclone.

Panel Dimensions:

Table. 3.1: Panel Dimensions

Panel Type	**SS250P**
Length of each panel	**164 cm**
Width of each panel	**100 cm**
Tilt angle (θ)	**11.3^0**
Rows parallel to slope	**2**
Rows in other direction	**5**
Weight of each panel	**17.8 kg**

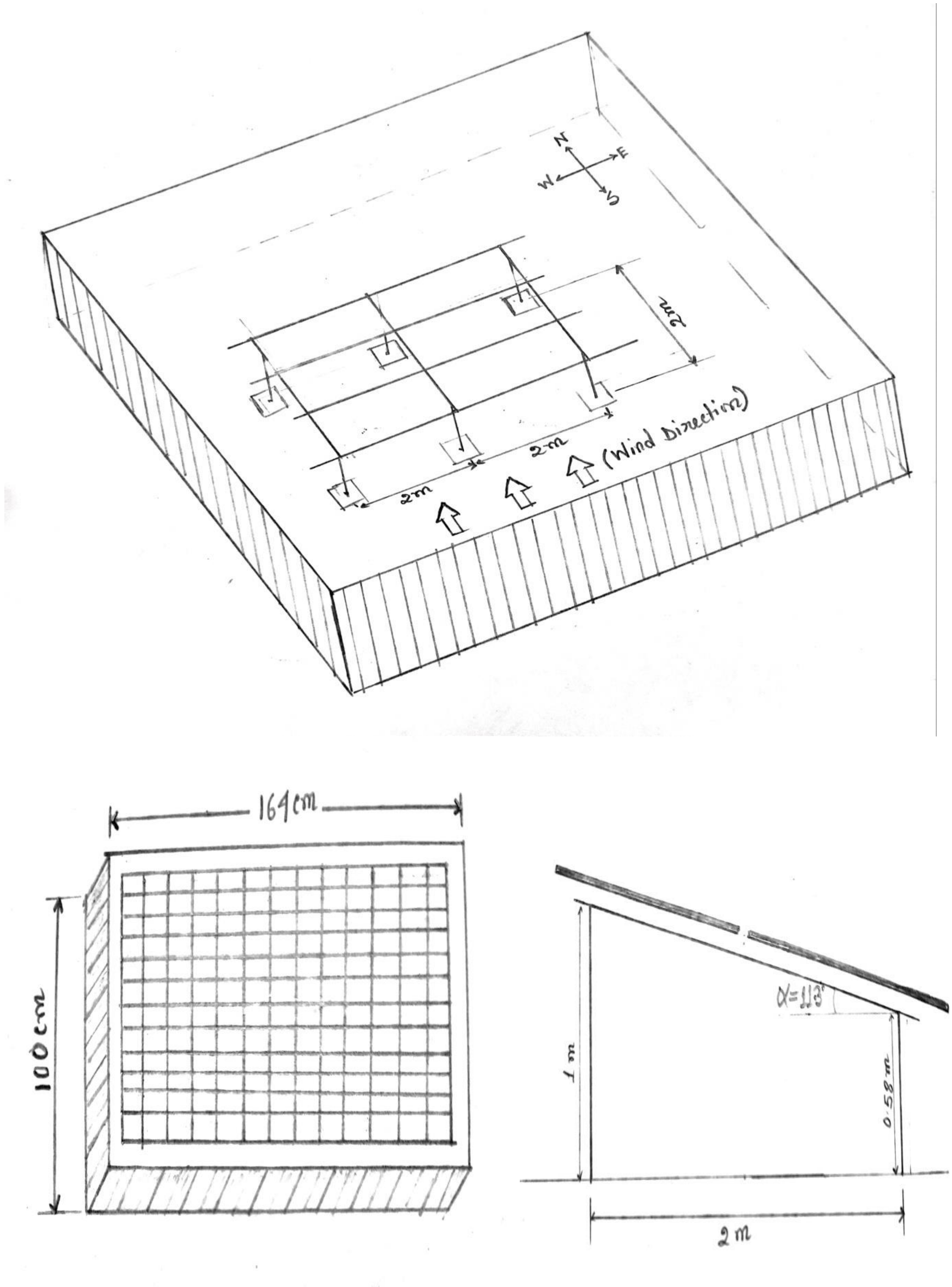

Fig. 3.2: Drawings of Panels & Mountings

3.2.2 Assessment Criteria Based on ASCE 7-10

The design wind force for open buildings and other structures shall be determined by the following formula:

$$F = q_z G C_N A_P \text{ ……………………… (3.1)}$$

Where:

q_z= Velocity pressure evaluated at height z of the centroid of area A_f;

G = gust effect factor

C_N = Net pressure coefficient

A_P= Projected area normal to the wind except where $C_N$is specified for the actual surface area, (m^2)

q_z = velocity pressure, in psf, given by the formula:

q_z =0.00256K_z K_{zt} K_d V^2 (lb/ft2) ……………………… (3.2)

In SI the given formula will be :

q_z =0.613K_z K_{zt} K_d V^2 (N/m2) ………………………… (3.3)

Where,

K_z = velocity pressure coefficient

K_{zt} = topographic factor

K_d = wind directionality factor

V = basic wind speed in kph

We will dive deep into the details of each parameter below. Moreover, we will be using the Directional Procedure (Chapter 30 of ASCE 7-10) in solving the design wind pressures.

