From
the People of Japan

UNDP

MAPPING THE RESILIENCE OF RENEWABLE ENERGY SYSTEMS AND ASSETS IN Maharashtra, Gujarat, Tamil Nadu, and Rajasthan TO EXTREME WEATHER EVENTS

From
the People of Japan

MAPPING THE RESILIENCE OF RENEWABLE ENERGY SYSTEMS AND ASSETS IN Maharashtra, Gujarat, Tamil Nadu, and Rajasthan TO EXTREME WEATHER EVENTS

Recommended Citation: UNDP 2024.
Mapping the Resilience of Renewable Energy Systems and Assets in Maharashtra, Gujarat, Tamil Nadu and Rajasthan to extreme weather events.

EXECUTIVE SUMMARY

Climate hazards such as floods, droughts, and cyclones are becoming more frequent and intense, posing a threat to the resilience of renewable energy (RE) systems. India has a target to install 500 gigawatts of RE by 2030 and reach net-zero emissions by 2070. The country is seeing a significant increase in its installed non-fossil fuel capacity. RE assets such as solar photovoltaics (PV) and wind turbines are at risk under a changing climate with the increase in magnitude and frequency of extreme events.

To evaluate the current climate risk of RE infrastructure to multiple extreme events, the United Nations Development Programme (UNDP), India collaborated with the Center for Study of Science, Technology and Policy (CSTEP), to conduct a study in four Indian states: Maharashtra, Gujarat, Tamil Nadu, and Rajasthan. These states have the highest percentage of solar PV and wind assets in India. The study employed the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) risk assessment framework. Risk was computed as a function of the probability of occurrence of a hazard, the exposure of assets to the hazard, and the inherent vulnerability of RE assets. The resilience of assets was qualitatively captured. The study findings have informed the policy recommendations presented in the report.

Spatial extent and the probability of occurrence of hazards: The first step involved the identification and selection of climate hazards relevant to the project states. Six hazards—floods, droughts, heatwaves, tropical cyclones, earthquakes, and hailstorms—were considered. The study used historical climate data to estimate the probability of occurrence of climate hazards in each state. A multidisciplinary approach was employed to compute the spatial extent of hazards. All the necessary data were gathered from both primary and secondary sources. Geographic information system (GIS) techniques were applied to map hazards.

The results showed that Tamil Nadu has the highest probability of occurrence of tropical cyclones. On the contrary, the probability of an earthquake occurring in Tamil Nadu is zero. Hailstorms generally have a low probability of occurrence across most states, but Rajasthan is most likely to experience them. Floods are most likely to occur in Gujarat and Maharashtra.

Exposure was assessed on a GIS platform. The exposure of RE assets to multiple hazards was assessed quantitatively in three steps. The first step involved building an RE assets database. This was followed by the disaggregation of the six hazards according to their intensity or frequency, and finally, the percentage of RE assets exposed to these hazards was computed.

The exposure of both solar PV and wind assets to drought is relatively low across all states. Most wind assets in Rajasthan are exposed to hailstorms and heatwaves. On the other hand, they are not exposed to floods. A significant number of RE assets in Maharashtra are exposed to heatwaves. Gujarat has the highest probability of occurrence of earthquakes and the highest exposure of both solar PV and wind assets to the hazard.

Vulnerability assessment: An indicator-based 12-step methodology was employed to assess vulnerability at the state level. For solar PV and wind assets, five indicators were chosen with different numbers of sub-indicators based on data collected through surveys. Out of these, one indicator represents sensitivity, and the other four indicators represent the adaptive capacity of RE assets. The assessment allowed for the ranking of states on a three-point scale of high, moderate, and low vulnerability.

The vulnerability assessment showcased that wind assets in Maharashtra are the most vulnerable, followed by Gujarat. For solar PV assets, Rajasthan is the most vulnerable, followed by Gujarat. The analysis shows that in states with high vulnerability, solar PV plants have low adaptive capacity.

The drivers of vulnerability were also determined for each state. Compromised robustness and recovery of solar PV plants are the major drivers of vulnerability, while poor structural integrity, a lack of redundant water and power supply, and compromised recovery drive the vulnerability of wind plants. Field surveys assisted with the quantification of indicators and allowed for the collection of qualitative information that was used to highlight the resilience of sampled RE plants, including their state in the event of extreme events and the measures that are implemented to climate-proof them.

Risk assessment aggregated hazard, exposure, and vulnerability information at the state level to produce a unique risk score for each state. These scores were then used to rank the states on a three-point scale of high, moderate, and low risk to the hazards chosen for this study.

Solar PV assets in Gujarat are most at risk to earthquakes followed by tropical cyclones and floods. The ones in Rajasthan are most at risk to hailstorms and heatwaves, and the solar PV assets in Maharashtra and Tamil Nadu are most at risk to tropical cyclones. Also, solar PV assets in Maharashtra are at risk to heatwaves.

Wind assets in Gujarat and Maharashtra are most at risk to earthquakes and tropical cyclones. Wind assets in Rajasthan are most at risk to hailstorms and heatwaves, and the ones in Tamil Nadu are most at risk to tropical cyclones and hailstorms. Moreover, the study found that Gujarat is most at risk to four of the six hazards for both solar PV and wind assets. Furthermore, the average cyclone risk is the highest for solar PV assets, and the average flood risk is the lowest for wind assets.

Policy recommendations: The report provides policy recommendations to address the drivers of risk and enhance the resilience of RE assets to extreme events. The recommendations are based on literature review, risk assessment, and stakeholder consultations.

The drivers of vulnerability and risk were used to inform the formulation of policy recommendations. Some of the key policy recommendations include:

- Improving audit mechanisms
- Improving infrastructure and promoting the use of technology
- Installing early warning systems and building the capacity of emergency response teams
- Increasing maintenance and allocation of emergency funds
- Increasing the number of internal quality checks
- Providing insurance as a means of transferring risks

Various recommendations on improving resilience to specific hazards (floods, tropical cyclones, hailstorms, and heatwaves) are also presented in this report. The risk-informed policy recommendations were used as discussion points to deep dive into the topic and facilitate the development of new and context-specific recommendations during four state-level stakeholder consultations and a round table discussion hosted by UNDP in New Delhi.

CONTENTS

TABLES

FIGURES

ABBREVIATIONS

AHP: Analytic hierarchy process
AREAS: Association of Renewable Energy Agencies of States
BIS: Bureau of Indian Standards
CEA: Central Electricity Authority
CERC: Central Energy Regulatory Commission
CSTEP: Center for Study of Science, Technology and Policy
CDRI: Coalition for Disaster Resilient Infrastructure
DISCOM: Distribution company
DISH: Directorate of Industrial Health and Safety
DSO: Distribution system operators
EDI: Effective Drought Index
EPC: Engineering, Procurement, and Construction
ESU: Energy storage units
FAO: Food and Agriculture Organisation
FCF: Flood conditioning factor
GIS: Geographic information system
IEC: International Electrotechnical Commission
IMD: India Meteorological Department
IPCC: Intergovernmental Panel on Climate Change
IRDAI: Insurance Regulatory and Development Authority of India
IREDA: Indian Renewable Energy Development Agency
ISO: International Organization for Standardization
ISRO: Indian Space Research Organisation
MNRE: Ministry of New and Renewable Energy
MOEFCC: Ministry of Environment, Forest and Climate Change
MOHFW: Ministry of Health and Family Welfare
MOL&E: Ministry of Labour and Employment
MOP: Ministry of Power
NCMRWF: National Centre for Medium Range Weather Forecasting
NDMA: National Disaster Management Authority
NISE: National Institute of Solar Energy
NIWE: National Institute of Wind Energy
NRSC: National Remote Sensing Centre

OEM: Original equipment manufacturer
O&M: Operation & maintenance
OSHA: Occupational Safety and Health Administration
PV: Photovoltaic
RE: Renewable energy
SDMA: State Disaster Management Authority
SNA: State Nodal Agency
SPI: Standardised Precipitation Index
TRANSCO: Transmission company
TSO: Transmission system operators

1. INTRODUCTION

India has emerged as a significant player in the global renewable energy (RE) industry with ambitious goals of achieving net-zero emissions and generating 500 gigawatts of energy from non-fossil fuel sources by 2030. According to the Renewables 2022 Global Status Report by REN21, India ranks fourth in the world in terms of RE installed capacity. The report also stated that India is the third-highest country in adding solar and wind power capacity. Moreover, India experienced the highest growth in electricity demand globally (at 8.4%) during the year 2022–23 (REN21, 2023). In the past decade, India has seen a remarkable rise in its installed non-fossil fuel capacity (by 396%). As of May 2023, the total installed non-fossil fuel capacity, including large hydro, reached 178.79 gigawatts, accounting for about 43% of the country's energy capacity. India has shown its commitment to addressing climate change and promoting a sustainable energy future by leading the call to phase down fossil fuels at the 27th Conference of the Parties (COP27).

The Government of India has also implemented various measures to support RE projects across the country, such as financial incentives, tax benefits, and simplified regulatory frameworks. These measures have enabled the growth of solar power installations, facilitated by favourable policies such as the Jawaharlal Nehru National Solar Mission and the development of solar parks across the country. India's Production Linked Incentive Scheme the National Programme on High Efficiency Solar PV Modules aims to boost the domestic manufacturing capacity of RE and enabling technologies.

However, as India pursues its RE pathways, it faces increasing challenges from climate change. India is highly vulnerable to climate change, which has caused devastating losses and damages from extreme events such as floods, droughts, and tropical cyclones in the last decade. RE, while being a key solution to reducing emissions, is exposed to the risks of climate change. The power sector has suffered significant losses and damages from climate-related disruptions. Therefore, it is essential to enhance the resilience of RE infrastructure, which can reduce the impact of disruptive events, save lives, minimise economic losses, and improve community well-being.

The Center for Study of Science, Technology and Policy (CSTEP) conducted a study to assess the current climate risk to RE infrastructure in four Indian states that have the highest percentage of solar PV and wind assets—Maharashtra, Gujarat, Tamil Nadu, and Rajasthan—using the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) risk assessment framework. Risk was calculated as the geometric mean of the probability of occurrence of hazards and the exposure and vulnerability of the RE infrastructure. The study provides policy recommendations based on risk assessment, literature review, and stakeholder engagement.

1.1 OBJECTIVES OF THE STUDY

The analytical study conducted by CSTEP aims to address the following questions:

- What is the current level of exposure of RE assets to extreme events such as tropical cyclones, floods, droughts, heatwaves, hailstorms, and earthquakes?
- What is the current level of risk-information integration into the designing and planning of RE deployments by relevant stakeholders?
- What are the global or national best practices in disaster-proofing RE assets?
- What are the gaps, and how can these gaps be overcome?

2. METHODOLOGY

This section presents the various methodologies employed to undertake hazard, exposure, and vulnerability assessments and assess the overall risk of solar and wind assets at a state level. It also presents the methodology used to collect relevant literature to inform policy recommendations presented in the report.

2.1. COMPUTING THE SPATIAL EXTENT OF HAZARDS

The IPCC defines hazards as 'the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources'. For the assessment of climate risks in this study, the term hazard will refer to climate-related physical events or trends or their physical impacts.

The first step in assessing the probability of occurrence of climate hazards is the identification and selection of climate hazards relevant to the project states. Given India's size, the country observes a significant variation in climate and geographies; thus, different regions experience different climate hazards.

Floods, droughts, heatwaves, hailstorms, and tropical cyclones are the most common climate hazards observed in the four project states. Apart from these, earthquakes also impact three out of the four states, barring Tamil Nadu. Therefore, these six hazards were considered for the assessment of risk.

In this study, historical climate data were used to assess the probability of occurrence of the climate hazards in each project state. Along with this, the spatial extent of climate hazards was mapped in a geographic information system (GIS) platform to be used for the exposure assessment. A similar exercise was conducted for earthquakes. The data sets and methods used for each hazard assessment are presented in Table 1.

Table 1: Data sets and methods used for the assessment of six hazards

Hazard	Data	Source
Droughts	Daily rainfall gridded data of spatial resolution 0.25° × 0.25° for the period 1993 to 2022	India Meteorological Department (IMD)
Floods	Digital elevation model (DEM), soil texture, land use land cover, geomorphology, rainfall data	National Remote Sensing Centre, ISRO, HydroSHEDs, FAO-UNESCO, IMD, Geological Survey of India
Heatwaves	Daily gridded maximum temperature data of resolution 0.25° x 0.25° from 1993 to 2022	IMD
Tropical cyclones	Number of events and types from January 2011 to November 2023	IMD and Global Disaster Alert and Coordination System (GDACS, n.d.)
Earthquakes	Epicentres of earthquakes from 1989 to 2019	Geological Survey of India and Bureau of Indian Standards
Hailstorms	Number of events from 1981 to 2010	IMD (2020)

Given the multiplicity of hazards, a multidisciplinary approach was used to compute their spatial extent. All the required data were collected from both primary and secondary sources. GIS techniques were used to analyse and map hazards. The detailed methodology for assessing each hazard is presented in Figure 1.

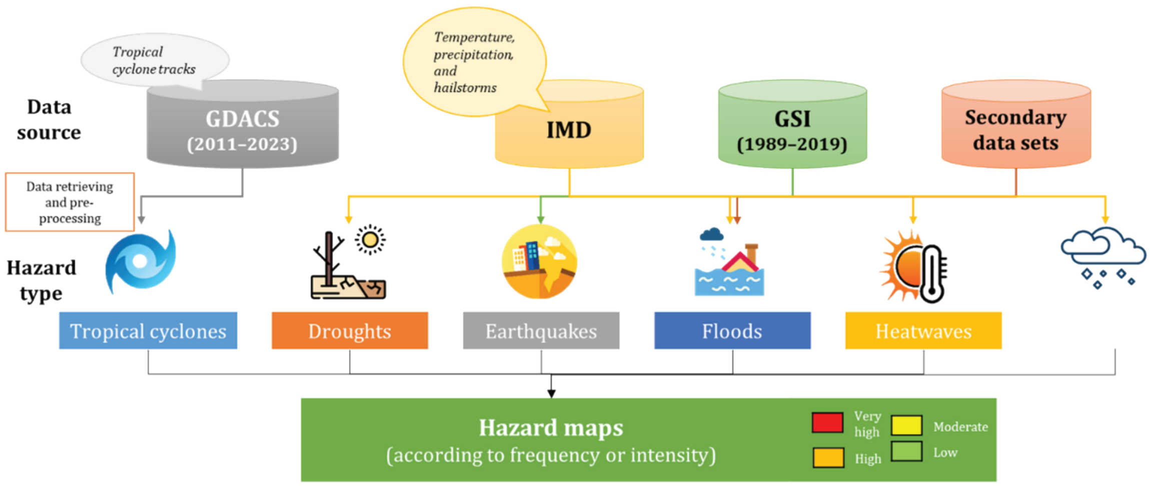


Figure 1: Methodologies used for mapping multiple hazards
Source: CSTEP research

2.1.1. DROUGHTS

Droughts, defined as a prolonged lack of precipitation, lead to water scarcity. They affect agriculture and industries and significantly impact the people of India. This phenomenon, escalating in severity and extent, poses a major threat to the economy. From 2013 to 2016, water scarcity caused India's thermal power sector to miss out on 30 TWh of potential energy generation, with 2016 alone seeing a loss of nearly 14 TWh because of drought-induced shutdowns (Luo, 2017). Consequently, droughts greatly influence RE plant operations.

Droughts may be quantified using several different indices. The Standardised Precipitation Index (SPI), Standardised Precipitation Evapotranspiration Index (SPEI), Decile Index, Palmer Drought Severity Index (PDSI), Percentage Departure from Normal (PDN), and Effective Drought Index (EDI) are just a few of the drought indices that have been developed over time. This study uses SPI developed by McKee et al. (1993), which helps in identifying meteorological, agricultural, and long-term hydrological droughts on one-, three-, six-, and twelve-month timelines.

The analysis of drought conditions in this study employed gridded rainfall data at a spatial resolution of 0.25° x 0.25° from 1993 to 2022. This data set was obtained from the India Meteorological Department (IMD) and pertains specifically to the four study states. SPI values for medium accumulation periods (9-month period) were calculated. Subsequently, these SPI values were utilised to estimate drought events across state territories. A spatial autocorrelation technique called inverse distance weighting was applied to achieve this estimation (Shepard et al., 1968; Chen et al., 2012; and Gong et al., 2014). Then the drought events were categorised based on the McKee et al. (1993) classification (Table 2) and mapped using the GIS platform.

Table 2: Categorisation of drought using SPI (Source: McKee et al., 1993)

Drought type	SPI
Extreme drought	–2 or less
Severe drought	–1.50 to –1.99
Moderate drought	–1.00 to 1.49-
Near normal	–0.99 to 0.99
Moderately wet	1 to 1.49

Drought type	SPI
Severely wet	1.5 to 2
Extremely wet	2 or above

2.1.2. FLOODS

Floods are regarded as a destructive natural disaster in terms of fatalities and property loss (Osman et al., 2023). Floods can disrupt the regular operation of RE systems (Pugh & Stack, 2021). They have the potential to damage solar power plant equipment, including support structures and solar panels (Ibrahim et al., 2022). Solar panels submerged in water may experience electrical problems and produce less electricity (Simsek et al., 2021). They also have the potential to harm wind turbines' structural and electrical components. Turbine bases submerged in water can erode and compromise the stability of foundations (Waseem & Manshadi, 2020).

Many investigations specify 'flood susceptibility mapping' as an essential preventive measure in the planning, management, and observation of risk to property or assets (Das, 2020; Lin et al., 2019). To prepare the flood susceptibility map over four states, multi-sourced environmental flood conditioning factors (FCF) were used (Table 3), and the analytic hierarchy process (AHP) approach was followed (Chen et al., 2010). The method used is detailed in Figure 2.

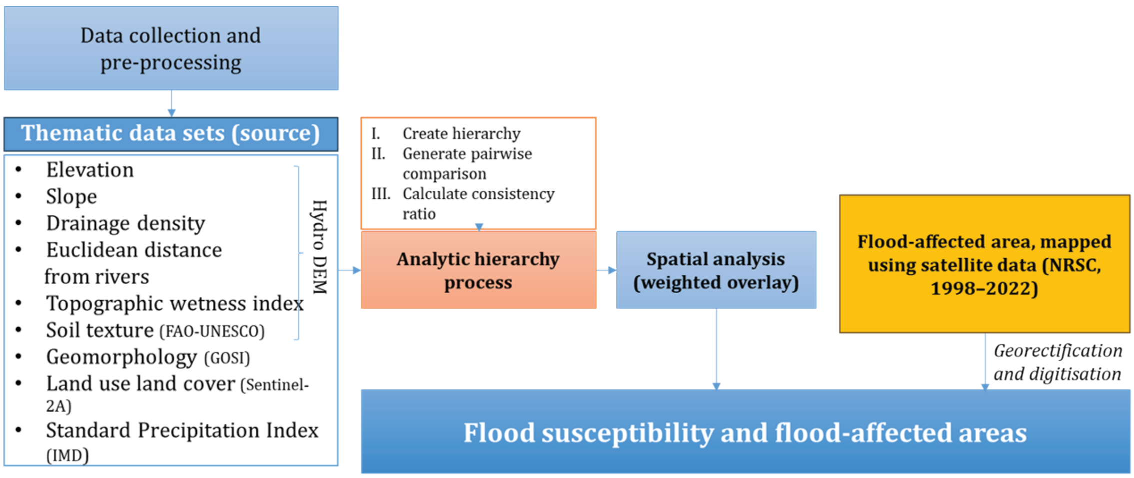


Figure 2: Methodology used to map flood susceptibility areas in the four project states

Source: CSTEP research

Based on the influence on floods, each FCF was categorised into classes. Further, each factor was run under a weighted overlay tool, which allows to pick high- to low-scale flood susceptibility zones. The weighted influence factor was calculated using the AHP method. AHP is one of the most popular and widely employed multi-criteria methods in flood susceptibility mapping (Das, 2020). AHP was employed to rank each FCF with other FCFs. The ranking or selection was made with respect to a flood susceptibility weightage, which is broken down into a set of criteria (Table 3). The final map was reclassified into moderate, high, and very high flood susceptible classes. Flood-affected areas derived from satellite data, from 1998 to 2022, as identified by the National Remote Sensing Centre (NRSC) of the Indian Space Research Organisation (ISRO), were considered under the very high flood susceptibility classes.

Table 3: Flood condition weights for thematic layers

Flood conditioning factor	Weight (%)
Elevation	6
Slope	6
Drainage density	17
Topographic wetness index	24
Euclidean distance from rivers	20
Geomorphology	19
Soil texture	5
Precipitation index	3

2.1.3. HEATWAVES

A heatwave is typically defined as a period of significantly hotter-than-average temperatures. However, no universal metric exists to uniformly assess heatwaves across various sectors and regions (Russo et al., 2014). IMD considers only maximum temperatures (Tmax) for defining heatwaves. According to IMD, 'if the maximum temperature of a station reaches at least 40°C or more over the plains and at least 30°C or more in hilly regions,' it is considered a heatwave event. To declare a heatwave, these criteria should be met for at least two consecutive days. Heatwaves, characterised by intense temperature fluctuations, can impact both energy infrastructure and the people operating them, hindering power production and escalating the demand for cooling.

In India, heatwaves predominantly strike during the summer season, March to June. These severe weather events primarily affect the northern, northwestern, central, and eastern coastal regions, marking a period characterised by intensely elevated temperatures and climatic discomfort (Pai et al., 2013).

Solar panels are built to operate optimally at a certain temperature. The temperature range where most solar panels perform best is between 15°C and 35°C. Increased temperatures can influence solar panels' efficiency, particularly if they are subjected to extended periods of high temperatures. High temperatures have the potential to degrade a solar panel’s electricity output efficiency by 10% to 25% (Mishra, 2022). Likewise, extreme weather conditions can impact wind turbine operation, regardless of the temperature. Abnormally high temperatures have the potential to lower air density, which could lower wind turbine efficiency.

Considering the IMD definition and referring to the heat action plans of the respective states, a heatwave analysis was undertaken. Daily maximum temperature data from IMD were used for the analysis. The maximum threshold temperature was noted from the state action plans, and the number of days exceeding this temperature consecutively for two or more days was noted as events. These heatwave events were then mapped using the spatial autocorrelation inverse distance weighting technique over areas of the project states.

2.1.4. TROPICAL CYCLONES

Tropical cyclones are the most significant weather-related calamities to affect India's coast. Tropical cyclones are regions of very low pressure with an outward-moving pressure centre. The intensity of tropical cyclones and wind strength are determined by the magnitude of the pressure drop at the centre and the rate at which it increases outward. Solar panels can be harmed by flying debris, strong winds, and rain. Tropical cyclone-related hailstorms can seriously damage solar modules as well. Strong winds can put an additional strain on solar panel mounting structures, which might affect their stability.

Though the 2020 windy season in India was longer than typical, the amount of electricity produced by wind was low because of a string of tropical cyclones that struck the nation's coast. National wind electricity production fell by 20% as operators had to turn off turbines during storms to avoid damaging them.

The available tropical cyclone data of the Global Disaster Alert and Coordination System (GDACS) from January 2011 to November 2023 were considered to examine the number of tropical cyclones over the Indian coast with wind speeds above 60 km/h. Tropical cyclones are among the many natural threats for which the Global Disaster Alert and Coordination System automatically issues alerts. The system uses analytical models to continuously monitor scientific data and determine the location, strength, and other features of such events. All the calculations that determine the impacted region, possible impact, and population susceptibility are carried out automatically so that important information is disseminated promptly and accurately.

2.1.5. EARTHQUAKES

Earthquakes result from movements within the Earth's crust or volcanic action. They are primarily caused by the tectonic forces generated by the movement of Earth's lithospheric plates. These movements can occur in the form of faulting, where stress on the Earth's crust exceeds its strength, or by volcanic activity due to the eruption of magma. The point on the Earth's surface directly above an earthquake source is called the epicentre. Seismic waves, originating from the focus of the earthquake, travel through the Earth and cause the shaking that we experience. These waves can be of different types, mainly P-waves (primary waves) and S-waves (secondary waves), each having distinct characteristics and speeds. The study of these seismic waves provides valuable information about the interior of the Earth, as well as the size and nature of the earthquake. The magnitude of an earthquake, often measured on the Richter scale, indicates the energy released at the source of the earthquake. Understanding earthquakes and their underlying mechanisms is crucial for developing effective prediction methods and implementing safety measures to buffer and mitigate impact.

The structural integrity of wind turbines may be in danger during a seismic activity. The stability of the tower, foundation, and other elements may be affected by the trembling earth. Blades of wind turbines may deteriorate because of shaking and movement during an earthquake. Structures supporting solar panels could be stressed during an earthquake. This may have an impact on the solar array's overall stability. Solar panels that are not adequately anchored may shatter because of the trembling ground.

Earthquake data of the Geological Survey of India from 1989 to 2019 were considered and mapped to understand seismic zones within the four states. The data also included cluster earthquakes that happened on the same day within the buffer zone of about 20 km area.

2.1.6. HAILSTORMS

Hailstorms are intense weather events characterised by the fall of hail, balls or irregular lumps of ice. They typically occur during severe thunderstorms when updrafts carry droplets of water high into the atmosphere where temperatures are below freezing point. In these cold conditions, the droplets freeze into tiny ice particles. If the updrafts are strong enough, these particles can remain suspended in the air, allowing them to collide with additional water droplets, further increasing their size. Eventually, when the hailstorms become too heavy for the updrafts to support, they fall to the ground as hail. The process of hailstorms travelling up and down in the storm, collecting layers of water and freezing, can repeat several times, causing them to grow significantly before they finally fall. Factors such as the strength of the updrafts, the size of the water droplets, and the duration of the transportation process in the cloud all contribute to the size of the hail. These storms can cause significant damage to crops, property, and even pose a threat to animals and humans because of the potential size and speed at which hail can fall.

Hailstorms have the potential to physically damage solar panels, resulting in glass breakage, dents, or cracks. The solar array's overall output and efficiency may be lowered because of this damage. Large hailstones can wear down turbine blades, even though wind turbines are typically less susceptible to hail damage than solar panels.

The hazard atlas developed by IMD provided comprehensive data on hailstorms occurring in India from 1981 to 2010. This data set, detailing the annual frequency of hailstorm days, was employed to construct a series of maps across the four designated states. Additionally, district-specific hailstorm data, collated manually, were integrated and represented cartographically.

2.2. QUANTIFYING THE EXPOSURE OF SOLAR PV AND WIND ASSETS TO HAZARDS

In its Sixth Assessment Report (AR6), the Intergovernmental Panel on Climate Change (IPCC) defines exposure as the presence of various elements in areas vulnerable to adverse effects. Elements here can include people; livelihoods; ecosystems; infrastructure; and economic, social, and cultural assets situated in at-risk settings. Recognising the diversity and interconnectedness of these elements is crucial for assessing risk and formulating comprehensive strategies to mitigate the impacts of climate change and environmental degradation.

The exposure of RE assets to multiple hazards was quantitatively assessed in three steps. The first step involved building an RE assets database. This was followed by the disaggregation of the six hazards in terms of their intensity or frequency; lastly, the percentage of RE assets exposed to these hazards was computed (Figure 3).

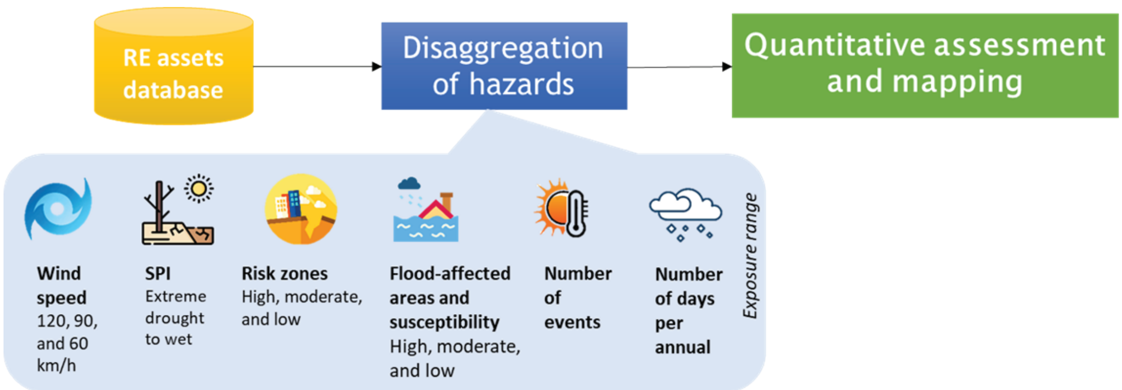


Figure 3: Methodology used to assess exposure of RE assets
Source: CSTEP

2.2.1. BUILDING AN RE ASSET DATABASE

A geocoded version of RE assets was downloaded from the OpenStreetMap (OSM) using the QGIS Quick OSM plug-in. Further, the data sets were verified with Google Earth satellite images to assess location accuracy and were found to be reliable (Figure 4). Downloaded data were available in two vector types (point and line). Each wind turbine was geotagged and represented in the point feature. Solar PV sites were available in a line feature and to get it in a single dimension (latitude and longitude), a centroid tool was used on a GIS platform. However, because of lack of attributes such as ownership and capacity, these points do not represent solar PV plants but a distribution of grouped solar PV panels, which is termed as 'solar PV assets' in this study.

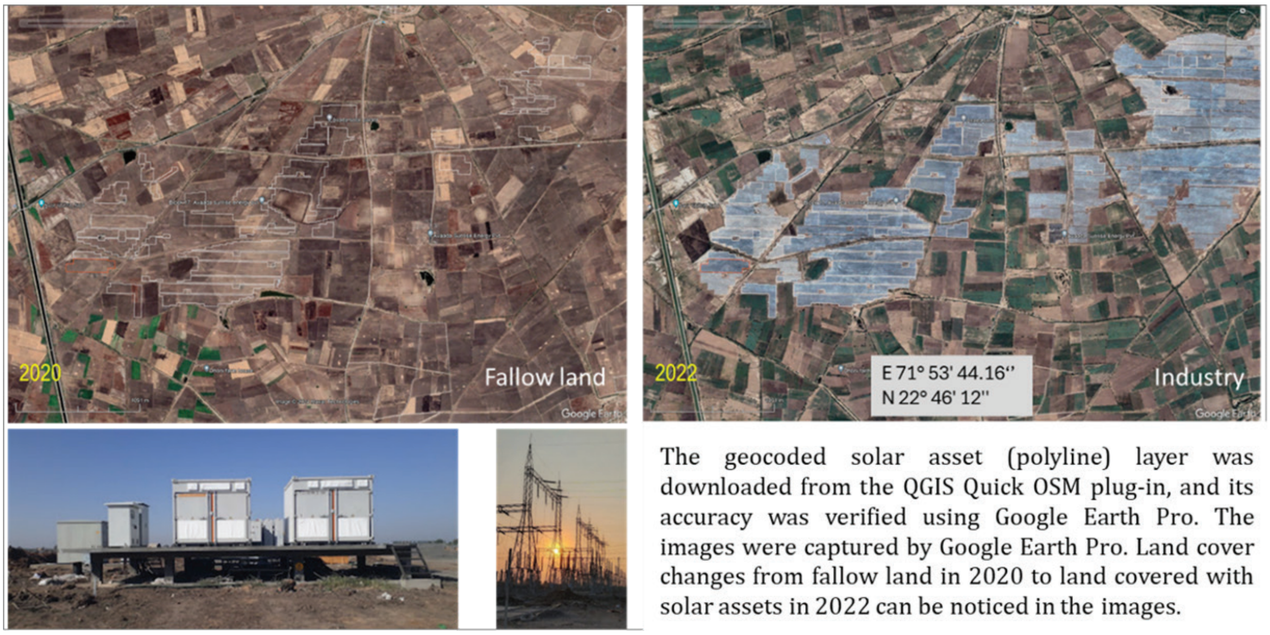


Figure 4: Avada solar plant, Talsana Village, Lakhtar Taluka of the Surendranagar district, Gujarat
Source: OSM & Google Earth Pro

2.2.2. DISAGGREGATION OF HAZARDS

The six hazards selected for this study were disaggregated based on their severity and impact on RE assets. Finally, the percentage of solar PV and wind assets that were exposed to these different classes of hazards were computed, and the results are presented in Section 3.2.2.

1. **Droughts:** Based on SPI values (Table 2), drought classes were considered and categorised into three zones in the four states: severe drought, moderate drought, and near normal.

2. **Floods:** Flood susceptibility zones derived from a spatial AHP (Figure 4) were directly considered to disaggregate flood output into three zones: very high, high, and moderate. Flood susceptibility zones indicate the probability of flood occurrence. The Flood Affected Area Atlas of India (NRSC, 2023) was considered to validate flood susceptibility zones and used to represent very high hazard zones.

