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Hydrology and Flood Risk Assessment studies for Ground-Mounted Solar Power Plants: Integrating Climate Change

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Abstract - *Ground mounted solar PV power plants are increasingly deployed as part of global efforts to transition to renewable energy. However, their development significantly alters local hydrological regimes and introduces new challenges in flood risk management. This study presents an integrated approach to Hydrology and Flood Risk Assessment for solar installations, emphasizing the influence of climate change and land use dynamics. The findings of this aim are to guide engineers, planners, and policymakers in optimizing solar PV Plant layouts while safeguarding environmental and community interests.*

***Key Words*: Hydrology, Climate Change, Runoff processes, Erosion, Topography, Mitigation strategies**

1. INTRODUCTION

Hydrological risks pose a significant threat to the ongoing global investment in ground-mounted solar photovoltaic (PV) systems, highlighting the critical need for proactive risk assessment and mitigation strategies. As the world rapidly transitions to renewable energy sources to combat climate change, solar energy has emerged as a key player, with large-scale ground-mounted installations becoming increasingly common. However, these ground mounted solar plants are often sited in open areas, including flood plains or areas with poor drainage, making them particularly vulnerable to flood events.

Escalating occurrences of extreme weather events associated with climate change significantly amplify flooding hazards. Moreover, modifications in surrounding land use near ground-mounted solar installations can disrupt natural drainage systems, resulting in higher surface runoff and an elevated probability of site inundation. Therefore, there is an urgent need for comprehensive flood risk assessments tailored to the specific vulnerabilities of solar PV plant infrastructure & these assessments are essential for:

- **Protecting Investments:** Safeguarding the substantial financial capital invested in solar PV ground mounted projects.
- **Ensuring Energy Security:** Maintaining the reliability and resilience of renewable energy supply chains.
- **Minimizing Environmental Impact:** Prevent potential contamination caused by damaged equipment or module failure during flood events.

By incorporating comprehensive hydrological and flood risk assessments along with forward-looking climate projections into planning, the renewable energy sector can proactively address flood-related hazards, enhance resilience and promote a sustainable energy future.

2. TYPES OF FLOODING

Flooding at ground-mounted solar power plants, caused by heavy rainfall, flash floods, inadequate drainage systems, or overflow from nearby water bodies, poses a significant risk of site inundation. This can lead to equipment damage, operational disruptions, and generation losses, impacting overall plant performance and reliability.

Different types of floods are categories as below,

2.1 Fluvial flooding (River Flooding)

Fluvial flooding occurs when water levels in a river, stream, or lake rises and exceeds the capacity of the channel, overflowing onto the adjacent floodplain.

Fig -1: Fluvial Flooding

2.2 Pluvial Flooding (Surface Water Flooding)

Pluvial flooding is caused by intense rainfall that creates a flood event independent of an overflowing body of water. It occurs when the rate of precipitation exceeds the capacity of the ground to absorb it or the local drainage systems to carry it away.

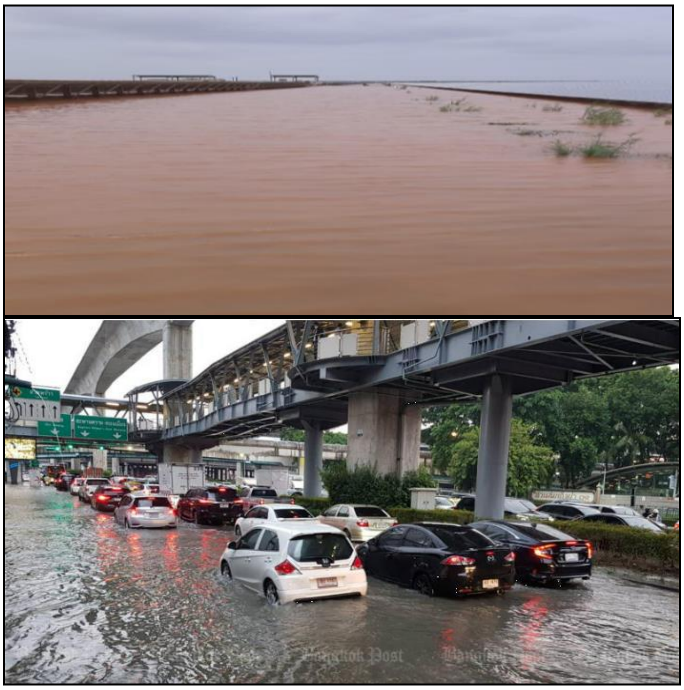

Fig -2: Pluvial Flooding

2.3 Coastal Flooding

This is the inundation of land along the coast by seawater.

