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Review article

Solar PV systems under weather extremes: Case studies, classification, vulnerability assessment, and adaptation pathways

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ABSTRACT

This study examines the significant challenges presented by the rising frequency and severity of climate change-induced extreme weather events—such as hurricanes, floods, heatwaves, and snowstorms—on the reliability and efficacy of solar photovoltaic (PV) systems. Utilizing case studies from various global places, it underscores the susceptibilities of photovoltaic systems to environmental harm, encompassing structural failure, efficiency decline, and operational interruptions. The study presents a novel, resilience-oriented paradigm that incorporates sophisticated design principles, operational techniques, and policy innovations to alleviate these risks. Principal findings underscore the significance of site-specific risk evaluations, modular and adaptable system architectures, and cohesive resilience planning in photovoltaic system engineering. Proactive operational techniques, such as regular maintenance, emergency reaction plans, and intelligent system monitoring, are deemed essential for sustaining performance in extreme weather conditions. Innovative technological solutions, including resilient materials, sophisticated coatings, durable mounting methods, and thermal management technologies, are emphasized for their capacity to endure intense environmental stressors. The study delineates future research goals, encompassing the creation of innovative materials with superior durability, scalable energy storage integration, structural advances, and greater grid interconnectivity via smart grid technology. It emphasizes the significance of cybersecurity protocols to safeguard photovoltaic infrastructure and promotes legislative and regulatory enhancements to facilitate resilience implementation. Collaboration among researchers, industry executives, and policymakers is considered crucial for addressing the increasing difficulties presented by climate change. This paper establishes a framework for integrating resilience into all facets of solar PV system design and operation, thereby ensuring the long-term sustainability, efficiency, and efficacy of solar energy systems in a swiftly changing climate environment. This comprehensive strategy is essential for ensuring the future of renewable energy amid global environmental difficulties.

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1. Introduction

The rising demand for energy during the past four decades, globalization, and the tendency for economic growth have expedited energy production and, as a result, carbon dioxide (CO2) emissions (Anser et al., 2021; Pais et al., 2019). Wang et al. assert that electricity generation is the predominant source of CO2 emissions, representing roughly 42 % of worldwide energy-related CO2 emissions (Wang et al., 2024). This includes emissions from electricity generation, which primarily uses coal, natural gas, and oil (Ward et al., 2017). The manufacturing, chemicals, cement, and steel sectors provide around 23 % of global emissions. The transportation sector ranks as the third greatest source of CO2 emissions, representing around 16 % of global emissions, primarily from road cars, aircraft, and maritime shipping (Wang et al., 2020). Collectively, these three sectors constitute the predominant share of global CO2 emissions, underscoring the necessity for coordinated initiatives to reduce emissions in these domains (Lamb et al., 2021). Huang et al. assert that the construction and building sectors contribute around 18 % of total emissions, encompassing both direct and indirect sources (Huang et al., 2018).

Liang et al. report that global CO2 emissions from oil rose around 1.5 % in 2023 (Liang and You, 2023), primarily due to the transportation sector's dependence on oil as a fuel source. This persisted to escalate at a diminished pace compared to the global GDP, which grew by approximately 3.7 % in 2023. Liang et al. indicate that aviation-related CO2 emissions are projected to increase by 3.9 % in 2023 relative to the prior year (Liang et al., 2023), attributed to a significant rebound in air traffic following the global reopening post-COVID-19 pandemic. This increase was primarily attributed to a rise in long-haul flights, which produce higher emissions than domestic travel. Liang et al. reported that global energy-related CO2 emissions increased by 2.4 % in 2023 (Liang et al., 2023), marking the highest annual rise in over a decade. This increase was chiefly attributable to the economic recovery post-epidemic, with energy demand significantly rising in several regions. In 2023, emissions rose by approximately 2.4 billion metric tons of CO2, resulting in a total of 38.2 billion tons of energy-related CO2 emissions, a record high. This occurred in the context of a trend disturbed in 2022 by the rapid and emissions-intensive economic recovery post-COVID crisis (Bošnjaković et al., 2023a). Elevated emissions lead to heightened CO2 concentrations in the atmosphere and an increase in global temperatures due to the greenhouse effect. Climate change results in an increase in the frequency and intensity of natural disasters such as storms, droughts, and wildfires. Extreme weather events can severely impact ecosystems (Peng et al., 2024), the economy (H. Xu et al., 2024), and human health (Meng et al., 2024). The World Meteorological Organization reported that the mean annual absolute increase in CO2 over the past decade is 246 ppm/year for the period 2020–2021 (World Meteorological Organisation (MWO), 2022). A relative increase of 0.01 % in CO2 concentration was noted, with an absolute increase of 2.5 ppm recorded during the same period. In 2021, CO2 levels exceeded 149 % relative to pre-industrial levels, with a global mean concentration of 415.7 ppm documented. The rise in atmospheric CO2 levels, referred to as the greenhouse effect, is the principal driver of climate change, manifesting in severe polar ice melt, heightened wind intensity, extreme regional temperatures, wildfires, droughts, floods, hurricanes, heatwaves, and landslides.

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A multitude of researchers have investigated extreme weather phenomena throughout many geographies, continents, nations, and locales. Most studies indicate that heat waves are becoming increasingly prevalent in southern and western Europe (Ozturk et al., 2023), the Mediterranean region (Weisheimer and Palmer, 2005), the Mediterranean basin (Bošnjaković et al., 2023b, 2023a), and Europe overall. The findings indicate a rising frequency and intensity of heat waves in these areas, potentially resulting in significant repercussions for public health, agriculture, and infrastructure. Bosnjakovic et al. assert that seasonal thermal anomalies in the northern hemisphere are more pronounced during summer than winter (Bošnjaković et al., 2023b). Knutson et al. recently found that global warming is expected to elevate the occurrence of more intense storms (Knutson et al., 2021), increase storm surges, and cause more severe precipitation events. The findings suggest that the ongoing increase in global temperatures may exacerbate weather patterns, especially in the summer months.