Parameter explanations

Risk Category

The first thing to do in determining the design wind pressures is to classify the risk category of the structure which is based on the use or occupancy of the structure.

Basic Wind Speed, V

The basic wind speed at Jadavpur University during Cyclone Amphan, we gather meteorological data from reliable sources such as the Indian Meteorological Department (IMD) and local weather stations, and from there, the basic wind speed, V, is 140 km/hr **[6].**

Exposure Category

In structural engineering, particularly in wind load calculations, the concept of **Exposure Category** is crucial. It defines the characteristics of the surrounding environment and terrain that influence the wind forces acting on a structure. This categorization helps engineers determine the appropriate wind load factors to ensure structural safety and integrity.

The American Society of Civil Engineers (ASCE) outlines several Exposure Categories in ASCE 7-10, "Minimum Design Loads for Buildings and Other Structures". These categories are defined based on the type of terrain and the presence of obstructions that can affect wind speeds near the ground level.

Table. 3.2: Exposure Categories and their Examples

Exposure Category	Exposure Example
Exposure B	• Suburban residential area with mostly single-family dwellings – Low-rise structures, less than 30 ft high, in the center of the photograph have sites designated as exposure b with surface roughness Category B terrain around the site for a distance greater than 1500 ft in any wind direction. • An urban area with numerous closely spaced obstructions having the size of single-family dwellings or larger – For all structures shown, terrain representative of surface roughness category b extends more than twenty times the height of the structure or 2600 ft, whichever is greater, in the upwind direction. Structures in the foreground are located in exposure B – Structures in the center top of the photograph adjacent to the clearing to the left, which is greater than approximately 656 ft in length, are located in exposure c when the wind comes from the left over the clearing.
Exposure C	• Flat open grassland with scattered obstructions having heights generally less than 30 ft. • Open terrain with scattered obstructions having heights generally less than 30 ft for most wind directions, all 1-story structures with a mean roof height less than 30 ft in the photograph are less than 1500 ft or ten times the height of the structure, whichever is greater, from an open field that prevents the use of exposure B.
Exposure D	• A building at the shoreline (excluding shorelines in hurricane-prone regions) with wind flowing over open water for a distance of at least 1 mile. Shorelines in exposure D include inland waterways, the great lakes, and coastal areas of California, Oregon, Washington, and Alaska.

Based on the urban setting and the presence of multiple buildings and trees, Jadavpur University would most likely fall under **Exposure Category B**.

Wind Directionality Factor, K_d

The wind directionality factors, $\boldsymbol{K_d}$, for our structure are both equal to 0.85 since the building is the main wind force resisting system and also has components and cladding attached to the structure.

Table. 3.3: Wind directionality factor based on structure type.

Structure Type	Directionality Factor, K_d
Buildings	
Main wind force resistance system	0.85
Components and cladding	0.85
Arched Roofs	0.85
Chimney, Tanks, and similar structures	
Square	0.90
Hexagonal	0.95
Round	0.95
Solid Freestanding Walls and Solid Freestanding and Attached Signs	0.85
Open Signs and Lattice Framework	0.85
Trussed Towers	
Triangular, Square, Rectangular	0.85
All other cross sections	0.85

Topographic Factor, K_{zt}

The Topographic Factor (K_{zt}) is used in wind load calculations to account for the effects of topography, such as hills, ridges, and escarpments, which can amplify wind speeds at certain locations. This factor is determined based on the height above the base of the topographic feature, the horizontal distance from the crest of the topographic feature, and the characteristic height of the topographic feature. If your site does not meet all of the conditions listed, then the topographic factor can be taken as 1.0.

Jadavpur University is located in Kolkata, which is largely a flat region with no significant topographic features like hills or escarpments. So the value of K_{zt} is taken as 1.0.

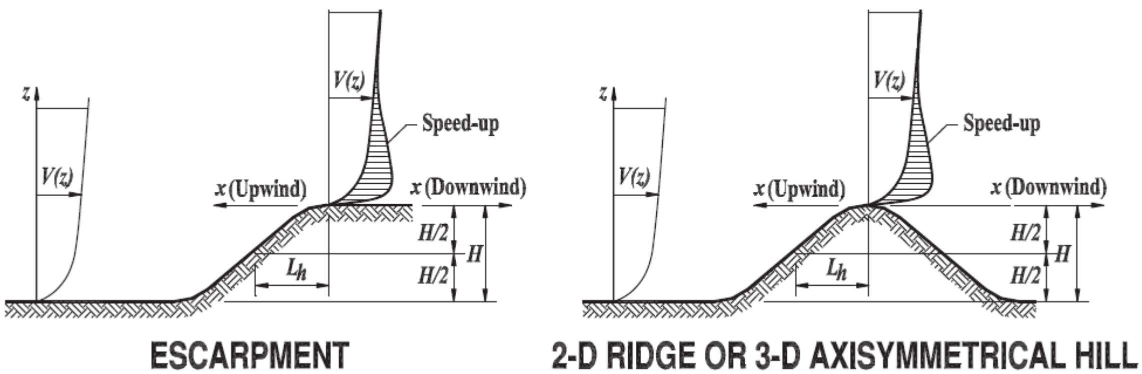

Fig. 3.3: Parameters needed in calculation topographic factor, K_{zt}

Velocity Pressure Coefficient, K_z

The velocity pressure coefficient, K_z, can be calculated using Table 3.4. This parameter depends on the height above ground level of the point where the wind pressure is considered, and the exposure category. Moreover, the values shown in the table is based on the following formula:

For 15ft < z < zg : Kz=$2.01(z/z_g)2/\alpha$ ……………………… (3.4)

For z < 15ft: K_z=$2.01(15/z_g)2/\alpha$ ……………………… (3.5)

Table. 3.4: Values of and z_g according to the Exposure Category.

Exposure	α	z_g(ft)
B	7.5	1200
C	9.5	900
D	11.5	700

Usually, velocity pressure coefficients at the mean roof height and at each floor level are the values we would need in order to solve for the design wind pressures. For this example, since the wind pressure on the windward side is parabolic in nature, we can simplify this load by assuming that uniform pressure is applied on walls between floor levels.

The plant structure has four (4) floors, so we will divide the windward pressure into these levels. Moreover, since the roof is a gable-style roof, the roof mean height can be taken as the average of roof eaves and apex elevation, which is 60 ft.

For exposure category B,

α= 7, zg=1200 ft

so, K_z = 2.01*(60/1200)^(2/7)=0.854

Net Pressure Coefficient, C_N

The net pressure coefficient is a critical parameter in structural engineering, particularly in the design of buildings and structures subjected to wind loads. This concept is crucial for ensuring that structures can withstand wind forces, including those from extreme weather events like cyclones.

Due to wind the system will face two kinds of loading. The lower half will face Windward force and the lower half will face Leeward force.

Also we will take two load cases, load case- A & load case-B

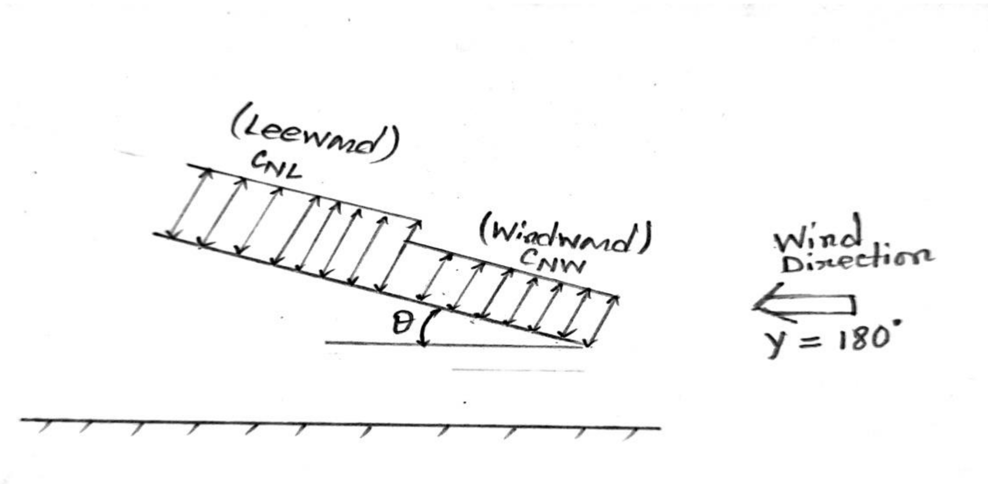

Fig. 3.4: Windward & Leeward Loading Zones

The values of Net Pressure Coefficient along with the tilt angle is shown below. The net pressure coefficient values for Windward and Leeward forces are given as C_{NW} and C_{NL} respectively.

Net Pressure Coefficient, C_N

		Wind Direction, $\gamma = 0°$				Wind Direction, $\gamma = 180°$			
		Clear Wind Flow		Obstructed Wind Flow		Clear Wind Flow		Obstructed Wind Flow	
Roof Angle, θ	Load Case	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}
0°	A	1.2	0.3	−0.5	−1.2	1.2	0.3	−0.5	−1.2
	B	−1.1	−0.1	−1.1	−0.6	−1.1	−0.1	−1.1	−0.6
7.5°	A	−0.6	−1.0	−1.0	−1.5	0.9	1.5	−0.2	−1.2
	B	−1.4	0.0	−1.7	−0.8	1.6	0.3	0.8	−0.3
15°	A	−0.9	−1.3	−1.1	−1.5	1.3	1.6	0.4	−1.1
	B	−1.9	0.0	−2.1	−0.6	1.8	0.6	1.2	−0.3
22.5°	A	−1.5	−1.6	−1.5	−1.7	1.7	1.8	0.5	−1.0
	B	−2.4	−0.3	−2.3	−0.9	2.2	0.7	1.3	0.0
30°	A	−1.8	−1.8	−1.5	−1.8	2.1	2.1	0.6	−1.0
	B	−2.5	−0.5	−2.3	−1.1	2.6	1.0	1.6	0.1
37.5°	A	−1.8	−1.8	−1.5	−1.8	2.1	2.2	0.7	−0.9
	B	−2.4	−0.6	−2.2	−1.1	2.7	1.1	1.9	0.3
45°	A	−1.6	−1.8	−1.3	−1.8	2.2	2.5	0.8	−0.9
	B	−2.3	−0.7	−1.9	−1.2	2.6	1.4	2.1	0.4