Fig -3: Coastal Flooding

2.4 Flash Flooding

A flash flood happens when water levels in rivers or canals rise very quickly, often due to heavy rain or sudden water release. This rapid increase causes water to overflow the banks at high speed, which can damage land and structures.

Fig -4: Flash Flooding

3. DATA REQUIRED FOR FLOOD RISK ASSESSMENT

Flood risk assessment involves evaluating the likelihood and potential impact of flooding in a given study area of ground mounted solar power plant.

For conducting detailed flood risk assessments for ground mount solar power plants, generally below datasets are required.

3.1 Topography & Soil testing data

1. Topography survey of study area conducted through land base, drone base or through Lidar survey.
2. Cross sections and L-Sections of nearby nala/stream/river crossing through site vicinity area.
3. A Digital Terrain Model (DTM) of the site and its surrounding area with the highest possible resolution is essential to achieve accurate flood simulation results.
4. Soil test data is required to know about runoff potential of site soil as per the bore log data.

3.2 Rainfall Intensity and stream flow measurements

1. Daily Rain gauge station data of at least past 30 years obtained through gauge station nearby to site.
2. Catchment characteristics (soil type, land use, slope etc).
3. Evapotranspiration rates.
4. Streamflow measurements.

3.3 Historical Data Analysis of past flooding

1. Historical flood records (dates, severity, duration)
2. Rainfall and river discharge data
3. Flood Damage reports and inundation maps.

4. METHODS OF HYDRAULIC MODELLING

Hydraulic modelling can be performed based on the various methods. Methods are enlisted below:

4.1 1D, 2D & Coupled 1D-2D Hydrological Modelling

The process involves simulating rainfall-runoff as input and generating outputs such as flood inundation maps, water surface elevations, and flood velocity maps.

Depending on the flooding risk whether from a nearby river/nala/stream or due to direct rainfall impact within the site vicinity, appropriate modelling techniques are adopted. These include:

- 1D Modelling (1dimensional modelling)
- 2D Modelling (2 dimensional)
- Coupled 1D–2D Flood Modelling

This method of flood analysis typically requires specialized software to predict water movement in stream/nala/rivers and floodplains. Commonly used tools include:

- HEC-RAS
- TUFLOW
- IBER
- MIKE11

4.2 GIS-Based Flood Mapping

This approach integrates spatial data with hydrological and hydraulic outputs to develop comprehensive flood hazard maps.

The process typically requires GIS-based software for spatial data processing and analysis. Commonly used tools include:

- QGIS
- ArcGIS
- Global Mapper Pro

4.3 Statistical and Probabilistic Analysis

This approach involves conducting flood frequency analysis using statistical methods such as:

- Gumbel Distribution
- Log-Pearson Type III Distribution
- The objective is to estimate flood return periods and assess the likelihood of extreme flood events.

4.4 Remote Sensing and Satellite Data

This method utilizes satellite imagery and remote sensing techniques to monitor flood extent and track changes over time.

5. IMPACT OF FLOODING IN SOLAR PV PROJECTS

Flooding can damage or disable critical solar PV components, leading to degraded system performance and significant losses in both energy generation and revenue.

5.1 Impact on Solar Modules

Although solar modules are designed for outdoor conditions, flooding can submerge the entire array, creating risks that require careful assessment. Objects such as mud, debris, and stone chips carried by floodwaters may strike the panels, causing microcracks that are not immediately visible. These microcracks can allow moisture to penetrate the system, eventually leading to electrical faults.

Fig -5: Flood Impact on Solar PV module

5.2 Impact on Module Mounting structure

Module mounting structures are typically made from various steel materials such as HDG, ZAM, and AZ. Direct exposure of these steel components to water during flooding can lead to corrosion, depending on soil aggressiveness. In highly severe environments, complete replacement of the mounting structure may be required. Therefore, a thorough inspection is critical to ensure system integrity and prevent long-term operational issues.