Studies from the past have shown how devastating the extreme weather events in June and July 2023 were, when temperatures in many parts of Europe reached their highest levels ever. By July 2023, a severe storm with winds of more than 200 km/h had devastated a sizable portion of Europe, particularly Northern Italy, Slovenia, and Croatia. The strong winds uprooted trees effortlessly, causing significant damage to numerous roofs of dwellings. Thousands were displaced and rendered homeless due to the storm, highlighting the urgent necessity for enhanced disaster preparedness and response strategies in the region. The vast extent of devastation acts as a stark warning on the increasing frequency and severity of extreme weather phenomena attributable to climate change. A greater proportion of the electrical grid was obliterated, along with solar PV modules removed off building rooftops. Comparable events transpired in March 2019 in the Galadimawa district of Abuja, FCT, Nigeria, when intense winds detached roofs from multiple residences, including the solar PV modules affixed to them. The powerful wind resulted in the fatalities of two young residents and severely damaged almost all electricity poles. The damage the storm in Galadimawa caused was similar to a recent disaster in another area, highlighting how vulnerable infrastructure is to extreme weather. The Galadimawa village had significant restoration and recovery challenges after the tragedy.

Given the diverse effects of extreme weather events on solar PV modules and other life-threatening situations globally, one can conclude that climate change has emerged as a paramount issue of this century, prompting concern among geopolitical experts regarding its implications and necessitating a comprehensive global response. The Paris Agreement creates a framework to restrict global temperature rises to "well below 2°C" and, preferably, to 1.5°C over pre-industrial levels. Numerous research findings indicate that several locations on Earth have undergone temperature increases above 1.5 °C, with minimal or no measures implemented to reduce emissions (S.C. Nwokolo et al., 2023a, 2023b). Many individuals in affluent nations acknowledge the necessity of altering their energy production methods, which are the principal contributors to greenhouse gas emissions responsible for climate change (Samuel Chukwujindu Nwokolo et al., 2023b). The swift implementation of low- or zero-carbon technologies to supplant conventional fossil fuels can lead to transformations across various localities, ethnicities, regions, and continents globally. The instability of conventional fuel supplies (natural gas and oil) as a result of conflicts and strained political relations among important nations was the driving force behind the transition to sustainable net-zero energy generation (Samuel Chukwujindu Nwokolo et al., 2023a, 2023c). Electricity is projected to be the

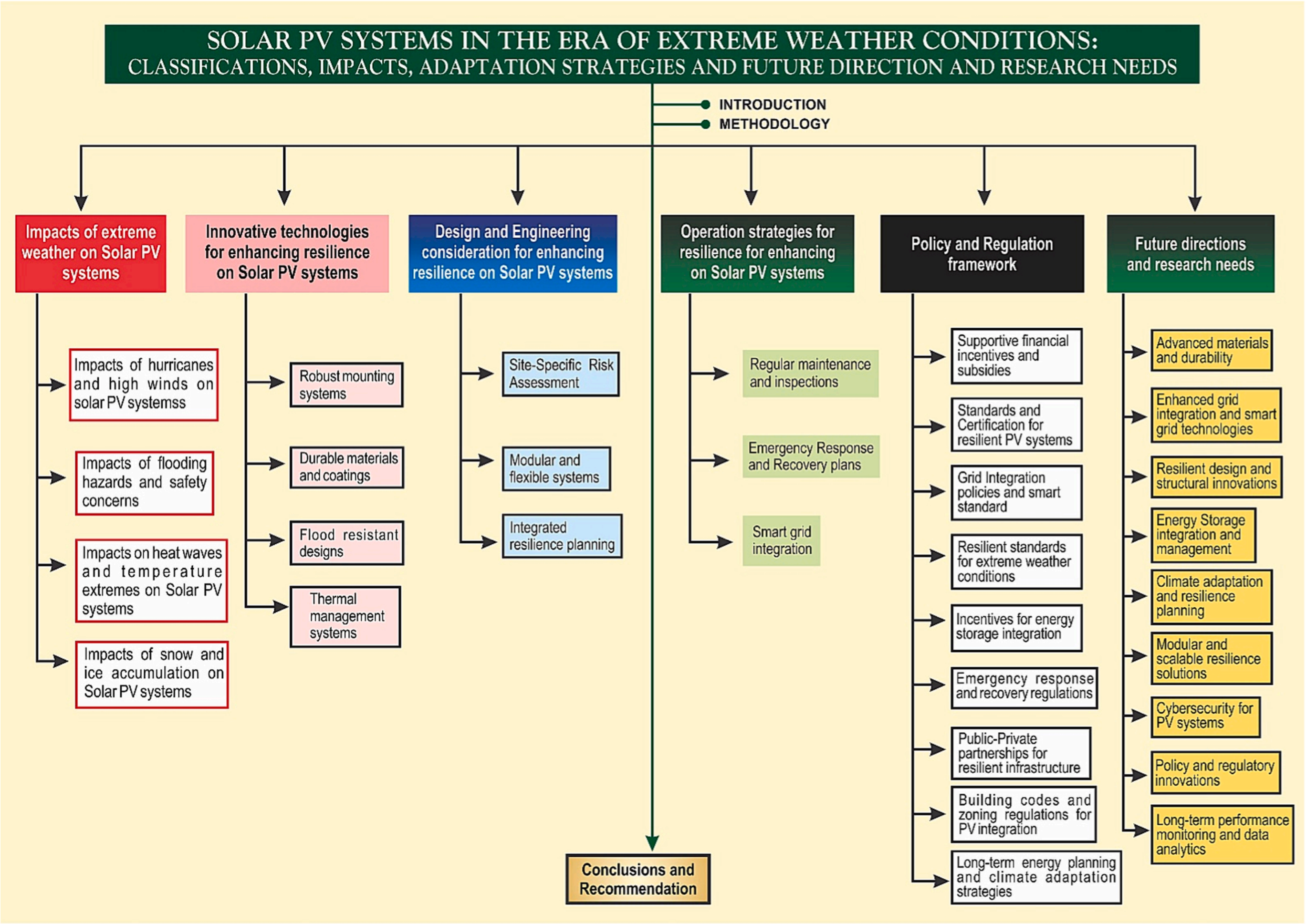

Fig. 1. Solar PV systems in the era of extreme weather conditions: classifications, impacts, adaptation strategies, and future direction and research needs.