Fig. 3.5: Net Pressure Coefficient Values along with tilt angle

In our case,

Tilt angle (θ) = 11.3°

Wind Direction = From Southwards i.e. ***γ*** = 180°

Flow Obstruction = Clear Wind Flow

So, using Interpolation between θ = 7.5° & θ = 15° we get,

Table. 3.5: Net Pressure Coefficient values at tilt angle 11.3°

Tilt Angle (θ)	Load Case	C_{Nw}	C_{Nl}
7.5°	A	0.9	1.5
	B	1.6	0.3
15°	A	1.3	1.6
	B	1.8	0.6
11.3°	A	1.1026	1.5506
	B	1.7013	0.4520

3.2.3 Wind Load Calculation

Given data,

Table. 3.6: Given Data for calculating Wind Load

Basic Wind Speed **(V)**	140 kph or 38.89 m/s
Length of Each Panel	164 cm
Width of Each Panel	100 cm
Tilt angle (θ)	11.3°
Rows parallel to slope	2
Rows in other direction	5
Length parallel to slope (L)	3.28 m
Length in other direction (W)	5 m
Velocity pressure coefficient (K_z)	0.854
Topographic factor **(K_{zt})**	1
Wind directionality factor **(K_d)**	0.85
Guest effect factor **(G)**	0.85

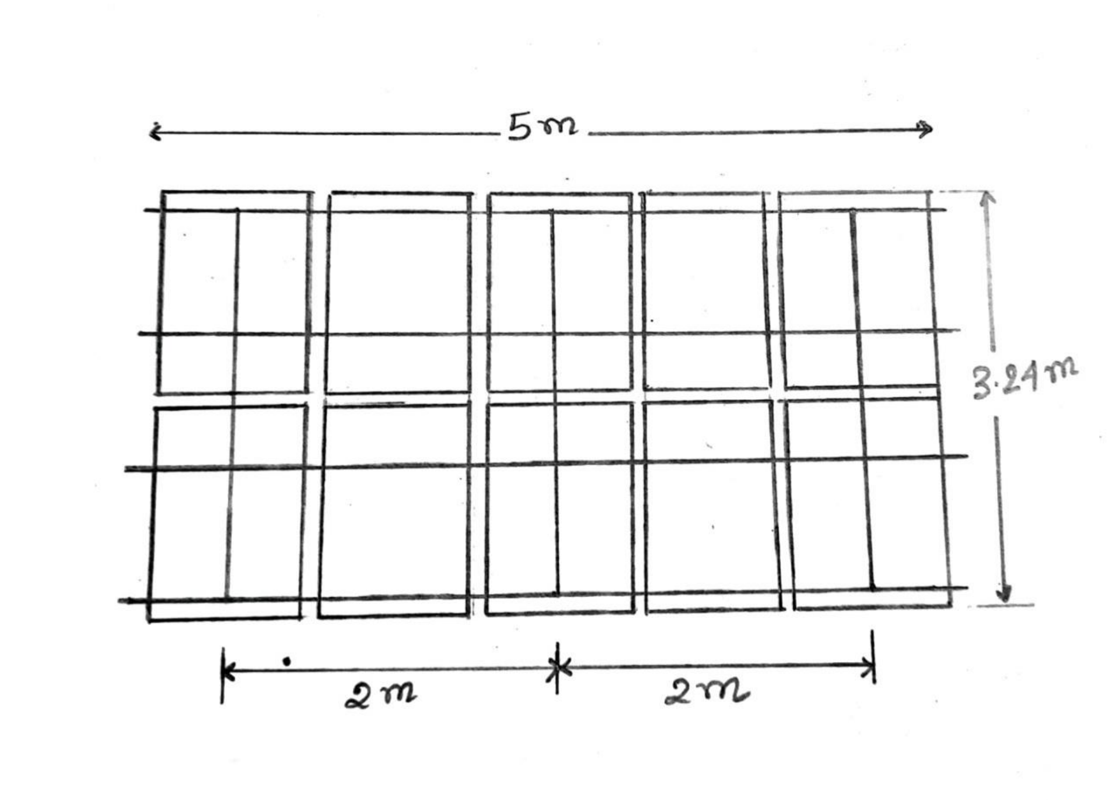

Fig. 3.6: Drawing & Dimension of the Solar Array

From Equation **(3.3)**, Velocity pressure evaluated at height z is given as,

$$q_z = 0.613 K_z\ K_{zt}\ K_d\ V^2$$

$$\text{Or, } q_z = 0.613 \times 0.854 \times 1 \times 0.85 \times (38.89)^2\ N/m^2$$

$$\text{Or, } q_z = 673\ N/m^2$$

Now, from Equation (3.1) the design wind force on the solar system is given as:

$$F = q_z G C_N A_P$$

Where, A_P = Projected area normal to the wind

For both Windward & Leeward Loading region the values of A_P will be same due to symmetry and it will be-