3. **Heatwaves:** Based on the number of heatwave events experienced in different areas in the four project states, heatwaves were disaggregated into five zones, ranging from areas experiencing one heatwave event per year to five heatwave events per year

4. Tropical cyclones: To assess the presence of solar PV and wind assets in tropical cyclone damage zones in the four states, IMD's categorisation (Table 4) was considered. Consequently, wind buffer zones of tropical cyclone paths were reclassified into three categories: 60 to 90 km/h, 90 to 120 km/h, and above 120 km/h. The proportion of RE assets exposed to each heatwave zone was quantified and is discussed in Section 3.2.2.

Table 4: Characterisation of tropical cyclone winds in km/h

Category	Sustained winds (3-min average in km/h)
Super cyclonic storm	≥221
Extremely severe cyclonic storm	166–220
Very severe cyclonic storm	118–165
Severe cyclonic storm	89–117
Cyclonic storm	63–88
Deep depression	51–62
Depression	31–50

Source: IMD (2021)

5. Earthquakes: The seismic zonation map of India published by the Bureau of Indian Standards (IS-2002) was used to assess the proportion of RE assets exposed to different seismic zones in the four project states. The seismic zonation map was georeferenced and vectorised on a GIS platform. Based on peak horizontal ground acceleration (PGA) or peak ground velocity (PGV) during earthquake events, the whole country was divided into four seismic zones: Zones V, IV, III, and II (Ministry of Earth Sciences, 2021).

6. Hailstorms: IMD data were used to compute the average number of days with hailstorms per year from 1981 to 2010, and this was then disaggregated into three zones using the quantile classification method for the four project states. Quantile classification is a data classification method that separates a set of values into groups with the same number of values (Data classification methods, 2018).

2.3. ASSESSING VULNERABILITY AND RESILIENCE

The IPCC AR5 (2014) defines vulnerability as 'the propensity or predisposition to be adversely affected.' Further, vulnerability encompasses sensitivity, 'the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change,' and adaptive capacity, 'the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences' (Agard & Schipper, 2014).

The Arctic Council, 2016, defines resilience as 'the capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation.'

These definitions have been adapted and applied to RE assets in the four project states (Figure 5). An indicator-based quantitative vulnerability assessment was undertaken to answer 'What is an RE asset's predisposition to be adversely affected by extreme climate events?' and a qualitative resilience assessment was undertaken to answer 'What is the capacity of an RE asset to cope with a hazardous event and how do asset owners, operators, and/or managers respond to maintain the assets essential structure and function?'

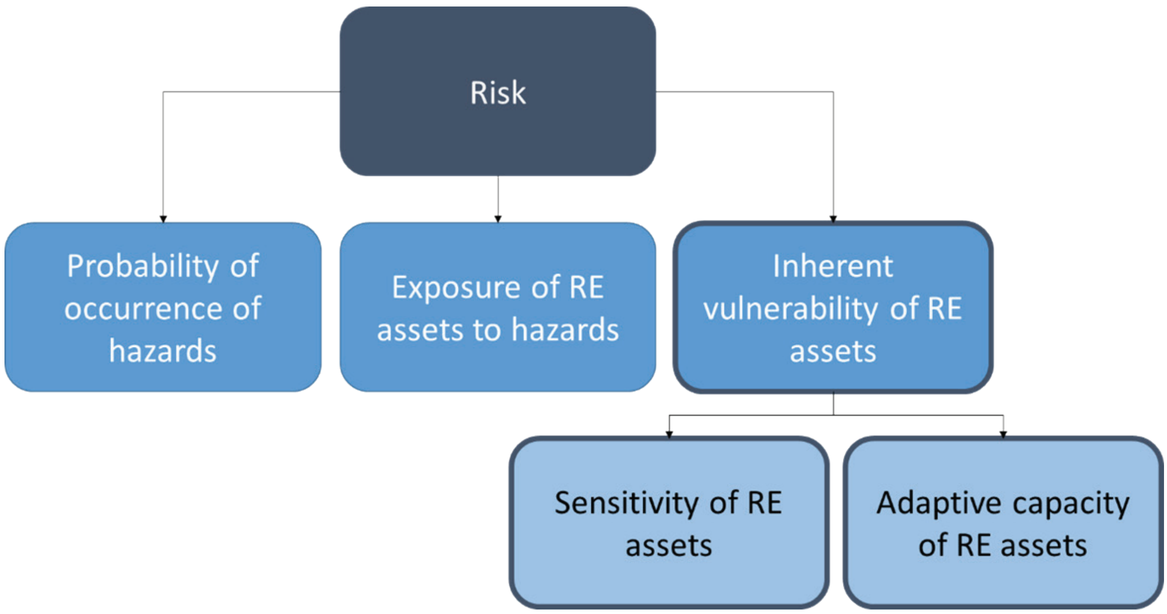


Figure 5: Application of the IPCC risk assessment framework to RE assets
Source: IPCC 2014

To assess the vulnerability and resilience of RE assets, the following broad steps were followed (Figure 6).

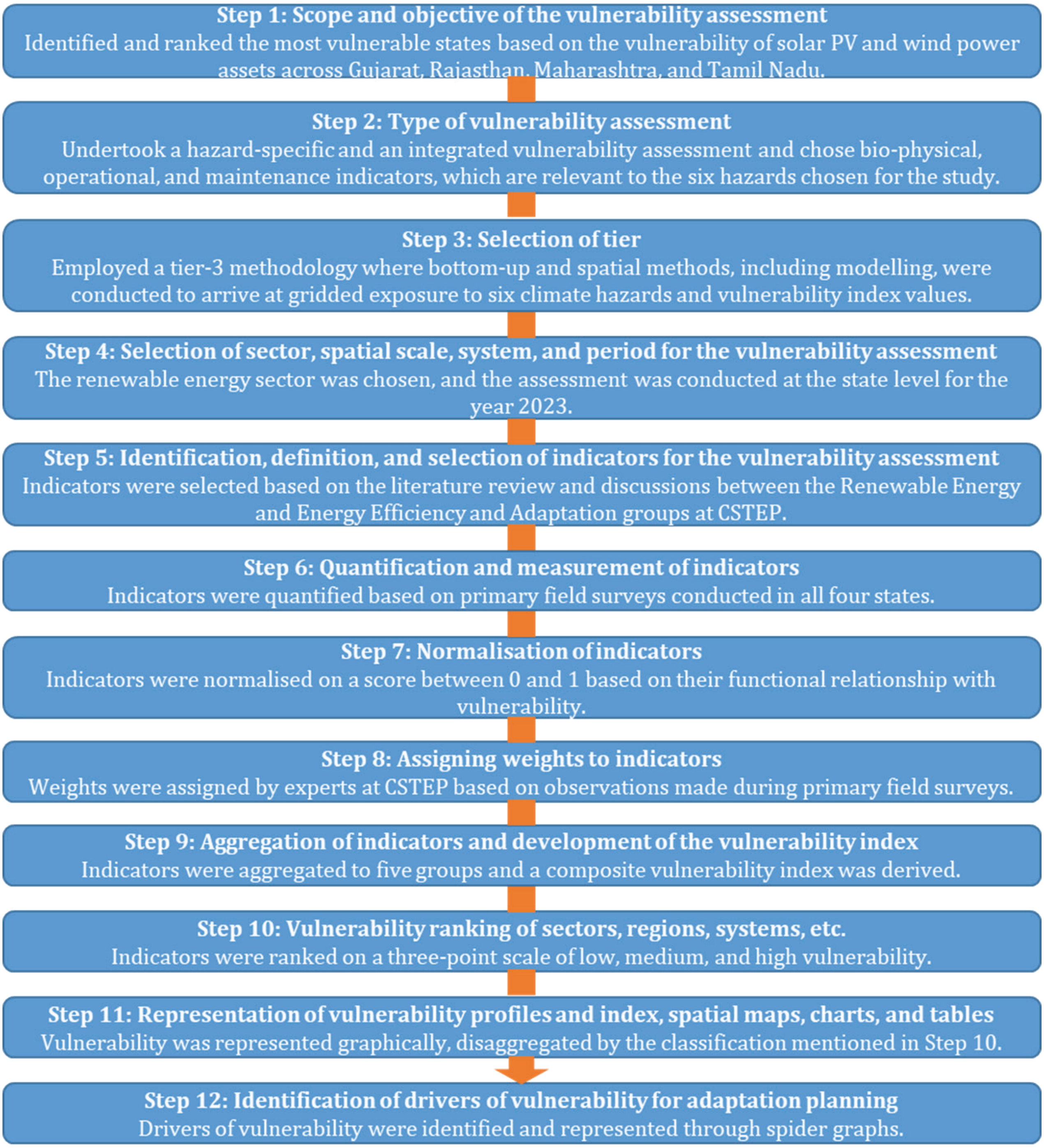


Figure 6: Broad steps to undertake vulnerability assessment of RE assets
Source: CSTEP research

Steps 1 to 4, presented in Figure 6, are self-descriptive. After Step 4, an additional step (choosing a sample) was required.

Step 4.1: Choosing a sample

A rapid assessment was conducted, given the time frame of the project. RE assets were stratified according to whether they were ground-mounted solar PV or wind projects. Based on CSTEP's experience in engaging with RE developers, 15 RE plants were surveyed, 11 of which were site visits and 4 were online meetings with site managers (Table 5). Furthermore, the capacity of RE plants sampled ranged between 15–360 MW and 30–101 MW for solar and wind plants, respectively. Figure 7 presents some pictures taken during site visits.

Table 5: Number of sites visited (in person or virtually) to undertake surveys

State	Solar PV		Wind	
	Site visit	Virtual	Site visit	Virtual
Gujarat	3	1	0	1
Maharashtra	1	0	1	0
Rajasthan	2	1	2	1
Tamil Nadu	1	0	1	0

Step 5: Identification, definition, and selection of indicators for the vulnerability assessment

As vulnerability is a function of the sensitivity and adaptive capacity of a system, indicators representing these two functions were identified and selected in relation to RE assets for quantification through surveys. Indicators need to represent key characteristics of RE assets to gauge their inherent vulnerability. A rapid literature review and expert judgement were used to identify and select indicators. An indicator is categorised as a sensitivity indicator when it represents characteristics of the RE asset that would increase the impact of a climate hazard on the asset. It helps gauge the robustness of RE assets.

Similarly, an indicator is categorised as an adaptive capacity indicator when it represents characteristics of RE assets that would allow the asset to quickly recover from climate hazard impacts and continue to produce electricity. Thus, adaptive capacity indicators of RE assets or systems reflect the adaptability, recovery, and redundancy measures in place. These characteristics are crucial to ensure the continuity and recovery of RE operations during adverse conditions.

Five indicators were selected for solar PV and wind plants, with varying numbers of sub-indicators based on the data collected through surveys. One indicator directly represents sensitivity, and four indicators represent the adaptive capacity of RE plants.

Figure 7: Pictures taken during site visits to solar PV and wind assets in the four project states

The indicators, the sub-indicators, and the rationale for selection are as follows:

1. Distance to sub-stations: This indicator represents sensitivity. It was measured in kilometre and selected for both solar PV and wind plants. Shorter distances between RE assets and the grid reduce the vulnerability of transmission infrastructure, such as connection cables, to external factors. For instance, during extreme weather conditions, shorter transmission distances are less likely to experience disruptions because of damage to power lines or other equipment.

2.Structural integrity: This indicator has four sub-indicators for both solar PV and wind plants and represents adaptive capacity. However, for solar PV, this indicator combines two sensitivity and two adaptive capacity sub-indicators.

a. Sub-indicators for solar PV: The four sub-indicators are degradation loss (%), the downtime of an asset (days/year), the cooling of solar panels (yes/no), and the presence of flood-control measures (yes/no).

i. Degradation loss: This sub-indicator represents sensitivity. It was measured as the percentage of degradation that solar PV panels undergo with time because of exposure to external stressors. Plants with solar PV panels that have a larger percentage of degradation loss are more likely to stop functioning when exposed to extreme climate events.

ii. Downtime of an asset: This sub-indicator also represents sensitivity. The unit of measurement was days per year. Downtime is the amount of time that an RE asset is unable to generate power. This could be because of operational issues, technical faults, or other external factors. A higher downtime may indicate frequent equipment failures, poor quality of materials used, improper maintenance practices, more frequent extreme events, and so on.

iii. Cooling of solar panels: This is an adaptive capacity sub-indicator representing the ability of RE asset operation and maintenance (O&M) teams to deal with a warming future. Extreme heat can have a significant impact on the degradation loss of solar PV panels. This sub-indicator measured whether solar panels required cooling and if they were cooled with water to maintain panel integrity.

iv Presence of flood-control measures: This is also an adaptive capacity sub-indicator. Apart from a warmer future, we are also looking at a wetter future. Floods can cause significant damage to solar PV plants and hinder O&M. Thus, this sub-indicator measured the preparedness of RE assets to mitigate the impacts of floods and maintain the structural integrity of the asset.

b. Sub-indicators for wind: The four sub-indicators are power generation forecasting (days/year), maximum wind speed the blade can handle (m/s), maximum wind speed that the tower can handle (m/s), and the presence of flood-control measures (yes/no). All four sub-indicators represent adaptive capacity.

i. Power generation forecasting: This sub-indicator was quantified as the number of days in a year a wind plant forecasts its power generation potential. It provides a snapshot of the plant's ability to prepare and plan for optimal power generation and schedule required downtime for maintenance to preserve structural integrity.

ii. Maximum wind speed the blade can handle: Given that India is expected to experience more frequent and severe tropical cyclones because of climate change, this sub-indicator gauges a wind plant's capacity to maintain structural integrity when exposed to extreme wind speeds. Wind plants with assets that can handle higher wind speeds (m/s) are less likely to be damaged and are thus less vulnerable.

iii. Maximum wind speed that the tower can handle: This sub-indicator also gauges a wind plant's capacity to maintain structural integrity when exposed to extreme wind speeds (m/s).

iv. Presence of flood-control measures: The rationale and unit of measurement for this sub-indicator is the same as that provided for solar assets.

3. Redundancies: To ensure the smooth functioning of RE assets during adverse climatic conditions, redundancy measures are essential. For the quantification of this indicator, two sub-indicators were identified: the availability of redundant water supply and the presence of on-site backup power facilities. All sampled solar plants had on-site backup power, and this sub-indicator was not considered for assessing vulnerability at a state level in terms of solar power generation. This is an adaptive capacity indicator.

a. Availability of redundant water supply: Solar panels need to be cleaned, mostly with water. Access to clean water for on-site human resources is essential for their health, well-being, and the smooth O&M of RE assets. Availability and access to a sufficient and continuous supply of water are paramount. The lack of redundant water supply, along with the projection of more intense and longer durations of dry spells and droughts, will impact the O&M of solar assets, making them more vulnerable.

b. Presence of a backup power facility: This sub-indicator was considered for the vulnerability assessment of wind plants as wind turbines generally require a small current to run their electromagnets. During periods of power failure, a backup power facility is essential to power the turbines to ensure electricity is generated.

4. Robustness: The robustness of solar and wind plants was assessed by considering four sub-indicators: the number of external audits; the number of regular audits; the number of internal quality checks undertaken per year; and the percentage of International Organization for Standardization (ISO), Bureau of Indian Standards (BIS), Occupational Safety and Health Administration (OSHA), and International Electrotechnical Commission (IEC) standards that the plants adhere to. By undertaking regular audits and quality checks and complying with standards, the ability of RE assets to withstand or overcome adverse conditions is enhanced. This is an adaptive capacity indicator.

a. Number of external audits per year: External audits are extremely rigorous and will highlight all issues pertaining to the structural integrity of RE plants and their O&M. Regular and more frequent external audits will ensure that RE plants are maintained well and continue to seamlessly generate power.

b. Number of regular audits per year: Internal audits are just as important, allowing asset owners and managers to understand the challenges and opportunities to ensure continued energy production from their plants.

c. Number of internal quality checks per year: Internal quality checks allow site personnel to check for heat, hail, and wind resistance and the capacity to withstand impacts due to extreme weather conditions. This prepares plants to ensure smooth operation during such extreme conditions.

d. Percentage of ISO, BIS, OSHA, and IEC standards adhered to: Compliance with different standards ensures that materials, processes, and so on, are optimised and the plant is robust enough to withstand extreme conditions. To quantify this sub-indicator, a ratio of the number of standards adhered to by the RE plant to the total number of standards that RE plants are required to comply with was taken. The ratio is then represented as a percentage.

5. Recovery: The ability of an RE asset to recover operations is represented by this indicator. It is an adaptive capacity indicator. For solar, this indicator is composed of four sub-indicators. For wind, it is composed of two additional sub-indicators. They are workforce per unit capacity, percentage of skilled workforce, tie-ups with district weather forecasting authorities (yes/no), emergency response team training per year and the presence of on-site monitoring system in place to detect extreme weather events (yes/no), and funds set aside for the management of damages caused by extreme climate events (yes/no). All solar PV plants had on-site weather monitoring systems in place, and they also had comprehensive insurance coverage and, thus, had no need to set aside additional funds. Therefore, these two indicators were not considered for the vulnerability assessment of solar PV plants.

a. Workforce per unit capacity: The intermittent nature and technical O&M of solar and wind assets demand a dedicated team responsible for monitoring and regulating power generation at the site.

b. Percentage of skilled workforce: Having an adequate number of engineers and/or operators experienced in the O&M of RE assets is essential and can reflect the ability of RE assets to recover and continue operations when conditions are extreme.

c. Tie-ups with district weather forecasting authorities (yes/no): District collectors chair District Disaster Management Committees and, thus, have access to disaster forecasts, which they share with all other relevant departments and stakeholders. Having tie-ups with such departments can help RE plants prepare for disasters and mitigate impacts.

d. Emergency response team training sessions per year: Having well-trained emergency response teams can significantly lower the impact of disasters and allow faster recovery for continued power generation.

e. Presence of an on-site monitoring system in place to detect extreme weather events (yes/no): The installation of weather monitoring systems on-site can act as early warning systems and allow on-site teams to prepare and lower impacts of potentially hazardous events.

f. Funds set aside for management of damages caused by extreme climate events (yes/no): For repairs after disasters, having earmarked funds available to site managers can expedite recovery.

Step 6: Quantifying indicators

Indicators were quantified through structured questionnaires (Appendix B, Table 25 and 26) that were used to interview site managers during field visits or online meetings of sample RE assets. The information from these questionnaires was then cleaned and processed to assess vulnerability. The data used are presented in Appendix B, Table 27 and 28.

Step 7: Normalisation of indicators

Because different physical, institutional, or governance-centric variables with different units are involved, they are required to be normalised to dimensionless units. Normalisation will be based on their functional relationship with vulnerability to facilitate aggregation into a vulnerability index (VI).

Two types of functional relationships are possible:

A positive relationship, where vulnerability increases with an increase in the value of the indicator. In this case, we say that the variables have a direct and positive functional relationship with vulnerability, and the normalisation is performed using the following equation:

$$x_{ij} = \frac{X_{ij} - Min\, i\, X_{ij}}{Max\, i\, \{X_{ij}\} - Min\, i\, X_{ij}} \text{ ---------------------------- } (1)$$

where Xij is the value of the indicator j corresponding to the region i. In (1), Xij is the variable that is being normalised, and xij is the normalised value of Xij. All xij scores will lie between 0 and 1. Value 1 will correspond to the state with maximum sensitivity, and 0 will correspond to the state with minimum sensitivity.

Similarly, indicators can have a negative relationship, where vulnerability increases with a decrease in the value of the indicator. Here, indicators have a negative or inverse functional relationship with vulnerability. In this case, the normalised score is computed using the following equation:

$$x_{ij} = \frac{Max\, i\, X_{ij} - X_{ij}}{Max\, i\, \{X_{ij}\} - Min\, i\, X_{ij}} \text{ --------------------------- } (2)$$

Steps 8–10: Assigning weights, aggregation, and ranking

Not all indicators contribute to the vulnerability of a system equally. Furthermore, as there are four indicators that are composed of varying number of sub-indicators, unequal weights were assigned to indicators to assess vulnerability. Expert judgement was used to assign weights for the indicators selected (Appendix B, Table 29 and 30). The weights were then multiplied with the normalised indicator values and aggregated through a simple summation to obtain a VI.

VI values were used to rank the four project states on a three-point scale of high, moderate, and low vulnerability. The drivers of vulnerability identified through this assessment have been used to bolster policy recommendations presented in Section 4.

Apart from the VI computation and ranking of states, several insights into the inherent vulnerability and resilience of RE assets were gleaned from the surveys that were undertaken as part of this study. They are presented in Sections 3.3.3 and 3.3.4. Vulnerability assessment Steps 11 and 12 are presented in Sections 3.3.1 and 3.3.2.

2.4. ASSESSING RISK AT THE STATE LEVEL

The risk framework introduced by the IPCC in 2014, also utilised in IPCC AR6 (IPCC, 2022), is illustrated in Figure 8. In the context of climate change impacts, the IPCC defines risk as the outcome of dynamic interactions among climate-related hazards, the exposure of human or ecological systems to these hazards, and the vulnerability of those systems. The elements of hazards, exposure, and vulnerability are all prone to uncertainties regarding their magnitude and likelihood of occurrence. Furthermore, these factors can undergo changes over time and across different geographical areas because of socio-economic developments, adaptation responses, and human decision-making.

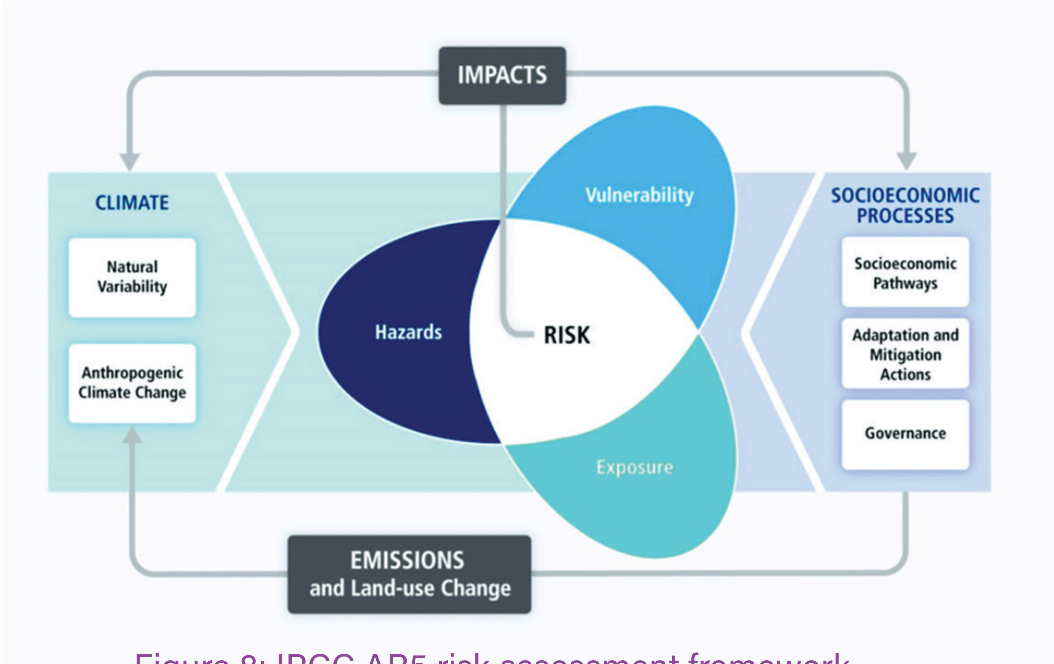


Figure 8: IPCC AR5 risk assessment framework
Source: IPCC AR5 (2014)

Risk assessment employs hazard, exposure, and vulnerability assessments conducted for the four states to finally produce a unique risk score for each state. These scores are then used to rank the states on a three-point scale of high, moderate, and low risk to the hazards selected for this study.

Risk is computed as the product of the probability of occurrence of a hazard, exposure, and vulnerability, as shown in the following equation:

$$Risk = \sqrt[3]{(P \times E \times V)} \text{ ---------------------------- } (3)$$

where P is the probability of occurrence of a hazard, E is exposure, and V is vulnerability.

Given that the present study employs six hazards, the risk score will be presented separately for each hazard. Therefore, (3) will be modified as follows:

$$Risk_{(hazard)} = \sqrt[3]{(P \times E \times V)} \text{ ---------------------------- } (4)$$

where hazards are droughts, floods, heatwaves, tropical cyclones, hailstorms, and earthquakes.

The methodology for the computation of the probability of occurrence of hazard, exposure, and vulnerability is detailed below:

Probability of occurrence of a hazard: To arrive at the probability of occurrence of a hazard at the state level, the general formula that is used is as follows:

$$P = \frac{Number\ of\ hazard\ events}{Time\ period} \text{ --------------------------- } (5)$$

where an 'event' is defined based on definitions provided by various governmental and research institutions (Table 6) and the respective time periods considered are accessed from Table 1.

Exposure: The exposure analysis is conducted by overlaying the total number of solar and wind assets in the area impacted by the six different hazards for each state, as displayed in Section 3.2.2. Only those assets that are within the hazard impact zones are considered to be exposed.

Table 6: Conditions to be met to classify an area as a 'hazard impact zone'

Hazard	Conditions to qualify as a 'hazard zone'
Droughts	SPI values <–1
Floods	The occurrence of a flood event based on the 'Flood Affected Area Atlas of India' (2023)
Heatwaves	≥3 events per year
Tropical cyclones	>90 km/hr wind speed
Hailstorms	>0.6 days/year
Earthquakes	≥ Zone IV

Exposure is calculated as follows:

$$Exposure = \frac{Total\ number\ of\ assets\ within\ the\ hazard\ zone}{Total\ number\ of\ assets\ within\ the\ state} \text{ --------------------------- } (6)$$

2.5. LITERATURE REVIEW TO INFORM POLICY RECOMMENDATIONS

Relevant literature such as journal articles, policy briefs, guidelines, and O&M plans were collected. A detailed search plan with keywords and timelines was prepared to guide the literature collection and review process. The search plan was designed for three different sections: solar power plants, wind power plants, and a combination of both solar and wind power plants. The keyword 'climate resilience' was included in every search plan for all the three sections.

Searches were made one by one using ten different keywords: ‘Design standards’, ‘Climate risk assessment’, ‘Climate hazards’, ‘Standard operating procedures’, ‘Good practice guidelines’, ‘Operation and maintenance’, ‘Disaster management’, ‘Infrastructure resilience’, ‘Recommendation for resilient RE assets’, and ‘Emergency response plan’. The advanced search option in Google Scholar was used to find the relevant literature, with a defined timeline of 2020–2023.

Out of the 4,884 results displayed (solar: 2,142, wind: 2,239, and combination: 503), titles and abstracts/summaries were screened for relevance, and 170 (solar: 105, wind: 33, and combination: 32) were selected for review. Only open-access literature, which amounted to 150 papers/reports, was reviewed. Around 25 journal articles that were referenced within the 150 papers were also reviewed. In addition to the Google Scholar search methodology, website articles, good practice guidelines, and O&M plans were reviewed. They were mainly obtained through Google searches and were sorted by relevance, that is, only the literature which contained information on power infrastructure’s resilience, structural integrity, impacts of hazards on RE power infrastructure, and the resilience of solar PV and wind power plants were selected. Literature was reviewed for policy recommendations that were then prioritised using the drivers of vulnerability and risk.

3. RESULTS

3.1. SPATIAL EXTENT OF HAZARDS

A rise in the frequency and severity of extreme weather events makes it imperative for the RE industry to implement adaptation and resilience-building strategies to buffer the impacts of natural disasters. All potential hazards that occurred in the recent past in all four states are presented, along with spatial maps. Appropriate planning, design, and maintenance can aid in reducing the impacts on and increasing the resilience of the RE industry in areas affected by calamities.

3.1.1. DROUGHTS

The SPI analysis revealed that most of the study area experienced near-normal conditions from 1991 to 2022. The Gulf of Kachchh's coastal area in Gujarat experienced severe drought, and the state's central region was marked by moderate drought. Some parts of central Maharashtra experienced moderate to severe drought. Tamil Nadu did not experience any drought conditions during the considered timescale (Figure 9).

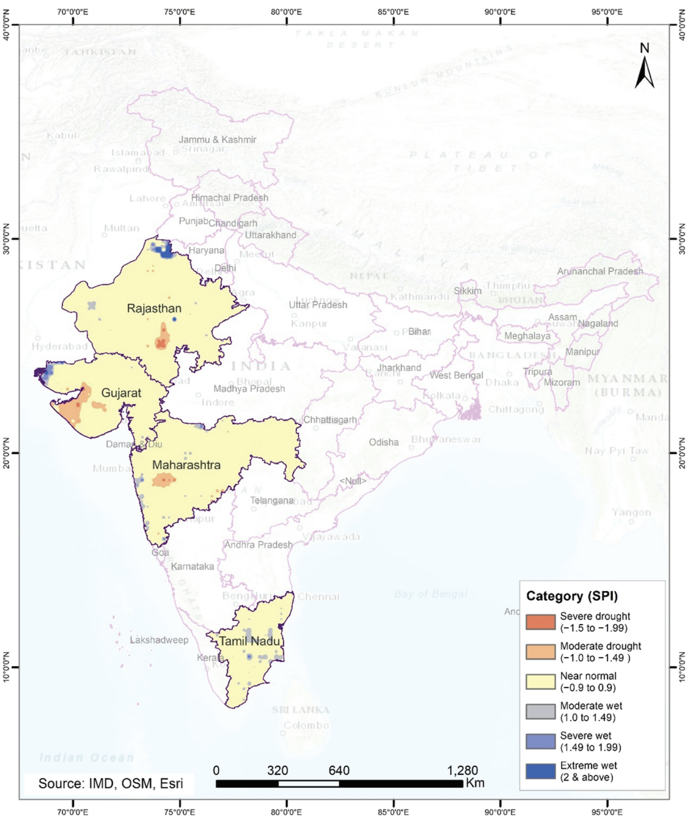


Figure 9: Drought Index
Source: CSTEP research

3.1.2. FLOODS

State-wise flood susceptibility analysis has allowed for the classification of grids into three zones: very high, high, and moderate flood susceptibility.

The analysis revealed that 20% of Gujarat was highly susceptibility to floods. It was followed by 10%, 7%, and 2% of areas having a high susceptibility to flooding in Maharashtra, Rajasthan, and Tamil Nadu, respectively. A significant area (55% to 70%) in all four states was categorised as having moderate susceptibility to floods. Small fractions of areas in Gujarat (0.6%) and Maharashtra (0.26%) were under very high susceptibility (Figure 10).

Flood Affected Area Atlas of India report by NRSC (2023) revealed that a total of 4.24% area of Tamil Nadu, 2.64% of Gujarat, 0.76% of Maharashtra, and 0.45% of Rajasthan were affected by floods from 1998 to 2022 (Figure 11). It is important to note the differences between flood susceptibility mapping and areas affected by floods using satellite imagery. This study considered both NRSC flood-affected area maps and flood susceptibility maps for exposure analysis.