Fig -6: Flood Impact on Module Mounting Structure

5.3 Impact on Electrical Infrastructure of Solar PV plants

Flooding also affects conduits, wiring, and other electrical components. In many cases, these elements may need complete replacement. A thorough inspection is essential to ensure system integrity and prevent long-term operational issues.

Fig -7: Flood Impact on Electrical infrastructure

5.4 Impact of Flooding in Switchyard of PV Plants

Flooding in the switchyard of a photovoltaic (PV) plant can lead to severe operational and safety risks. Water ingress into switchyard equipment such as transformers, circuit breakers, isolators, and control panels can cause insulation failure, short circuits, and equipment damage. Prolonged exposure to moisture may result in corrosion of metallic parts and deterioration of protective devices, compromising system reliability. Additionally, flooding can hinder access for maintenance personnel, delay restoration efforts and increase the likelihood of fire hazards or electrical faults upon re-energization. These impacts can lead to extended downtime, costly repairs, and significant generation losses.

6. CLIMATE CHANGE IMPACTS ON SOLAR PV PROJECTS

Projected climate variability is expected to increase both the frequency and magnitude of extreme weather events, creating substantial challenges for the design and operational reliability of solar photovoltaic (PV) systems. These dynamic conditions necessitate comprehensive risk assessments and adaptive strategies across all project stages ranging from initial planning and engineering design to construction, commissioning, and long-term maintenance (IPCC, 2022; IEA, 2023).
(Source - ipcc.ch], [iea.org]

According to the IPCC Sixth Assessment Report (AR6) and regional climate projections, the Khavada region in Gujarat and solar-rich areas of Rajasthan are expected to face significant climate variability over the next 25 years.
These regions will likely experience average temperature increases of 2–2.5°C and intensified monsoon rainfall, leading to frequent heatwaves and flash flooding events. Such extremes pose critical risks to ground mounted solar PV infrastructure, including structural degradation, electrical component failures, and operational downtime.

To mitigate these risks, early-stage design interventions are essential. Integrating adaptive measures during the planning phase will enhance climate resilience, reduce financial exposure, and ensure uninterrupted renewable energy generation in these risk prone zones.

An extensive analysis conducted by NREL on a large fleet of photovoltaic installations assessed the influence of extreme weather conditions on system performance. Findings indicate that, routine weather-related disturbances generally lead to an average annual energy reduction of approximately 1%. However, infrequent but severe events such as high-intensity floods or extreme windstorms can trigger substantial operational disruptions, resulting in energy losses that may escalate to nearly 60% of expected output (NREL, 2023).

Hailstorms and strong winds were identified as major contributors to structural damage, while heatwaves accelerate long-term degradation rates, nearly doubling them in hot climates compared to cooler ones.
Extended cloud cover and soiling events were shown to cause short-term yield reductions, compounding overall performance decline.

These findings highlight the critical need for climate-resilient design, robust maintenance strategies, and risk-informed planning to safeguard PV assets against both frequent minor impacts and infrequent but severe weather hazards.

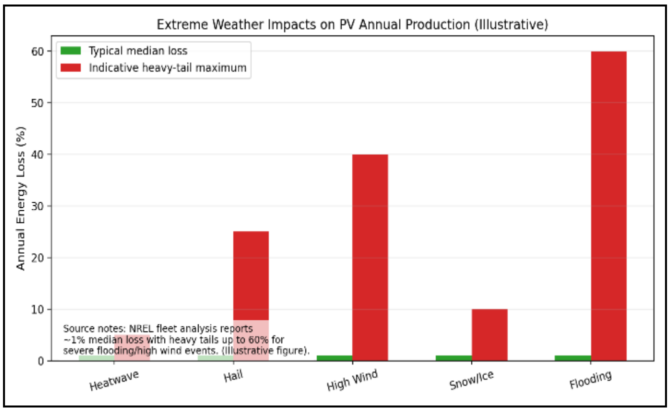

Fig -8: Illustrative distribution of extreme weather impacts on annual PV production for severe flooding/high wind events
(Source- NREL fleet analyses**).**

- **Infrastructure Risk-**

Panels, mounting structures, inverters, and electrical systems face growing exposure to extreme weather hazards, including storms, flooding, high winds, hail, and heavy snow.