A_{Pw} **= A_{Pl} = 0.5 L × W = 0.5 × 3.28 × 5 m^2 = 8.2 m^2**

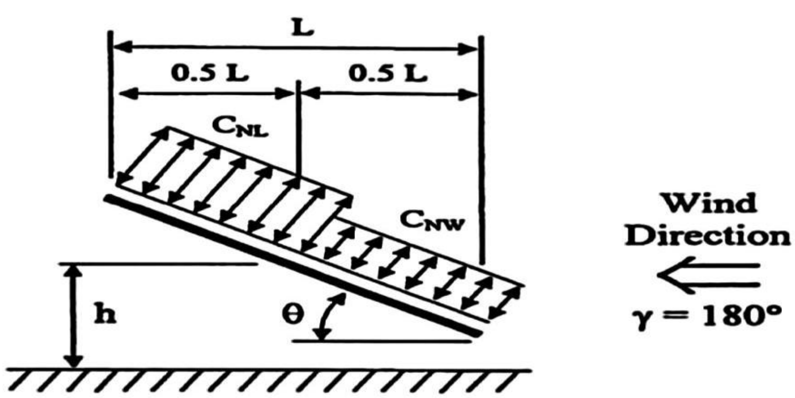

Fig. 3.7: Figure to calculate projected area normal to the wind

<u>Wind Load on the Solar System Mounted at Tilt Angle 11.3°</u>

<u>Load Case-A</u>

$$F_{Aw} = q_z G C_{Nw} A_{Pw}$$

= 673 × 0.85 × 1.1026 × 8.2 N

= 5172 N = 5.172 KN (Windward)

And, $F_{Al} = q_z G C_{Nl} A_{Pl}$

= 673 × 0.85 × 1.5506 × 8.2 N

= 7273.57 N = 7.274 KN (Leeward)

Load Case-B

$$F_{Bw} = q_z G C_{Nw} A_{Pw}$$

= 673 × 0.85 × 1.7013× 8.2 N

= 7980 N = 7.98 KN (Windward)

And, $F_{Bl} = q_z G C_{Nl} A_{Pl}$

= 673 × 0.85 × 0.4520 × 8.2 N

= 2120 N = 2.12 KN (Leeward)

Table. 3.7: Wind Load on the Solar System Mounted at Tilt Angle 11.3^o

Load Case	Wind Load (KN)	
	Windward	Leeward
A	5.172	7.274
B	7.98	2.12

Now, the optimal tilt angle for solar panels depends on the geographical location to maximize solar energy capture throughout the year. For Kolkata, which is located at approximately 22.5°N latitude, the standard tilt angle of solar system should be 22.5°, but it was actually mounted at 11.5°. So we need to calculate the same load at tilt angle 22.5° also to compare between them.

Wind Load on the Solar System Mounted at Tilt Angle 22.5°

Before calculating the wind load at tilt angle 22.5°, we need to find the net pressure coefficient value accordingly.

Table. 3.8: Net pressure coefficient values at tilt angle 22.5°

Tilt Angle (θ)	Load Case	C_{Nw}	C_{Nl}
22.5°	A	1.7	1.8
	B	2.2	0.7

Now, the wind load Wind Load on the Solar System Mounted at Tilt Angle 22.5° can be calculated as,

Load Case-A

$$F_{Aw} = q_z G C_{Nw} A_{Pw}$$
$$= 673 \times 0.85 \times 1.7 \times 8.2 \text{ N}$$
$$= 7975 \text{ N} = 7.975 \text{ KN (Windward)}$$

And, $$F_{Al} = q_z G C_{Nl} A_{Pl}$$
$$= 673 \times 0.85 \times 1.8 \times 8.2 \text{ N}$$
$$= 8444 \text{ N} = 8.444 \text{ KN (Leeward)}$$

Load Case-B

$$F_{Bw} = q_z G C_{Nw} A_{Pw}$$
$$= 673 \times 0.85 \times 2.2 \times 8.2 \text{ N}$$
$$= 10320 \text{ N} = 10.32 \text{ KN (Windward)}$$

And, $$F_{Bl} = q_z G C_{Nl} A_{Pl}$$
$$= 673 \times 0.85 \times 0.7 \times 8.2 \text{ N}$$
$$= 3284 \text{ N} = 3.284 \text{ KN (Leeward)}$$

Table. 3.9: Wind Load on the Solar System Mounted at Tilt Angle 22.5^o

Load Case	Wind Load (KN)	
	Windward	Leeward
A	7.975	8.444
B	10.32	3.284

From the above two load calculations, we can clearly compare that the maximum wind load will be generated on the solar panels when the panels would be mounted at a tilt angle of 22.5°.