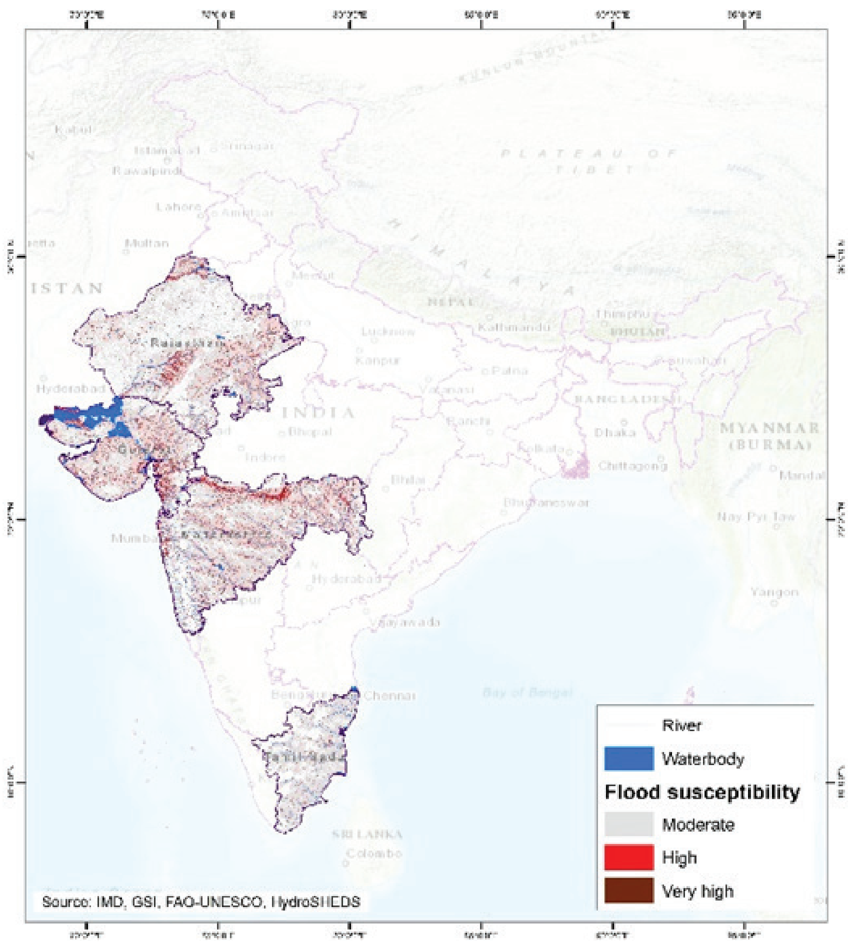


Figure 10: Flood susceptibility map
Source: CSTEP research

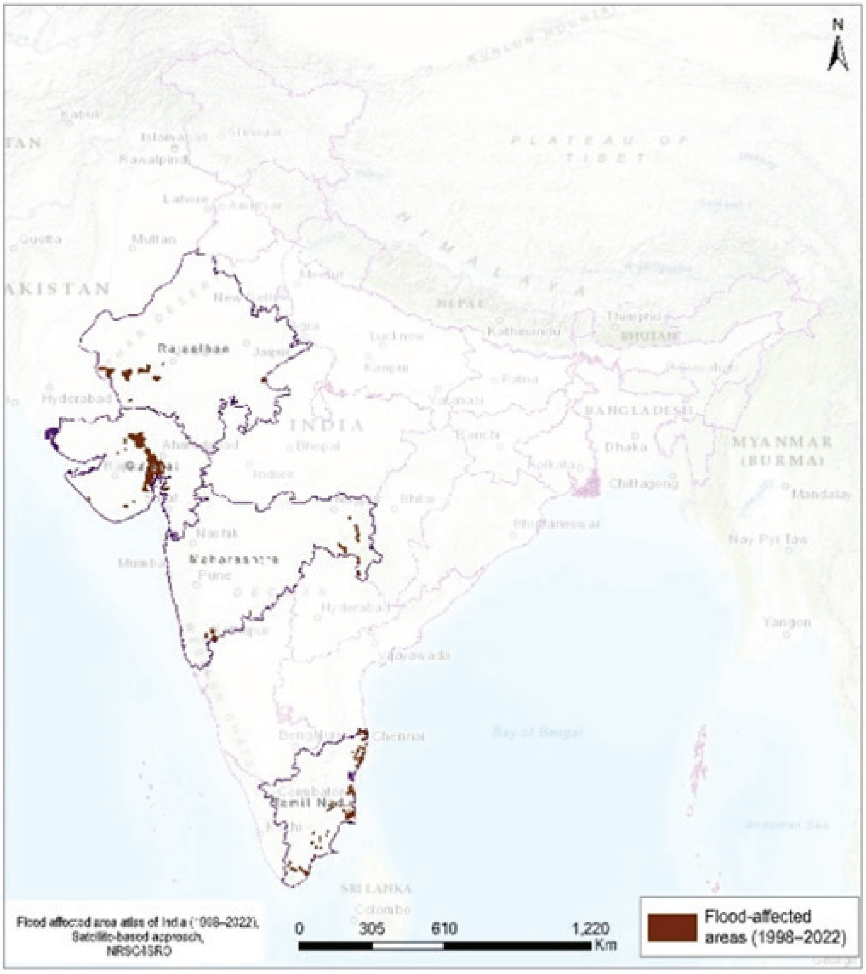


Figure 11: Flood-affected area map
Source: Flood Affected Area Atlas of India (NRSC,

3.1.3. HEATWAVES

The northern part of Rajasthan experienced the greatest number of heatwave events with up to five events annually for two or more consecutive days, whereas the southern part had three heatwave events annually. The Maharashtra, Vidarbha, and Madhya Maharashtra regions were more susceptible to heatwaves and had experienced four to five events per year, whereas the coastal regions experienced just one event per year. Gujarat and Tamil Nadu experienced one event annually, except the northern tip of Tamil Nadu, which experienced two events (Figure 12).

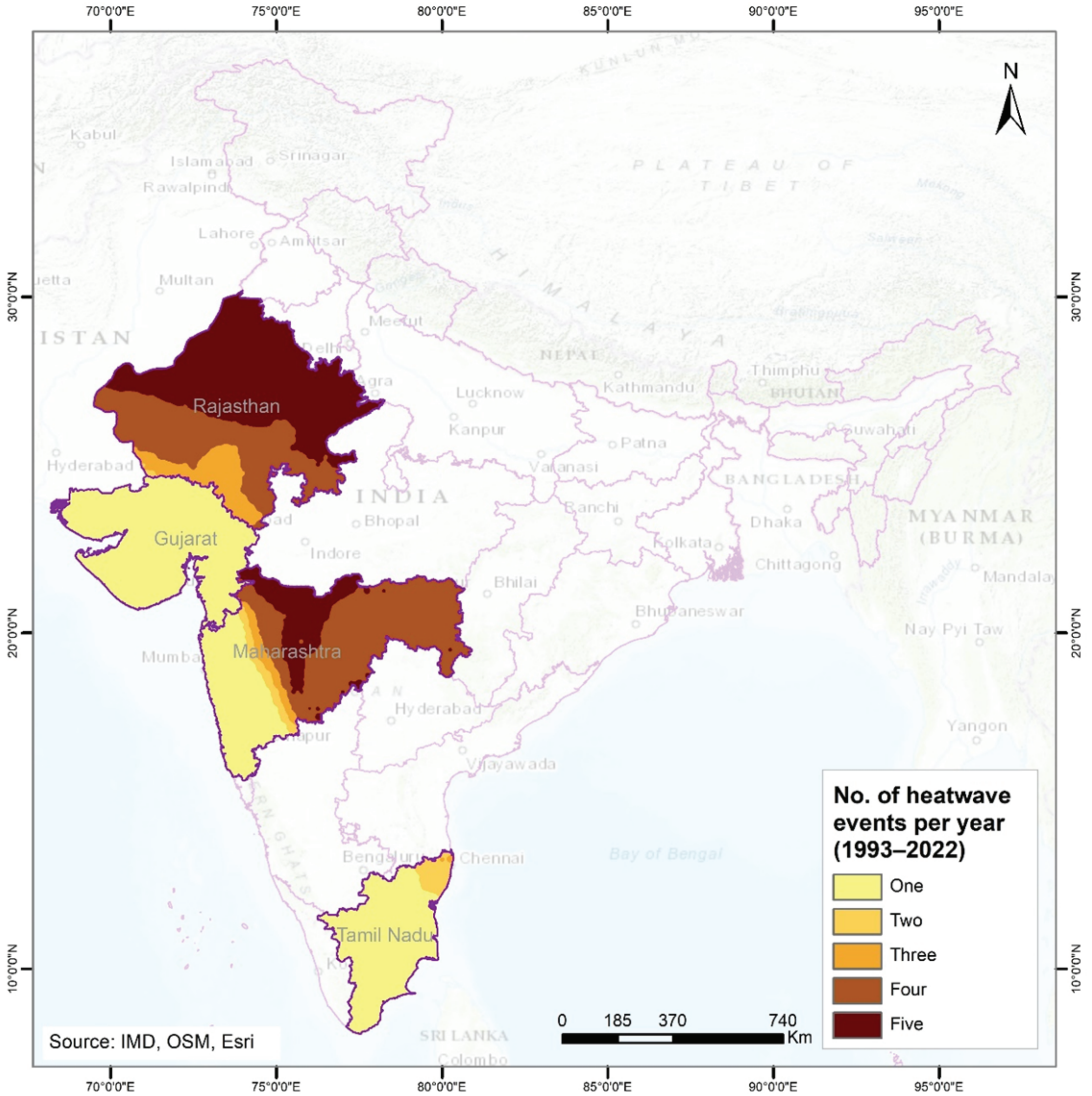


Figure 12: Number of heatwave events per year (1993–2022)
Source: CSTEP research

3.1.4. TROPICAL CYCLONES

Since 2011, 53 tropical cyclones have formed over the Indian Ocean, of which 39 have crossed over the Indian coast (Figure 13).

The coast of Tamil Nadu experienced five tropical cyclones over the past ten years: Vardah (Category 2), Nivar (Category 1), Nada (Category 1), Mandous (Category 2), and Gaja (Category 1). The state of Maharashtra experienced only one cyclonic event, which was Nisarga (Category 1). Additionally, two cyclonic events were noted to have crossed between the Gujarat and Rajasthan regions (Appendix A, Table 24) The map emphasises cyclones that have wind speeds above 60 km/h in the buffer area, which is as per the IMD norms. The entire area of Tamil Nadu experienced tropical cyclones with wind speed exceeding 60 km/h. Similarly, Gujarat was affected, apart from a small area in the eastern region. The entire coastal and the northeastern area of Maharashtra experienced wind speeds of 60 km/h. Additionally, two tropical cyclone tracks left their mark in the southwestern part of Rajasthan. Overall, tropical cyclone hazard mapping revealed a higher number of tropical cyclone tracks passing over Tamil Nadu.

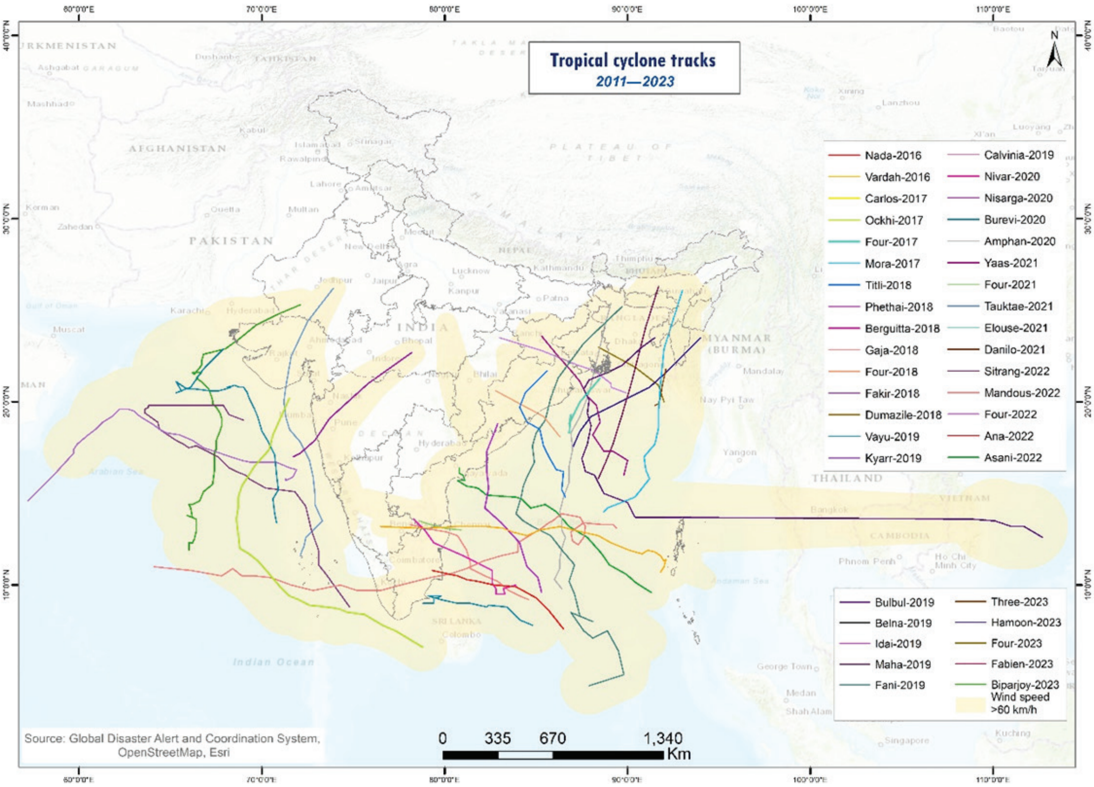


Figure 13: Tropical cyclone tracks
Source: CSTEP research

3.1.5. EARTHQUAKES

A higher number of earthquakes (clusters) were observed in the northwestern region of Gujarat with a magnitude less than 4.80 and in the southern area of Gujarat with a magnitude over 4.80. Earthquake magnitudes between 4.78 and 4.80 were observed along the boundary of Maharashtra. Like Gujarat, a cluster of earthquakes were observed in the southern coastal part of Maharashtra, with two that had magnitudes of above 5. These two destructive earthquakes occurred over Osmanabad, Solapur, and Latur districts. The desert regions of Rajasthan and the southern regions of the state experienced earthquakes that were over a magnitude of 5. Earthquakes with a magnitude of less than 5 have occurred in the northwest region of Rajasthan. The least number of earthquakes was noticed in Tamil Nadu from 1989 to 2019 (Figure 14).

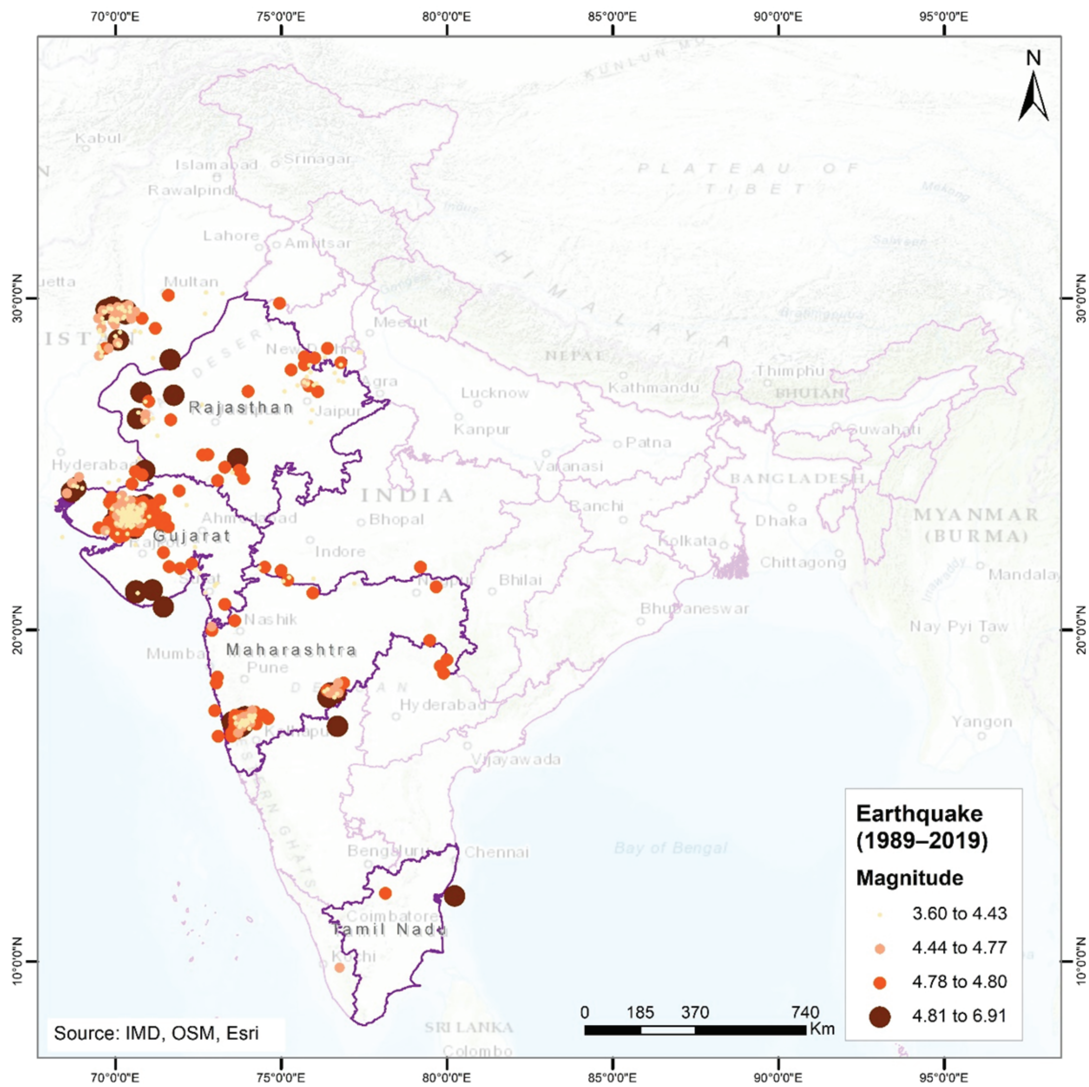


Figure 14: Location and magnitude of earthquakes in the four project states
Source: CSTEP research

3.1.6. HAILSTORMS

Based on the hailstorm frequency per annum from 1981 to 2010 (IMD, 2020), the highest frequency was observed in Rajasthan, the northern part of Gujarat, the eastern boundary of Maharashtra, and the western part of Tamil Nadu. Coastal regions of all states witnessed a lower hailstorm frequency range. Conversely, the northern segments of Gujarat and the central zones of Maharashtra were characterised by moderate incidence of hailstorms (Figure 15).

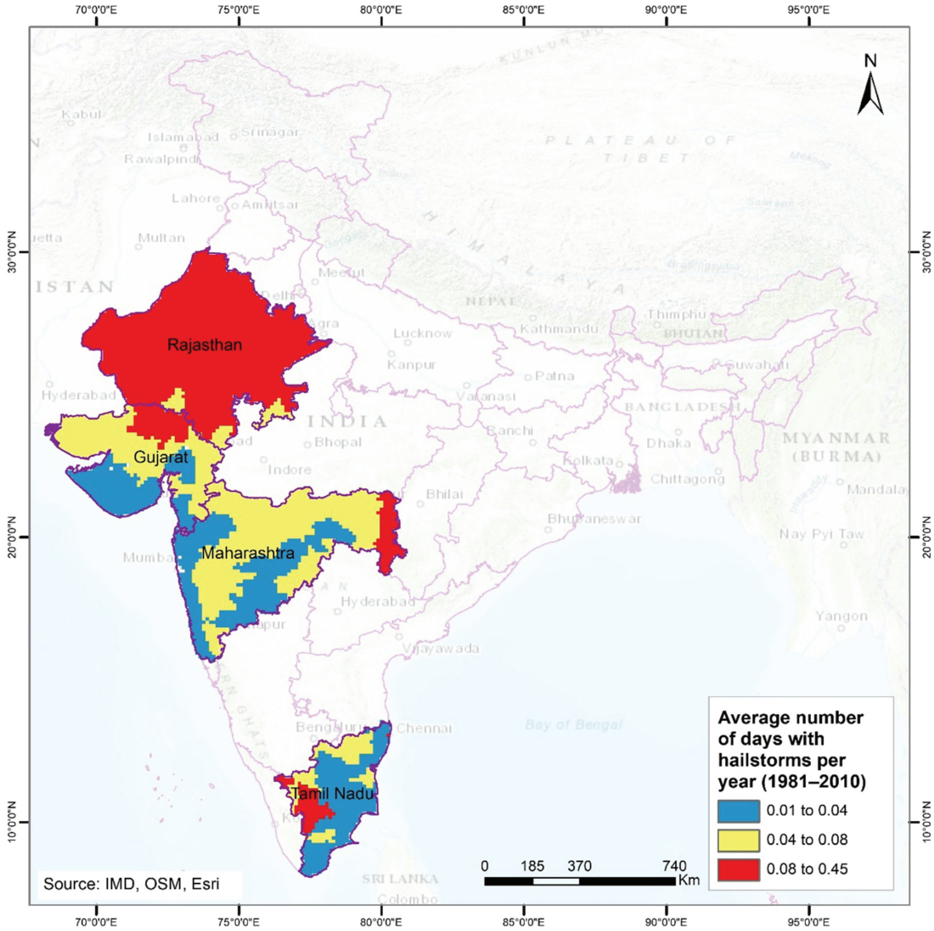


Figure 15: Average number of days with hailstorms in the four project states
Source: CSTEP research

3.2. EXPOSURE OF SOLAR PV AND WIND ASSETS TO HAZARDS

The total number of solar PV and wind assets in the four project states and the percentage exposed to different classes of hazards were computed on a GIS platform, and the results are presented in the subsequent sections.

3.2.1. SOLAR PV AND WIND ASSETS IN THE STUDY STATES

As per the data, Rajasthan had the highest number of solar PV assets (4,767). It was followed by Tamil Nadu with 3,042, Maharashtra with 1,925, and Gujarat with 1,123 solar PV assets (Figure 16). The highest number of wind turbines were installed in Tamil Nadu (12,068), followed by Gujarat, Maharashtra, and Rajasthan (Figure 17).

Among the four states, the Dhule district in Maharashtra had the highest number of solar PV assets (with approximately 700 assets), followed by Jodhpur in Rajasthan (with 650 assets).

Over 60% of the districts in Tamil Nadu, Maharashtra, and Gujarat are actively contributing to solar power generation. . Tirunelveli in Tamil Nadu had the highest number of wind assets (4,000 wind turbines). Similarly, the Jaisalmer district in Rajasthan, Kachchh in Gujarat, and Satara in Maharashtra were the highest producers of wind energy.

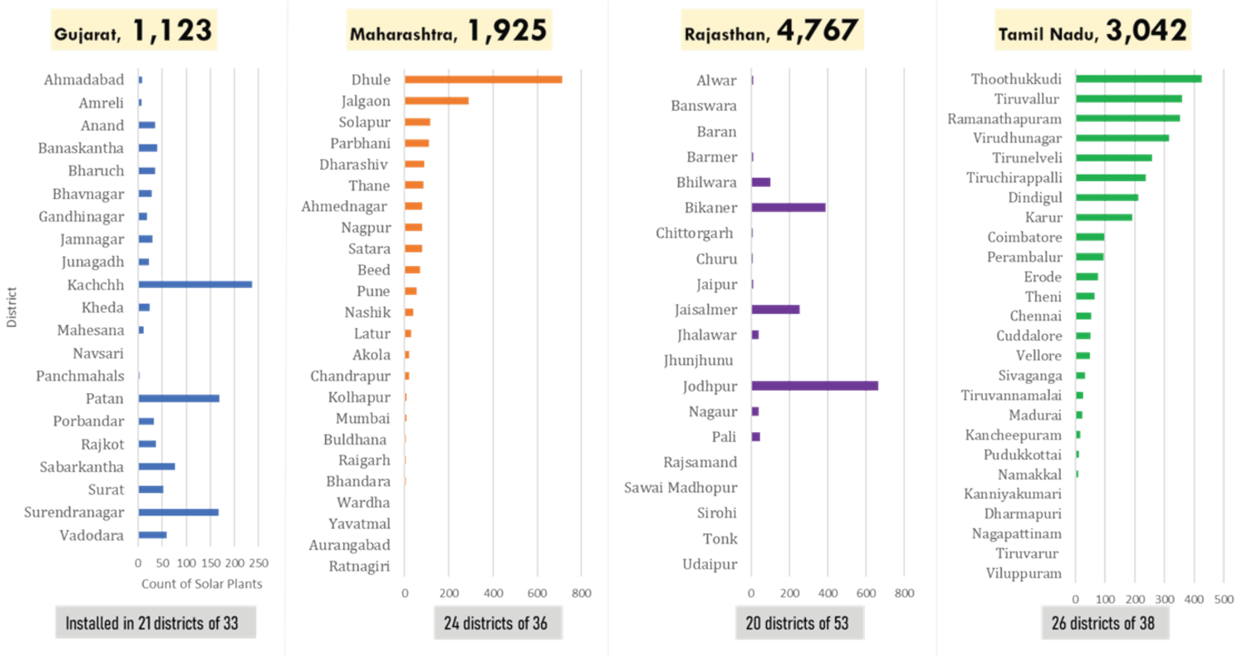


Figure 16: District-wise solar PV assets in the four states

Source: CSTEP research

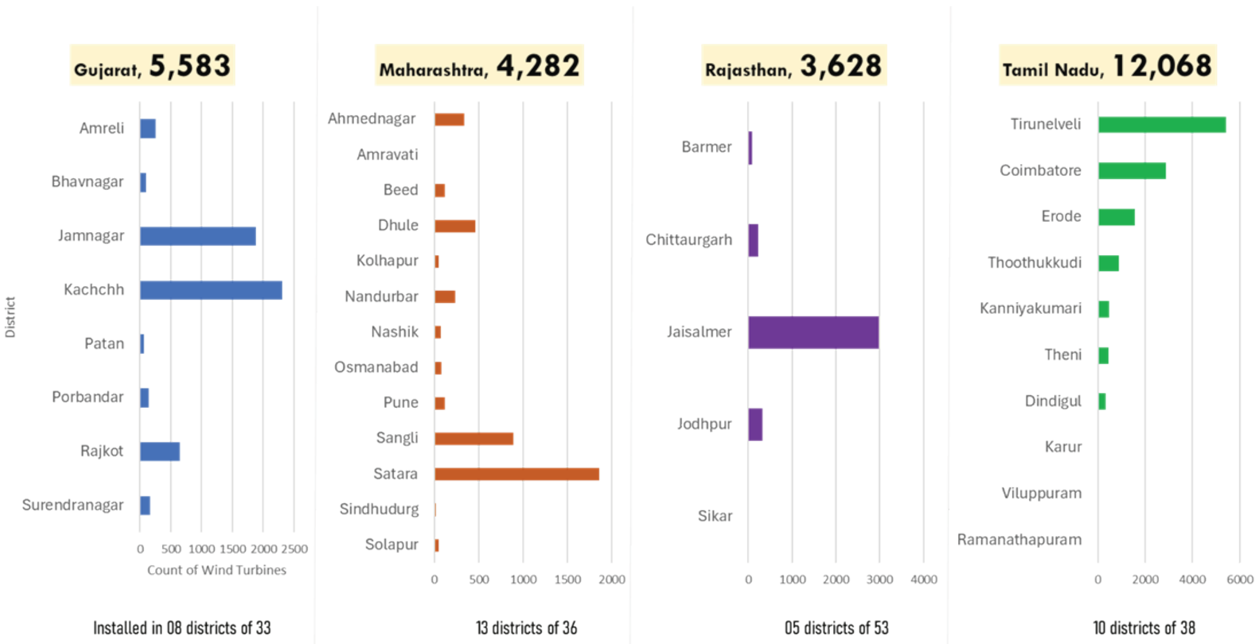


Figure 17: District-wise installed wind turbines in the four states

Source: CSTEP research

3.2.2. PERCENTAGE OF SOLAR PV AND WIND ASSETS EXPOSED TO HAZARDS

This analysis was done on a GIS platform, and the results for each of the six hazards are presented. These results are also used to compute the risk of solar PV and wind assets (Section 3.4).

1. Droughts

a.Solar PV

State-wise exposure analysis of solar PV assets to droughts revealed that more than 92% of assets were not exposed. In terms of severe to moderate drought, only 7.2%, 1.35%, and 0.2% of assets were exposed in Gujarat, Maharashtra, and Rajasthan. No assets were exposed to droughts in Tamil Nadu (Table 7 and Figure 18).

b.Wind turbines

State-wise exposure analysis of wind turbines revealed that more than 98% of assets in Maharashtra and Tamil Nadu were not exposed to droughts. Similarly, 76% and 48% of assets in Rajasthan and Gujarat, respectively, were not exposed to droughts. In terms of moderate to severe droughts, 42% and 1.45% of assets were exposed in Gujarat and Maharashtra, respectively (Table 7 and Figure 19).

Table 7: RE assets exposed to droughts

Drought type	Gujarat		Maharashtra		Rajasthan		Tamilnadu	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
Severe drought	-	92	-	-	8	-	-	-
Moderate drought	81	2253	26	62	-	-	-	-
Near normal	1033	2626	1899	4119	4758	2772	3000	11945
Total number of assets exposed to severe and moderate droughts	81	2345	26	62	8	-	-	-
State-wise total number of assets	1123	5583	1925	4282	4767	3628	3042	12068
Percentage of assets exposed to severe and moderate droughts	0.07	0.42	0.01	0.01	0.002			

Source: CSTEP research

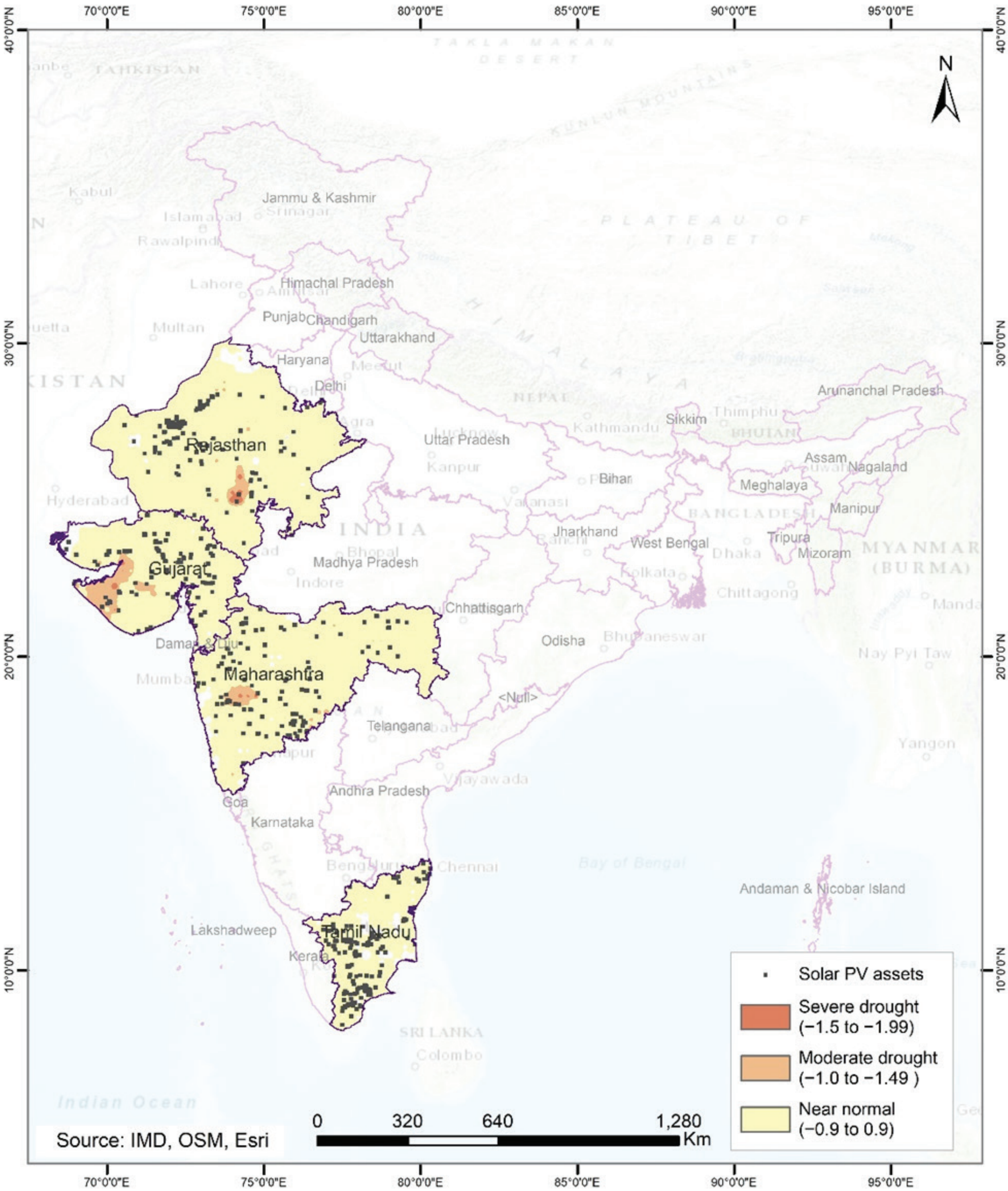


Figure 18: Exposure of solar PV assets to droughts
Source: CSTEP research

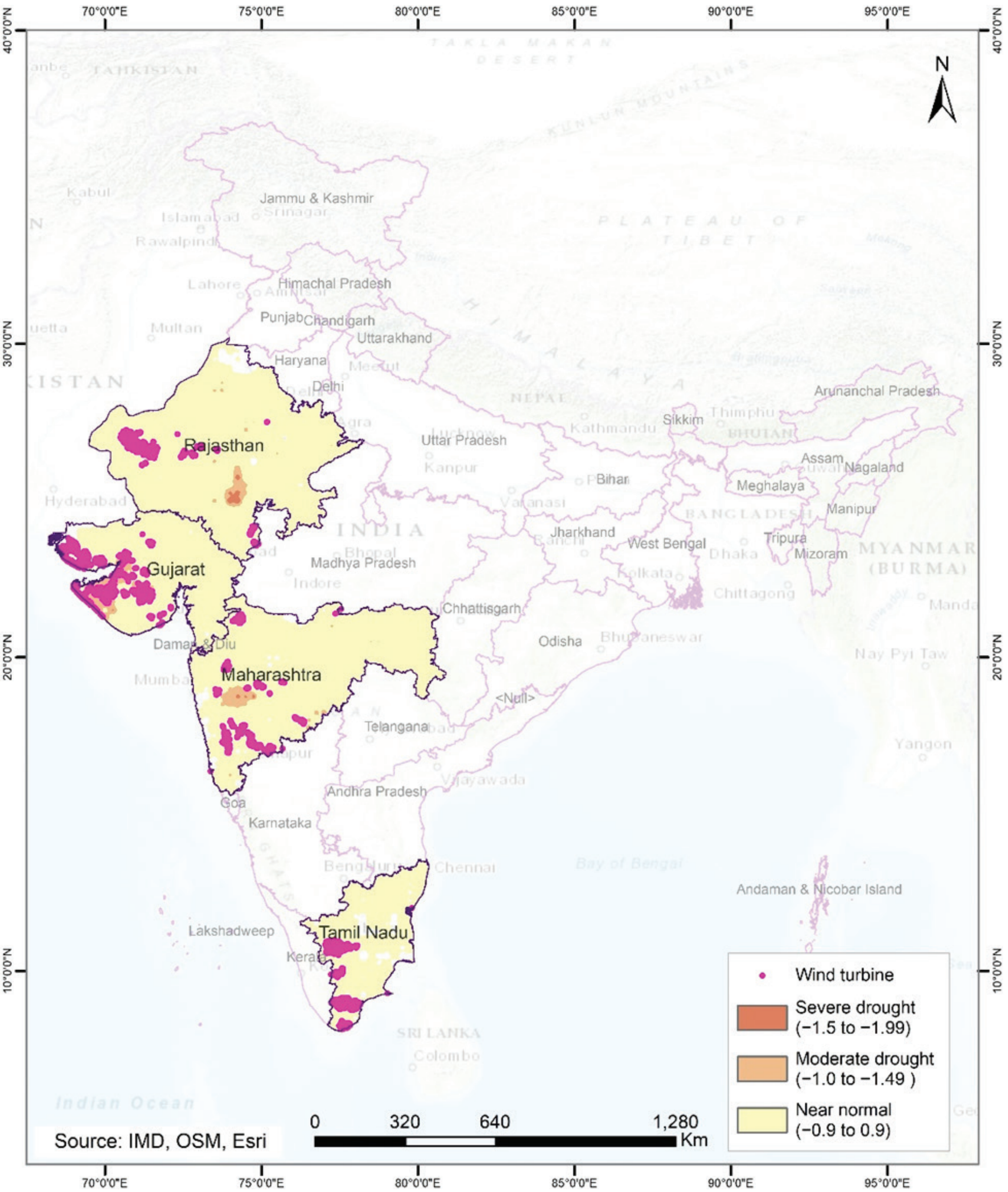


Figure 19: Exposure of wind turbines to droughts

Source: CSTEP research

2. Floods

a. Solar PV

State-wise exposure analysis of solar PV assets to floods revealed that 13%, 3.7%, 3%, and 1.2% of assets in Gujarat, Maharashtra, Rajasthan, and Tamil Nadu, respectively, were in the very high flood susceptible zone. Most solar PV assets in

Maharashtra and Gujarat were located in the moderate flood susceptible zone (Table 8, Figure 20, and Figure 21).

b. Wind turbines

State-wise exposure analysis of wind turbines to floods revealed that 5.5% and 1.2% of assets in Gujarat and Tamil Nadu, respectively, were in the very high flood susceptible zone. No assets were exposed to floods in Maharashtra and Rajasthan (Table 8, Figure 22, and Figure 23).