primary source of renewable energy in global plans for 2050, with wind turbines and solar photovoltaic plants at the forefront. The IEA (IEA, 2021a) forecasts that global installed photovoltaic capacity would attain 440 GW by 2030 and 14 TW by 2050 in a net zero emission scenario. The pressing necessity to reduce greenhouse gas emissions and address climate change has driven the shift to renewable energy sources.

The manufacturing of photovoltaic power plant components requires substantial energy consumption. The energy payback time (EPBT) differs by plant location, spanning from 2 to 5 years (Okonkwo et al., 2024a, 2024b). This indicates that CO2 emissions from the production of photovoltaic power plant components are substantial, potentially surpassing the environmental advantages of solar energy utilization. Given the anticipated construction of extensive solar PV capacity by 2050, especially in China, alongside a reduction in fossil fuel use in thermal power plants, it is essential to evaluate the worldwide CO2 emissions expected by that year. This research will facilitate the estimation of the overall environmental impact of a large-scale transition to solar energy. The IEA forecasts indicate that, under the current policy and legislative framework, CO2 emissions may rise until 2035 (IEA, 2021a). This indicates that atmospheric CO2 levels will increase, along with the incidence of extreme weather events. According to the IEA, CO2 emissions may decline post-2035, although climate change is anticipated to persist far longer, potentially until 2070 (IEA, 2021a, 2021b).

Solar photovoltaic systems are deployed in open spaces to maximize solar energy collection; nevertheless, the solar modules are often subjected to environmental conditions. Solar photovoltaic plants are anticipated to have a lifespan of 25–30 years (Agbor et al., 2023; Nwokolo et al., 2024). PV plants are constructed to withstand progressively severe and extreme weather conditions to ensure consistent and safe performance. It is uncertain to what degree solar PV systems are designed to withstand elevated wind speeds, as they are susceptible to damage from gale-force winds, regardless of whether they are installed on rooftops or on the ground. Wind gusts may originate from multiple directions simultaneously, causing the modules to detach from their supports. This corroborates our earlier findings indicating that, according to multiple solar PV review publications, rooftop modules are less vulnerable to wind damage compared to tracking systems and elevated mounted structures (Nwokolo et al., 2024). Solar photovoltaic systems are vulnerable to objects propelled by the wind (Nwokolo, 2025).

Hail can damage solar PV systems by directly impacting them or by leaving debris that obstructs sunlight and causes water accumulation on the panels (Lucy and Petty, 2017). Lightning is the primary cause of damage to solar photovoltaic installations. It can damage solar photovoltaic modules, inverters, and other electrical apparatus (Lucy, 2013). Elevated temperatures affect solar PV system power output, expedite component deterioration, and increase the likelihood of fire incidents (Kurtz et al., 2011). Flood risk evaluates the peak short-term precipitation and the elevation at which water can inundate electrical apparatus and enclosures (Samuel Chukwujindu, 2017). Storms can damage power transmission systems. Solar photovoltaic systems exhibit significant storm resilience and can supply energy to local communities and essential services while the restoration of electrical transmission infrastructure (Cole et al., 2020). Although significant weather events adversely impact solar PV systems, Fthenakis' research suggests that these systems exhibit greater resilience to extreme weather disasters

Table 1
Methods for selecting, including, and excluding articles.

Indicator	Methods
Inclusion approach (IA)	
Inclusion approach (IA):	The title, abstract, or keywords of an article or review article that discusses solar PV systems in extreme weather conditions and uses related terms are considered applicable
IAI	
IA2	Papers written in English that are either research or review articles
Exclusion approach (EA)	
EA1	The term "extreme weather conditions" discusses other renewable energy sources such as wind, hydropower, geothermal, or hydrogen energies/technologies
EA2	The term "solar PV system" discusses other aspect of solar PV system research areas such as prediction or forecasting of solar PV systems, critical materials, solid state materials or nanomaterials used for manufacturing of solar PV system or energy storage systems used for storing solar PV energy output or techno-economic analysis of renewable hydrogen production system
EA3	The research or review paper that is being discussed does not focus on adaptation strategies for solar PV systems in extreme weather conditions
EA4	At this time, the full research or review papers is not available for download

compared to conventional energy systems (Fthenakis, 2013). The earthquake and tsunami in Fukushima devastated three nuclear reactors and sent radiation into the environment; yet, the majority of rooftop solar photovoltaic systems remained unscathed (Fthenakis, 2013). This article aims to thoroughly examine the effects of extreme weather on solar PV systems and the potential of innovative technologies, design and technical factors, operational strategies, policies, and regulatory frameworks to enhance resilience. The study uses a structured approach to group new technologies, design and engineering factors, and operational strategies. It focuses on recent developments and suggests a way to include resilience in planning and implementing solar PV systems. It also shows future directions and research needs, as shown in Fig. 1.

2. Methodology and current research status

The initial phase of the systematic review method entails exhaustive database searches to pinpoint pertinent material. In light of the emphasis on the effects of extreme weather events on solar PV systems, the Scopus, Web of Science, and Google Scholar databases were employed to conduct a comprehensive search of peer-reviewed papers and grey literature. The Scopus database is a multidisciplinary repository offering access to peer-reviewed journal articles, conference proceedings, and various scholarly publications. Web of Science is a comprehensive citation database encompassing journals, conference proceedings, and patents across multiple disciplines. Google Scholar is a publicly available search engine that catalogs academic articles, theses, books, and conference proceedings. These databases were selected for their comprehensive coverage of academic literature, guaranteeing a meticulous search of pertinent materials. The amalgamation of these three databases facilitated an exhaustive examination of both peer-reviewed and grey literature on the subject.