Chapter 4

Damage Assessment

4.1 Overview

Cyclone Amphan, which struck Kolkata and its surroundings in May 2020, caused significant damage to the solar plant at Jadavpur University. This section details the extent of damage, focusing specifically on the failure of solar panels, while noting that the mounting structures largely remained intact. The analysis provides insights into the specific types of damage sustained by the panels, the potential causes, and the implications for the solar plant's operation and future resilience.

4.2 Extent of Damage

4.2.2 Damage to Solar Panels

The high wind speeds and flying debris during Cyclone Amphan resulted in significant physical damage to the solar panels. Observations included:

- **Broken and Shattered Panels**: A substantial number of solar panels were found broken or shattered due to the high wind speeds and flying debris. The intense force of the cyclone, combined with the impact from debris, resulted in cracked glass surfaces and damaged photovoltaic cells.
- **Dislodged Panels**: Despite the mounting structures remaining largely intact, many panels were dislodged from their mounts. The force of the wind was sufficient to overcome the securing mechanisms, causing the panels to become detached and in some cases, completely blown away.

4.2.2 Damage to Mounting Structures

The mounting structures, which were designed to hold the solar panels in place, were subjected to huge amount of stresses but no significant failures were observed in the mounting structures. A few structures exhibited noticeable bending despite the connection points and joints remaining intact.

4.2.3 Electrical and Functional Damage

- **Disconnected Electrical Connections**: The dislodgement and movement of the panels caused many electrical connections to become loose or disconnected. This disrupted the power generation circuit and led to significant operational downtime.
- **Microcracks in Cells**: Some panels, although not visibly shattered, developed microcracks in the photovoltaic cells. These microcracks can severely affect the efficiency of the panels and lead to long-term degradation of performance.

4.2.4 Causes of Panel Failure

4.2.4.1 Wind Forces

- **High Wind Speeds**: Cyclone Amphan brought wind speeds exceeding 150 km/h. These winds exerted enormous pressure on the panels, which were not designed to withstand such extreme forces. The pressure caused the panels to flex, leading to cracks and eventual breakage.
- **Aerodynamic Lift**: The aerodynamic forces acting on the flat surfaces of the panels generated lift, which contributed to the dislodgement of the panels from their mounts.

4.2.4.2 Impact from Debris

- **Flying Debris**: The cyclone caused extensive damage to the surrounding environment, generating flying debris such as tree branches, roof tiles, and other materials. These high-velocity projectiles struck the panels, causing immediate and severe physical damage.
- **Secondary Impacts**: Even after the initial strike, debris continued to impact the panels, exacerbating the extent of the damage.

4.2.4.3 Design and Installation Flaws

- **Insufficient Securing Mechanisms**: Although the mounting structures were strong, the mechanisms securing the panels to these mounts were inadequate for such extreme conditions. The securing bolts and clamps were not designed to handle the dynamic loads imposed by cyclonic winds.

- **Material Vulnerability**: The glass used in the panels, while designed for standard weather conditions, proved insufficient against the extreme impacts of debris. The material's brittleness under high-stress conditions led to widespread breakage.

4.2.5 Implications of Panel Damage

4.2.5.1 Operational Downtime

- **Immediate Power Loss**: The damage led to a near-total cessation of energy production during and immediately after the cyclone. The disconnected panels and broken cells meant that the solar plant could not generate electricity, impacting the university's power supply.
- **Prolonged Repair Time**: The extent of the damage required extensive repairs and replacements, leading to prolonged downtime. Sourcing new panels, re-installing them, and ensuring proper electrical connections took several weeks, if not months.

4.2.5.2 Financial Impact

- **Replacement Costs**: The financial cost of replacing the damaged panels was significant. This included the cost of new panels, labor for removal and installation, and any additional structural adjustments required.
- **Loss of Revenue**: The interruption in power generation resulted in a loss of potential revenue from the solar plant, especially critical if the plant was supplying power to the grid or reducing the university's electricity expenses.

4.2.5.3 Future Resilience Concerns

- **Vulnerability Awareness**: The damage highlighted the vulnerability of the solar panels to extreme weather events, underscoring the need for more resilient design and materials.
- **Design Modification Needs**: The findings necessitated a review and modification of the solar panel securing mechanisms and the selection of materials to better withstand such events in the future.

4.3 Conclusion

The extent of damage to the solar panels at Jadavpur University's solar plant due to Cyclone Amphan was substantial, despite the mounting structures remaining intact. The failure of the panels was primarily due to high wind speeds, aerodynamic lift, and impact from debris, exacerbated by design and material inadequacies. This underscores the importance of enhancing the resilience of solar panels through improved securing mechanisms, use of more durable materials, and better aerodynamic designs to mitigate future risks. The lessons learned from this damage assessment are critical for guiding future modifications and ensuring the long-term viability of solar energy projects in cyclone-prone regions.

Chapter 5

Design Modifications

5.1 Overview

This chapter outlines the strategic design modifications proposed to enhance the resilience of the solar plant at Jadavpur University, focusing on preventing future failures of the solar panels while ensuring the mounting structures' integrity remains intact. These modifications are based on the findings from the damage assessment and are intended to mitigate the risks posed by extreme weather events such as Cyclone Amphan..