Table 8: RE assets exposed to floods

Flood susceptible zone	Gujarat		Maharashtra		Rajasthan		Tamilnadu	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
Moderate	866	2821	1131	0	1985	0	31	8161
High	119	244	72	0	137	0	36	128
Very high	28	63	0	0	7	0	0	13
Total number of assets in high and very high flood zones	147	307	72	0	144	0	36	141
State-wise total number of assets	1123	5583	1925	4282	4767	3628	3042	12068
Percentage of assets in high and very high flood zones	0.131	0.055	0.037	0.000	0.030	0.000	0.012	0.012

Source: CSTEP research

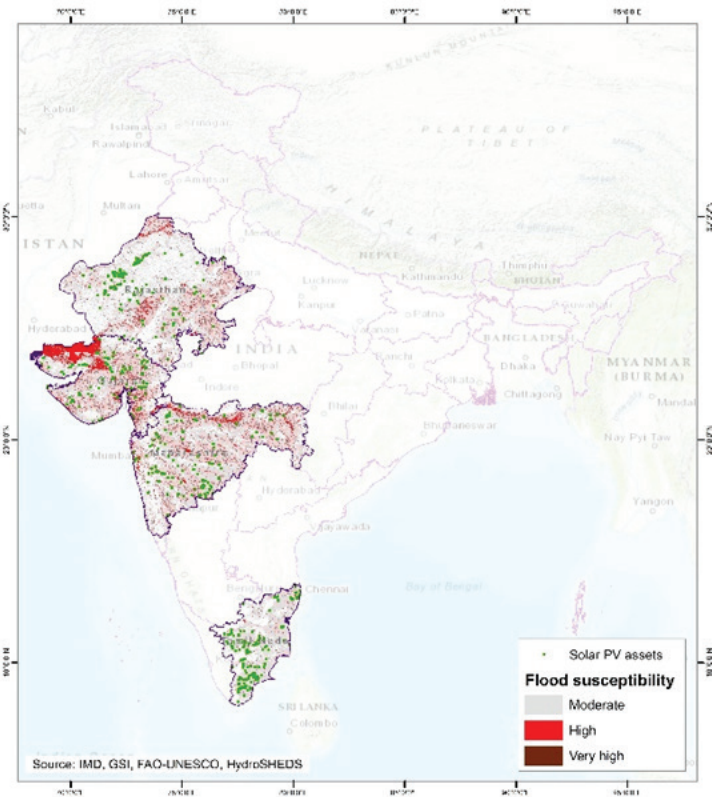


Figure 20: Exposure of solar PV assets to floods (flood susceptibility zones)
Source: CSTEP research

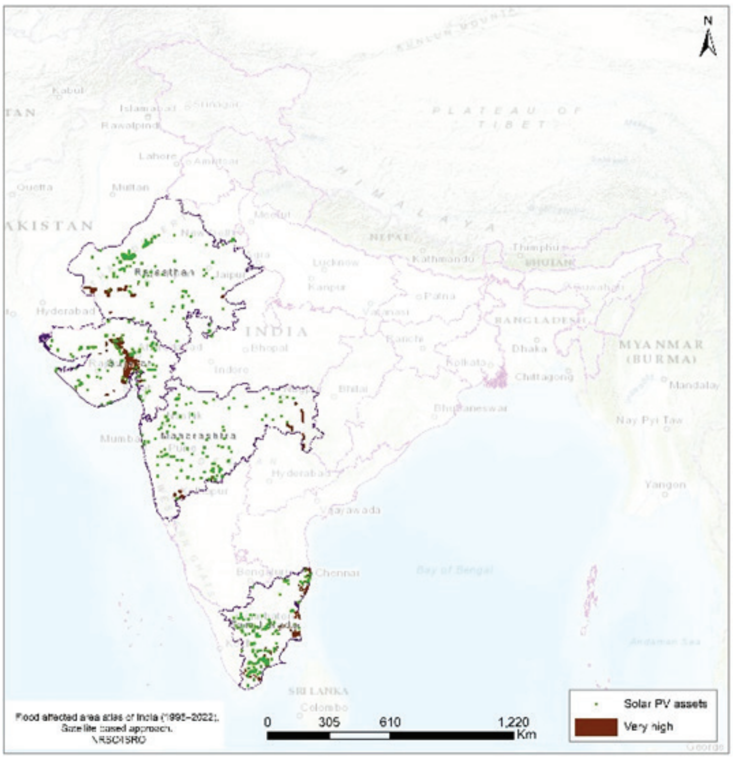


Figure 21: Exposure of solar PV assets to NRSC flood-affected areas
Source: NRSC, 2023

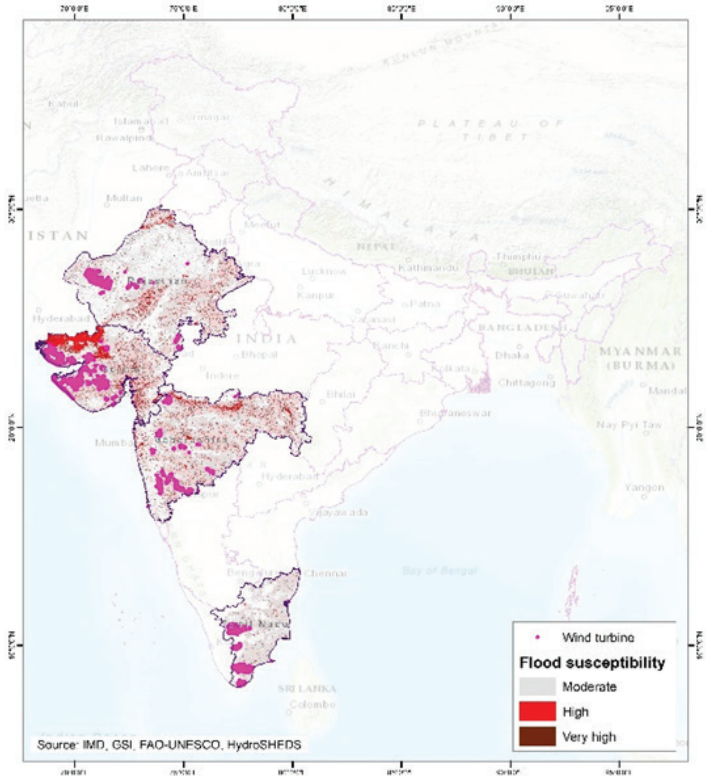


Figure 22: Exposure of wind turbines to floods (flood susceptibility zones)
Source: CSTEP research

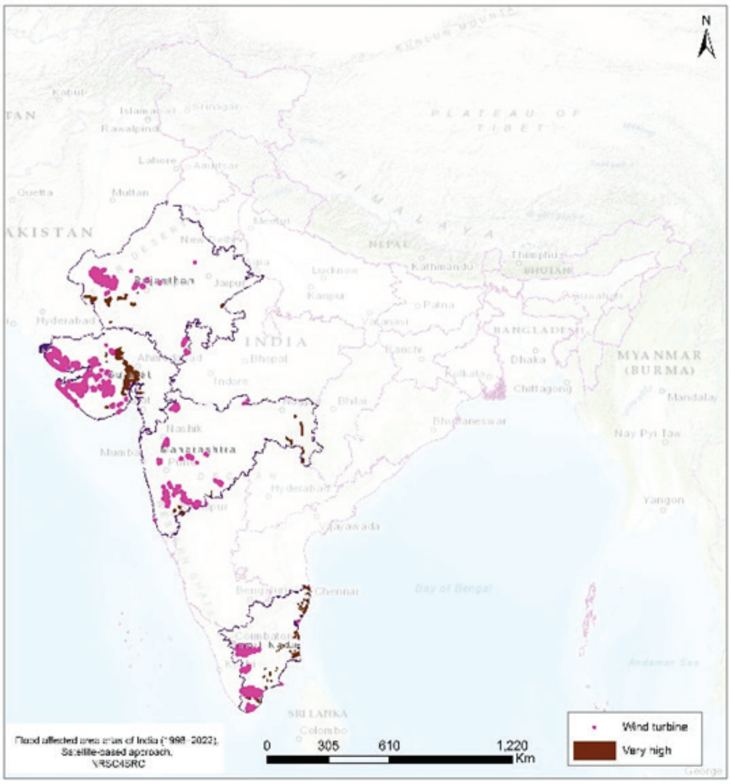


Figure 23: Exposure of wind turbines to NRSC flood-affected areas
Source: NRSC, 2023

3. Heatwaves

a. Solar PV

State-wise exposure analysis of solar assets to heatwaves revealed that 85%, 82%, and 11% of solar PV assets in Rajasthan, Maharashtra, and Tamil Nadu, respectively, were exposed to more than three heatwave events per year. All solar PV assets in Gujarat were exposed to at least one heatwave event per year (Table 9, Figure 24).

b. Wind turbines

All wind turbines in Rajasthan were exposed to more than three heatwave events per year, and about 25% of wind turbines in Maharashtra were exposed to as many heatwave events per year (Table 9, Figure 25). On the other hand, all wind assets in Gujarat and a majority (72%) in Maharashtra were exposed to only one heatwave event per year.

Table 9: RE assets exposed to heatwaves

Number of heat waves per year	Gujarat		Maharashtra		Rajasthan		Tamilnadu	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
1	1123	5549	312	3095	-	-	2587	12062
2	-	-	20	99	-	-	106	-
3	-	-	26	111	51	-	349	-
4	-	-	1,414	825	249	3,385	-	-
5	-	-	145	129	3790	243	-	-
Total number of assets exposed to ≥3 heatwaves	-	-	1585	1065	4090	3628	349	-
State-wise total number of assets	1123	5583	1925	4282	4767	3628	3042	12068
Percentage of assets exposed to ≥3 heatwaves	-	-	0.823	0.249	0.858	1.000	0.115	-

Source: CSTEP research

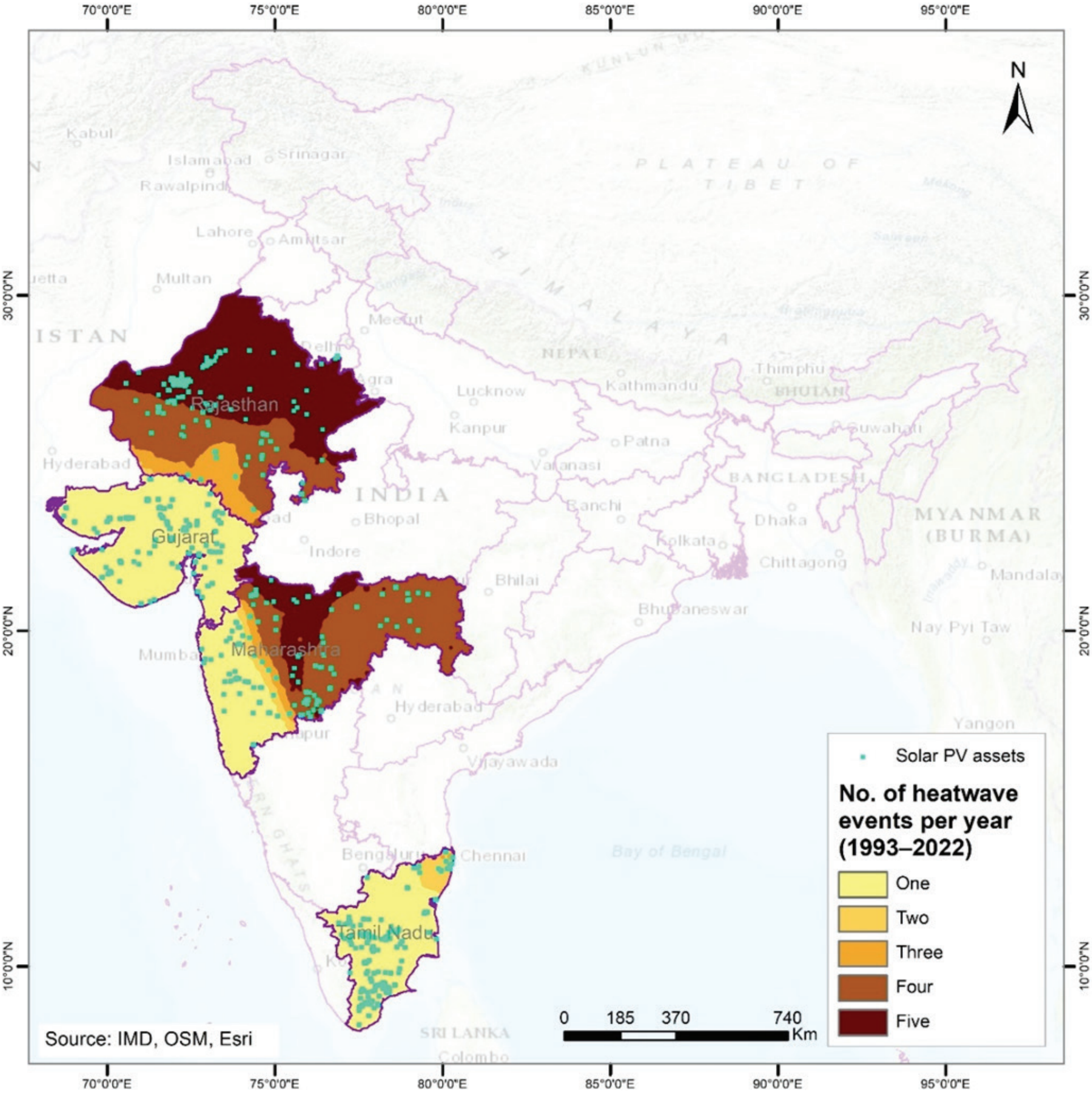


Figure 24: Exposure of solar PV assets to heatwaves
Source: CSTEP research

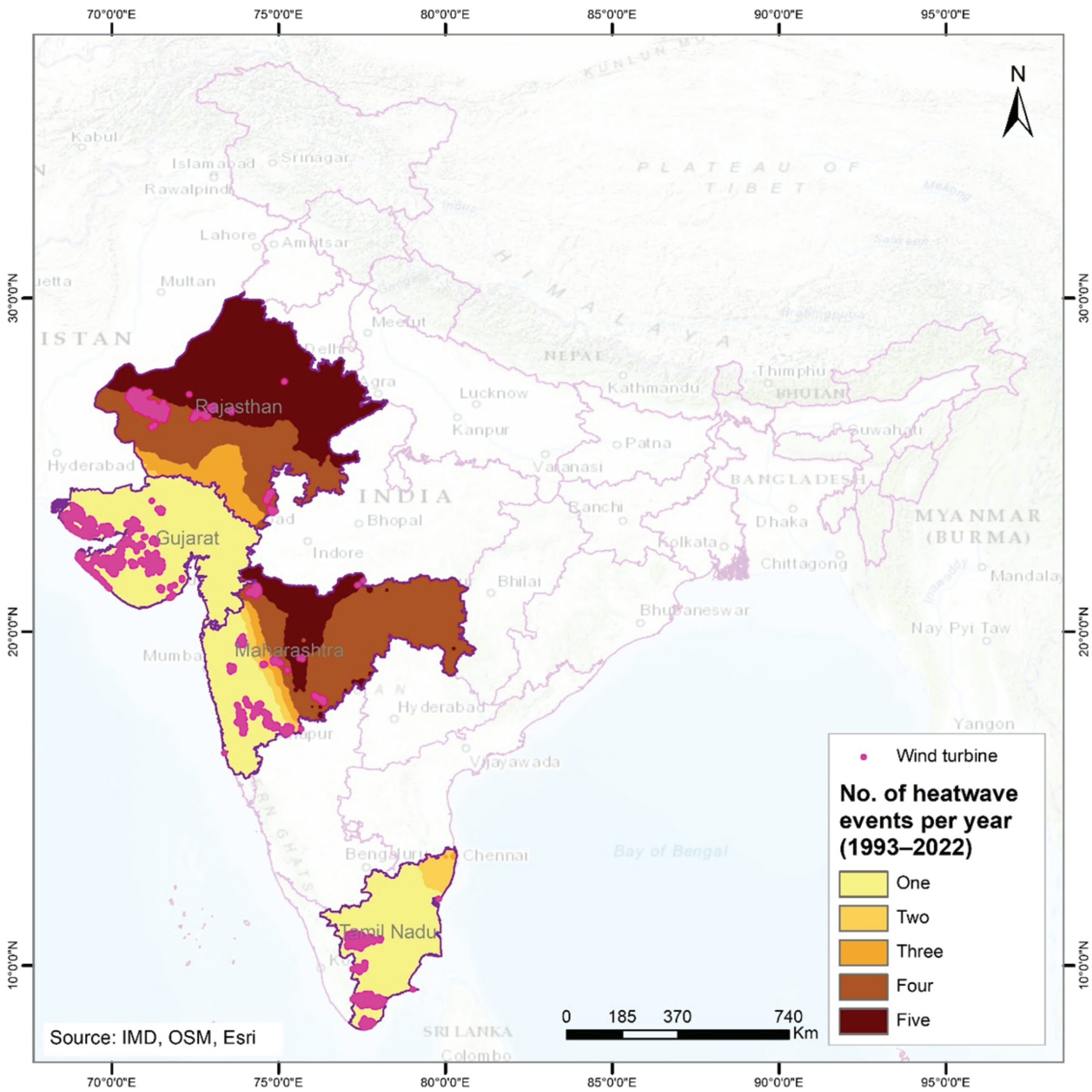


Figure 25: Exposure of wind turbines to heatwaves
Source: CSTEP research

4. Tropical cyclone

Solar PV

State-wise exposure analysis of solar PV assets for tropical cyclones revealed that a. 21%, 20%, and 8% of assets in Maharashtra, Tamil Nadu, and Gujarat, respectively, were exposed to very severe tropical cyclone storms (>120 km/h wind speed). Thirty-six percentage and 18% of assets in Gujarat and Tamil Nadu, respectively, were exposed to severe cyclonic storms (90–120 km/h wind speed). According to the tropical cyclone data analysed, 98% and 30% of assets in Rajasthan and Maharashtra were not impacted by any tropical cyclones (Table 10, Figure 26).

b. Wind turbines

Similarly, 9%, 7%, and 3% of wind turbines in Gujarat, Maharashtra, and Tamil Nadu were exposed to very severe tropical cyclone storms, and 53% and 9% of assets in Gujarat and Maharashtra were exposed to severe cyclonic storms. Almost all assets in Rajasthan (99%), 14% in Maharashtra, and 8% in Tamil Nadu were not impacted by any tropical cyclones (Table 10, Figure 27).

Table 10: RE assets exposed to tropical cyclones

Tropical cyclone type	Gujarat		Maharashtra		Rajasthan		Tamilnadu	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
Very severe cyclonic storm (120 km/h)	93	485	395	306	-	-	613	388
Severe cyclonic storm (90–120 km/h)	401	2953	124	401	3	-	553	76
Cyclonic storm (60–90 km/h)	626	2145	823	2953	70	22	1861	10568
Total number of assets exposed to very severe and severe tropical cyclone wind speed	494	3438	519	707	3	-	1166	464
State-wise total number of assets	1123	5583	1925	4282	4767	3628	3042	12068
Percentage of assets exposed to very severe and severe tropical cyclone wind speed	0.440	0.616	0.270	0.165	0.001	-	0.383	0.038

Source: CSTEP research

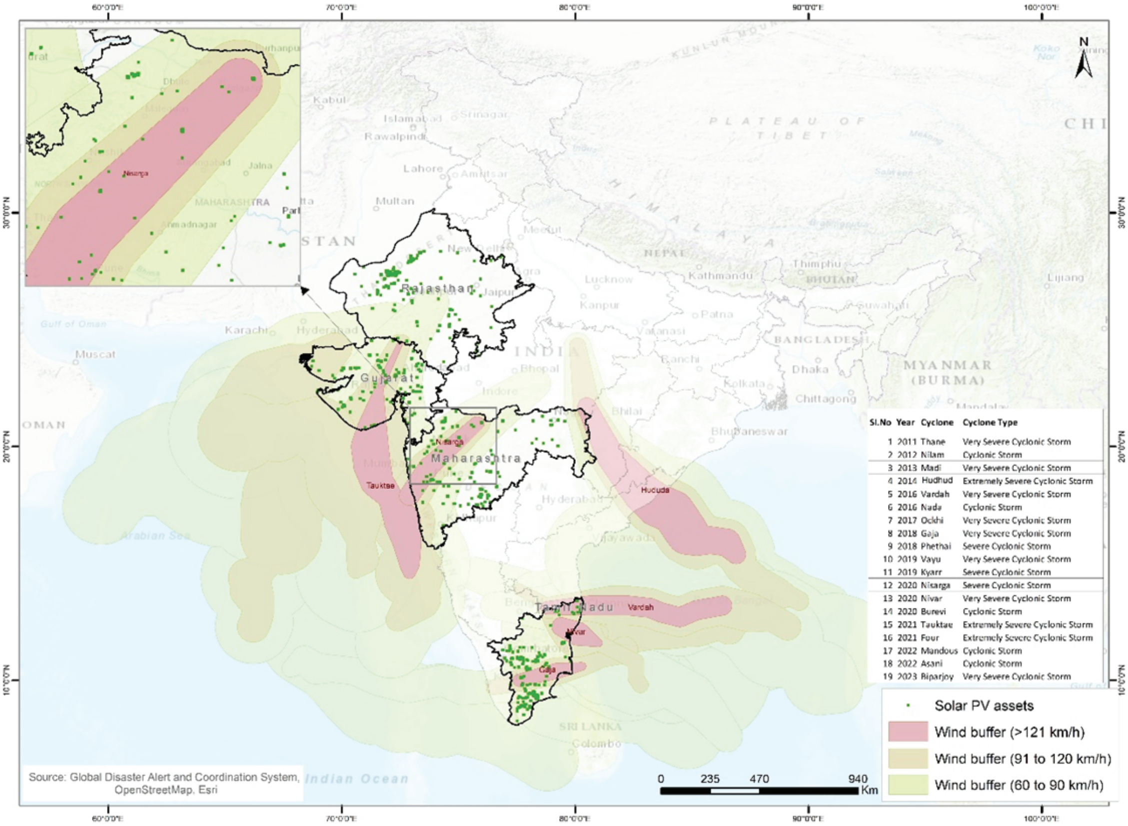


Figure 26: Exposure of solar PV assets to tropical cyclones

Source: CSTEP research

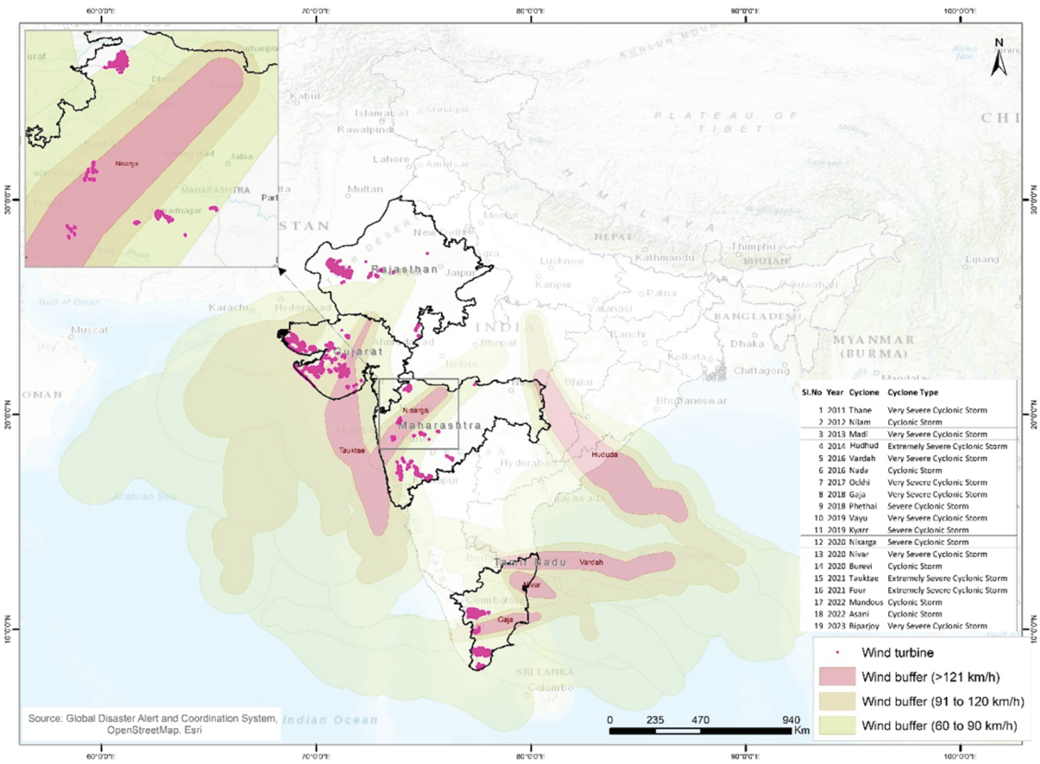


Figure 27: Exposure of wind turbines to tropical cyclones

Source: CSTEP research

5. Earthquakes

a. Solar PV

State-wise exposure analysis of solar PV assets to earthquakes revealed that 41% of assets in Gujarat and only 1% of assets in Maharashtra were located in seismic zone IV, which is high risk, and seismic zone V, which is very high risk (Table 11, Figure 28)

b. Wind turbines

About 48% of assets in Gujarat and 34% of assets in Maharashtra were located in seismic zones IV and V (Table 11, Figure 29).

Table 11: RE assets exposed to earthquakes

Seismic zone	Gujarat		Maharashtra		Rajasthan		Tamilnadu	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
Zone II	1123	5549	312	3095	-	-	2587	12062
Zone III	-	-	20	99	-	-	106	-
Zone IV	-	-	26	111	51	-	349	-
Zone V	-	-	1,414	825	249	3,385	-	-
Total number of assets in seismic zones IV and V	- -	- -	1585	129 1065	3790 4090	243 3628	- 349	- -
State-wise total number of assets	1123	5583	1925	4282	4767	3628	3042	12068
Percentage of assets in seismic zones IV and V	0.41	0.48	0.01	0.34	0.002	-	-	-

Source: CSTEP research

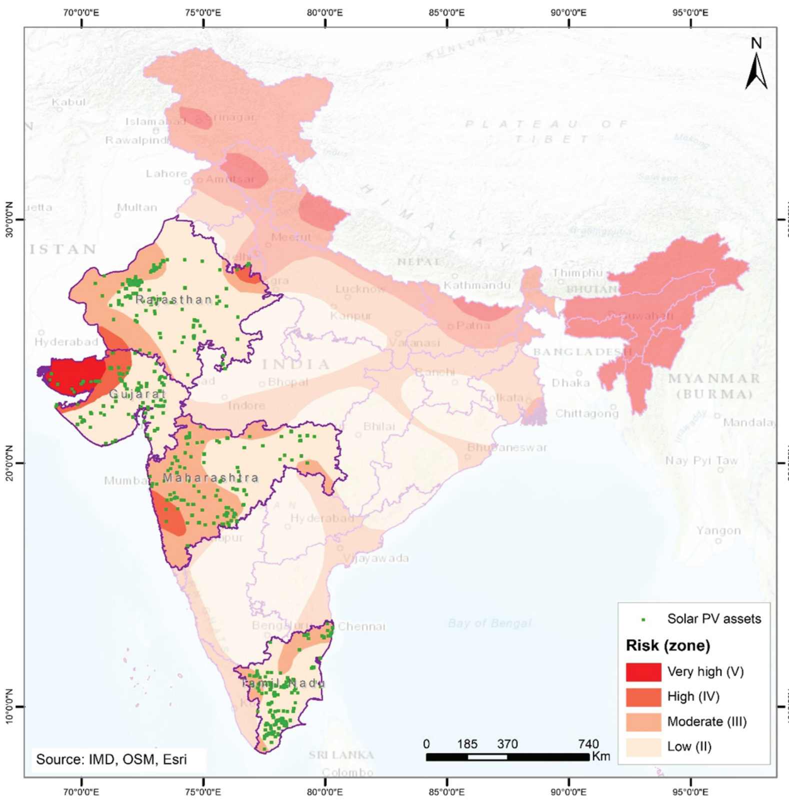


Figure 28: Exposure of solar PV assets to earthquakes
Source: CSTEP research

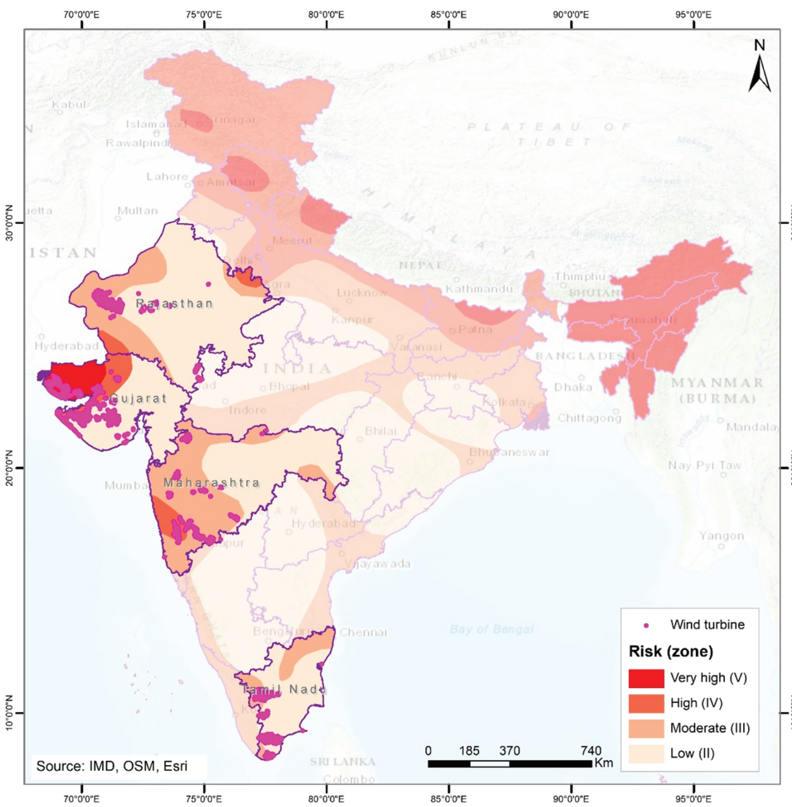


Figure 29: Exposure of wind turbines to earthquakes
Source: CSTEP research

6. Hailstroms

a. Solar PV

State-wise exposure analysis of solar PV assets to hailstorms revealed that 85%, 20%, and 17% of assets in Rajasthan, Gujarat, and Tamil Nadu, respectively, were exposed to hailstorms for an average of two to eleven hours annually. The remaining assets in the project states were exposed to hailstorms on an average of below two hours annually (Table 12, Figure 30).

b. Wind turbines

Similarly, 99.5%, 40%, and 1% of wind assets in Rajasthan, Tamil Nadu, and Gujarat, respectively, were exposed to hailstorms for an average of two to eleven hours annually. The remaining assets in the project states were exposed to hailstorms on an average of below two hours annually (Table 12, Figure 31). For the representation of exposure of RE assets to hailstorms, hours of hailstorms per day has been converted to the average number of days with hailstorms per year.