The research and review papers were selected and modified based on the title, abstract, and full text. This was accomplished utilizing the inclusion and exclusion techniques indicated in Table 1 and Fig. 2. During the snowballing process, conference articles identified in the reference sections of the majority of the selected articles were also incorporated into the article inclusion criteria. This thorough methodology guaranteed the inclusion of a diverse array of pertinent material, augmenting the depth and scope of the research outcomes. Upon completion of this process, 64 papers were selected from an initial pool of 1770 articles identified through the Scopus, Web of Science, and Google Scholar databases, as illustrated in Fig. 3.

Subsequent to the refinement process, a quantitative analysis was performed to assess the annual publications, geographic distribution of authors, and distribution of research directions included. Fig. 4 illustrates the annual publication. Although research commenced in 2012, only one publication was published that year.

The number of publications had substantial growth, particularly in 2022 and 2023, totaling 9 and 18, respectively. In 2024, achieving a total of 8. This signifies a consistent rise in research production over the years, demonstrating a favourable trend in academic productivity. The increasing trend indicates a robust dedication to academic research on the effects of extreme weather events on solar PV systems worldwide throughout this timeframe. The increase in publications may signify an escalating interest and expenditure in examining the impacts of extreme weather on renewable energy sources. This trend indicates an increased recognition of the significance of sustainability and resilience in addressing climate change challenges.

Fig. 5 illustrates that the United States, China, and India possessed the greatest number of contributing authors among all nations. The United States was the foremost contributor with 11 papers, while China and India both produced 6 publications concerning the impacts of extreme weather events on solar PV systems. This indicates the significant research efforts being made in these countries to understand the effects of extreme weather on solar PV systems. It also suggests a growing global interest in this topic as countries with varying climates and geographies are conducting research in this area.

Italy and Spain each contributed a total of four publications. This signifies that European nations are also actively engaged in investigating the effects of extreme weather on solar photovoltaic systems. The variety of countries involved in this research underscores the need of comprehending how diverse environmental circumstances influence solar energy generation.

Countries that together contributed three papers from the research database include Hong Kong, Indonesia, Iraq, Saudi Arabia, and Taiwan. This signifies that nations from diverse global locations are acknowledging the importance of examining the impacts of harsh weather on solar photovoltaic systems. International cooperation in this study domain will facilitate the development of solutions to enhance the dependability and efficiency of solar energy generation globally.

Countries that contributed a total of two papers from the research database include Canada, Colombia, Pakistan, Turkey, and the United Kingdom. This signifies that the examination of harsh weather's effects on solar PV systems is a worldwide issue, not confined to certain places. Collaborating on research across many nations can yield a more thorough comprehension of the difficulties and possible solutions in this domain.

Countries that each contributed a single publication from the research database include Algeria, Australia, Bahrain, Bangladesh, Brazil, Croatia, Dominican Republic, Jordan, Libyan Arab Jamahiriya, Malaysia, Mauritius, Mexico, Morocco, Netherlands, Nigeria, Norway, Philippines, Romania, Russian Federation, Tanzania, and United Arab Emirates. This varied assortment of nations illustrates the worldwide character of the problem and the necessity for international cooperation. Cooperation among academics and policymakers from many nations is crucial for tackling the intricate difficulties associated with this domain. Through the dissemination of knowledge and resources, advancements can be achieved in identifying viable solutions that advantage all participating nations.

Fig. 6 illustrates that energy constitutes the primary study domain, encompassing a total of 64 studies that are closely linked to solar photovoltaic systems. The energy sector was identified as the most extensively researched domain, comprising a total of 44 papers. The engineering field recorded the second greatest number of research studies, totaling 33. Subsequently, computer science documented a total of 18 studies each. This signifies that energy, especially concerning solar photovoltaic systems, is a significant study priority. The substantial