These conditions can cause structural damage, electrical failures, and accelerated wear, underscoring the need for robust design standards, storm handling measures, and proactive maintenance strategies (Sources: NREL, Solar Builder Magazine).

- **Operational Delays-**

Severe weather conditions can restrict site accessibility and interrupt construction and commissioning activities, resulting in extended project timelines and increased costs.

Such disruptions emphasize the need for robust contingency plans and flexible scheduling approaches to ensure project continuity and resilience.

- **Changes in Solar Irradiance -**

Climate change can modify cloud patterns and atmospheric conditions, leading to variability in solar radiation.

This affects predictability of energy generation and long-term yield forecasts. (Sources - swissre.com)

- **Water Resource Challenges -**

Altered precipitation patterns and prolonged drought conditions can limit the availability of water required for module cleaning and auxiliary cooling systems, potentially impacting plant performance and operational efficiency (Source: IEA)

- **Soil and Microclimate Changes-**

Ground-mounted solar PV installations can modify local microclimatic conditions, influencing both soil and vegetation dynamics. Research indicates that areas beneath PV panels may experience soil temperature reductions of up to 7°C and redistribution of soil moisture, which can lead to soil instability or vegetation stress. These impacts are likely to intensify under climate-driven variations in rainfall and temperature patterns (Source: MDPI).

- **Increased Corrosion and Material Degradation-**

Environmental factors such as high humidity, acidic precipitation, and frequent temperature fluctuations can significantly accelerate corrosion of mounting structures and electrical components.

This degradation reduces the operational lifespan of critical assets and drives higher maintenance costs, underscoring the need for corrosion-resistant materials and protective coatings in PV system design (Source: extension.psu.edu).

- **Energy Yield Reduction-**

Solar PV systems can experience short term production losses due to factors such as dust storms, extended cloud cover, and extreme temperatures.

Additionally long-term performance degradation may occur from the gradual accumulation of micro-cracks and material fatigue, impacting overall energy output and system reliability (Sources: NREL; MDPI)

- **Transmission and Grid Risks -**

Severe weather events can damage transmission lines and substations, resulting in grid instability, power interruptions, and potential outages (Source: IEA).

- **Fluctuating Demand Profiles -**

Higher cooling needs during heatwaves drive increased electricity demand, affecting system sizing and planning.)

- **Health and Safety Concerns -**

Worker exposure to extreme heat, flooding, or post-storm hazards elevates risks during operations.

- **Reputation and Compliance**

Inadequate management of climate-related risks can compromise regulatory compliance frameworks, trigger community opposition, and lead to significant reputational damage.

These outcomes not only affect project approvals and stakeholder trust but can also escalate financial exposure and operational uncertainty.

Proactive integration of climate resilience measures into design and governance processes is therefore critical for long-term sustainability and risk mitigation.

- **Financial Exposure**

Increased insurance premiums, repair costs, and production losses pose economic risks to project viability.

A comparative cost analysis highlights the economic advantage of proactive flood mitigation measures. Implementing mitigation strategies requires an estimated investment of USD 1.5–3 million, whereas potential flood-related damages could range from USD 7–15 million if left unaddressed.

This significant cost difference underscores the cost-effectiveness of upfront investment in flood control infrastructure and design adaptations. By allocating resources toward preventive measures, project stakeholders can substantially reduce long-term financial exposure, safeguard critical assets, and ensure operational continuity under extreme weather conditions. Figure 2 illustrates the flood mitigation costs and projected flood damage, reinforcing the strategic importance of early intervention in project planning.