Table 12: RE assets exposed to hailstorms

Hailstorms (average number of days per year)	Gujarat		Maharashtra		Rajasthan		Tamilnadu	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
High (0.08 to 0.45)	233	64			4035	3610	526	4919
Moderate (0.04 to 0.08)	559	2541	1402	3131	45	0	498	314
Low (0.01 to 0.04)	319	2476	515	1127	0	0	1657	6756
Total number of assets in the high zone	233	64	0	0	4035	3610	526	4919
State-wise total number of assets	1123	5583	1925	4282	4767	3628	3042	12068
Percentage of assets in high and very high flood zones	0.207	0.011	0.000	0.000	0.846	0.995	0.173	0.408

Source: CSTEP research

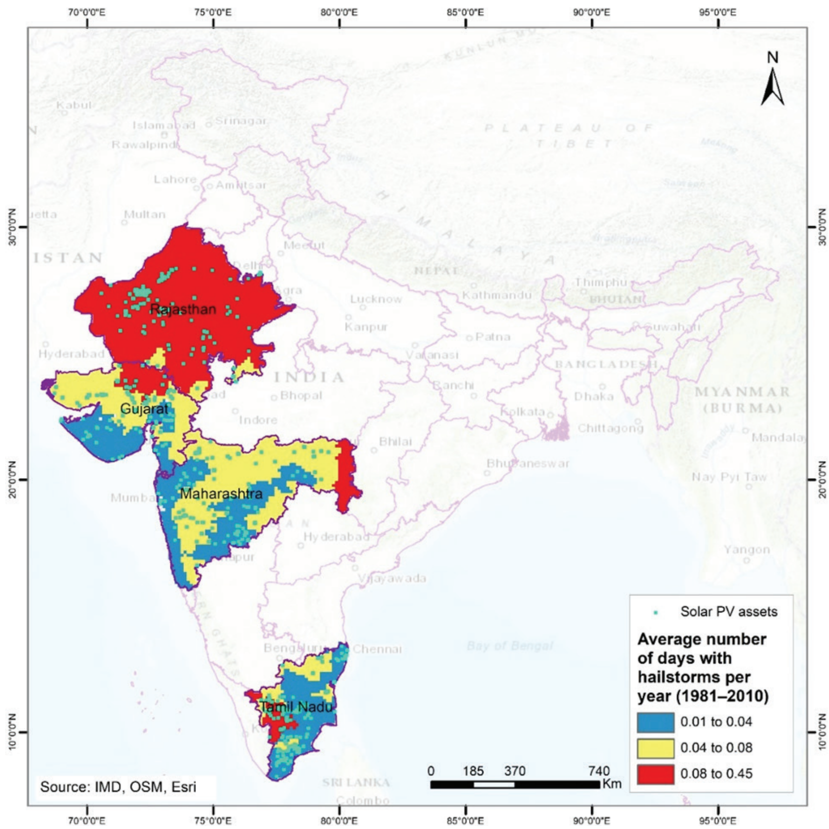


Figure 30: Exposure of solar PV assets to hailstorms
Source: CSTEP research

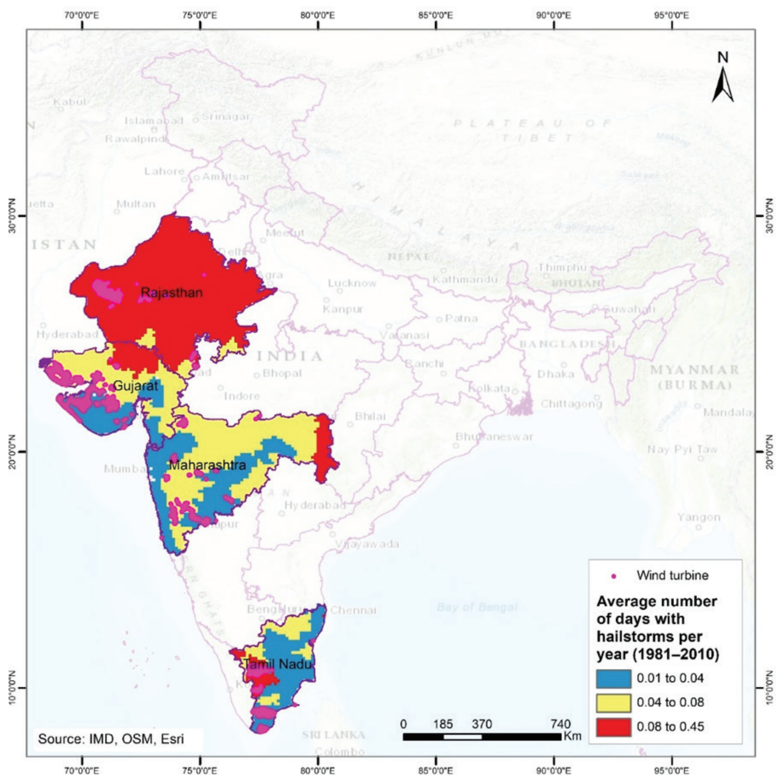


Figure 31: Exposure of wind turbines to hailstorms
Source: CSTEP research

3.3. VULNERABILITY OF PROJECT STATES

The vulnerability assessment was conducted separately for solar PV and wind plants and states were ranked accordingly.

3.3.1. VULNERABILITY RANKING OF STATES

Based on the VI values, the state of Tamil Nadu was found to have the highest vulnerability, followed by Rajasthan when solar PV plants were considered (Figure 32). Similarly, Maharashtra and Gujarat were ranked as having high vulnerability when wind plants were considered (Figure 33).

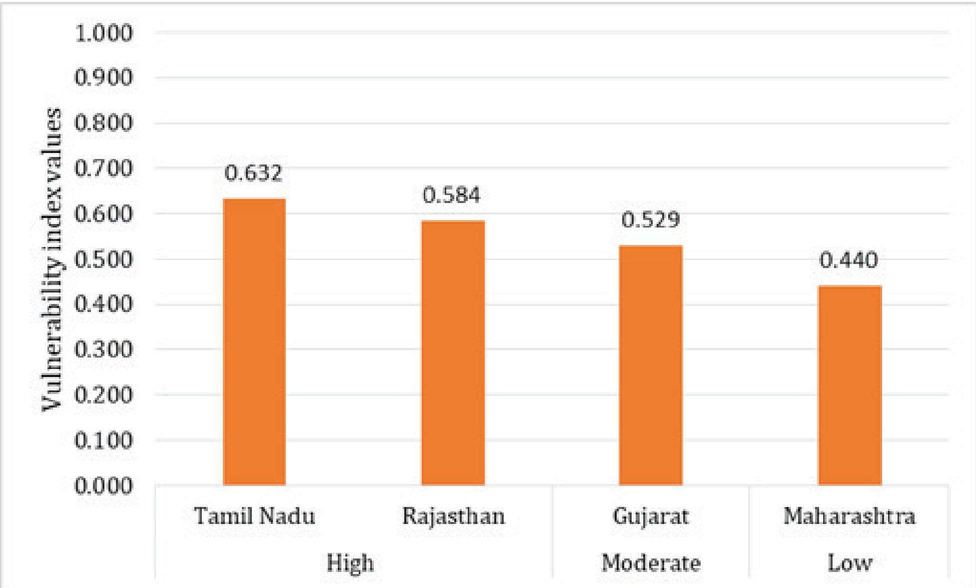


Figure 32: Vulnerability ranking of states in terms of solar PV plants

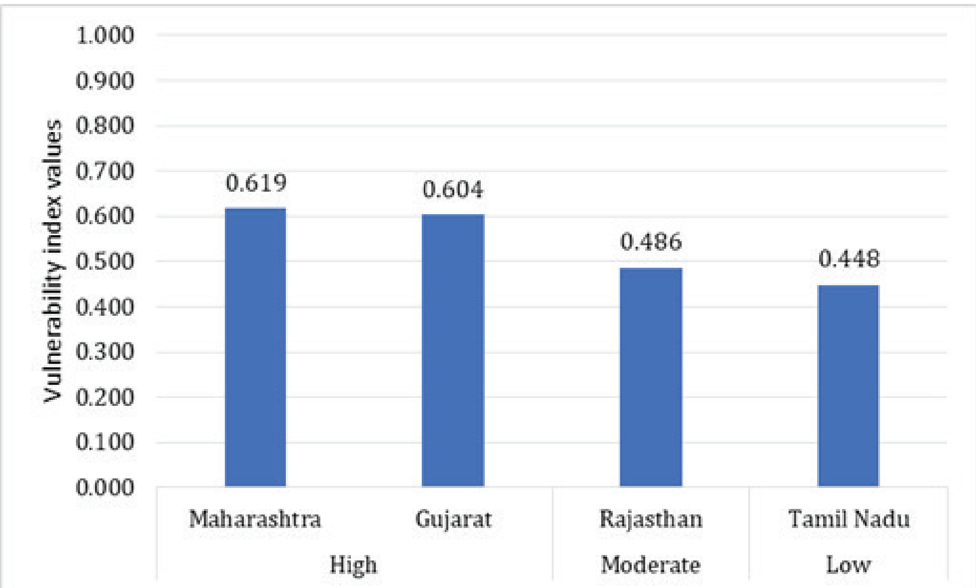


Figure 33: Vulnerability ranking of states in terms of wind plants

3.3.2. DRIVERS OF VULNERABILITY

Further analysis helped to identify indicators and sub-indicators that were driving the vulnerability of solar PV and wind plants in the four project states. Table 13 provides the drivers of solar PV and wind vulnerability at an indicator level. While compromised robustness and recovery of solar PV plants were the major drivers of vulnerability, poor structural integrity, a lack of redundant water and power supply, and compromised recovery drove the vulnerability of wind plants.

Table 13: Indicators driving the vulnerability of solar PV and wind plants

RE type	Vulnerability class	Significant drivers	Moderate drivers
Solar PV	High (Tamil Nadu and Rajasthan)	Compromised robustness and recovery	Poor structural integrity
	Moderate (Gujarat)	Compromised robustness and recovery	Nil
	Low (Maharashtra)	Compromised robustness	Compromised recovery
Wind	High (Maharashtra and Gujarat)	▪ Poor structural integrity ▪ No redundancies in place (water and backup power supply) ▪ Compromised recovery	Compromised robustness
	Moderate (Rajasthan)	Compromised recovery	▪ Poor structural integrity ▪ No redundancies in place (water and backup power supply) ▪ Compromised robustness
	Low (Tamil Nadu)	▪ Poor structural integrity ▪ Compromised recovery	Nil

Figure 34 and 35 show the drivers of vulnerability at a sub-indicator level for solar PV and wind plants, respectively. The analysis revealed that in states categorised as having high vulnerability, solar plants lacked adaptive capacity. The significant drivers were a lack of flood-control measures and relatively fewer internal quality checks, fewer standards adhered to, and fewer regular audits conducted.

Additionally, solar PV plants in these states did not have tie-ups with district weather forecasting authorities; had fewer emergency response team training sessions; did not have as many on-site staff and, thus, had fewer skilled personnel; conducted fewer external audits; did not practice cooling of solar panels; and had no redundant water supply. Drivers of all vulnerability classes are provided in Appendix B, Table 31 and 33.

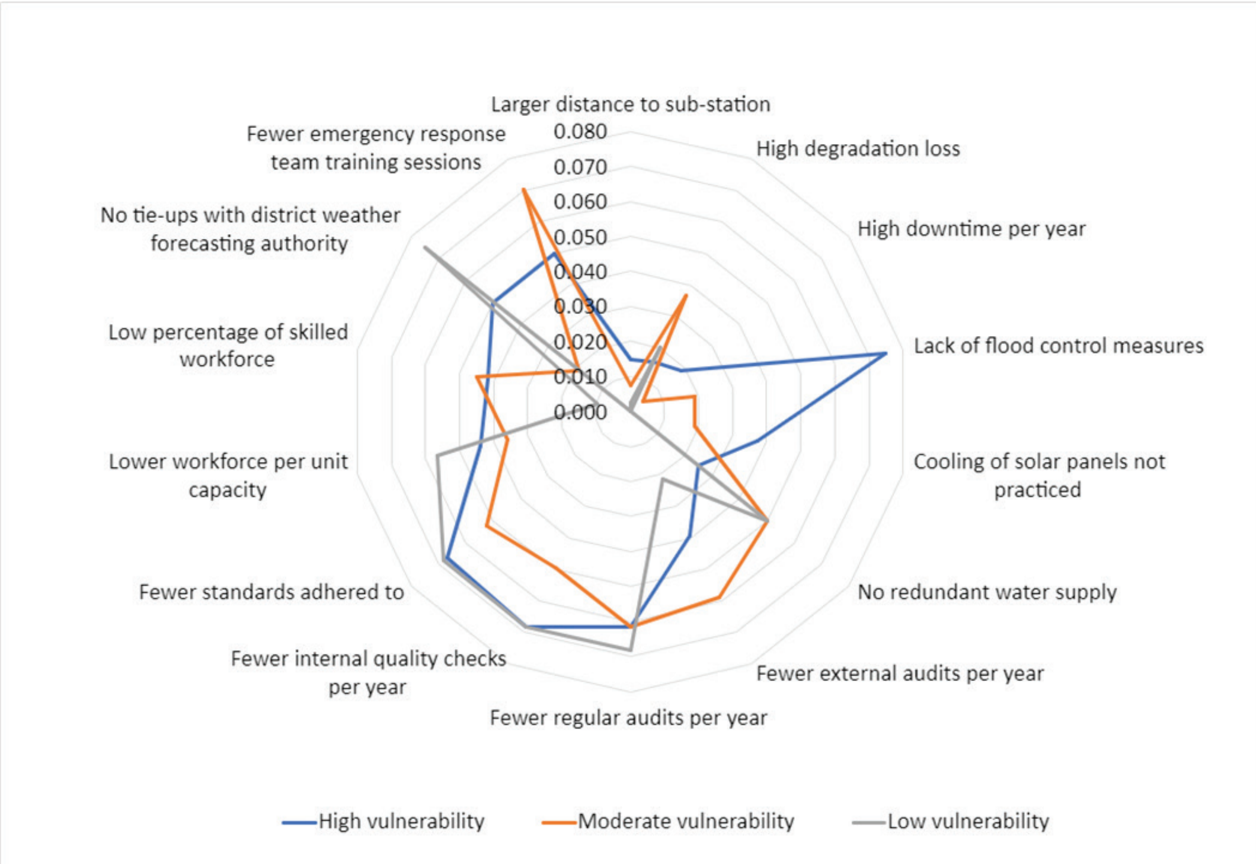


Figure 34: Sub-indicators driving vulnerability of solar PV plants in states ranked as having high, moderate, and low vulnerability

For wind plants in states that were ranked as having high vulnerability, one single sub-indicator appeared to significantly drive vulnerability—the lack of a backup power facility. Additionally, the lack of flood-control measures, the fact that wind turbine towers could handle relatively lower maximum wind speeds, and fewer emergency response team training sessions drove the vulnerability of these plants moderately. Drivers of all vulnerability classes are provided in Appendix B, Table 32 and 34.

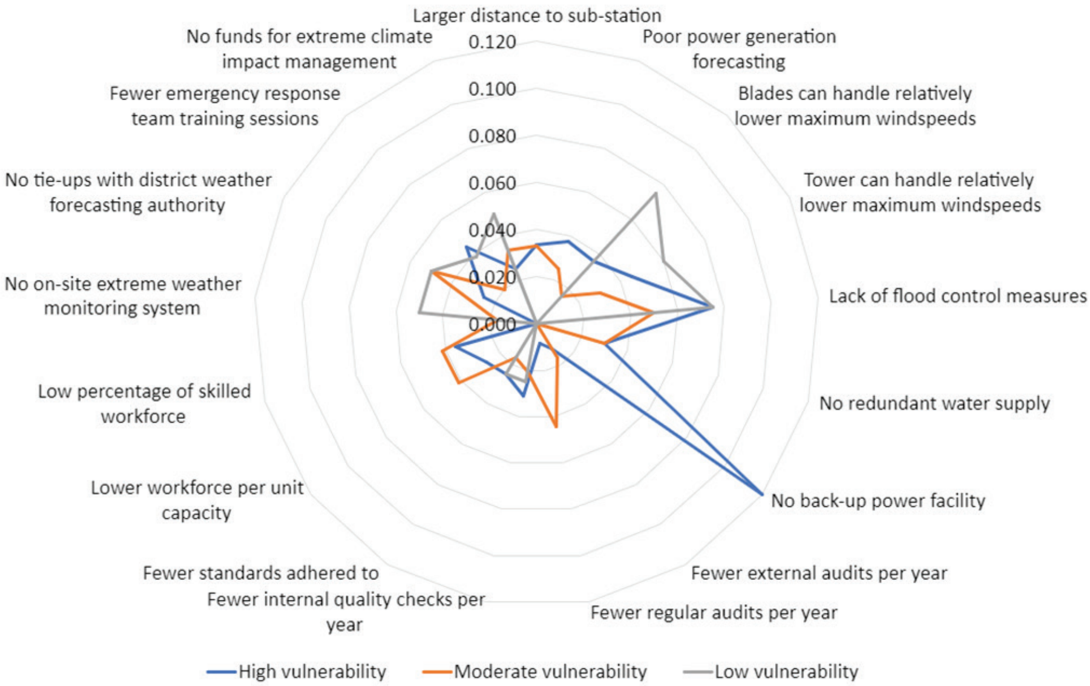


Figure 35: Sub-indicators driving vulnerability of wind plants

3.3.3. RESILIENCE

Surveys that were undertaken assisted with the quantification of indicators and allowed for the collection of qualitative information that provided an understanding of how resilient the sampled RE plants were, their responses to extreme events, and the measures put in place to enhance resilience.

a. Solar PV

When asked if and how plants were protected from damaging cyclonic winds:

- A majority responded that they undertook pre-monsoon checks and tightened all infrastructure on-site.
- Two sites out of nine were designed for wind speeds greater than 46 m/s.
- Two other sites reported using high-quality materials for their module mounting structures (MMS), with a concrete piling depth between 1.8–2.5 m.
- One site reported undertaking preventive maintenance checks.

When asked what measures were in place to prevent electrical components from overheating due to high temperatures:

- All sites, except one, had a cooling system in place.
- These systems could be exhaust fans and insulation wires (in the case of one site), monitoring systems that could detect unusual temperatures through thermal

cameras, supervisory control and data acquisition (SCADA) systems, and temperature monitors.

- The remaining site conducted preventative maintenance checks to ensure that the temperature was controlled.

In terms of preparation for extreme events, data collected either through monitoring systems within the site or from other sources helped site managers mitigate dangers from extreme events. Three sites reported that weather-related information was relayed from their respective head offices. Another site used information provided by the government. In one site, extensive monitoring systems informed plant managers about any extreme event.

All sites had taken measures to ensure a certain degree of infrastructural resilience. Two sites had built adequate drainage systems to ensure that water did not stagnate within the site, preventing flooding. Further, four sites had reported using adequate piling depth ranging from 1.5 m to 2.5 m. Another site reported that the components that were used were rated for IP65, which is the highest rating for dust protection. One site reported that lightening arresters were used.

The availability of spares ensured redundancy. When asked, all respondents reported that almost all mandatory spares were stocked, and further reported that stocks were checked once a month.

When asked about how the plant communicated with local authorities and relevant agencies during extreme weather events:

- A majority reported that a simple phone call or email sufficed, given that most sites were in areas with network coverage.

When asked about the nature of insurance that the sites possess:

All sites claimed that their respective comprehensive insurance packages accounted for damages from extreme weather events.

Wind

When asked about how wind turbines were protected from high speeds and tropical cyclones:

- Four sites reported that they relied on an automatic cut-off system that switched off the turbines when wind speeds exceeded a certain speed threshold.

▪ Two sites reported pitch control through hydraulic braking.

When asked about how electrical components of the system were protected from overheating in high temperatures:

▪ A majority relied on temperature sensors that could alert the operators when temperatures exceeded a certain threshold. One site used an alarm when temperatures exceeded 100°C.

▪ Further, most turbines were equipped with cooling fans that could moderate heat levels.

▪ Apart from the turbines, control systems were also cooled, usually employing exhaust fans.

▪ Finally, two sites reported that preventative checks were undertaken, of which one site mentioned that these checks were conducted during peak summer months.

In terms of collecting data to prepare for extreme weather events, most sites relied on external agencies such as state agencies, IMD, Google's weather forecasting app, or their respective head offices. One site reported the use of an application called 'Windy', a professional weather forecasting application. One site hosted an in-site supervisory control and data acquisition system that could inform operators of a potential extreme weather event.

When asked about the measures taken to increase infrastructural resilience, including the construction and materials used:

▪ Most respondents reported that a concrete foundation and steel-based tower provided the structure strength to withstand climate extremes.

▪ Specifically, one site mentioned that their towers used a mixture of steel and concrete, which enhanced their strength.

▪ The same site had also designed its structure to withstand a maximum speed of 50 m/s (according to the National Disaster Management Authority, the average speed of a 'severe cyclonic storm' is between 24.4–32.5 m/s).

▪ Another site reported that protecting their nacelle and visually inspecting the turbines after a sandstorm ensured the site was resilient.

When asked about how the plants communicated with local authorities during extreme weather events:

▪ Most reported that phone calls were adequate. One site reported that they used WhatsApp groups to communicate with various concerned agencies.

Finally, similar to solar sites, all wind sites reported that they had comprehensive insurance coverage to mitigate damages from extreme weather events.

3.3.4. CASE STUDIES

Site visits to solar power plants in Gujarat, particularly those situated near the seashore, provided valuable insights. Station officers revealed persistent challenges posed by climate extremes, that is, tropical cyclones, associated storm surges, and flooding that occurred in 2019, 2022, and 2023.

Site 1: The flooding of the solar plant in 2022 impacted power generation partially, lasting around 3 days. In response, a peripheral drainage was constructed to prevent future flooding of the site, with additional sluice gates and valves also being installed to prevent seawater from entering the site. Subsequently, Tropical cyclone Biparjoy displaced and damaged some modules in 2023. After this incident, additional tightness checks were conducted. This site was ranked as having moderate vulnerability.

Site 2: This solar plant was inundated in 2019, which impacted power generation partially for around 2 days. As a response, a drainage system across the entire plant and loose flange arrangements near the sea were implemented to prevent future impact due to heavy rains and seawater from entering the site. Tropical cyclone Biparjoy impacted this site also in 2023, causing displacement of modules and damage to some tables. Strengthening measures similar to Site 1 were put into place to improve the site's resilience to tropical cyclones and high winds. According to the vulnerability assessment, this site was ranked as having low vulnerability.

Site 3: Tropical cyclone Biparjoy caused the displacement of around 25 modules and damaged a roof in 2023. The plant was old and thus reported high degradation loss. Furthermore, the plant reported a relatively lower number of training sessions for its emergency response team in a year, when compared to the other sites, and it was ranked as having high vulnerability.

These observations underscored the exposure of solar power plants to climate extremes, particularly tropical cyclones and associated flooding. The responses to these events included the installation of additional valves, structural strengthening, and various drainage arrangements, highlighting that these plants were learning to adapt and were building resilience. Climate change and an associated increase in the frequency and magnitude of extreme weather events will require these plants to invest in climate-proofing their infrastructure and building the capacity of personnel to manage and lower the impacts and risks of future climate hazards.

Sites in Tamil Nadu situated in the centre of the state, away from the coastline, provided evidence that proper site selection is a key element for RE assets. Tamil Nadu is typically prone to severe tropical cyclones, coastline floods, heatwaves, and inland droughts, requiring well-thought-out site selection and planning. Most solar plants are commissioned inland in the heart of Tamil Nadu and away from the coastline. As a result, these sites have a higher chance of facing heatwaves and droughts compared to floods and tropical cyclones.

Site 1: The site had rarely faced extreme weather events primarily because of its location. The solar plant usually witnesses high wind speeds and yearly heatwaves as part of the region's climatic cycle. To withstand and prevent damage from high wind speeds at the site location, solar modules erected on concrete piles were installed at depths of 1.5 m to 2 m. Although the modules were air-cooled, the site had access to periodic water supply for cleaning the modules, which could be used for cooling if required. The electrical components were well insulated with the provision of exhaust fans. To prevent any damage from lightning during rare thunderstorms, lightning arresters were placed strategically throughout the site location.

The survey of such site locations, especially in Tamil Nadu, highlights the importance of strategic site selection and resilience planning. It emphasises the need to implement location-specific adaptation measures such as enhanced module infrastructure, lightning arresters, and assessing their water needs well in advance.

While the site has not experienced extreme weather events in the past, it might experience them in the future because of climate change. However, the plant is not prepared to face such extremes as it does not undertake as many audits, carry out as many quality checks, or adhere to as many standards as the other sampled sites. It also does not have tie-ups with the district weather forecasting authority and does not conduct adequate training for its emergency response teams. Therefore, this site was ranked as having high vulnerability.

Similarly, none of the wind assets visited during the study reported any damage due to extreme events. With climate change, apart from extreme events, the variations observed in local climate may drastically change. According to a study by Boopathi et al. 2021, such variations can hasten the erosion (due to rain, sand, and hail) of various components of wind turbines, particularly the blades. While this surface damage reduces the aerodynamic performance of blades and lowers energy generation, if not corrected, it can lead to significant structural damage over time. The study also reports that lightning strike damage was the most common reason for downtime of wind turbines in India, which could be exacerbated with climate change.

Evidence from across the country also suggests that climate change and extreme events have the potential to lower power generation capacities of wind plants. For example, variations in wind speed due to tropical cyclonic storms has been known to increase or decrease the output power of wind turbines, posing a major challenge for system operators (IMD & POSOCO, 2022). A recent, very severe tropical cyclonic storm, Biparjoy, made its landfall in Gujarat's Kutch district and was reported to have damaged power infrastructure, particularly electricity poles, disrupting overhead power lines and signaling systems, which resulted in a massive power outage in the affected area. This further hampered the power generation potential of wind turbines (IMD, 2023; Mishra, 2023).

Similarly, changes in wind cycles and ocean currents due to climate change has reduced the generation potential or the average capacity utilization factor of wind turbines (Gopal, 2019). Wind power potential in India is heavily influenced by the Indian summer monsoon—the better the monsoon, higher the wind potential and as the monsoon weakens, wind power systems become less productive (Gao et al., 2018). An analysis by Jai, 2020 showcased that while there has been an increase in the number of wind turbines installed, India's wind energy generation fell by 16% in its peak season in 2020. The changing monsoons patterns impacted wind speeds, and it was reported that in the year 2020, the average wind speed was 20-27 kmph, which was one of the lowest in the last 100 years (Bhaskar, 2021).

A recent study by the Indian Institute of Tropical Meteorology suggested that the seasonal and annual wind speed is likely to decrease over North India and increase along South India, which is likely to hamper the generation potential of wind power plants in North India (Anandh et al., 2022). The effects of El Nino, which occurs due to the warming of the Pacific Ocean waters, on wind power generation in India could also lead to lower than average capacity utilization factor of wind turbines in India according to a study by Baruah & Bhaskar, 2023.

3.4. RISK OF PROJECT STATES TO EXTREME EVENTS

The following tables (Table 14–17) provide the probability of occurrence of each hazard, the exposure of solar and wind assets to the hazards, and the vulnerability of the RE systems. All values are represented between 0 and 1 to allow for the computation of risk.

Note: Values that are 0 have been converted to 0.00001 to calculate risk. This is done to ensure that risk is not 0 for any state.

3.4.1. PROBABILITY OF OCCURRENCE OF HAZARDS

The probability of occurrence of tropical cyclones was the highest for Tamil Nadu, whereas the probability of an earthquake occurring in Tamil Nadu was zero. Hailstorms, in general, posed a low probability of occurrence across most states but was a hazard that was most likely going to occur in Rajasthan. The highest chance of floods occurring was in Gujarat and Maharashtra. Table 14 presents a list of the probability of occurrence of the six hazards considered, for each state.

Table 14: The average probability of occurrence of six different hazards in the project states

State	Droughts	Floods	Heatwaves	Tropical cyclones	Hailstorms	Earthquakes
Gujarat	0.143	0.667	0.010	0.384	0.048	0.545
Maharashtra	0.152	0.444	0.114	0.384	0.051	0.363
Rajasthan	0.168	0.167	0.121	0.153	0.205	0.136
Tamil Nadu	0.133	0.278	0.028	0.980	0.056	0.000

3.4.2. EXPOSURE

The exposure of both solar and wind assets to droughts was relatively low across all states. Most wind assets in Rajasthan were exposed to hailstorms and heatwaves. On the other hand, none were exposed to floods. Gujarat, which had a high probability of occurrence of earthquakes, also had the highest exposure of both solar and wind assets to the hazard. Tables 15 and 16 present the percentage of wind and solar PV assets exposed to each hazard across the study states

Table 15: The percentage of solar PV assets exposed to six different hazards in the project states

State	Droughts	Floods	Heatwaves	Tropical cyclones	Hailstorms	Earthquakes
Gujarat	0.072	0.131	0.000	0.440	0.270	0.409
Maharashtra	0.013	0.037	0.821	0.270	0.000	0.010
Rajasthan	0.002	0.030	0.857	0.001	0.846	0.005
Tamil Nadu	0.000	0.012	0.114	0.383	0.172	0.000

Table 16: The percentage of wind assets exposed to six different hazards in the project states

State	Droughts	Floods	Heatwaves	Tropical cyclones	Hailstorms	Earthquakes
Gujarat	0.420	0.055	0.000	0.616	0.011	0.484
Maharashtra	0.015	0.000	0.248	0.165	0.000	0.343
Rajasthan	0.000	0.000	0.980	0.000	0.995	0.000
Tamil Nadu	0.000	0.012	0.000	0.038	0.407	0.000

3.4.3. VULNERABILITY

The vulnerability assessment revealed that wind assets in Maharashtra were the most vulnerable, closely followed by Gujarat. In the case of solar PV assets, Rajasthan was the most vulnerable, followed by Gujarat. Results for all states across solar PV and wind assets are presented in Table 17.

Table 17: The vulnerability of the four project states in terms of solar PV and wind assets

State	Solar PV	Wind
Gujarat	0.529	0.604
Maharashtra	0.440	0.619
Rajasthan	0.584	0.486
Tamil Nadu	0.632	0.448

3.4.4. RISK

The aggregation of hazard, exposure, and vulnerability provided a risk value for each state to a particular hazard. The key risk results are summarised here. However, it must be noted that a state being most at risk to a certain hazard does not imply that the hazard is driving risk for that particular state as risk is a function of hazard, exposure, and vulnerability (Section 2.4). Additional details on the drivers of risk are presented in Section 3.4.5.