5.2 Structural Design Enhancements

5.2.1 Reinforcement of Mounting Structures

5.2.1.1 Use of High-Strength Materials

One of the primary reasons for the failure of mounting structures was the use of materials that were not strong enough to withstand extreme wind loads. The following enhancements are proposed:

- **High-Strength Steel**: Replacing existing supports with high-strength, corrosion-resistant steel to provide better resistance to bending and twisting under high wind pressures.
- **Composite Materials**: Utilizing advanced composite materials that offer superior strength-to-weight ratios and corrosion resistance, thereby enhancing the structural integrity of the mounts.

5.2.1.2 Enhanced Joint and Connection Design

Improving the design of joints and connections is crucial for preventing failures at these critical points:

- **Bolted Joints with Locking Mechanisms**: Incorporating locking mechanisms in bolted joints to prevent loosening under dynamic wind loads.
- **Redundant Connections**: Adding redundant connections that can provide additional support in case primary connections fail, thereby enhancing overall structural resilience.

5.2.2 Aerodynamic Optimization

5.2.2.1 Streamlined Panel Designs

Adopting aerodynamic designs for solar panels can reduce the impact of wind loads:

- **Tilted and Curved Panels**: Designing panels with a tilt and curvature that allows wind to flow over them more smoothly, reducing the wind pressure on the panels.
- **Low-Profile Mounts**: Using low-profile mounts that minimize the exposure of the panels to direct wind, thereby reducing the risk of dislodgement.

5.2.2.2 Wind Breaks and Deflectors

Installing wind breaks and deflectors can protect the solar panels from direct wind impacts:

- **Strategic Placement**: Placing wind breaks and deflectors around the most exposed parts of the installation to reduce wind speed and turbulence near the panels.
- **Flexible Barriers**: Using flexible barriers that can absorb and dissipate wind energy, providing additional protection without significantly increasing structural loads

5.3 Material Upgrades

5.3.1 Advanced Alloys

Incorporating advanced alloys with superior corrosion resistance properties:

- **Aluminum Alloys**: Using high-strength aluminum alloys that offer excellent resistance to corrosion and are lightweight, reducing the overall structural load.
- **Stainless Steel**: Employing stainless steel for critical components to provide long-term durability and resistance to environmental degradation.

5.3.2 Durable Panel Glass

Enhancing the durability of the glass used in solar panels:

- **Tempered Glass**: Using tempered glass that is more resistant to impact and shattering, thereby reducing the risk of panel breakage from flying debris.
- **Anti-Reflective Coatings**: Applying anti-reflective coatings that not only improve light absorption but also enhance the scratch resistance and durability of the glass surface.

5.3 Conclusion

The design modifications proposed in this chapter aim to significantly enhance the resilience of the solar plant at Jadavpur University. By addressing the specific causes of panel failure during Cyclone Amphan, these modifications ensure that the solar panels are better equipped to withstand future extreme weather events. Through the use of high-strength materials, improved securing mechanisms, and comprehensive preventive measures, the solar plant can achieve greater durability, operational continuity, and long-term economic viability. These enhancements not only protect the university's investment but also contribute to the broader goal of sustainable and resilient renewable energy infrastructure.

Chapter 6

Discussion

6.1 Overview

This chapter delves into the detailed analysis of the findings from the damage assessment, focusing specifically on the failure of solar panels while the mounting structures remained intact. The discussion aims to interpret these findings, exploring the underlying causes, implications, and potential strategies for enhancing the resilience of solar energy systems against similar future events.

6.2 Analysis of Panel Failure

6.2.1 Wind Forces and Panel Vulnerability

The primary cause of panel failure was the extreme wind forces generated by Cyclone Amphan. Wind speeds exceeding 140 km/hr exerted tremendous pressure on the panels, leading to several critical failure modes:

- **Wind Pressure**: The high wind pressure caused the panels to flex and eventually crack. Despite being designed for standard wind loads, the panels could not withstand the pressure from the cyclone-force winds.
- **Aerodynamic Lift**: The flat surfaces of the solar panels created significant aerodynamic lift, similar to the wings of an airplane. This lift force contributed to the dislodgement of the panels from their mounts, indicating that the securing mechanisms were insufficient to counteract these dynamic loads.

6.2.2 Impact of Flying Debris

The cyclone not only brought high winds but also substantial amounts of flying debris, which significantly contributed to the damage:

- **Direct Impacts**: Objects such as tree branches, roof tiles, and other debris struck the panels with high velocity, causing immediate breakage and shattering of the glass surfaces.
- **Secondary Impacts**: Even panels that were initially intact suffered secondary impacts as debris continued to be propelled by the wind, leading to additional damage over time.

6.2.3 Securing Mechanism Flaws

Although the mounting structures themselves remained intact, the mechanisms securing the panels were inadequate for the extreme conditions experienced during the cyclone:

- **Bolt and Clamp Failures**: The securing bolts and clamps failed to maintain their hold under the dynamic and uplift forces, resulting in the panels becoming dislodged. This suggests that while the structural design of the mounts was sound, the connections between the panels and mounts were a weak point.
- **Design for Extreme Conditions**: The original design likely did not account for the potential of such extreme weather conditions, indicating a need for reevaluation of design criteria in cyclone-prone regions.