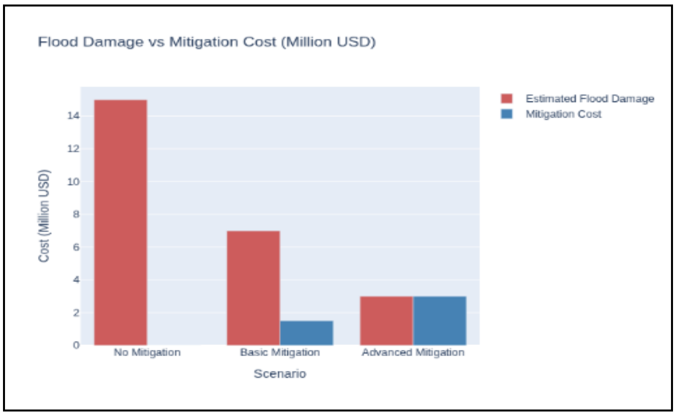

Fig -9: Flood Damage vs Mitigation Cost (Million USD)

(**Sources -** A Chubb Resilience assessment, The U.S. Federal Energy Management Program (FEMP), Swiss Re. Billion-dollar Rain: Why India can't afford to ignore urban flood risk)

➢ Integration of National Renewable Energy Goals with Disaster Risk Management Strategies

India has set ambitious climate and energy objectives to align with global sustainability commitments including as:

- **Carbon Intensity Reduction:**

Reduce the nation's carbon intensity by at least 45% by 2030, relative to 2005 levels.

Renewable Energy Integration:

Achieve 50% cumulative installed electric power capacity from renewable sources by 2030.

- **Net-Zero Goal:**

Attain net-zero greenhouse gas emissions by 2070.

As per the Ministry of New and Renewable Energy (MNRE), by March 2024, India had achieved:

Solar Power Capacity: 81.81 GW

Wind Power Capacity: 45.88 GW

India now aims for 500 GW of renewable energy installed capacity by 2030, positioning proposed renewable energy projects in alignment with these national commitments.

➢ Embedding Disaster Risk Reduction Strategies into Renewable Energy Project Planning

The National Policy on Disaster Management (NPDM) acknowledges that natural hazards such as earthquakes, floods, riverbank erosion, cyclones, and tsunamis pose significant threats to infrastructure and economic stability. The policy mandates a systematic approach comprising six key elements:

- Preparedness
- Response
- Prevention
- Mitigation
- Rehabilitation
- Recovery

Embedding these principles into renewable energy project planning ensures climate resilience, operational continuity, and regulatory compliance.

➢ Strategic Imperatives for Solar PV Projects

- **Protecting Investments:**

Safeguard substantial financial capital deployed in solar infrastructure through robust design and risk mitigation strategies.

- **Ensuring Energy Security:**

Maintain reliability and resilience of renewable energy supply chains under evolving climate conditions.

- **Minimizing Environmental Impact:**

Prevent contamination risks from damaged equipment or module failures during flood events.

By integrating detailed hydrological analysis and forward-looking climate projections into project planning, the renewable energy sector can proactively address flood-related hazards, ensuring a sustainable and resilient energy future.

7. CASE STUDIES OF SOLAR PLANTS AFFECTED DUE TO EXTREME FLOODING

Flood events pose a growing challenge to ground-mounted solar installations due to increasingly unpredictable weather, inadequate drainage design, and rising extreme rainfall.

In India, unusual monsoon surges or cloudbursts can inundate vast arrays of panels, damaging electrical components, causing short-circuits, panel corrosion, and foundational erosion.

Ground-level inverters, cabling, and mounting structures are particularly vulnerable.

Strategic site selection, topographical assessment, and hydrological infrastructure are essential to mitigating such flood risks. [heavendesigns.in], [energy.gov]

Below are several case studies illustrating how severe flooding events have disrupted the functioning of ground-mounted solar power plants.

- **Jaisalmer's Dhirubhai Ambani Solar Park**

In August 2024, record breaking rainfall in Jaisalmer submerged the Dhirubhai Ambani solar park (40 MW PV) under nearly 2 meters of water. This plant is operational since 2012. The 350-acre installation near Pokhran was severely impacted its low-lying terrain turned into a reservoir, interrupting operations and highlighting vulnerability in desert adjacent plains. (**Source** - *Heavy rainfall flooded solar park and GIB hatching area in Jaisalmer*)
The occurrence of intense rainfall in Jaisalmer highlights the emerging vulnerability of arid regions to extreme weather phenomena, emphasizing the need for climate-resilient infrastructure and adaptive planning strategies in such environments.
The flooding that impacted both the Dhirubhai Ambani Solar Park and the Great Indian Bustard (GIB) hatching area highlights the vulnerability of renewable energy infrastructure and sensitive ecosystems in desert landscapes.
As abnormal rainfall patterns become more frequent, site planning and design for solar projects in desert regions must incorporate advanced hydrological assessments and disaster management strategies. Failure to address these risks can lead to severe operational disruptions, habitat degradation, and long-term sustainability concerns for both energy and biodiversity.