Risk ranking of project states to six different hazards:

1. Solar PV

Figure 36 presents solar PV assets in the four states that are most at risk to a particular hazard. Solar assets in

- Gujarat were most at risk to earthquakes, closely followed by tropical cyclones and floods
- Rajasthan were most at risk to hailstorms and heatwaves
- Maharashtra and Tamil Nadu were most at risk to tropical cyclones, and assets in Maharashtra were also at risk to heatwaves

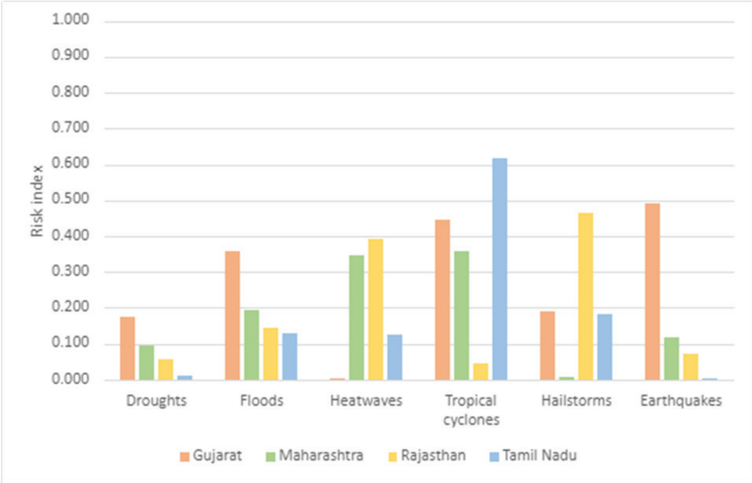


Figure 36: Risk to solar PV assets in all states for each hazard
Source: CSTEP research

2. Wind

Similarly, Figure 37 does the same for wind assets in the four states. Wind assets in

- Gujarat and Maharashtra were most at risk to earthquakes. Wind assets in Gujarat were also at risk to tropical cyclones
- Rajasthan were most at risk to hailstorms and heatwaves
- Tamil Nadu were most at risk to tropical cyclones and hailstorms

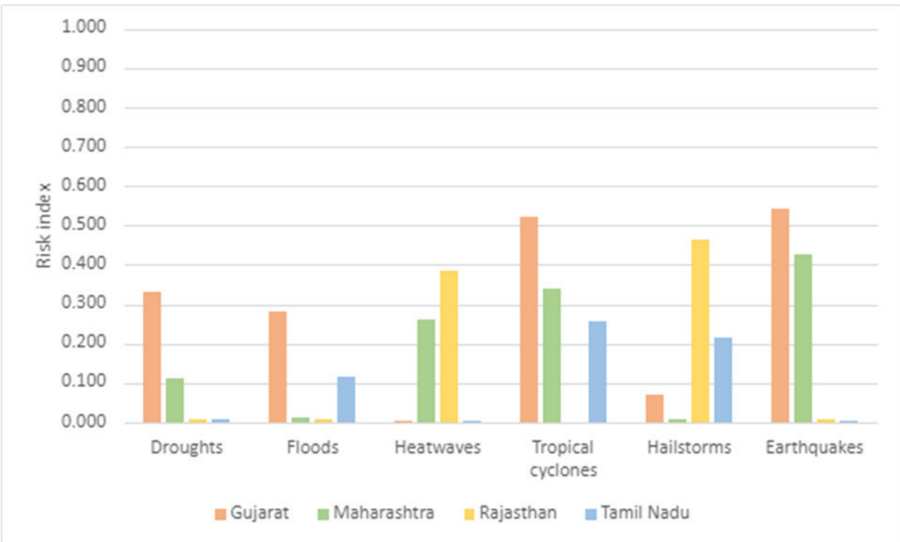


Figure 37: Risk to wind assets in all states for each hazard
Source: CSTEP research

Additionally, we found that Gujarat led in being most at risk to four of the six hazards in consideration for both solar and wind assets. Furthermore, the average tropical cyclone risk was the highest for solar assets and the average flood risk was the lowest for wind assets in Gujarat.

3.4.5. DRIVERS OF RISK

Further analysis identified the key drivers of risk, presented in Figure 38 and 39. The drivers have been ranked according to their contribution to the overall risk score for each hazard.

State	Drivers of drought risk		
	First	Second	Third
Gujarat	V	H	E
Maharashtra	V	H	E
Rajasthan	V	H	E
Tamil Nadu	V	H	E

State	Drivers of flood risk		
	First	Second	Third
Gujarat	H	V	E
Maharashtra	H, V	E	
Rajasthan	V	H	E
Tamil Nadu	V	H	E

State	Drivers of heatwave risk		
	First	Second	Third
Gujarat	V	H	E
Maharashtra	E	V	H
Rajasthan	E	V	H
Tamil Nadu	V	E	H

State	Drivers of tropical cyclone risk		
	First	Second	Third
Gujarat	V	E	H
Maharashtra	V	H	E
Rajasthan	V	H	E
Tamil Nadu	H	V	E

State	Drivers of hailstorm risk		
	First	Second	Third
Gujarat	V	E	H
Maharashtra	V	H	E
Rajasthan	E	V	H
Tamil Nadu	V	E	H

State	Drivers of earthquake risk		
	First	Second	Third
Gujarat	V	H	E
Maharashtra	V	H	E
Rajasthan	V	H	E
Tamil Nadu	V	H, E	

Figure 38: Drivers of risk for solar PV assets across all states

State	Drivers of drought risk		
	First	Second	Third
Gujarat	V	E	H
Maharashtra	V	H	E
Rajasthan	V	H	E
Tamil Nadu	V	H	E

State	Drivers of flood risk		
	First	Second	Third
Gujarat	H	V	E
Maharashtra	V	H	E
Rajasthan	V	H	E
Tamil Nadu	V	H	E

State	Drivers of heatwave risk		
	First	Second	Third
Gujarat	V	H	E
Maharashtra	V	E	H
Rajasthan	E	V	H
Tamil Nadu	V	H	E

State	Drivers of tropical cyclone risk		
	First	Second	Third
Gujarat	E	V	H
Maharashtra	V	H	E
Rajasthan	E	V	H
Tamil Nadu	H	V	E

State	Drivers of hailstorm risk		
	First	Second	Third
Gujarat	V	H	E
Maharashtra	V	H	E
Rajasthan	E	V	H
Tamil Nadu	V	E	H

State	Drivers of earthquake risk		
	First	Second	Third
Gujarat	V	H	E
Maharashtra	V	H	E
Rajasthan	V	H	E
Tamil Nadu	V	H, E	

Figure 39: Drivers of risk for wind assets across all states

We can broadly conclude that vulnerability is a key driver for both solar and wind assets for most hazards. From a policymaking perspective, this is a solvable problem. Of the three drivers of risk, vulnerability can be addressed in the short term, whereas exposure and hazard require long-term interventions.

The occurrence of hazards is determined by global climate patterns and global cumulative emissions. Reducing the probability of occurrence of hazards, while achievable, is only possible with concerted global efforts over a significant period of time, making it a variable that cannot be influenced in the short term.

Exposure in this project is defined as the number of RE assets within a hazard zone. Given the capital investment required for the establishment of an RE asset, it is practically impossible to change the location of these assets away from hazard zones in the short term, making exposure a variable that can only be addressed in the medium to long term.

On the other hand, vulnerability comprises variables such as those listed in Section 2.3., which can be addressed through policies in the short to medium term.
A few general observations from Figures 34 and 35 are as follows:

Solar

- For both flood and drought risk, vulnerability leads the drivers of risk, followed by hazard and exposure for all states.
- Hazards are the main drivers of risk in the case of tropical cyclones in Tamil Nadu and flood risk in Gujarat and Tamil Nadu.
- Exposure is a key driver of hailstorm risk in Rajasthan and heatwave risk in Maharashtra and Rajasthan.

Wind

- Drought and earthquake risks are purely driven by vulnerability in all states.
- Similar to solar assets, hazard is the main driver of risk in the case of tropical cyclones in Tamil Nadu and flood risk in Gujarat.
- Exposure is the main driver of tropical cyclone risk in Gujarat and Maharashtra and hailstorm and heatwave risk in Rajasthan.

4. POLICY RECOMMENDATIONS

Natural hazards such as floods, droughts, and tropical cyclones are becoming more frequent and severe in India. Therefore, the resilience of energy systems, especially RE, is crucial to ensure their dependability and efficacy. The ability of RE sources to adapt to shifting climatic conditions becomes vital as climate change brings new uncertainties and challenges.

A resilient energy system can operate under adverse conditions or recover quickly from unexpected disruptions. Proper planning, resilient infrastructure, quick restoration, and informed governance are essential to cope with unforeseen and uncontrollable events that interfere with and disrupt energy system operations (Hu, 2022). Efforts to enhance overall resilience must be designed methodically and comprehensively, including the interdependencies and interconnection of critical infrastructure systems based on their life cycles and the hazards they are exposed to (UNDP, 2022).

Governments and regulatory agencies can encourage the development of resilient RE systems that are better suited to withstand the effects of climate change by putting in place proactive policies that address climate risks. Through the incorporation of climate risk assessments into policy and decision-making procedures, stakeholders can develop strategies to enhance the resilience of RE infrastructure. While policy frameworks receive considerable attention, it is imperative to give equal importance to implementation strategies. Policy recommendations for climate-resilient RE in the future are informed by the findings of the rapid literature review and risk assessment and stakeholder engagement.

a. Policy recommendations from the literature review

A thorough review of numerous research papers, reports, articles, and journals pertaining to solar and wind power plants in India and globally was conducted. Emphasis was placed on the various critical aspects of resilient infrastructure design, advanced technology, O&M, audit and inspection, disaster preparedness, and collaboration with stakeholders. Recent bidding documents were also reviewed to include relevant design standards (Appendix C). Some best practices reported globally and locally are as follows:

Greece: OneNet in Greece has planned to set up a new generation of grid services that fully utilise distributed generation, storage, and demand responses. Such technological advances are made to ensure proper communication channels are set in place and coordination procedures between the transmission system operators (TSOs) and distribution system operators (DSOs) are efficient. To help TSOs and DSOs manage the energy systems affordably and safely, a universal web-based platform with inputs from cloud computation engines, georeferenced map-based GUI, artificial intelligence (AI) techniques, and high-resolution weather forecasts can be developed and implemented for seamless communication. The TSOs and DSOs can then effectively work together to face the unprecedented threat to the power distribution system (Zafeiropoulou et al., 2023).

This will improve the active management of the RE power plant through effective TSO–DSO coordination and will increase the reliability of outage and maintenance plans for system operators (SOs) by granting them a more accurate insight into the conditions such as climate hazards under which the RE power plant may be forced to operate in the upcoming period and the challenges that it might face during such hazards. This web-based platform will serve as an early warning system so that SOs will have accurate forecasts of relevant weather parameters at their disposal.

Malaysia: By adopting best practices from Malaysia, India can enhance the safety, resilience, cost-effectiveness, and sustainability of hybrid power systems. India, facing similar challenges such as extreme weather and sustainable energy needs, can learn from Malaysia's comprehensive safety and resilience approach, especially in the face of natural disasters. Decision matrix risk assessment techniques, like those in Malaysia, could help India mitigate power system failure risks. Prioritising renewable sources such as solar and wind aligns with India's ambitious targets while optimising costs ensures viability across its diverse energy landscape. Leveraging government support and policies, as seen in Malaysia, can expedite hybrid power system deployment, advancing India's energy security and sustainability goals (Jamaluddin et al., 2018).

Florida, USA: India can draw lessons from global best practices in building disaster-resilient and climate-resilient RE assets. Following initiatives like the Babcock Ranch in Florida, prioritising underground infrastructure for power and internet cables can minimise damage during extreme weather events.Adopting robust solar panel designs capable of withstanding high wind speeds and temperature extremes enhances the durability of solar installations (Sherriff, 2023). India's coastline offers opportunities for offshore wind energy development, with investments in resilient offshore wind farms being essential. Encouraging research and innovation in RE technologies tailored to India's climate can further drive advancements in resilient energy infrastructure, ensuring reliable access to clean energy while mitigating climate risks (Fearon, 2022).

Caribbean Countries (Grenada and Trinidad and Tobago): To integrate Caribbean best practices into India's RE sector for disaster resilience, key steps are imperative. Upgrade energy infrastructure for reliability. Implement sector reforms and governance enhancements alongside capacity building. Prioritise energy efficiency for affordability and green economy goals. Accelerate the adoption of renewables for sustainability. Strengthen legislative and institutional frameworks. Diversify energy mix with renewables. Increase awareness and stakeholder engagement. Invest in research and development and collaborate internationally for expertise. Lastly, ensure disaster resilience in all phases of RE projects for a resilient energy future (Flores & Peralta Quesada, 2020).

France: The design of active damping systems have proved to be resilient for wind turbine towers, particularly in the continuous rotation mode. The widely used Twin Rotor Damper (TRD) system emerges as a promising solution to effectively counteract vibrations induced by gusty winds. The implementation of the TRD not only aims to enhance structural safety but also seeks to elevate the quality of power production by mitigating tower vibrations (Bai et al., 2021). Flood-resistant materials are to be implemented, and strategic landscaping is to be integrated. This approach is anticipated to fortify the structural integrity of RE assets and diminish the impact of extreme weather events. By adopting these measures, an overall enhancement in the resilience of RE assets is expected, ensuring their capability to withstand climate change disruptions and promoting longevity (Ibrahim et al., 2021; Fearon, 2022; Ahmadi et al., 2022).

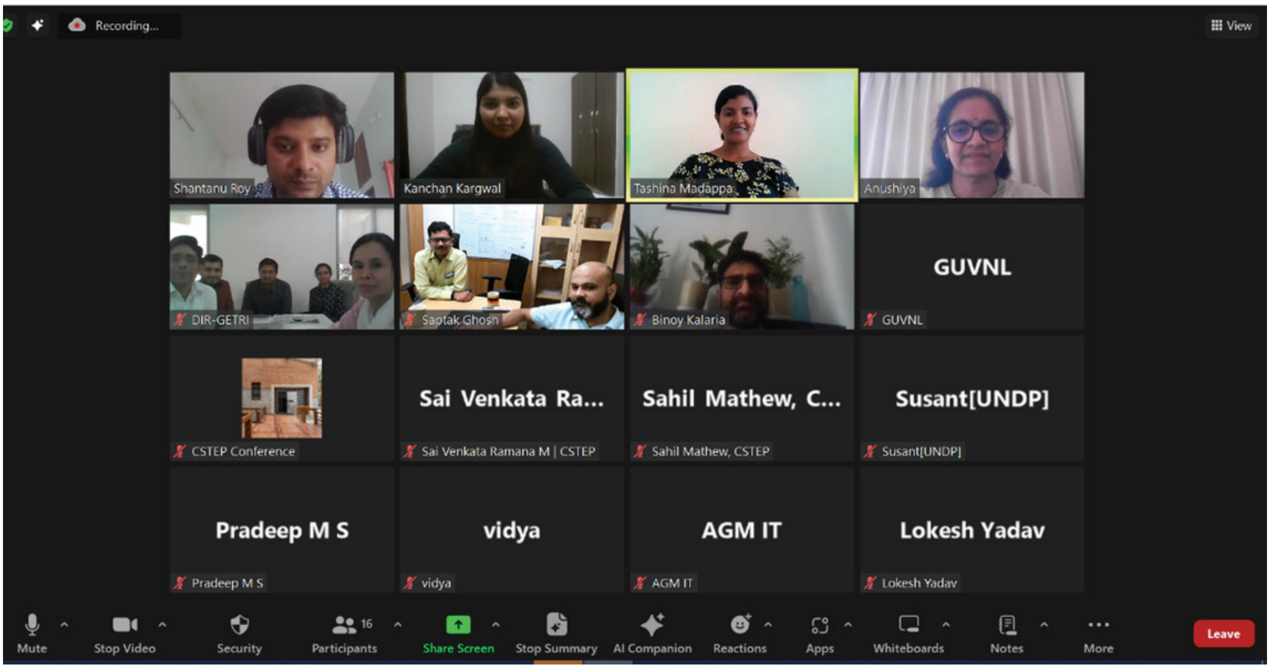
India: Flood-proofing can be done for various segments in an RE power plant, such as the generating station and transmission and distribution systems. For generating buildings using appropriate composite materials, and so on. For transmission systems, it usually involves building sub-stations on a raised platform and upgrading aluminium structures to galvanised steel, lattice, or concrete. For distribution systems, upgrading concrete poles to steel or a composite material and installing support wires and other structural supports may be done to reduce the impact of floods (Ministry of Power, GoI, 2017).

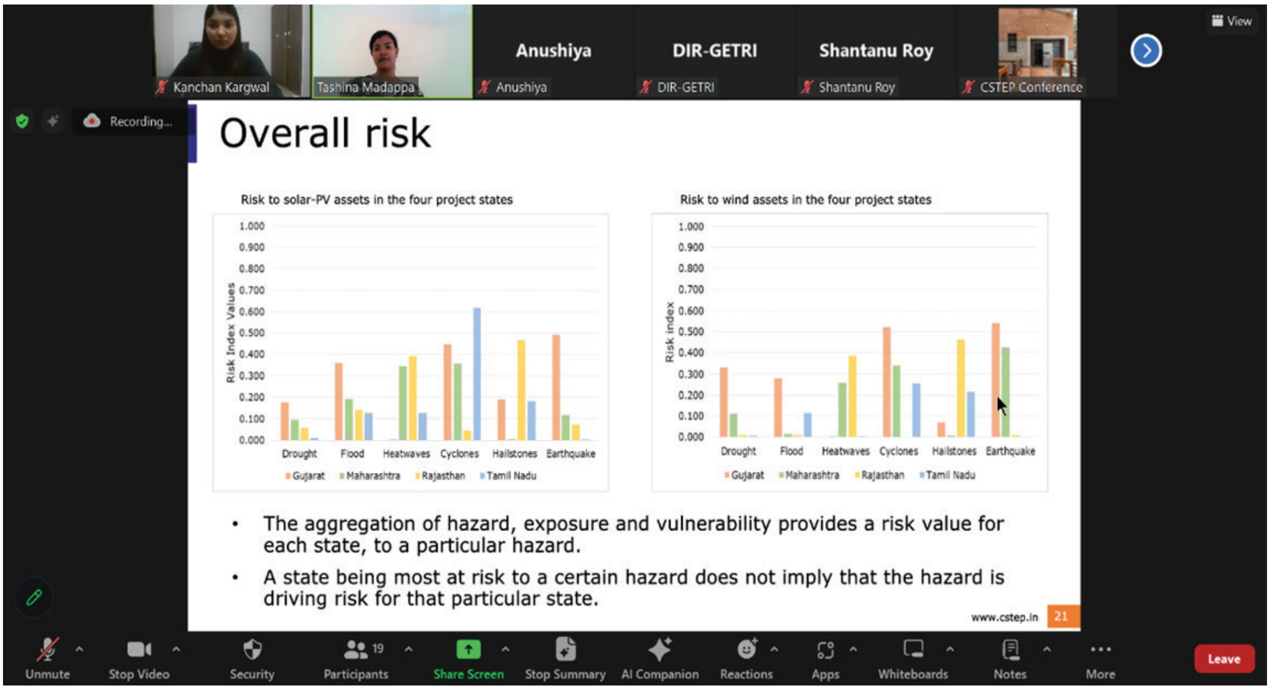
b. Risk-informed policy recommendations

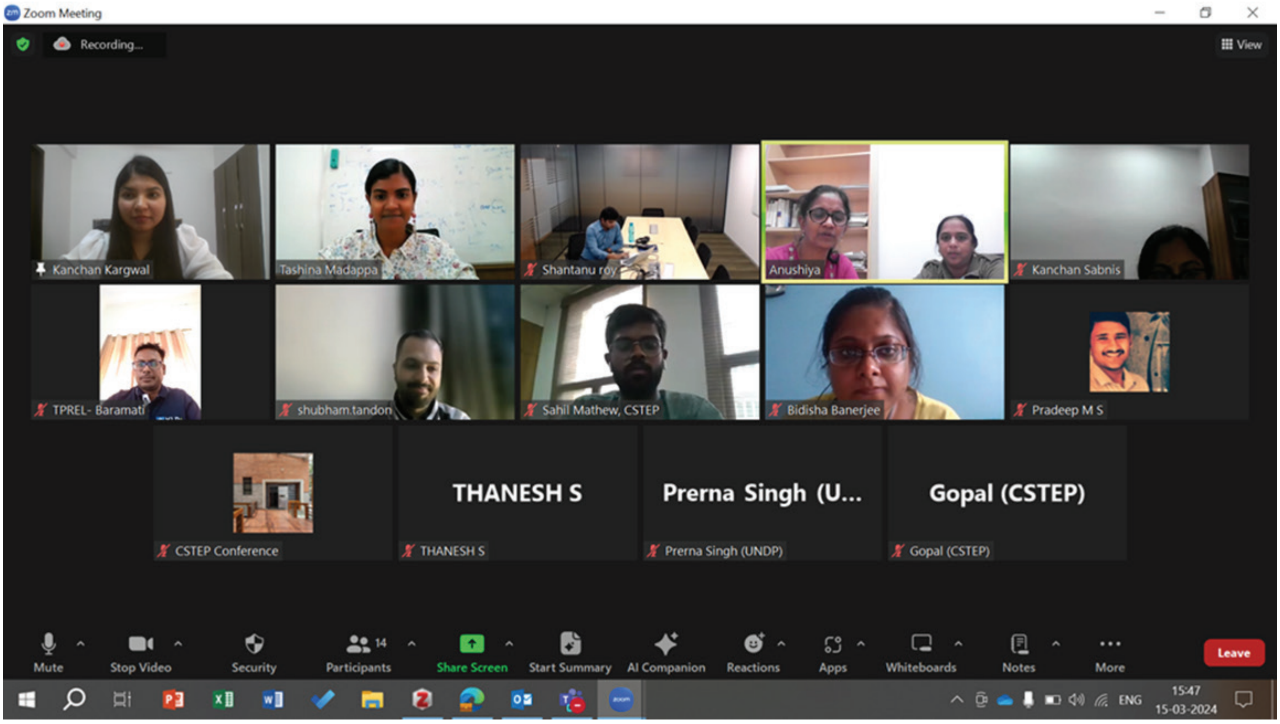
The drivers of vulnerability and risk were used to inform the selection of policy recommendations identified through the literature review.

c. Recommendations prioritised by stakeholders

State-level stakeholder consultations were conducted to present study findings and risk-informed policy recommendations (Appendix D). This exercise provided invaluable feedback, contextualised solutions, and the prioritisation of recommendations identified through the literature review. Some screenshots from the virtual and hybrid mode state-level stakeholder consultations conducted in all four project states are presented below.


Recording...
View
Shantanu Roy
Kanchan Kargwal
Tashina Madappa
Anushiya
DIR-GETRI
Saptak Ghosh
Binoy Kalaria
GUVNL
CSTEP Conference
Sai Venkata Ra...
Sai Venkata Ramana M | CSTEP
Sahil Mathew, C...
Sahil Mathew, CSTEP
Susant[UNDP]
Pradeep M S
vidya
AGM IT
Lokesh Yadav
Mute
Stop Video
Security
Participants
Share Screen
Stop Summary
AI Companion
Reactions
Apps
Whiteboards
Notes
More
Leave


Kanchan Kargwal
Tashina Madappa
Anushiya
DIR-GETRI
Shantanu Roy
CSTEP Conference
Recording...
Overall risk
Risk to solar-PV assets in the four project states
Risk Index Values
Drought Flood Heatwaves Cyclones Hailstones Earthquake
Gujarat Maharashtra Rajasthan Tamil Nadu
Risk to wind assets in the four project states
Risk index
The aggregation of hazard, exposure and vulnerability provides a risk value for each state, to a particular hazard.
A state being most at risk to a certain hazard does not imply that the hazard is driving risk for that particular state.
www.cstep.in
21
Unmute
Stop Video
Security
Participants
Share Screen
Stop Summary
AI Companion
Reactions
Apps
Whiteboards
Notes
More
Leave



Almost 40 policy recommendations that were identified were discussed with state-level stakeholders during these consultations. The policy recommendations are divided into four categories:

1) Infrastructure, design standards, and technology (Table 18)
2) Financial mechanisms and audits (Table 19)
3) Operation and maintenance (Table 20)
4) Disaster risk reduction (Table 21)

Recommendations highlighted in orange are risk-informed, while those in blue are other relevant recommendations. The rationale for their selection has also been provided. Key stakeholders have been mapped against the identified policy recommendation based on their ability to take necessary actions. A three-point timescale—short (1–2 years), medium (3–5 years), and long term (more than 5 years)—required for the implementation of recommendations has been provided. Furthermore, the recommendations have been ranked or prioritised by state-level stakeholders and presented in the order of preference of stakeholders.

4.1. CATEGORY 1: INFRASTRUCTURE, DESIGN STANDARDS, AND TECHNOLOGY

Table 18: Policy recommendations under Category 1

Policy recommendations	Rationale	References	Stakeholders	Timeline
Establish region-specific infrastructure modifications and promote the use of new materials for developing RE assets.	With regions prone to floods, food-resistant materials need to be used, and strategic landscaping needs to be integrated. This approach is anticipated to not only fortify the structural integrity of RE assets but also diminish the impact of extreme weather events. By adopting these measures, an overall enhancement in the resilience of RE assets is expected, ensuring their capability to withstand climate change disruptions and promoting longevity. In earthquake-prone zones, buildings and other equipment are required to be designed to withstand earthquakes as per required accelerations. It is recommended to employ strategic undergrounding which involves burying specific sections of the power network to safeguard critical transmission wires near the root nodes of power	Menon, 2023; UNDP, 2022; Ibrahim et al., 2021; Fearon, 2022; Ahmadi et al., 2022; Ministry of Power, GoI, 2017; Zlateva & Hadjitodorov, 2022; Feng et al., 20	OEM, BIS, NDMA, SDMA, State Nodal Agencies (SNAs), developers, EPCs	Long term

Policy recommendations	Rationale	References	Stakeholders	Timeline
	distribution networks. Such targeted strategies will enhance the resilience of power systems, thereby reducing critical infrastructure vulnerability to climate hazards.			
Develop micro-grids and distributed generation systems that operate independently or with the main grid.	Micro-grids and distributed generation systems can reduce total operating costs and increase the flexibility and adaptability of power supply and demand, especially during extreme weather events.	Xu et al., 2024; Cong & Gomi, 2020; Liu et al., 2023; Mokryani, 2022	CEA, OEM, AREAS, DISCOMs, developers, EPCs	Long term
Implement updated grid codes and specific low-voltage ride-through requirements to prevent power loss and maintain stability during disturbances.	Formulate specific low-voltage ride-through (LVRT) requirements in grid codes, considering normal operation and transformation during disasters as it can play a critical role in preventing power loss and maintaining stability during grid disturbances caused by various factors, including extreme events. Enforce updated grid code standards for RE	Yadav et al., 2023	CEA, OEM, developers, EPCs	Long term

Policy recommendations	Rationale	References	Stakeholders	Timeline
	system integration to mitigate the impact of natural disasters, such as earthquakes and floods, on distribution grids, ensuring long-term resilience.			
Ensure optimal placement, allocation, and operation of energy storage units.	It will enhance the resilience and flexibility of the grid.	Venkateswaran et al., 2020; Gong & Ionel, 2021	MOP, MNRE, DISCOMs and TRANSCOs, SNAs, developers, EPCs	Medium term
Develop uniform data acquisition methods and monitoring systems.	The use of a wide variety of data acquisition methods should be avoided as a uniform method enhances resource efficiency and transparency	SolarPower Europe, 2021	BIS, CEA	Medium term
Develop advanced analysis to assess the flexibility of distributed energy resources, manage uncertainties, and promote standardisation and collaboration	It will help in analysing demand response and energy storage potential, which can be further used to increase efficiency.	Singh & Al-Durra, 2023	BIS	Medium term
Create a regulatory framework to expedite innovative energy technology deployment during emergencies	Standardised testing and certification for deployable wind technologies would enhance credibility, ensuring that the	Cox et al., 2015	CEA, OEM	Medium term

Policy recommendations	Rationale	References	Stakeholders	Timeline
	infrastructure is designed to withstand and recover from unforeseen challenges.			
Develop affordable wireless smart meters, which measure power quality parameters, notify outages in real-time, and track the location of disruptions.	The smart grid technology has the capability to notify outages in real-time, identify the precise location of disruptions and restoration time, and help address hazards by allocating distributed energy resources in strategic places according to their vulnerability. The smart grid technology will further enhance the data availability on various grid parameters, which can help in predicting failures during extreme weather events. In addition, to enhance the monitoring and control of distribution networks, the application of the Internet of Things and big data analytics is recommended.	Afzal et al., 2020; Nazaripouya, 2020; Selga et al., 2022; Stürmer et al., 2021; Mokryani, 2022; Sousa et al., 2023	OEM, developers, EPCs	Medium term
Develop and adopt fragility models that account for multi-hazards, considering climate change projections.	It will help in making precise, timely, and informed policy decisions. Further, the exploration of probabilistic approaches for	Karagiannakis et al., 2023; Stürmer et al., 2021	IMD, NDMA, SDMA	Medium term

Policy recommendations	Rationale	References	Stakeholders	Timeline
	weather-induced failures and extensive testing with varied scenarios are crucial to comprehensive resilience planning.			
Explore the integration of AI in decision-making, planning, and condition monitoring.	Using AI and leveraging granular data from digital connectivity will enhance system efficiency and responsiveness to hazards.	Ting, 2021	BIS, developers	Medium term
Link international quality standards to cater for the local context.	Detailed guidelines and descriptive videos can be added to follow international quality standards.	Münch & Marian, 2022; McNiff et al., 2023	MNRE, CEA, SNAs	Short term

4.2. CATEGORY 2: FINANCIAL MECHANISMS AND AUDITS

Table 19: Policy recommendations under Category 2

Policy recommendations	Rationale	References	Stakeholders	Timeline
Ensure sustained funding for ongoing research and development in resilient energy systems.	Securing funding ensures that innovative solutions are developed to address emerging challenges and enhance the resilience of RE assets.	Cong & Gomi, 2020; Gomez et al., 2023	Financiers, NISE, NIWE	Long term
Incentivise domestic and foreign investors to align with global quality standards, fostering	Incentivising investors to meet global RE standards encourages the adoption of resilient infrastructure practices. Aligning with these	Gajjar, 2023; CDRI, 2023	BIS, CEA, financiers	Medium term

Policy recommendations	Rationale	References	Stakeholders	Timeline
international and long-term investment in RE.	standards enhances the overall resilience of RE assets, making them better equipped to withstand climate-related risks.			
Establish transparent, well-defined protocols to ensure that RE infrastructure adheres to standards, contributing to overall system resilience.	Transparent protocols ensure that resilient infrastructure practices are consistently followed, leading to the improved resilience of RE assets. Clear guidelines promote accountability and facilitate effective risk management strategies.	Energy5, 2023a; Mustafa & Barabadi, 2022	NDMA, SDMA, MNRE, State Energy Departments, IREDA	Medium term
Undertake community engagement projects and regular audits to ensure local education and compliance, bolstering resilience to climate hazards.	Community engagement fosters collaboration and ensures that infrastructure meets the needs and expectations of stakeholders.	CDRI, 2023	MOL&E, IREDA, CEA, MOP, NDMA, SDMA	Medium term
Provide insurance to absorb financial losses and expedite recovery and replacement processes associated with climate-related risks.	Climate-related risks pose a significant threat to RE assets, potentially leading to financial losses. Having a climate-risk insurance can help absorb these losses and expedite the recovery process, ensuring the continuity of energy generation.	Saur Energy, 2021; Karagiannakis et al., 2023; Jian et al., 2023	IRDAI, financiers, NDMA, SDMA, developers	Short term

Policy recommendations	Rationale	References	Stakeholders	Timeline
Establish a dedicated task force for regular inspections and penalties for non-compliance to ensure safety standards.	Regular safety inspections and penalties for non-compliance are essential to ensure that RE infrastructure meets safety standards, thereby enhancing resilience to climatic hazards and minimising the risk of accidents or failures during extreme weather events.	Gajjar, 2023; Energy5, 2023b	BIS, IEC, ISO, DISH, MOL&E	Short term
Undertake regular quality checks, audits, inspections, and risk assessments throughout a plant's lifetime.	Regular audits and risk assessments are crucial for identifying vulnerabilities and potential risks to RE assets. By addressing these issues proactively, the resilience of the infrastructure can be improved, minimising the impact of climatic hazards.	SolarPower Europe, 2021; Energy5, 2023c	CEA, BIS, IEC, ISO, DISH	Short term
Financial institutions should conduct risk assessments using global general equilibrium models to understand climate impacts on RE assets.	Utilising global models for climate risk assessments provides comprehensive insights into potential risks and vulnerabilities faced by RE assets. This enables better-informed decision-making and proactive planning to enhance resilience.	Chen et al., 2021	OEM, IRDAI	Short term

Policy recommendations	Rationale	References	Stakeholders	Timeline
Enhance transparency in reporting climate-related financial risks, ensuring financial institutions consider stranded assets in risk assessments.	Transparent reporting of financial risks associated with climate impacts on RE assets helps investors and stakeholders make informed decisions. Increased transparency fosters trust and facilitates the allocation of resources to enhance resilience.	Chen et al., 2021	Financiers, IRDAI	Short term

4.3. CATEGORY 3: OPERATION AND MAINTENANCE

Table 20: Policy recommendations under Category 3

Policy recommendations	Rationale	References	Stakeholders	Timeline
Upgrade ageing infrastructure and establish sufficient ancillary services and backup generation to ensure the reliability and security of supply.	Upgrading ageing infrastructure improves the reliability and resilience of RE assets by reducing the risk of failures and disruptions. Additionally, having sufficient ancillary services and backup generation ensures the security of supply during emergencies or unforeseen events	Karagiannakis et al., 2023; Mokryani, 2022; Plaza, 2021; Ranka et al., 2022	OEM, BIS, CEA, MNRE, developers	Long term
Elevate PV racks and incorporate open spaces between ballast materials to enhance drainage efficiency, reducing	Elevating PV racks and incorporating open spaces between ballast materials improve drainage efficiency within solar power plants. Efficient	Walker, 2018; Sengupta, 2020; Saur Energy, 2021	OEM, MNRE, State Nodal Agencies, developers, EPCs	Long term

Policy recommendations	Rationale	References	Stakeholders	Timeline
the risk of corrosion.	drainage reduces the accumulation of water around PV racks, minimising the risk of corrosion on the supporting structures and electrical components. Corrosion can compromise the structural integrity and electrical performance of a PV system, leading to potential failures and reduced lifespan. By enhancing drainage, this measure contributes to the overall resilience of solar power plants, ensuring their long-term functionality and performance even during extreme weather events.			
Develop a universal web-based platform with inputs from various sources for seamless communication to face power distribution system threats.	A universal web-based platform facilitates seamless communication between various stakeholders, including power operators and meteorological agencies, enhancing coordination and enabling efficient responses to threats faced by the power distribution system, thus improving resilience.	Zafeiropoulou et al., 2023	IMD, MOEFCC, MNRE	Medium term