6.3 Implications of Findings

6.3.1 Operational Impact

The failure of the panels had significant operational implications for the solar plant:

- **Energy Production Loss**: The immediate and extensive damage led to a complete halt in energy production. This not only affected the university's power supply but also highlighted the vulnerability of relying heavily on a single source of renewable energy without adequate safeguards.
- **Recovery and Downtime**: The recovery process was lengthy and costly, involving the replacement of a significant number of panels. This downtime not only resulted in financial losses but also underscored the need for a more resilient system design.

6.3.2 Economic Impact

The financial implications of the panel failures were considerable:

- **Replacement Costs**: The cost of replacing damaged panels, including procurement, shipping, and installation, was substantial. This financial burden was exacerbated by the need for immediate action to restore energy production.

- **Revenue Loss**: The downtime resulted in lost revenue, both from potential energy sales and savings on electricity costs for the university. This highlighted the economic risk associated with insufficiently resilient solar installations.

6.3.3 Design and Material Considerations

The findings from the damage assessment have significant implications for future design and material choices:

- **Material Durability**: The panels need to be made from materials that are not only durable but also capable of withstanding high-impact forces from flying debris. This might involve using more robust, laminated glass or other advanced materials.
- **Improved Securing Mechanisms**: The securing mechanisms must be redesigned to handle higher dynamic and uplift forces. This could include using more robust bolts and clamps, as well as implementing additional securing points or methods.

6.4 Recommendations for Enhancing Resilience

Based on the analysis of the panel failures, several recommendations are proposed to enhance the resilience of solar plants against extreme weather events like cyclones:

6.4.1 Structural and Material Upgrades

- **High-Strength Materials**: Use of high-strength, impact-resistant materials for the panels. Laminated safety glass, which can absorb impacts without shattering, could be a viable option.
- **Advanced Coatings**: Application of protective coatings to the panels to enhance their durability and resistance to impacts and environmental wear.

6.4.2 Enhanced Securing Mechanisms

- **Reinforced Bolts and Clamps**: Implementation of reinforced bolts and clamps designed to withstand higher wind loads and uplift forces.
- **Redundant Securing Points**: Adding redundant securing points to distribute the load more evenly and provide additional stability.

6.4.3 Design Improvements

- **Aerodynamic Designs**: Designing panels and mounting structures to be more aerodynamic, reducing the lift forces generated by high winds.
- **Modular and Replaceable Components**: Designing the system with modular components that can be easily replaced or upgraded, minimizing downtime and repair costs.

6.4.4 Preventive Measures

- **Pre-Storm Securing**: Developing protocols for securing and protecting the panels in advance of predicted extreme weather events, such as temporary coverings or additional supports.
- **Real-Time Monitoring**: Implementing real-time monitoring systems to provide immediate feedback on the integrity of the panels and securing mechanisms, allowing for rapid response to emerging issues.

6.5 Future Research Directions

The findings from this study highlight the need for further research in several key areas:

- **Material Science**: Research into new materials that offer enhanced durability and resilience to extreme weather conditions.
- **Dynamic Load Testing**: Conducting dynamic load testing of securing mechanisms and panel designs to better understand their behavior under extreme conditions.
- **Climate Adaptation Strategies**: Developing comprehensive climate adaptation strategies that integrate resilience into the planning and design of renewable energy systems.

6.6 Conclusion

The failure of solar panels at Jadavpur University's solar plant due to Cyclone Amphan provides critical lessons in the importance of designing for resilience. By addressing the identified weaknesses in securing mechanisms, materials, and overall design, future solar installations can be better equipped to withstand extreme weather events, ensuring consistent energy production and financial stability. These findings and recommendations form a basis for enhancing the resilience of solar energy systems, contributing to the broader goal of sustainable and reliable renewable energy infrastructure.

Chapter 7

Conclusions

7.1 Conclusions

The assessment of the solar plant at Jadavpur University following Cyclone Amphan revealed significant damage to the solar panels, despite the mounting structures remaining intact. This discrepancy between the performance of the panels and the mounts highlights critical insights into the design and resilience of solar energy systems. The solar panels experienced extensive damage, including breakage and dislodgement, under wind speeds of 140 km/hr. This failure occurred despite the panels being designed for a minimum wind load of 180 km/hr **[44].** The mounting structures, designed for the same wind load, remained intact, indicating that though the mountings were designed at 11.3° tilt angle rather than 22.5° was capable to withstand a minimum wind load of 140 km/hr. Also from our calculations as the wind load at 22.5° tilt angle is more than wind load at 11.3°. So the panels will also fail at 22.5° tilt angle.

Chapter 8

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These references cover a range of topics relevant to the thesis, including the impact of cyclones on renewable energy infrastructure, resilience assessment of solar energy systems, design modification strategies, and guidelines for renewable energy implementation.