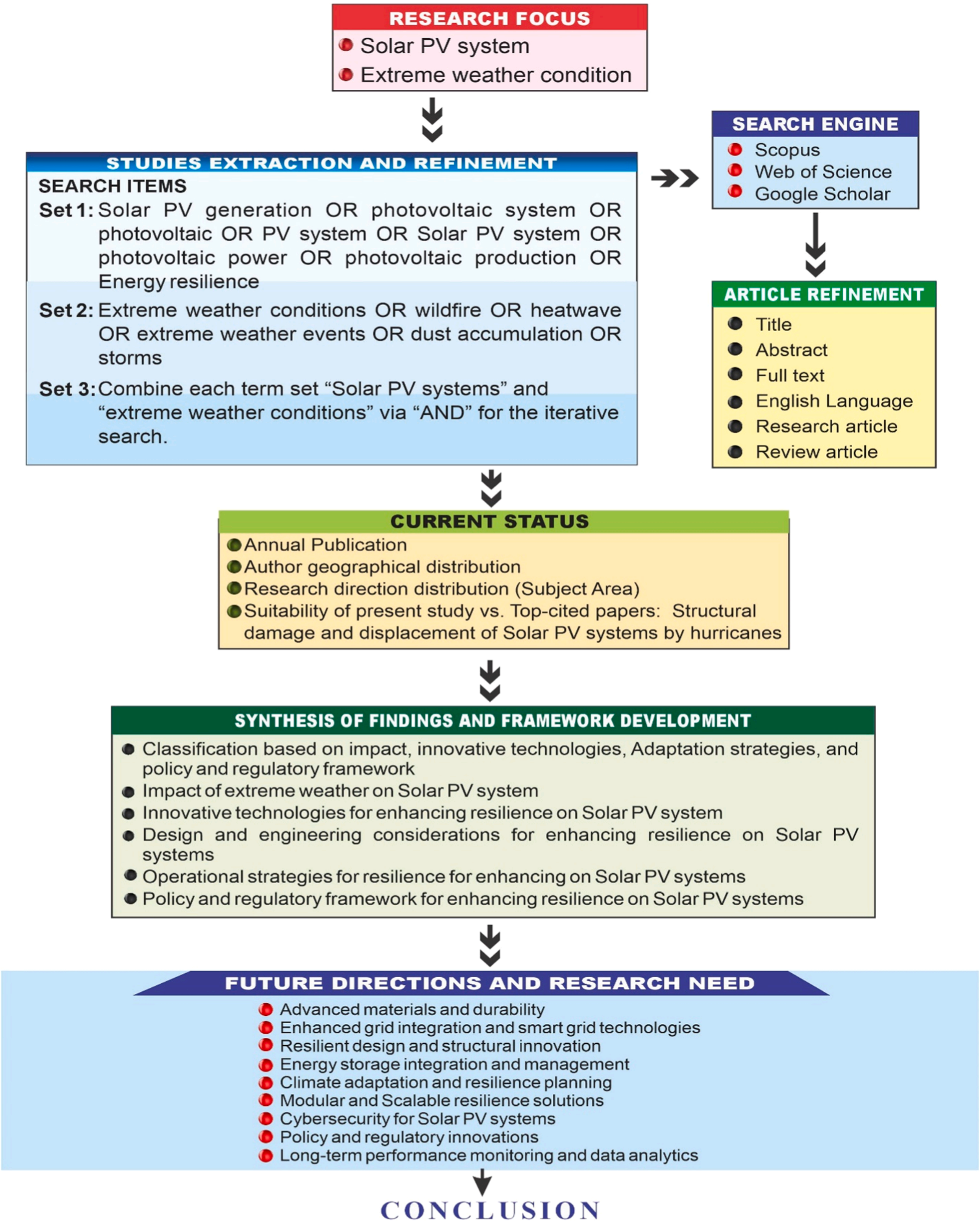

Fig. 2. Methods for selecting, including, and excluding articles.

quantity of research in the energy sector indicates considerable interest and investment in the advancement of knowledge and technology within this domain. The engineering domain prioritizes research on solar photovoltaic systems, while energy continues to be the principal subject of inquiry. This indicates an increasing acknowledgment of the significance of the importance of renewable energy sources, such as solar power, in meeting global energy demands and sustainability objectives. The computer science discipline may contain some research on solar photovoltaic systems, but it is probably less prominent than in the engineering and energy industries. Furthermore, multidisciplinary collaboration among engineers, energy specialists, and computer scientists may yield novel solutions to enhance the efficiency and efficacy of solar energy technology. The research directions laid the technical groundwork for the impacts of extreme weather conditions on solar PV systems adaptation measures, policy and regulation framework, and future directions and research needs.

Fig. 3 illustrates that, following the screening process to identify pertinent journals and strategic papers regarding the impact of extreme weather on solar PV systems, emerging technologies, adaptation strategies, policy and regulatory frameworks, future directions, research requirements, and the comprehensive synthesis of findings and framework development for this study, only 64 studies were deemed relevant. The remaining 1706 articles were discarded. The selected studies included a wide range of topics, such as solar energy production, photovoltaic systems, meteorological forecasting, electric power transmission networks, climate change, storms, outages, extreme weather