Policy recommendations	Rationale	References	Stakeholders	Timeline
Dry cleaning technology should be available for cleaning solar panels as a backup to cleaning solar panels using water in case of water scarcity or droughts.	Dry cleaning technology serves as a backup method for cleaning solar panels in case of water scarcity or droughts, ensuring that the panels remain free from debris and maintain optimal performance, thus contributing to the resilience of solar power plants.	ERM, 2022	OEM, developers, EPCs	Medium term
Improve the overall resilience of RE assets by incorporating digital monitoring and cost control techniques.	Digital monitoring and cost control techniques enable the proactive identification of issues and efficient resource allocation, enhancing the overall resilience of RE assets by ensuring timely maintenance and cost-effective operation.	Mao et al., 2022	OEM, developers, MNRE	Medium term
Follow an asset-centric approach to operations, promoting the free flow of data and transparency between stakeholders for the life cycle of the asset.	An asset-centric approach promotes transparency and facilitates the free flow of data between stakeholders throughout the life cycle of RE assets, enabling informed decision-making and proactive maintenance, thus enhancing resilience.	SolarPower Europe, 2021; Peng et al., 2023	MNRE, CEA	Medium term

Policy recommendations	Rationale	References	Stakeholders	Timeline
Create dedicated reserve accounts aimed specifically at covering operational and maintenance expenses.	Having dedicated reserve accounts ensures that there are funds specifically allocated to cover O&M expenses, which are crucial for the ongoing reliability and performance of RE assets. This ensures that these expenses do not strain the overall finances of a project and enable proactive maintenance to enhance resilience.	Walker, 2018	IRDAI, financiers, AREAS, NDMA, SDMA	Short term
Establish communication channels between power operators and meteorological agencies and efficient coordination between TSOs and DSOs	Effective communication channels between key stakeholders such as power operators, meteorological agencies, TSOs, and DSOs are essential for timely information exchange and coordination, leading to improved resilience and responsiveness to threats.	Zafeiropoulou et al., 2023	IMD, NDMA, SDMA	Short term
Incorporate water-harvesting and irrigation systems to enhance water availability and efficiency for PV cooling.	Water-harvesting and irrigation systems enhance water availability and efficiency for cooling PV panels, thereby improving their performance and longevity, especially during periods of water	McTiernan et al., 2023	OEM, CEA, MNRE, MOP	Short term

Policy recommendations	Rationale	References	Stakeholders	Timeline
	Having dedicated rscarcity or droughts, which contribute to the overall resilience of solar power plants.			
O&M service providers should propose ‘stakeholder training’ for people working next to the installations.	Stakeholder training ensures that personnel working next to RE installations are equipped with the necessary skills and knowledge to identify and respond to potential hazards, thereby enhancing safety and resilience.	SolarPower Europe, 2021	MNRE, MOP, MOL&E, developers	Short term
Mitigate run-off and erosion in solar power plant areas by employing soil conditioners, which prevent soil displacement and enhance site integrity.	Soil conditioners mitigate run-off and erosion, enhancing the overall integrity of solar power plant sites and reducing maintenance requirements, thereby contributing to the resilience of solar infrastructure.	Walker, 2018; Sengupta, 2020; Saur Energy, 2021	OEM, State Nodal Agencies, developers, EPCs	Short term

4.4. CATEGORY 4: DISASTER RISK REDUCTION

Table 21: Policy recommendations under Category 4

Policy recommendations	Rationale	References	Stakeholders	Timeline
Implement robust safety and emergency management plans and involve disaster management cells for preparedness.	Implementing robust safety and emergency management plans is critical for minimising risks and ensuring effective response mechanisms during disasters. These plans outline procedures for identifying hazards, mitigating risks, and responding to emergencies promptly. Involving disaster management cells in preparedness efforts enhances coordination and collaboration between stakeholders, including government agencies, industry partners, and local communities. Disaster management cells contribute expertise in disaster risk reduction and facilitate proactive measures to enhance the resilience of RE assets and personnel.	Arcadis, 2022; Energy5, 2023	NDMA, SDMA, MOP, OEM, OSHA	Long term
Promote an optimal machine-learning model to predict the risk level of the transmission line	Promoting the use of an optimal machine-learning model for predicting the risk level of transmission line	Huang et al., 2023; Yadav et al., 2023	MNRE, OEM, research institutions	Long term

Policy recommendations	Rationale	References	Stakeholders	Timeline
section and take preventive measures.	sections enables proactive risk management and preventive measures. Machine-learning algorithms can analyse historical data, weather patterns, and other relevant factors to forecast potential risks accurately. By identifying high-risk areas in transmission lines, preventive measures such as infrastructure modifications, maintenance activities, and vegetation management can be implemented to mitigate the impact of climate hazards. This proactive approach minimises the likelihood of disruptions to power transmission and enhances the resilience of the grid infrastructure.			
Promote a dual-segmented software approach for effective weather warnings in RE systems.	Developing early warning systems, integrating resilience into disaster risk management plans, and implementing safety and emergency management plans ensure swift response mechanisms and safeguard the functionality of RE	Sánchez-Sierra et al., 2021; ERM, 2022; Pasman et al., 2020; Son et al., 2022; Arcadis, 2022; Garcia & Bruschi, 2016	IMD, NDMA, research institutions	Long term

Policy recommendations	Rationale	References	Stakeholders	Timeline
	infrastructure during climatic hazards.			
Develop early warning systems with state/national disaster management authorities.	Include the impact of climate hazards on RE assets and disaster-preparedness guidelines in national disaster management plans. The guidelines outline specific measures to enhance the resilience of RE infrastructure, protect personnel, and minimise disruptions to energy supply during disasters. Using these guidelines, efficient early warning systems can be developed to enhance short-, long-term planning for resilient infrastructure.	Menon, 2023; UNDP, 2022; Ibrahim et al., 2021; Fearon, 2022; Ahmadi et al., 2022; Amini et al., 2023; Pasman et al., 2020; Son et al., 2022; Ministry of Power, GoI, 2017	NDMA, SDMA, IMD, MNRE, CEA, OEM, developers, local government bodies, NGOs	Medium term
Foster collaboration between government agencies, industry stakeholders, and experts from environmental and energy sectors to address challenges.	Collaboration between government agencies, industry stakeholders, and experts is crucial for jointly addressing challenges and developing guidelines for RE asset resilience.	Münch & Marian, 2022; GIZ, 2013; UNDRR, 2022; Baran et al., 2022; Bashir, 2022	IREDA, IMD, MNRE, MOEFCC, OEM, research institutions	Medium term

Policy recommendations	Rationale	References	Stakeholders	Timeline
Mandate first-aid training for all site employees and provide insurance for work-related injuries.	In the event of work-related injuries or accidents, employees equipped with first-aid skills can provide immediate assistance, potentially saving lives and reducing the severity of injuries. Providing insurance for work-related injuries further enhances employee safety and addresses potential financial burdens associated with medical expenses and compensation.	Garcia & Bruschi, 2016; Walker, 2018	MOL&E, MOHFW, NSC, IRDAI, OSHA	Short term
Conduct comprehensive risk assessments and geographic analysis before selecting sites to ensure the long-term viability and safety of RE assets.	Comprehensive risk assessments, the adoption of robust risk assessment frameworks, and detailed risk assessments by financial institutions are necessary to understand and mitigate climate-related risks. Risk assessment should incorporate climate impact metrics and should be customised for more accurate and contextualised results.	UNDRR, 2022; ERM, 2022; Chen et al., 2021; Saur Energy, 2021; Wang et al., 2021	MNRE, MOEFCC, CERC OEM, Local Government Bodies, Research Institutions	Short term

4.5. ROUND TABLE DISCUSSION ON BUILDING PATHWAYS FOR RENEWABLE ENERGY RESILIENCE

Overview:
UNDP hosted a roundtable discussion at the UN House, New Delhi, on July 4, 2024 to present the findings of the study conducted in collaboration with CSTEP, with support from the Embassy of Japan in India to key stakeholders from across the country. This discussion served as a platform to engage with participants and gather their views on enhancing the resilience of solar and wind power plants across India.

Participants included the National Disaster Management Authority (NDMA), Coalition for Disaster Resilient Infrastructure (CDRI), International Solar Alliance (ISA), National Institute of Solar Energy (NISE), The Energy and Resources Institute (TERI), Tata Power, Energy Efficiency Services Limited (EESL), Indian Institute of Technology (IIT) Delhi, Renew, Adani, Directorate of Industrial Safety and Health, Maharashtra State, Clean Energy Access Network (CLEAN), TARU, Gujarat State Disaster Management Authority (GSDMA) and the British High Commission. Some pictures form the event are presented below:


UNDP

The participants provided key insights and recommendations to build resilience of RE infrastructure, which are summarised below.

Key Recommendations:

1. Risk Assessment and guidelines for disaster resilient RE infrastructure:

a. The current study analysed historical climate data to assess risks to RE assets, focusing on solar and wind power plants. While this study can act as a steppingstone to accelerate work to build resilient RE infrastructure, an assessment looking at future climate change risks will need to be undertaken.

b. Detailed studies are needed to identify the socio-economic damages of RE infrastructure failure due to extreme events.

c. Clear guidelines need to be prepared to ensure RE infrastructure resilience.

2. Stakeholder Engagement and Capacity Building:

a. Engaging with industry stakeholders and particularly with the Ministry of New and Renewable Energy (MNRE) is crucial to accelerate the development of resilient RE infrastructure.

b. Collaboration between agencies and capacity building of all stakeholders is necessary.

c. The NDMA expressed a desire to designate the RE sector as critical infrastructure in the country and to prioritize it for building disaster-resilient RE infrastructure. To achieve this, the capabilities of State Disaster Management Authorities (SDMAs) wil need to be enhanced through guidelines and capacity building relevant to RE infrastructure.

3. Response and Recovery:

a. Formulate sector-specific policies for emergency response and recovery, including training for response teams.

b. Strategies for the rapid restoration of RE assets post-extreme weather events should be prioritized.

c. Encourage decentralization of power generation and modularity in RE infrastructure, allowing dismantling during extreme events and use in disaster response.

d. MNRE to mandate 'All Risk' insurance policies for RE assets.

e. Financial institutions should be involved early in RE project cycles to identify and mitigate risks from extreme events.

4. Resilience Standards:

a. Upgrade resilience standards and integrate them into the competitive bidding process for RE projects.

b. Address trade-offs between regulatory frameworks and deployment costs, ensuring that climate resilience is prioritized.

5. Land and Legal Frameworks:

a. Consider the viability of land used for RE projects, which may be exposed to extreme events. Prioritizing resilience in such project will be paramount. Furthermore, RE asset deployment should not be at the cost of vulnerable populations and farmers.

b. Initiate legal reforms to incorporate climate resilience into RE asset norms and laws.

This collaborative effort emphasizes the importance of integrating resilience into the planning, development, and operation of renewable energy systems to ensure sustainable and reliable energy access in the face of climate change.

5. REFERENCES

Anandh, T. S., Gopalakrishnan, D., & Mukhopadhyay, P. (2022). Analysis of future wind and solar potential over India using climate models. Current Science, 122(11), 1268. https://doi.org/10.18520/cs/v122/i11/1268-1278

Afzal, S., Mokhlis, H., Illias, H. A., Mansor, N. N., & Shareef, H. (2020). State-of-the-art review on power system resilience and assessment techniques. IET Generation, Transmission & Distribution, 14(25), 6107–6121. https://doi.org/10.1049/iet-gtd.2020.0531

Agard J. & Schipper L. F. E. (2014). IPCC AR 5 Synthesis Report. Annex II Glossary. Annex II - Glossary (ipcc.ch)

Ahmadi, S., Khorasani, A. H. F., Vakili, A., Saboohi, Y., & Tsatsaronis, G. (2022). Developing an innovating optimization framework for enhancing the long-term energy system resilience against climate change disruptive events. Energy Strategy Reviews, 40, 100820. https://doi.org/10.1016/j.esr.2022.100820

Amini, F., Ghassemzadeh, S., Rostami, N., & Tabar, V. S. (2023). Electrical energy systems resilience: A comprehensive review on definitions, challenges, enhancements and future proceedings. IET Renewable Power Generation, 17(7), 1835–1858. https://doi.org/10.1049/rpg2.12705

Arcadis India Private Limited. (2022). Executive Summary EP4 Study- Climate Change Risk Assessment (CCRA) 450 MW Hybrid (Wind & Solar) Project, Rivdi, District Jaisalmer and Sheo, District Barmer, Rajasthan. Executive-Summary-Climate-Change-Risk-Assessment-CCRA-for-450-MW-Hybrid-Power-Project.pdf (adanigreenenergy.com)

Arctic Council (2016). Arctic Resilience Report. M. Carson and G. Peterson (eds). Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm. https://arctic-council.org/

Astiaso Garcia, D., & Bruschi, D. (2016). A risk assessment tool for improving safety standards and emergency management in Italian onshore wind farms. Sustainable Energy Technologies and Assessments, 18, 48–58. https://doi.org/10.1016/j.seta.2016.09.009

Bae, I.-S., Kim, S.-Y., & Kim, D.-M. (2022). Repair Priority in Distribution Systems Considering Resilience Enhancement. Energies, 15(3), Article 3. https://doi.org/10.3390/en15031190

Bai, H., Aoues, Y., Cherfils, J.-M., & Lemosse, D. (2021). Design of an Active Damping System for Vibration Control of Wind Turbine Towers. Infrastructures, 6(11), 162. https://doi.org/10.3390/infrastructures6110162

Bhaskar, U. (2021, May 10). How climate change is slowing the hum of India's windmills. Mint. https://www.livemint.com/industry/energy/how-fickle-winds-hit-india-s-energy-dreams-11620659639657.html

Baran, M., Kłos, M., Chodorek, M., & Marchlewska-Patyk, K. (2022). The Resilient Smart City Model–Proposal for Polish Cities. Energies, 15(5), Article 5. https://doi.org/10.3390/en15051818

Baruah R., Bhaskar, U. (2023, April 18). Now, wind power braces for El Nino. Mint. https://www.livemint.com/news/india/el-nino-to-impact-wind-power-generation-in-india-as-wind-speeds-slow-during-historically-high-wind-months-of-june-to-september-warns-industry-11681841486277.html

Bashir, M. B. A. (2022). Principle Parameters and Environmental Impacts that Affect the Performance of Wind Turbine: An Overview. Arabian Journal for Science and Engineering, 47(7), 7891–7909. https://doi.org/10.1007/s13369-021-06357-1

Boopathi, K., Mishnaevsky Jr, L., Sumantraa, B., Premkumar, S. A., Thamodharan, K., & Balaraman, K. (2022). Failure mechanisms of wind turbine blades in India: Climatic, regional, and seasonal variability. Wind Energy, 25(5), 968–979. https://doi.org/10.1002/we.2706

CDRI. (2023). Cyclone Preparedness for Renewable Energy Projects. 1777537806470619_20230920064217242815553534 72_202202091037cdriadvisory.pdf

Chen, F.-W., & Liu, C.-W. (2012). Estimation of the spatial rainfall distribution using inverse distance weighting (IDW) in the middle of Taiwan. Paddy and Water Environment, 10(3), 209–222. https://doi.org/10.1007/s10333-012-0319-1

Chen, Y., Yu, J., & Khan, S. (2010). Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. Environmental Modelling & Software, 25(12), 1582–1591. https://doi.org/10.1016/j.envsoft.2010.06.001

Chen, Y.-H. H., Landry, E., & Reilly, J. (Eds.). (2021). An economy-wide framework for assessing global transition risk in the energy production sector.

Climate News Network. (2021, January 6). Cyclones reduce India's wind power generation.
https://www.eco-business.com/news/cyclones-reduce-indias-wind-power-generation/

Cong, R., & Gomi, K. (2020). Evidence for the development of energy resilience in Fukushima Prefecture after the Great East Japan earthquake. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLIV-3-W1-2020, 37–41.
https://doi.org/10.5194/isprs-archives-XLIV-3-W1-2020-37-2020

Cox, S., Walters, T., Esterly, S., & Booth, S. (2015). Solar Power. Policy Overview and Good Practices (NREL/TP--6A20-64178, 1215246; p. NREL/TP--6A20-64178, 1215246). https://doi.org/10.2172/1215246

Das, S. (2020). Flood susceptibility mapping of the Western Ghat coastal belt using multi-source geospatial data and analytical hierarchy process (AHP). Remote Sensing Applications: Society and Environment, 20, 100379.
https://doi.org/10.1016/j.rsase.2020.100379

Data classification methods—ArcGIS Pro. Arcgis.com. Published 2018.
https://pro.arcgis.com/en/pro-app/latest/help/mapping/layer-properties/data-classification-methods.htm

Dhirender Mishra. (2022, August 10). Heat Wave: A Challenge for Power Sector.
https://www.aranca.com/knowledge-library/articles/business-research/heat-wave-a-challenge-for-power-sector

Energy5. (2023a). The Synergy of Wind Turbines and Disaster Management. The Synergy of Wind Turbines and Disaster Management (energy5.com)

Energy5. (2023b). Leveraging Wind Turbines in Disaster Risk Reduction. Leveraging Wind Turbines in Disaster Risk Reduction (energy5.com)

Energy5. (2023c). The Role of Wind Turbines in Enhancing Disaster Response Strategies. The Role of Wind Turbines in Enhancing Disaster Response Strategies (energy5.com)

ERM. (2022). Screening level natural hazard and climate change assessment in Jaisalmer. Report (adanigreenenergy.com)

Fearon, R. (2022). Extreme Weather Tests the Durability of Solar and Wind Power. Extreme Weather Tests the Durability of Solar and Wind Power | Latest Science News and Articles | Discovery

Feng, K., Min, O., & Lin, N. (2020). Hurricane-blackout-heatwave Compound Hazard Risk and Resilience in a Changing Climate (arXiv:2012.04452). arXiv. https://doi.org/10.48550/arXiv.2012.04452

Flores, A., & Peralta Quesada, L. (2020). The enhancement of resilience to disasters and climate change in the Caribbean through the modernization of the energy sector. https://hdl.handle.net/11362/45098

Gajjar J. (2023). Impact of cyclones on India's solar rooftop photovoltaic systems.

Gao, M., Ding, Y., Song, S., Lu, X., Chen, X., & McElroy, M. B. (2018). Secular decrease of wind power potential in India associated with warming in the Indian Ocean. Science Advances, 4(12), eaat5256. https://doi.org/10.1126/sciadv.aat5256

GDACS, (n.d.). Global Disaster Alert and Coordination System. https://gdacs.org/

GIZ. (2013). Critical Infrastructures and Disaster Risk Reduction. Critical Infrastructures and Disaster Risk Reduction 46.cdr (nidm.gov.in)

Gong, G., Mattevada, S., & O'Bryant, S. E. (2014). Comparison of the accuracy of kriging and IDW interpolations in estimating groundwater arsenic concentrations in Texas. Environmental Research, 130, 59–69. https://doi.org/10.1016/j.envres.2013.12.005

Gong, H., & Ionel, D. M. (2021). Improving the Power Outage Resilience of Buildings with Solar PV through the Use of Battery Systems and EV Energy Storage. Energies, 14(18), Article 18. https://doi.org/10.3390/en14185749

Gopal, S. (2019, March 11). Study shows climate change impacts wind energy industry. Mongabay-India. https://india.mongabay.com/2019/03/study-shows-climate-change-impacts-wind-energy-industry/

Hu, J.-L. (2022). Energy Resilience in Presence of Natural and Social Uncertainties. Energies, 15(18), Article 18. https://doi.org/10.3390/en15186566

Huang, G., Wu, G., Guo, Y., Liang, M., Li, J., Dai, J., Yan, X., & Gao, G. (2023). Risk assessment models of power transmission lines undergoing heavy ice at mountain zones based on numerical model and machine learning. Journal of Cleaner Production, 415, 137623. https://doi.org/10.1016/j.jclepro.2023.137623

Ibrahim Nur Atirah, Wan Alwi Sharifah Rafidah, Abdul Manan Zainuddin, Mustaffa Azizul Azri, & Kidam Kamarizan. (2021). Flood Impact on Renewable Energy System in Malaysia. Chemical Engineering Transactions, 89, 193–198. https://doi.org/10.3303/CET2189033

Ibrahim, N. A., Wan Alwi, S. R., Manan, Z. A., Mustaffa, A. A., & Kidam, K. (2022). Risk matrix approach of extreme temperature and precipitation for renewable energy systems in Malaysia. Energy, 254, 124471.
https://doi.org/10.1016/j.energy.2022.124471

India Meteorological Department (IMD). (2023). Very Severe Cyclonic Storm "Biparjoy" over Northeast Arabian Sea: Cyclone Warning for Saurashtra & Kutch Coasts.
https://mausam.imd.gov.in/Forecast/marquee_data/76.%20National%20Bulletin%2020230615_1200.pdf

IMD & Power System Operation Corporation Limited (POSOCO). (2022). Use of weather information for secure, reliable and economic operation of Indian grid.
https://mausam.imd.gov.in/imd_latest/contents/pdf/IMDposoco.pdf

IMD., (2020). Average Number of Hailstorm Days in Annual-Hazard Atlas of India.
https://imdpune.gov.in/hazardatlas/hailnew.html

imdStürmer, J. M., Plietzsch, A., & Anvari, M. (2021). The Risk of Cascading Failures in Electrical Grids Triggered by Extreme Weather Events (arXiv:2107.00829). arXiv.
https://doi.org/10.48550/arXiv.2107.00829

IPCC. (2014). Climate change 2014: Impacts, adaptation, and vulnerability: Working Group II contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change (C. B. Field, V. R. Barros, & Intergovernmental Panel on Climate Change, Eds.). Cambridge University Press

IPCC. (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. doi:10.1017/9781009325844

Jai, S. (2020, November 20). Wind energy dips in peak season; industry fears climate change impact. Business Standard.
https://www.business-standard.com/article/economy-policy/wind-energy-dips-in-peak-season-industry-fears-climate-change-impact-120112000767_1.html

Jamaluddin, K., Wan Alwi, S. R., Manan, Z. A., Hamzah, K., & Klemeš, J. J. (2018). Hybrid power systems design considering safety and resilience. Process Safety and Environmental Protection, 120, 256–267. https://doi.org/10.1016/j.psep.2018.09.016

Jian, W., Lo, E. Y.-M., Stojanovski, P., & Pan, T.-C. (2023). Quantifying uncertainties in tropical cyclone wind hazard assessment due to synthetic track stochastic variability for Southeast Asia. Weather and Climate Extremes, 41, 100599.
https://doi.org/10.1016/j.wace.2023.100599

Karagiannakis, G., Panteli, M., & Argyroudis, S. (2023). Fragility modelling of power grid infrastructure for addressing climate change risks and adaptation.

Lin, L., Wu, Z., & Liang, Q. (2019). Urban flood susceptibility analysis using a GIS-based multi-criteria analysis framework. Natural Hazards, 97(2), 455–475. https://doi.org/10.1007/s11069-019-03615-2

Liu, Q., Qian, J., Neville, A., & Pessu, F. (2023). Solar thermal irradiation cycles and their influence on the corrosion behaviour of stainless steels with molten salt used in concentrated solar power plants. Solar Energy Materials and Solar Cells, 251, 112141. https://doi.org/10.1016/j.solmat.2022.112141

Luo, T. (2017). Droughts and Blackouts: How Water Shortages Cost India Enough Energy to Power Sri Lanka. https://www.wri.org/insights/droughts-and-blackouts-how-water-shortages-cost-india-enough-energy-power-sri-lanka

Mao, Q., Guo, M., Lv, J., Chen, J., Xie, P., & Li, M. (2022). A Risk Assessment Framework of Hybrid Offshore Wind–Solar PV Power Plants under a Probabilistic Linguistic Environment. Sustainability, 14(7), 4197. https://doi.org/10.3390/su14074197

McKee, T.B.; Doesken, N.J.; Kleist, J. (1993). The Relationship of Drought Frequency and Duration to Time Scales. Eighth Conference on Applied Climatology.

McNiff, B., Keller, J., Fernandez-Sison, A., & Demtröder, J. (2023). A Revised International Standard for Gearboxes in Wind Turbine Systems: Preprint. Renewable Energy. A Revised International Standard for Gearboxes in Wind Turbine Systems: Preprint (Conference) | OSTI.GOV

McTiernan et al. (2023, March 8). Modelling the suitability of agrivoltaics to deliver sustainable energy and food production in East Africa. https://doi.org/10.21203/rs.3.rs-2520319/v

Menon, A. (2023). As temperatures increase, India's solar sector feels the heat. Mongabay-India. https://india.mongabay.com/2023/06/as-temperatures-increase-indias-solar-sector-feels-the-heat/

Ministry of Earth Sciences. (2021). Seismic Mapping, PIB Delhi. https://pib.gov.in/PressReleasePage.aspx?PRID=1740656

Ministry of Power, Government of India. (2017). Crisis and disaster management plan for power sector. cmp_powersector.pdf (kar.nic.in)

Mishra, A. (2023). Biparjoy impact: Cyclone damages crops in Kutch, affected areas struggle to restore power. India Today. https://www.indiatoday.in/india/story/biparjoy-impact-cyclone-landfall-damages-cash-crops-in-kutch-most-affected-areas-struggle-to-restore-power-2394319-2023-06-17

Mokryani, G. (2022). Future Distribution Networks: Planning, Operation, and Control. AIP Publishing LLC. https://doi.org/10.1063/9780735422339

Münch, F. A., & Marian, A. (2022). The design of technical requirements in public solar auctions: Evidence from India. Renewable and Sustainable Energy Reviews, 154, 111713. https://doi.org/10.1016/j.rser.2021.111713

Mustafa, A. M., & Barabadi, A. (2022). Criteria-Based Fuzzy Logic Risk Analysis of Wind Farms Operation in Cold Climate Regions. Energies, 15(4), 1335. https://doi.org/10.3390/en15041335

National Remote Sensing Centre (2023). Flood Affected Area Atlas of India: Version 1 (1998-2022)- - Satellite based Study. https://ndem.nrsc.gov.in/documents/downloads/Flood%20Affected%20Area%20%20Atlas%20of%20India%20-Satellite%20based%20study.pdf

Nazaripouya, H. (2020). Power Grid Resilience under Wildfire: A Review on Challenges and Solutions. 2020 IEEE Power & Energy Society General Meeting (PESGM), 1–5. https://doi.org/10.1109/PESGM41954.2020.9281708

Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D. W., & Yap, P.-S. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. Environmental Chemistry Letters, 21(2), 741–764. https://doi.org/10.1007/s10311-022-01532-8

Pai, D. S., Nair, S., & Ramanathan, A. N. (2013). Long term climatology and trends of heatwaves over India during the recent 50 years (1961-2010). MAUSAM, 64(4), 585–604. https://doi.org/10.54302/mausam.v64i4.742

Pasman, H., Kottawar, K., & Jain, P. (2020). Resilience of Process Plant: What, Why, and How Resilience Can Improve Safety and Sustainability. Sustainability, 12(15), Article 15. https://doi.org/10.3390/su12156152

Patil, A., Pathak, C., & Alduse, B. (2023). Review of Natural Hazard Risks for Wind Farms. Energies, 16(3), 1207. https://doi.org/10.3390/en16031207

Peng, H., Li, S., Shangguan, L., Fan, Y., & Zhang, H. (2023). Analysis of Wind Turbine Equipment Failure and Intelligent Operation and Maintenance Research. Sustainability, 15(10), 8333. https://doi.org/10.3390/su15108333

Plaza, A. C. (2021). Accelerated aging and durability of selective materials for concentrating solar power plant receivers [Phdthesis, Université de Perpignan]. https://theses.hal.science/tel-03611325

Pugh, K., & Stack, M. M. (2021). Rain Erosion Maps for Wind Turbines Based on Geographical Locations: A Case Study in Ireland and Britain. Journal of Bio- and Tribo-Corrosion, 7(1), 34. https://doi.org/10.1007/s40735-021-00472-0

Ranka, P., Valldecabres, L., Schafhirt, S., & Bierbooms, W. (2022). Extreme wind speed ramp events: A measurement-based approach for improving the modelling of ultimate loads for wind turbine design. Journal of Physics: Conference Series, 2265(3), 032042. https://doi.org/10.1088/1742-6596/2265/3/032042

REN21. (2022). Renewables 2022 Global Status Report (Paris: REN21 Secretariat).

REN21. (2023). Renewables 2023 Global Status Report Collection, Global Overview (Paris: REN21 Secretariat).

Russo, S., Dosio, A., Graversen, R. G., Sillmann, J., Carrao, H., Dunbar, M. B., Singleton, A., Montagna, P., Barbola, P., & Vogt, J. V. (2014). Magnitude of extreme heatwaves in present climate and their projection in a warming world. Journal of Geophysical Research: Atmospheres, 119(22). https://doi.org/10.1002/2014JD022098

Sanchez Gomez, M., Lundquist, J. K., Deskos, G., Arwade, S. R., Myers, A. T., & Hajjar, J. F. (2023). Wind Fields in Category 1–3 Tropical Cyclones Are Not Fully Represented in Wind Turbine Design Standards. Journal of Geophysical Research: Atmospheres, 128(16), e2023JD039233. https://doi.org/10.1029/2023JD039233

Sánchez-Sierra, E. J., Grajales, D., & Galvis, O. (2021). A Methodological Approach for Climate Change Risk Assessment in the Power Sector: A Case Study in Colombia, January 1, 2016 - October 31, 2020 (NREL/SR-7A40-77289). National Renewable Energy Lab. (NREL), Golden, CO (United States). https://doi.org/10.2172/1762449

Saur Energy. (2021). Extreme Events & Operations and Maintenance (O&M) of Solar PV Plants. Retrieved January 22, 2024, from https://www.saurenergy.com/solar-energy-blog/extreme-events-om-of-solar-pv-plants

Selga, A. G., Muñoz, D. S., & Dominguez-García, J. L. (2022). Analysis and enhancement of Barcelona's power grid resilience. Energy Reports, 8, 1160–1167. https://doi.org/10.1016/j.egyr.2022.08.119

Sengupta D. (2020). Flood Risk Assessment Essential for Longevity of Solar Assets—Mercom India. (n.d.). Mercomindia.Com. Retrieved January 22, 2024, from https://mercomindia.com/flood-risk-assessment-essential

Shepard, D. (1968). A two-dimensional interpolation function for irregularly-spaced data. Proceedings of the 1968 23rd ACM National Conference on 27-29 August 1968, 517–524. https://doi.org/10.1145/800186.810616

Sherriff, L. (2023). Babcock Ranch: Florida's first hurricane-proof town. BBC. Babcock Ranch: Florida's first hurricane-proof town (bbc.com)

Simsek, E., Williams, M. J., & Pilon, L. (2021). Effect of dew and rain on photovoltaic solar cell performances. Solar Energy Materials and Solar Cells, 222, 110908. https://doi.org/10.1016/j.solmat.2020.110908

Singh, U., & Al-Durra, A. (2023). Implementing hosting capacity analysis in distribution networks: Practical considerations, advancements and future directions (arXiv:2312.06582). arXiv. https://doi.org/10.48550/arXiv.2312.06582

SolarPower Europe. (2021). Operation and Maintenance: Best Practice Guidelines Version 5.0. SolarPower Europe O&M Guidelines

Son, E.-T., Bae, I.-S., Kim, S.-Y., & Kim, D.-M. (2022). Resilience-Oriented Framework for Microgrid Planning in Distribution Systems. Energies, 15(6), Article 6. https://doi.org/10.3390/en15062145

Sousa, E. L. de, Marques, L. A. de A., Lima, I. da S. F. de, Neves, A. B. M., Cunha, E. N., Kreutz, M. E., & Neto, A. J. V. (2023). Development a Low-Cost Wireless Smart Meter with Power Quality Measurement for Smart Grid Applications. Sensors, 23(16), Article 16. https://doi.org/10.3390/s23167210

Ting, M. B. D. (2021). Inclusive energy transitions: An analysis of the potential for a digital revolution in South Africa's electricity system, pp 439.

UNDP (2022). Guidance notes on building critical infrastructure resilience in Europe and Central Asia | United Nations Development Programme. https://www.undp.org/eurasia/publications/guidance-notes-building-critical-infrastructure-resilience-europe-and-central-asia

UNDRR. (2022). Principles for Resilient Infrastructure.
https://www.undrr.org/media/78694/download?startDownload=true

Venkateswaran V. B., Saini K. D. & Sharma M. (2020). Approaches for Optimal Planning of Energy Storage Units in Distribution Network and Their Impacts on System Resiliency.