- **Pavagada Solar Park (Tumakuru, Karnataka) In October 2022**

Reports documented that, torrential rainfall and overflowing reservoirs led to the partial submergence of a 50 MW block and inundation of around 32 acres within the Pavagada Solar Park.
The flooding caused a substantial drop in power generation, prompting extensive damage assessments and restoration efforts.
Although specific monetary loss figures for this event aren't publicly disclosed, the affected block is part of a ₹16,500 crore facility, highlighting the potential financial impact.
Restoration likely involved cleaning or replacing submerged panels, repairing cabling and inverters, and rectifying structural damage each adding to operational downtime and restoration costs.
Source: *Karnataka Rains: Water enters Pavagada solar park, submerges 50MW unit | Bengaluru News - Times of India*

- **Solar power plant flooding in REWA 2018**

On July 5, 2019, the Rewa Ultra Mega Solar Power Project in Madhya Pradesh, one of the largest solar parks globally, suffered severe damage due to torrential rainfall and stormy weather.
A mudslide triggered by heavy rains critically impacted Unit III (250 MW), reducing generation from 250 MW to about 92.5 MW, a 63% capacity loss.
The flooding caused extensive damage to:

  - Inverters, PV modules, cable trays, and module mounting structures (MMS)
  - Water intrusion inside Switchyard and combiner boxes compromising electrical safety

Financial losses were estimated at over ₹20 crore, primarily due to equipment damage and halted generation.
Restoration efforts were immediately initiated by Rewa Ultra Mega Solar Limited (RUMSL) and its operator Sprng Energy to bring the unit back to full capacity.
Sources: (*Heavy Rains Wreak Havoc in Madhya Pradesh, Damage a 250 MW Solar Project*)

- **Saudi Arabia – Flood Risk to Ground-Mounted Solar Sites**

While no specific ground-mounted solar sites in Saudi Arabia have been reported to flood, flash floods are increasingly common during winter months. For instance, Jeddah and Makkah were hit by heavy rainfall in December 2025, causing widespread flooding in urban areas.
These events illustrate potential hazard to solar farms, especially those sited in low-lying valleys or near wadis, where sudden water surges could overwhelm panels, inverters, and mounting structures even if the damage hasn't yet been documented.
Sources: (Gulfnews.com)

- **Revenue loss due to extreme water flooding in 50MW size plant (General example)**

Extreme flooding caused by abnormal rainfall has led to partial or complete submergence of a say 50 MW ground-mounted solar plant. This event resulted in operational downtime, equipment damage, and significant reduction in energy generation.

Key Impacts:

- Plant Capacity: 50 MW
- Event: Flooding due to heavy rainfall
- Immediate Effect: Generation halted or reduced drastically

Potential Consequences:

- Loss of daily energy output
- Repair and restoration costs
- Long-term reliability concerns

Objective:
To estimate revenue loss during the downtime period based on plant capacity, expected generation, tariff rate, and duration of outage.

Assumptions

- Plant Capacity: 50 MW
- Plant Load Factor (PLF): 20%
- Tariff: ₹3 per kWh
- Duration of shutdown: 7 days
- Hours per day: 24

Step 1 Daily generation calculations

Calculation for 7-day plant shutdown

1) Hours = 7 × 24 = 168 hours.
2) Energy loss for 168 hours = 50MW ×168 h = 8,400 MWh.
3) Expected generation loss at 20% PLF = 8,400 × 0.2 = 1,680 MWh lost.
4) Revenue loss at ₹3/kWh /unit = 1,680,000 kWh × ₹3 = ₹50,40,000 INR

Hence, there would be a revenue loss of 5,040,000 INR due to flooding in 50 MW plant size and plant under shutdown for 7 days with ₹3 unit rate.

Below table shows, Revenue loss due to flooding with plant shutdown days ranges from 3 to 30 days.