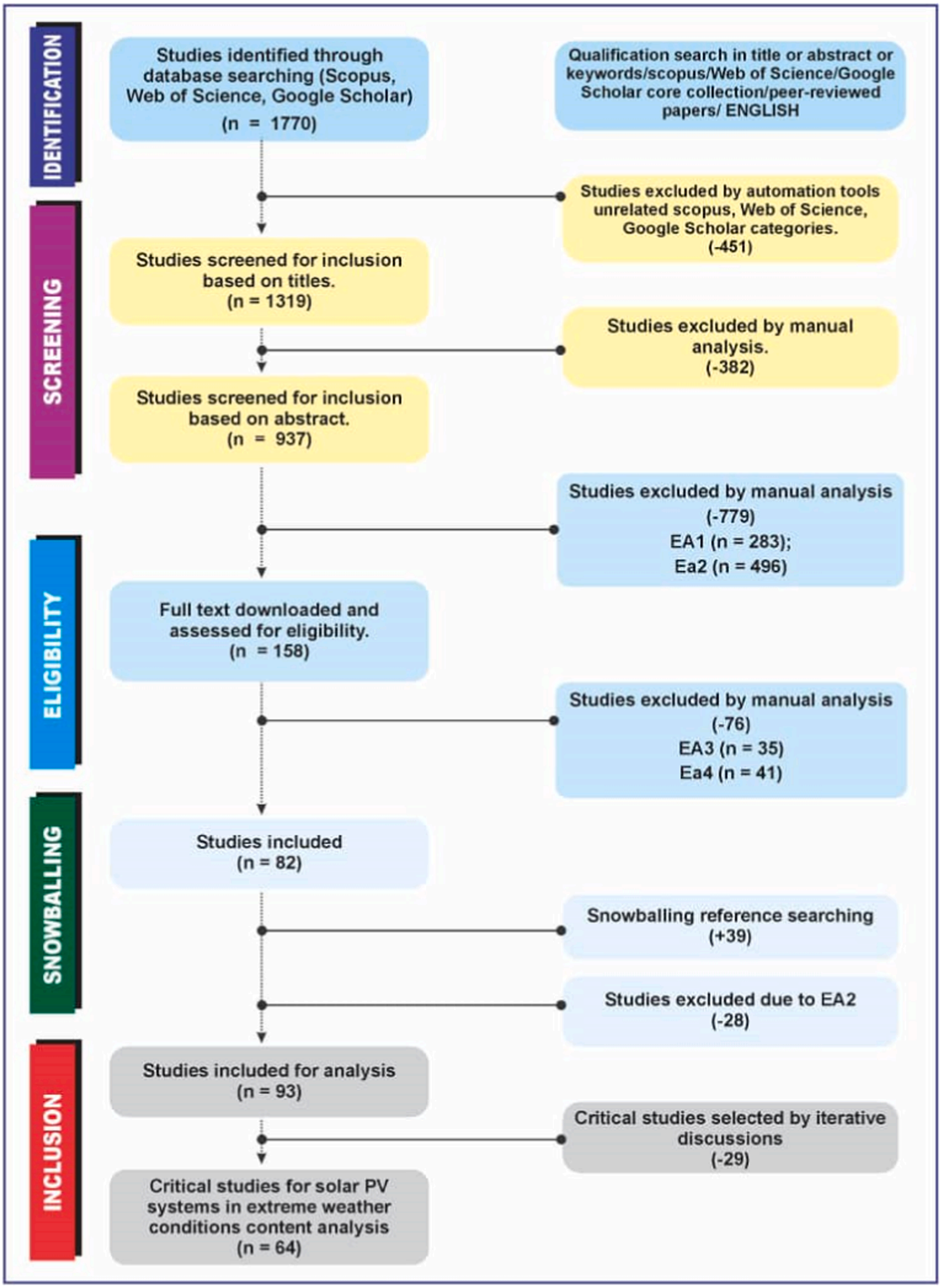

Fig. 3. Refinement and Inclusion of Studies in Research Process.

phenomena, electric power distribution, wildfires, natural disasters, heatwaves, global warming, forestry, climate conditions, arid environments, ambient conditions, and aerosols. The particular criterion focused on research that did not explicitly examine adaptation mechanisms for solar PV systems under extreme weather conditions.

3. Suitability of present study versus top-cited papers: structural damage and displacement of solar PV systems in hurricanes

Most prior research concentrated mostly on the impact of high-intensity wind phenomena, including hurricanes and tornadoes, on solar photovoltaic systems, as illustrated in Table 2. Hurricanes can inflict direct damage to solar modules by displacing and damaging them, as well as causing harm to electrical components through wind-driven

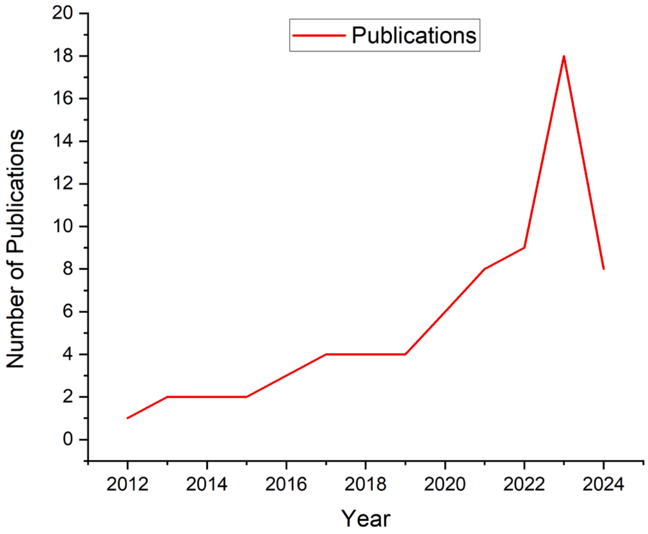

Fig. 4. Analysis of Annual Publication Trends.

debris. Tornadoes produce secondary consequences, including airborne debris that may harm solar photovoltaic systems. These impacts occur less often, although they are significantly more detrimental in terms of adverse effects compared to hurricanes. Hurricanes and tornadoes transpire annually, with hurricanes predominantly affecting coastal regions during the Atlantic hurricane season. Generally, hurricanes and high winds (tornadoes) possess a greater severity rating compared to flooding threats, heatwaves, temperature extremes, and snow and ice accumulation. Hurricanes and tornadoes, characterized by their intense winds and erratic behaviour, can cause significant physical damage to solar PV systems. Moreover, the potential for airborne debris during these severe weather events heightens the risk of structural damage to solar panels.

Hurricanes and tornadoes have exerted differing levels of impact on solar photovoltaic installations throughout various nations. These encompass Hurricane Maria, a devastating hurricane in Puerto Rico, United States, which inflicted extensive damage on solar PV installations in 2017. Typhoon Haiyan (Yolanda) impacted the Philippines in 2013, with wind speeds surpassing 195 mph. After Typhoon Jebi in 2018, inverter malfunctions were documented in Japanese solar photovoltaic installations. Typhoon Mangkhut ravaged China's Aulnui Province, which houses the world's largest floating solar facility. After Hurricane Patricia in 2015, solar farms in coastal Mexico saw considerable soil

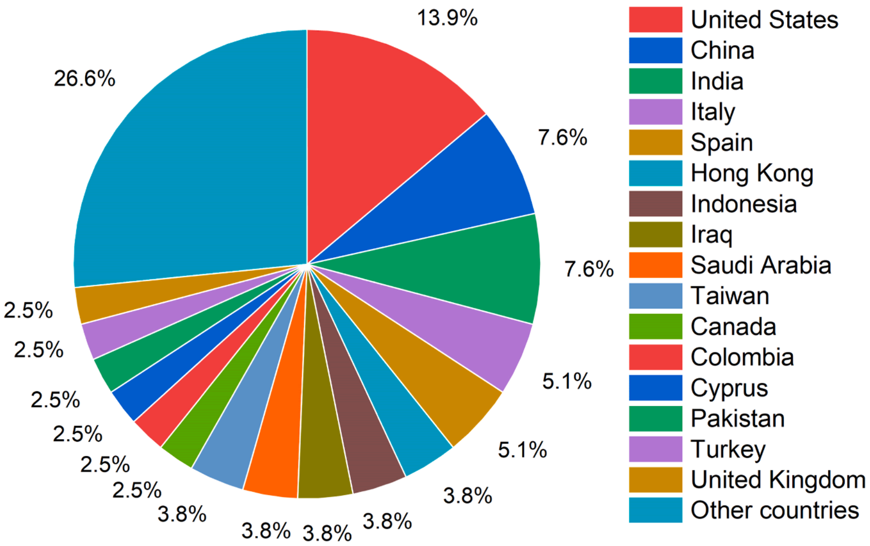

Fig. 5. Authorship Distribution by Geographic Region.