Walker, H. A. (2018). Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition (NREL/TP-7A40-73822, 1489002; p. NREL/TP-7A40-73822, 1489002). https://doi.org/10.2172/1489002

Wang C., N., Dang T. & Bayer J. (2021). A Two-Stage Multiple Criteria Decision Making for Site Selection of Solar Photovoltaic (PV) Power Plant: A Case Study in Taiwan | IEEE Journals & Magazine | IEEE Xplore. (n.d.). Retrieved December 27, 2023, from https://ieeexplore.ieee.org/abstract/document/9435320

Waseem, M., & Manshadi, S. D. (2020). Electricity grid resilience amid various natural disasters: Challenges and solutions. The Electricity Journal, 33(10), 106864.
https://doi.org/10.1016/j.tej.2020.106864

Xu, L., Feng, K., Lin, N., Perera, A. T. D., Poor, H. V., Xie, L., Ji, C., Sun, X. A., Guo, Q., & O'Malley, M. (2024). Resilience of renewable power systems under climate risks. Nature Reviews Electrical Engineering, 1(1), Article 1.
https://doi.org/10.1038/s44287-023-00003-8

Yadav, M., Pal, N., & Saini, D. K. (2023). Low voltage ride through capability for resilient electrical distribution system integrated with renewable energy resources. Energy Reports, 9, 833–858. https://doi.org/10.1016/j.egyr.2022.12.023

Zafeiropoulou, M., Sijakovic, N., Zarkovic, M., Ristic, V., Terzic, A., Makrygiorgou, D., Zoulias, E., Vita, V., Maris, T. I., & Fotis, G. (2023). A Flexibility Platform for Managing Outages and Ensuring the Power System's Resilience during Extreme Weather Conditions. Processes, 11(12), Article 12. https://doi.org/10.3390/pr11123432

Zlateva, P., & Hadjitodorov, S. (2022). An approach for analysis of critical infrastructure vulnerability to climate hazards. IOP Conference Series: Earth and Environmental Science, 1094(1), 012004.
https://doi.org/10.1088/1755-1315/1094/1/012004

6. APPENDIX

Appendix A: Data used for hazard and exposure assessments

Table 22: Details of data sets and sources

Sl.No	Data	Source
1	DEM	Hydro DEM https://www.hydrosheds.org/hydrosheds-core-downloads
2	Geomorphology	Geological Survey of India https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx
3	Earthquake	Geological Survey of India https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx
4	Precipitation	India Meteorological Department https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html
5	Temperature	India Meteorological Department https://www.imdpune.gov.in/cmpg/Griddata/Temperature_25_NetCDF.html
6	RE assets	OpenStreetMap https://www.openstreetmap.org
7	Soil texture	Food and Agriculture Organization Soils Portal FAO/UNESCO Soil Map of the World | FAO SOILS PORTAL | Food and Agriculture Organization of the United Nations

Table 23: Details of earthquakes above magnitude five

Sl.No	Place	Date	Magnitude
1	17 km NW of Bhachau, India	2001-01-26	7.7
2	20 km SSW of Ausa, India	1993-09-29	6.2
3	1 km SSW of Barela, India	1997-05-21	5.8
4	15 km WSW of Rapar, India	2001-01-28	5.8
5	13 km E of Bhachau, India	2006-04-06	5.5
6	22 km NNW of Anjar, India	2001-01-26	5.5
7	34 km NE of Rapar, India	2006-03-07	5.5
8	40 km NW of Bhachau, India	2001-02-19	5.4
9	6 km SE of Bhachau, India	2001-01-28	5.4
10	72 km SSW of Jaisalmer, India	1991-11-08	5.4
11	17 km E of Bhuj, India	2001-01-26	5.3
12	23 km WNW of Rapar, India	2001-02-03	5.3
13	163 km SSE of Kanniyakumari, India	1993-12-06	5.2
14	18 km NNW of Anjar, India	2001-01-26	5.2
15	23 km NNW of Pokaran, India	1998-05-11	5.2
16	39 km SE of Marakkanam, India	2001-09-25	5.2
17	5 km W of Patan, India	2000-09-05	5.2
18	8 km E of Patan, India	1983-09-25	5.1
19	11 km SSE of Rohtak, India	2012-03-05	5.1
20	15 km SE of Mendarda, India	2011-10-20	5.1
21	17 km S of Visavadar, India	2007-11-06	5.1
22	24 km WNW of Rapar, India	2001-02-08	5.1
23	25 km NNE of Lanja, India	1993-12-08	5.1
24	29 km NNW of Jaisalmer, India	2009-04-09	5.1
25	5 km S of Bhachau, India	2001-01-26	5.1
26	9 km N of Bhachau, India	2020-06-14	5.1

Sl.No	Place	Date	Magnitude
27	11 km SSE of Chincholi, India	1993-10-29	5
28	17 km NNE of Rapar, India	2006-04-06	5
29	18 km SSW of Ausa, India	1993-09-29	5
30	25 km WNW of Rapar, India	2003-08-05	5
31	26 km SE of Makhjan, India	2000-03-12	5
32	36 km ESE of Delvada, India	1993-08-24	5
33	39 km NNW of Bhachau, India	2012-06-19	5
34	5 km SSE of Makhjan, India	1994-02-01	5
35	7 km NNE of Patan, India	2008-09-16	5

Where N is north, S is south, E is East and W is west.

Table 24: Tropical cyclones that have impacted the project states over the past decade

State	Date and year	Cyclone name	Alert level
Gujarat and Rajasthan	14 to 17 May 2021	Tauktae	Red
	6 to 15 June 2023	Biparjoy	Orange
Maharashtra	2 to 3 June 2020	Nisarga	Red
Tamil Nadu	7 to 12 December 2016	Vardah	Red
	29 November to 1 December 2016	Nada	Orange
	10 to 18 November 2018	Gaja	Green
	23 to 26 November 2020	Nivar	Orange
	7 to 10 December 2022	Mandous	Green

Appendix B: Supporting information from the vulnerability assessment

Table 25: Site visit questionnaire – solar PV assets

Location of the solar power plant		
Elevation of the solar power plant (in metres or feet)		
Capacity of the solar power plant (MW)		
Age of the power plant		
Date of the site visit		
Name and contact information of the plant manager/ site in charge/ contact person	Name:	
	Phone number:	
	Email id:	

Sl.No	Question	Answer
Energy efficiency		
1	Degradation loss of solar cells	
2	Number of days in a year with downtime	
3	How long is power generation forecasted for?	
4	What is the distance from the nearest sub-station?	
Asset protection measures		
5	What measures are in place to protect solar panels from damage during high winds and tropical cyclones?	
6	Are there flood-control measures in place to safeguard equipment and infrastructure? (Yes/No)	
7	What measures are in place to prevent electrical components from overheating in high temperatures?	
8	How are solar panels cooled?	
9	If water is used, where is it sourced from?	Groundwater/ surface

Sl.No	Question	Answer	
10	Is this water available throughout the year? (Yes/No)	Piped/tanker	
11	Do you have a redundant water supply? (Yes/No)?	Piped/tanker	
Audits and standards			
12	How many external audits are conducted yearly?		
13	Based on the certifications available, how many regular audits are conducted to verify emergency response plans, risk mitigation measures, system health & so on?		
14	How is collected data used to make decisions regarding site operation and potential shutdowns during severe weather events?		
15	How many internal quality checks are conducted in a year?		
16	How many ISO standards are adhered to?		
Human resources			
17	Total workforce at the site		
18	Number of skilled workforce available at the site		
19	Do you have any backup staff? (Yes/No)		
20	If yes, how many backup staff do you have?		
21	What positions do they back up?	**Unskilled**	**skilled**
	1.	Unskilled	skilled
	2.	Unskilled	skilled
	3	Unskilled	skilled
	4	Unskilled	skilled
	5	Unskilled	skilled
	6.	Unskilled	skilled

<table>
<tr><th>Sl.No</th><th>Question</th><th>Answer</th></tr>
<tr><td colspan="3">Infrastructure</td></tr>
<tr><td>22</td><td>How is the plant's infrastructure designed and constructed to withstand extreme weather events? Please mention relevant standards</td><td></td></tr>
<tr><td>23</td><td>What materials and construction techniques have been used to enhance infrastructure resilience?</td><td></td></tr>
<tr><td>24</td><td>Do you have mandatory spares for all the critical components? (Yes/No)</td><td></td></tr>
<tr><td>25</td><td>How often does it need to be used in a year?</td><td></td></tr>
<tr><td colspan="3">Emergency response</td></tr>
<tr><td>26</td><td>Do you have any tie-ups with the district weather forecasting / disaster management authority? (Yes/No)</td><td></td></tr>
<tr><td>27</td><td>Is there a monitoring system in place to detect extreme weather events on site? (Yes/No)</td><td></td></tr>
<tr><td>28</td><td>Does the site have a backup power facility? (Yes/No)</td><td></td></tr>
<tr><td>29</td><td>Is there a designated emergency response team? (Yes/No)</td><td></td></tr>
<tr><td>30</td><td>If yes, how many training sessions do they undergo per year?</td><td></td></tr>
<tr><td>31</td><td>How does the plant communicate with local authorities and relevant agencies during extreme weather events?</td><td></td></tr>
<tr><td>32</td><td>Has the site experienced any extreme weather events in the past that resulted in damage or disruption? (Yes/No)</td><td><table>
<tr><th>Event</th><th>No.</th></tr>
<tr><td>1.Flood</td><td></td></tr>
<tr><td>2.Drought</td><td></td></tr>
<tr><td>3.Hailstorm</td><td></td></tr>
<tr><td>4.Tropical cyclone
5.Heatwave</td><td></td></tr>
<tr><td>6.Earthquake</td><td></td></tr>
</table></td></tr>
</table>

Sl.No	Question	Answer
Insurance		
33	Does the plant have comprehensive insurance coverage that includes protection against damage from extreme weather events?	
34	How many climate hazards are included as part of the insurance?	
35	Are funds set aside for the management of damage caused by extreme climate events? (Yes/No)	
36	If yes, what percentage of the funds of the total budget of the plant (per year) are kept aside for such extremities?	

Table 26: Site visit questionnaire – wind assets

Location of the wind power plant	
Elevation of the wind power plant (in metres or feet)	
Capacity of the wind power plant (MW)	
Date of the site visit	
Age of the power plant	
Name and contact information of the Plant manager/ site in charge/ contact person	Name:
	Phone number:
	Email id:

Sl.No	Question	Answer
Energy efficiency		
1	Number of days in a year with downtime because of breakdown maintenance (number of hours per plant)	
2	How long is power generation forecasted for?	
3	What is the distance from the nearest sub-station?	
Asset protection measures		
4	What measures are in place to protect wind turbines from damage during high winds and tropical cyclones?	
5	What is the maximum wind speed that the blade can handle? (m/s)	
6	What is the maximum wind speed that the tower can handle? (m/s)	
7	What is the foundation depth of the asset? (m)	
8	Are there flood-control measures in place to safeguard equipment and infrastructure?	

Sl.No	Question	Answer
9	What measures are in place to prevent electrical components from overheating in high temperatures?	
10	How does the plant mitigate heat stress on turbine components during extreme heatwaves?	
11	If water is used, where is it sourced from?	Groundwater
12	Is this water available throughout the year? (Yes/No)	Piped/tanker
13	Do you have a redundant water supply? (Yes/No)	Piped/tanker
Audits and standards		
14	How many external audits are conducted yearly?	
15	Based on the certifications available, how many regular audits are conducted to verify emergency response plans, risk mitigation measures, system health, and so on?	
16	How is collected data used to make decisions regarding site operation and potential shutdowns during severe weather events?	
17	How many internal quality checks are conducted in a year?	
18	How many ISO standards are adhered to?	
19	How many IEC standards are adhered to? (each turbine has an IEC class – class 1 to 4)	
Human resources		
20	Total workforce at the site	
21	Number of skilled workforce available at the site	
22	Do you have any backup staff (Yes/No)	
23	If yes, how many backup staff do you have?	

Sl.No	Question	Answer	
24	What positions do they back up?	**Unskilled**	**skilled**
	1.	Unskilled	skilled
	2.	Unskilled	skilled
	3.	Unskilled	skilled
	4.	Unskilled	skilled
	5.	Unskilled	skilled
	6.	Unskilled	skilled
Infrastructure			
25	How is the plant's infrastructure designed and constructed to withstand extreme weather events? Please mention relevant standards		
26	What materials and construction techniques have been used to enhance infrastructure resilience?		
27	Do you have mandatory spares for all the critical components? (Yes/No)		
28	How often does it need to be used in a year?		
Emergency response			
29	Do you have any tie-ups with the district weather forecasting / disaster management authority? (Yes/No)		
30	Is there a monitoring system in place to detect extreme weather events on site? (Yes/No)		
31	Does the site have a backup power facility? (Yes/No)		
32	Is there a designated emergency response team? (Yes/No)		
33	If yes, how many training sessions do they undergo per year?		

Sl.No	Question	Answer	
34	How does the plant communicate with local authorities and relevant agencies during extreme weather events?		
35	Has the site experienced any extreme weather events in the past that resulted in damage or disruption? (Yes/No)	**Event**	**No.**
		1.Flood	
		2.Drought	
		3.Hailstorm	
		4.Tropical cyclone	
		5.Heatwave	
		6.Earthquake	
Insurance			
36	Does the plant have comprehensive insurance coverage that includes protection against damage from extreme weather events?		
37	How many climate hazards are included as part of the insurance?		
38	Are funds set aside for the management of damage caused by extreme climate events? (Yes/No)		
39	If yes, what percentage of the funds of the total budget of the plant (per year) are kept aside for such extremities?		

Table 27: Data used for vulnerability assessments of solar PV assets at a state level

State		Structural integrity				Redundancy	Robustness				Recovery			
	Distance to sub-station (km)	Degradation loss	Downtime of asset (days/year)	Presence of flood-control measures (1 = yes, 0 = no)	Practice of solar panel cooling (1 = yes, 0 = no)	Availability of redundant water supply (1 = yes, 0 = no)	Number of external audits (number of audits per year)	Number of regular audits (number of audits per year)	Number of internal quality checks (number of checks per year)	Percentage of ISO/BIS/OSHA/IEC standards adhered to (number of standards adhered to/14)	Workforce per unit capacity (Total workforce reported / capacity of the plant)	Percentage of skilled workforce (Total skilled workforce / total workforce)	Tie-ups with the district weather forecasting authority (1=yes, 0=no)	Emergency response team training sessions (number of training sessions per year)
Gujarat A	12	7.8	1	1	0	0	2	1	1	1.00	1.08	0.19	0	6
Gujarat B	30	11	0	0	1	0	2	4	4	0.38	1.33	0.25	1	4
Gujarat C	2.3	1.4	0	1	1	0	1	2	2	0.21	0.21	0.75	1	4
Gujarat D	2	3.5	0	1	1	0	1	5	12	0.21	0.28	0.86	1	4
Maharashtra A	5	3.69	0	1	1	0	3	2	2	0.29	0.38	0.89	0	12
Rajasthan A	7.5	1	4	0	0	0	4	1	1	0.21	0.13	1.00	1	12
Rajasthan B	34	1	0	0	0	0	4	12	4	0.36	0.07	1.00	1	12
Rajasthan C	65	2	2	0	0	0	2	2	4	0.57	0.49	0.35	0	4
Tamil Nadu A	6	4.9	0	0	1	1	1	1	1	0.21	0.96	0.31	0	4

Source: Surveys conducted with solar PV plant managers either on-site or via virtual meetings.

Indicators highlighted in orange represent sensitivity, while indicators highlighted in blue represent adaptive capacity.

Table 28: Data used for vulnerability assessments of wind assets at a state level

State	Distance to sub-station (km)	Structural integrity: Power generation forecasting (days/year)	Structural integrity: Maximum wind speed the blade can handle (m/s)	Structural integrity: Maximum wind speed that the tower can handle (m/s)	Structural integrity: Presence of flood-control measures (1 = yes, 0 = no)	Redundancies: Availability of redundant water supply (1 = yes, 0 = no)	Redundancies: Availability of a backup power facility (1 = yes, 0 = no)	Robustness: Number of external audits (number of audits per year)	Robustness: Number of regular audits (number of audits per year)	Robustness: Number of internal quality checks (number of checks per year)	Robustness: Percentage of ISO/BIS/OSHA/IEC standards adhered to (number of standards adhered to/14)	Recovery: Workforce per unit capacity (total workforce reported/capacity of the plant in megawatt)	Recovery: Percentage of skilled workforce (total skilled workforce reported / total workforce reported)	Recovery: On-site monitoring system in place to detect extreme weather events (1 = yes, 0 = no)	Recovery: Tie-ups with the district weather forecasting authority (1 = yes, 0 = no)	Recovery: Emergency response team training sessions (number of training sessions per year)	Recovery: Funds set aside for the management of damages caused by extreme climate events (1 = yes, 0 = no)
Rajasthan A	20	365	50	50	1	0	1	2	2	5	3	16	16	0	0	16	0
Rajasthan B	18	365	70	70	0	0	1	4	1	1	3	9	9	1	0	24	0
Rajasthan C	14	150	60	75	0	0	1	4	1	4	4	21	21	1	0	48	1
Maharashtra A	10	150	25	50	0	0	0	4	4	4	4	37	24	1	0	1	1
Gujarat A	25	365	70	70	0	0	0	3	3	1	2	15	15	1	1	12	0
Tamil Nadu A	2	365	23	55	0	1	1	4	4	3	3	46	46	0	0	12	0

Source: Surveys conducted with wind plant managers either on-site or via virtual meetings.

Indicators highlighted in orange represent sensitivity, while indicators highlighted in blue represent adaptive capacity.

Table 29: Weights assigned for vulnerability assessments of solar PV assets at a state level

Dimension	Indicator		Weights
	Distance to sub-station (km)	5	0.05
Structural integrity	Degradation loss	30	0.075
	Downtime of assets (days/year)		0.075
	Presence of flood-control measures (1 = yes, 0 = no)		0.075
	Practice of solar panel cooling (1 = yes, 0 = no)		0.075
Redundancy	Availability of redundant water supply (1 = yes, 0 = no)	5	0.05
Robustness	Number of external audits (number of audits per year)	30	0.075
	Number of regular audits (number of audits per year)		0.075
	Number of internal quality checks (number of checks per year)		0.075
	Percentage of ISO/BIS/OSHA/IEC standards adhered to (number of standards adhered to/14)		0.075
Recovery	Workforce per unit capacity (total workforce reported / capacity of the plant in megawatt)	30	0.075
	Percentage of skilled workforce (total skilled workforce reported/ total workforce reported)		0.075
	Tie-ups with the district weather forecasting authority (1 = yes, 0 = no)		0.075
	Emergency response team training sessions (number of training sessions per year)		0.075
	Total Weight	100	1

Source: CSTEP research

Table 30: Weights assigned for vulnerability assessments of wind assets at a state level

Category	Indicator	Weights	
	Distance to sub-station (km)	5	0.05
Structural integrity	Power generation forecasting (days/year)	30	0.075
	Maximum wind speed the blade can handle (m/s)		0.075
	Maximum wind speed that the tower can handle (m/s)		0.075
	Presence of flood-control measures (1 = yes, 0 = no)		0.075
Redundancies	Availability of redundant water supply (1 = yes, 0 = no)	15	0.03
	Availability of a backup power facility (1 = yes, 0 = no)		0.12
Robustness	Number of external audits (number of audits per year)	20	0.05
	Number of regular audits (number of audits per year)		0.05
	Number of internal quality checks (number of checks per year)		0.05
	Percentage of ISO/BIS/OSHA/IEC standards adhered to (number of standards adhered to/14)		0.05
Recovery	Workforce per unit capacity (total workforce reported / capacity of the plant in megawatt)	30	0.05
	Percentage of skilled workforce (total skilled workforce reported / total workforce reported)		0.05
	On-site monitoring system in place to detect extreme weather events (1 = yes, 0 = no)		0.05
	Tie-ups with the district weather forecasting authority (1 = yes, 0 = no)		0.05
	Emergency response team training sessions (number of training sessions per year)		0.05
	Funds set aside for the management of damages caused by extreme climate events (1 = yes, 0 = no)		0.05
	Total Weight	100	1

Source: CSTEP research

Table 31: Drivers of vulnerability for different vulnerability classes at an indicator level – solar PV assets

Vulnerability classes	Larger distance to sub-station	Poor structural integrity	No redundancies in place (water)	Robustness compromised	Compromised recovery	VI
High vulnerability	✅ 0.015	⚠️ 0.147	✅ 0.025	❌ 0.236	❌ 0.185	0.608
Moderate vulnerability	✅ 0.008	✅ 0.079	✅ 0.050	❌ 0.222	❌ 0.170	0.529
Low vulnerability	✅ 0.002	✅ 0.020	✅ 0.050	❌ 0.226	⚠️ 0.141	0.440

Source: CSTEP research

Significant drivers are marked with ❌, moderate drivers are marked with ⚠️, and non-drivers are marked with ✅

Table 32: Drivers of vulnerability for different vulnerability classes at an indicator level – wind assets

Vulnerability classes	Larger distance to sub-station	Poor structural integrity	No redundancies in place (water and backup power supply)	Robustness compromised	Compromised recovery	VI
High vulnerability	✅ 0.034	❌ 0.193	❌ 0.150	⚠️ 0.077	❌ 0.157	0.611
Moderate vulnerability	✅ 0.033	⚠️ 0.121	✅ 0.030	⚠️ 0.099	❌ 0.203	0.486
Low vulnerability	✅ 0.000	❌ 0.210	✅ 0.000	✅ 0.050	❌ 0.188	0.448

Source: CSTEP research

Significant drivers are marked with ❌, moderate drivers are marked with ⚠️, and non-drivers are marked with ✅

Table 33: Drivers of vulnerability for different vulnerability classes at a sub-indicator level – solar PV assets

Vulnerability classes	High	Moderate	Low
Larger distance to sub-station	✅ 0.015	✅ 0.008	✅ 0.002
High degradation loss	✅ 0.016	⚠️ 0.037	✅ 0.020
High downtime per year	✅ 0.019	✅ 0.005	✅ 0.000
Lack of flood-control measures	❌ 0.075	✅ 0.019	✅ 0.000
Cooling of solar panels not practiced	⚠️ 0.038	✅ 0.019	✅ 0.000
No redundant water supply	⚠️ 0.025	⚠️ 0.050	⚠️ 0.050
Fewer external audits per year	⚠️ 0.039	❌ 0.059	✅ 0.021
Fewer regular audits per year	❌ 0.061	❌ 0.061	❌ 0.068
Fewer internal quality checks per year	❌ 0.068	⚠️ 0.049	❌ 0.068
Fewer standards adhered to	❌ 0.067	❌ 0.052	❌ 0.068
Lower workforce per unit capacity	⚠️ 0.044	⚠️ 0.036	❌ 0.057
Low percentage of skilled workforce	⚠️ 0.042	⚠️ 0.045	✅ 0.010
No tie-ups with the district weather forecasting authority	⚠️ 0.050	✅ 0.019	❌ 0.075
Fewer emergency response team training sessions	⚠️ 0.050	❌ 0.070	✅ 0.000
VI	0.608	0.529	0.440

Source: CSTEP research

Significant drivers are marked with ❌, moderate drivers are marked with ⚠️, and non-drivers are marked with ✅

Table 34: Drivers of vulnerability for different vulnerability classes at a sub-indicator level – wind assets

Vulnerability classes	High	Moderate	Low
Larger distance to sub-station	0.034	0.033	0.000
Relatively poor power generation forecasting	0.038	0.025	0.000
Blades can handle relatively lower maximum windspeeds	0.036	0.016	0.075
Tower can handle relatively lower maximum windspeeds	0.045	0.030	0.060
Lack of flood-control measures	0.075	0.050	0.075
No redundant water supply	0.030	0.030	0.000
No backup power facility	0.120	0.000	0.000
Fewer external audits per year	0.013	0.017	0.000
Fewer regular audits per year	0.008	0.044	0.000
Fewer internal quality checks per year	0.031	0.021	0.025
Fewer standards adhered to	0.025	0.017	0.025
Lower workforce per unit capacity	0.027	0.041	0.000
Low percentage of skilled workforce	0.036	0.041	0.000
No on-site extreme weather monitoring system	0.000	0.017	0.050
No tie-ups with the district weather forecasting authority	0.025	0.050	0.050
Fewer emergency response team training sessions	0.044	0.020	0.038
No funds for extreme climate impact management	0.025	0.033	0.050
VI	0.611	0.486	0.448

Source: CSTEP research

Significant drivers are marked with ✖, moderate drivers are marked with !, and non-drivers are marked with ✔

Appendix C: Analysis of bidding documents

a. Ground-mounted solar power plants

	Tender ID/ link
Hubbali Airport 8 MW ground-mounted solar	2018_AAI_18106_1
Bhubaneshwar Airport 4 MW ground-mounted solar	2018_AAI_19926
279 MW cumulative ground-mounted solar projects in Maharashtra (individual projects ranging from 2 MW to 10 MW)	EESL/06/2018-19/OCB-SPGS-279MW/ 202108012 https://www.eqmagpro.com/eesl-floats-tender-for-279-mw-solar-power-plants-in-maharashtra/
140 MW solar PV plant ranging from 10 MW TO 40 MW in Gujarat	GSECL/ PP/ RE&BD/ 140 MW Solar PV/
7.5 MWp (DC) GCSPV power system at IOCL, Paradip Refinery	PDR17M7220

As per the bidding documents for several recent ground-mounted solar projects, the maximum wind speeds (e.g., 180 km/hr, 65 m/s) have been defined for any structure (including buildings and PV mounting structures) to handle.

The documents have stated that

1. 'The foundations should be designed considering the weight and distribution of the structure and assembly and wind speed as per IS 875 for calculations of Vz.'

2. 'The mounting structures should withstand wind speeds of up to 180 km/hr (or 50 m/s).'

As per Indian Standard 875, design wind speeds for a given location are calculated based on the formula where

Vz = design wind speed at any height z in m/s

Vb = basic wind speed (reference conditions as per location)
k1 = probability factor (risk coefficient)
K2 = terrain roughness and height factor
K3 = topography factor
K4 = importance factor for the cyclonic region

In particular, k4 is used to factor in extreme weather events that have an effect on design wind speed (tropical cyclones).

In addition, the bidding documents also mention that the structures and foundations should conform to the seismic conditions pertaining to the zone using relevant standards and codes. IS 1983 (earthquake resistant design) has been referenced in the bidding documents.

There is also a mention of considering the rainwater data, soil characteristics, land profile, high flood level of the site, and so on, while designing the structures. Some bidding documents also clearly mention that the minimum clearance between the lower edge of the module and the ground shall be the higher of (i) above the highest flood level of the site and (ii) a minimum of 500 mm.

b. Wind Power Plants

	Tender ID/ link
BHEL 4 MW to 5 MW wind plant in Karnataka	BG/10/02/29032023
Oil India 50 MW wind power project in Gujarat/MP	SLI0254P16
GIPCL: Setting up of up to 200 MW wind power projects	GIPCL/WIND-200 MW/2017

The maximum wind speed needs to be defined for two components:

- Rotor (wind turbine blades)
- Tower foundation

The rotor maximum wind speed is lower, with rotations of the wind turbine blades prevented beyond a certain wind speed. This is known as cut-out speed, in practice typically 25 m/s for most wind turbine manufacturers. Beyond 25 m/s, no energy generation is permitted on the wind turbine, but this does not mean the wind turbine blades will be unsafe in their stationary position.

The survival wind speed for the tower foundation is critical. Beyond this wind speed, there is a real risk of the entire structure collapsing. The maximum wind speed permissible for a project has not been mentioned, with all the examined tenders stating that 'The Vendor shall mention the survival wind speed considered for the design of WTG Tower Foundations.'

IEC 61400, which is taken as the reference standard, does not provide definitive wind speeds for the cut-out or survival of the wind tower foundation. It provides the formula and states that the calculation of these wind speeds is tailored to factors such as the unsteady loading of the wind turbines, the wind class, the hub height, the type of foundation, the type of soil, and wind resource (or wind class), which can vary for each location. Therefore, instead of installing standardised structures that will withstand fixed wind speeds, such as 50 m/s, each project must calculate its survival wind speed. The calculated wind speed will be compared against the location's wind speed during normal and extreme conditions.

The bidding documents also state that all constructions must be engineered to withstand the most severe combination of static loads, dynamic loads, such as live loads, equipment, wind, earthquakes, temperature variations, or any other imposed loads. The bidding documents mention that the tower foundations shall be designed to take adequate care of the possible soil conditions and adverse seismic effects based on the soil conditions of the site. IS 4326 (code of practice of earthquake-resistant design and construction of buildings) has been referenced in the bidding documents.

In addition, the bidding documents mention that all pieces of equipment need to be suitably protected against high temperature and dust storms.

Most bidding documents for solar and wind power plants mention the relevant standards, specifications, and practices to be referred to. However, the prime responsibility of designing and constructing the equipment, structures, and so on, to handle extreme weather events lies with the contractor. The contractor is expected to take into account all local climatic conditions, seismic conditions, soil conditions, high flood levels, and so on, along with the relevant standards, during the design and construction stages to ensure that RE assets are resilient to extreme weather events.

Some bidding documents mention that all design analysis for structures including stability, load-bearing capacity of existing facilities, anchoring arrangements, and so on, shall be vetted by institutes of repute, such as IITs. Further, the certification of on-site installation work as per vetted and approved design drawings by design representatives (from the designated institute) after completion of installation shall be done and arranged as part of the job. Such requirements make it necessary for the contractor to follow stringent design and installation practices. If made mandatory across solar and wind power plant bidding documents, these requirements would be a definitive step towards making the RE assets more resilient to extreme weather events.

Appendix D: State-level stakeholder consultations – participant list

State: Tamil Nadu

Date: 15 February 2024

Mode: Hybrid

Attendees:

Sl.No	Name	Designation	Affiliation
1	M Bhuvaneshwari	Executive Engineer Solar	Tamil Nadu Generation and Distribution Corporation
2	Mohan K	DGM	Tamil Nadu Energy Development Agency
3	Sindhuja	Engineer	Tamil Nadu Generation and Distribution Corporation
4	Pravin Patil	Site Head – Poolavadi Wind Farm	Tata Power
5	Vineet George	Mumbai team	Tata Power Renewable Energy Limited
6	Shubham Tandon	Project Officer	UNDP India
7	Sriram	Risk management team	UNDP India
8	Susant	Risk management team, Gujarat	UNDP India
9	Arun Yadav	Air pollution team	UNDP India
10	Md. Raza	Disaster resilience team	UNDP India
11	Bhavya	Risk management team, Bengaluru	UNDP India
12	Prerna Singh	Consultant, Pune flood management plan	UNDP India
13	Ebin Paul	Risk management team	UNDP India
14	Sayan Roy	Risk management team	UNDP India

State: Gujarat
Date: 1 March 2024
Mode: Virtual
Attendees:

Sl.No	Name	Designation	Affiliation
1	S R Sharma & team	Superintending Engineer (RE1)	Gujarat State Electricity Corporation Limited
2	Alka Yadav & team	Director	Green Energy Transition Research Institute
3	Binoy Kalaria	Zonal Head, Gujarat	Tata Power
4	M K Jani & team	Superintending Engineer (RE1)	Gujarat Urja Vikas Nigam Limited
5	Bhavani G	CFM	Gujarat Urja Vikas Nigam Limited
6	Mayur Bhalani	Engineer	Gujarat Urja Vikas Nigam Limited
7	Susantha Sahoo	Risk management team	UNDP India
8	Durgesh Kumar Gupta	Senior Manager	Adani Green Energy Ltd
9	Kandarp Mistry	Engineer	Gujarat Urja Vikas Nigam Limited
10	Lokesh Yadav	Manager	ACME Group
11	Vikas Trivedi		Gujarat Urja Vikas Nigam Limited

State: Rajasthan
Date: 14 March 2024
Mode: Virtual
Attendees:

Sl.No	Name	Designation	Affiliation
1	Deepak H Mahabale	Zonal Head O&M	Tata Power
2	Imran Khan	Manager Operations	Tata Power
3	Puneet Dwivedi	Asset Manager	ReNew Power
4	Himanshu Khurana	Director	Rajasthan Electricity Regulatory Commission
5	Piyush	Project Associate	Rajasthan Renewable Energy Corporation Ltd
6	Shubham	Project Officer	UNDP India
7	Manish Mohandas	Programme Officer (Resilience)	UNDP India

State: Maharashtra
Date: 15 March 2024
Mode: Virtual
Attendees:

Sl.No	Name	Designation	Affiliation
1	Thanesh S	Plant Manager	Tata Power Renewable Energy Limited (TPREL)
2	Kanchan Sabnis	-	Brihanmumbai Municipal Corporation
3	Premalwar Sarang	Station Head	Tata Power Renewable Energy Limited, Baramati
4	Vijay Kulkarni	Additional Executive Engineer	Maharashtra State Power Generation Company
5	Shubham Tandon	Project Officer	UNDP India
6	Prerna Singh	Urban Flood Consultant	UNDP India
7	Ashish Thorat	Senior Engineer	Energy Efficiency Services Ltd

United Nations Development Programme
55, Joseph Stein Lane, Lodhi Gardens, Lodhi Estate,
New Delhi, Delhi 110003