Table -1: Energy loss vs Plant shutdown duration — 50 MW block at 20% PLF.

Table 1- Revenue loss calculations

Plant shutdown (days)	Energy Generation (Mwh) at 20% PLF	Revenue loss (INR, @₹3/kWh)
3	240	720000
7	1680	5040000
15	3600	10800000
21	5040	15120000
30	7200	21600000

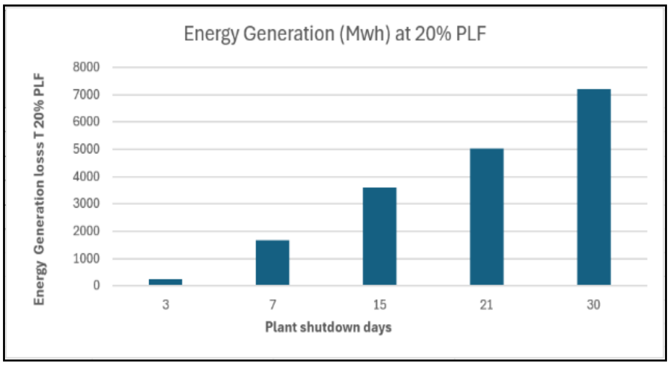

Fig.-10: Plant shutdown Vs Energy generation loss

8. FLOOD WATER MITIGATION MEASURES

To ensure the safety, reliability, and uninterrupted power generation of solar photovoltaic (PV) plants, it is essential to establish comprehensive engineering and operational measures that minimize flood-related risks. Implementing flood mitigation strategies during the initial stages of project planning and design is critical, as early integration reduces risk, prevents costly damage, and ensures long-term operational stability. Proactive measures not only safeguard infrastructure but also protect financial investments by avoiding revenue loss and expensive repairs. While these mitigations require upfront capital and financing, the cost is significantly lower compared to potential losses from flooding events. Therefore, adopting robust flood protection measures for ground-mounted solar plants is a strategic necessity for sustainable and resilient energy generation.

The following mitigations are recommended for implementation.

1. A site feasibility study shall be conducted at initial stage of the project, and based on identified risks such as flood risk, soil conditions, corrosion potential, and liquefaction, site shall be selected. Solar PV project shall be designed considering measures for all major risk identified in the site feasibility study.

2. Drainage and water management strategies shall be developed based on the findings of the detailed flood risk assessment study.

3. In the event of a flooding risk from a nearby river/Stream/nala, construct earthen embankments or levees along the plant boundary to provide adequate protection.

4. Implement electrical safety measures, including the use of water-soluble tape, in areas where the site has a high flood risk and shallow groundwater conditions.

5. Module Mounting structure, and all building structures present inside the project area shall be placed above High Flood level of the plant.

6. Internal finished road level shall be above high flood level of the plant, so major building structures shall be accessible all time.

7. Prepare emergency response planning.

8. Regularly inspect drainage systems and embankments. Conduct post-flood inspections for structural integrity and electrical safety.

9. CONCLUSIONS

Flood risk assessment for ground-mounted solar power plants is not optional as it is a fundamental requirement for sustainable and resilient project design.

Failure to integrate flood risk considerations at the early planning stage exposes projects to significant risks including infrastructure damage, prolonged downtime, and financial losses.
Incorporating hydrological analysis, climate change projections, and land-use dynamics ensures that solar assets remain robust under evolving environmental conditions.

Climate variability and rapid urbanization are altering runoff patterns, increasing the frequency and severity of extreme flooding events. Without proactive assessment, these risks can compromise plant performance and long-term viability. Utilization of advanced analytical techniques, including GIS-integrated flood mapping and predictive scenario modelling, facilitates precise risk assessment and supports data-driven decision making. Incorporating proactive measures such as optimal site selection, elevation of vital infrastructure, implementation of efficient drainage networks, and adoption of flexible design standards at the initial planning stage is crucial for minimizing flood-induced risks and ensuring long-term operational resilience.

Furthermore, continuous monitoring and periodic reassessment using updated climate data will strengthen resilience over the plant's lifecycle. Ultimately, a holistic approach combining engineering solutions with environmental foresight will safeguard solar investments, minimize operational disruptions, and contribute to long-term energy security in a changing climate.

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