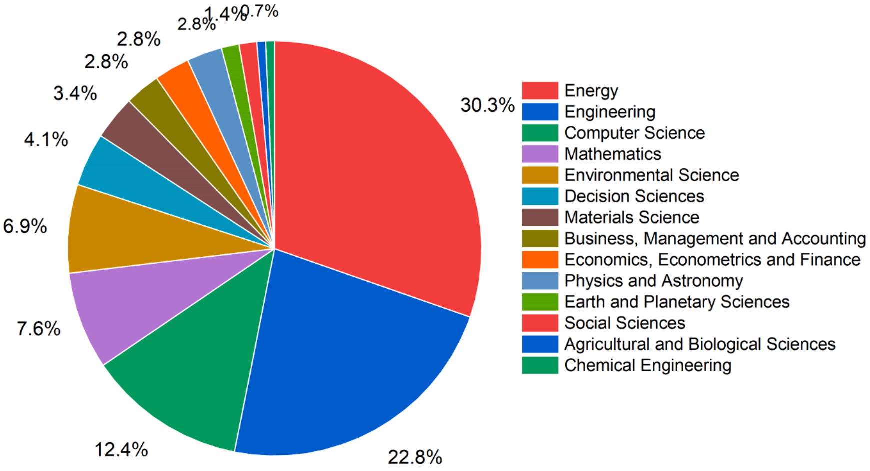

Fig. 6. Distribution of Research Domains in the Study.

Table 2
Comparison of most cited studies with other reviewed literature.

References	Study Title	Journal Title	Citation
(Kumar et al., 2024)	Control strategies for energy enhancement of discontinuous GPS tracking PV system under varying weather conditions	Electrical Engineering	2
(Bošnjaković et al., 2023b)	Effects of Extreme Weather Conditions on PV Systems	Sustainability (Switzerland)	11
(Brás et al., 2023)	How much extreme weather events have affected European power generation in the past three decades?	Renewable and Sustainable Energy Reviews	7
(Castro et al., 2023)	Storm hardening and insuring energy systems in typhoon-prone regions: A techno-economic analysis of hybrid renewable energy systems in the Philippines Busuanga island cluster	Energy Strategy Reviews	5
(Gilletly et al., 2023)	Evaluating the impact of wildfire smoke on solar photovoltaic production	Applied Energy	8
(Hanif et al., 2023)	Analyzing at-scale distribution grid response to extreme temperatures	Applied Energy	7
(B. Wang et al., 2023)	Analysis of photovoltaic system under over-irradiation conditions in arid climate	International Journal of Green Energy	2
(Sepúlveda-Mora and Hegedus, 2022)	Resilience analysis of renewable microgrids for commercial buildings with different usage patterns and weather conditions	Renewable Energy	30
(Faraz Ahmad et al., 2022)	Experimental performance evaluation of closed loop mist/fog cooling system for photovoltaic module application	Energy Conversion and Management: X	11
(Chanchangi et al., 2021)	Soiling on PV performance influenced by weather parameters in Northern Nigeria	Renewable Energy	35
(Jackson and Gunda, 2021)	Evaluation of extreme weather impacts on utility-scale photovoltaic plant performance in the United States	Aplied Energy	45
(Aguilar-Jiménez et al., 2020)	Techno-economic analysis of hybrid PV/T systems under different climate scenarios and energy tariffs	Solar Energy	30
(Kumar et al., 2020)	Power resilience enhancement of a residential electricity user using photovoltaics and a battery energy storage system under uncertainty conditions	Energies	49
(Hachicha et al., 2019)	Impact of dust on the performance of solar photovoltaic (PV) systems under United Arab Emirates weather conditions	Renewable Energy	300
(Pani and Nayak, 2019)	Forecasting solar irradiance with weather classification and chaotic gravitational search algorithm-based wavelet kernel extreme learning machine	International Journal of Renewable Energy Research	17
(Guo et al., 2019)	A new approach for interval forecasting of photovoltaic power based on generalized weather classification	International Transactions on Electrical Energy Systems	12
(Rieger et al., 2017)	Impact of the 4 April 2014 Saharan dust outbreak on the photovoltaic power generation in Germany	Atmospheric Chemistry and Physics	58
(Panteli et al., 2017)	Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures	IEEE Transactions on Power Systems	621
(Liu et al., 2015)	An Improved Photovoltaic Power Forecasting Model with the Assistance of Aerosol Index Data	IEEE Transactions on Sustainable Energy	383
(Lazzaroni et al., 2015)	Models for solar radiation prediction based on different measurement sites	Measurement: Journal of the International Measurement Confederation	77
(Ismail and Alabdrabalnabi, 2014)	Design and performance characteristics of a portable solar-driven thermoelectric heat pump under thunder bay extreme cold conditions in Northwestern Ontario, Canada	Journal of Green Engineering	6
(Han et al., 2013)	Performance of ventilated double-sided PV compared with conventional clear glass	Energy and Buildings	141
(Chen, 2013)	Bayesian approach for optimal PV system sizing under climate change	Omega (United Kingdom)	18
(Chen, 2012)	An efficient sizing method for a stand-alone PV system in terms of the observed block extremes	Applied Energy	51
(Dr. G. Genc, Celik 2019)	A case study of structural failure of mounting systems for solar panels from south-eastern Turkey: an investigation of design parameters under extreme weather events		2
(Gonçalves et al., 2024)	Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures	Sustainable Energy Research	13
S Liu, J Shu, M Qiao (2024)	Assessment of the Impact of Extreme Weather on Power System Reliability	2024 9th Asia Conference on Power and Electrical Engineering (ACPEE)	-
(Wei et al., 2023)	Energy Management and Control System for a	ASHRAE Transactions	3

(*continued on next page*)

Table 2 (*continued*)

References	Study Title	Journal Title	Citation
	PV-Battery System to Improve Residential Building Resiliency Under Extreme Weather Conditions		
V Fthenakis (2023)	The resilience of PV during natural disasters: The hurricane Sandy case	2013 IEEE 39th photovoltaic specialists conference (PVSC)	27
(Küfeoğlu et al., 2014)	A Summary of the Recent Extreme Weather Events and Their Impacts on Electricity	International Review of Electrical Engineering	24
(Zhao et al., 2024)	Photovoltaic Power Generation Power Prediction under Major Extreme Weather Based on VMD-KELM	cdn.techscience.cn	
(Zafeiropoulou et al., 2023)	A Flexibility Platform for Managing Outages and Ensuring the Power System’s Resilience during Extreme Weather Conditions	Processes	13
(Cadini et al., 2017)	A modeling and simulation framework for the reliability/availability assessment of a power transmission grid subject to cascading failures under extreme weather conditions	Applied energy	201
(Abdallah et al., 2022)	Experimental investigation of thermal management techniques for improving the efficiencies and levelized cost of energy of solar PV modules	Case Studies in Thermal Engineering	23
(L. Xu et al., 2024)	Resilience of renewable power systems under climate risks	*Nature Reviews Electrical Engineering*	41
(Kaloti and Chowdhury, 2023)	Toward Reaching a Consensus on the Concept of Power System Resilience: Definitions, Assessment Frameworks, and Metrics	scholarworks.utep.edu	
R Shirvani, T Parhizkar (2023)	Resilience based Electric Sector Optimization in Response to Extreme Weather Conditions with Distributed Generation Systems	*IEEE Access*	1
(Nain and Kumar, 2020)	Initial metal contents and leaching rate constants of metals leached from end-of-life solar photovoltaic waste: An integrative literature review and analysis	Renewable and Sustainable Energy Reviews	71
(Mujjuni et al., 2023)	Evaluation of Power Systems Resilience to Extreme Weather Events: A Review of Methods and Assumptions	*IEEE Access*	11
(Kumar and Raghuwanshi, 2023)	Efficiency estimation and hardware implementation of solar PV module system	Case Studies in Thermal Engineering	3
	assisted by using surface plasmon resonance sensor		
(Oulefki et al., 2024)	Detection and analysis of deteriorated areas in solar PV modules using unsupervised sensing algorithms and 3D augmented reality	Heliyon	6
(Venkatesan et al., 2022)	Investigating the impact of using a ND-PCM on the thermal management of solar PV panels	Materials Today: Proceedings	4
(Ganesan et al., 2023)	Performance analysis of n-type PERT bifacial solar PV module under diverse albedo conditions	Solar Energy	25
(PraveenKumar et al., 2023)	Performance evaluation with low-cost aluminum reflectors and phase change material integrated to solar PV modules using natural air convection: An experimental investigation	Energy	44
(Salamah et al., 2022)	Effect of dust and methods of cleaning on the performance of solar PV module for different climate regions: Comprehensive review	Science of The Total Environment	136
(Sethiya, 2020)	Cooling material for solar PV module to improve the generation efficiency	Materials Today: Proceedings	3
(Mallal et al., 2021)	Temperature prediction-based realistic performance analysis of various electrical configurations of solar PV panels	Solar Energy	13
(Lei et al., 2022)	Power economic dispatch against extreme weather conditions: The price of resilience	Renewable and Sustainable Energy Reviews	10
(Pachauri and Singh, 2023)	A novel shadow dispersion approach for solar PV modules in array using chess board game methodology: An experimental study	Solar Energy	3
	Performance evaluation of solar PV module with filters in an outdoor environment		
(Nagadurga et al., 2021)	Harness of maximum solar energy from solar PV strings using particle swarm optimisation technique	International Journal of Ambient Energy	14
(Ramkiran et al., 2020)	Performance evaluation of solar PV module with filters in an outdoor environment	Case Studies in Thermal Engineering	38
(Li et al., 2023)	A Fault and Capacity Loss Prediction Method of Wind Power Station under Extreme Weather	Mathematical Problems in Engineering	1
(Alamoudi et al., 2021)	Designing a solar photovoltaic system for generating renewable energy of a hospital:	Mathematics	10

(*continued on next page*)

Table 2 (*continued*)

References	Study Title	Journal Title	Citation
	Performance analysis and adjustment based on rsm and anfis approaches		
(Nagadurga et al., 2021)	Enhancing global maximum power point of solar photovoltaic strings under partial shading conditions using chimp optimization algorithm	Energies	26
(Lakshmi and Ramadas, 2022)	Dust Deposition's Effect on Solar Photovoltaic Module Performance: An Experimental Study in India's Tropical Region	Journal of Renewable Materials	13
(Caldas-Alvarez et al., 2022)	Meteorological, impact and climate perspectives of the 29 June 2017 heavy precipitation event in the Berlin metropolitan area	International Journal of Sustainable Engineering	6
(Guo et al., 2021)	A Multi-State Model for Transmission System Resilience Enhancement against Short-Circuit Faults Caused by Extreme Weather Events	IEEE Transactions on Power Delivery	117
(Postigo Marcos et al., 2022)	Improving distribution network resilience through automation, distributed energy resources, and undergrounding	International Journal of Electrical Power & Energy Systems	24
(Hsu and Mostafavi, 2024)	Untangling the relationship between power outage and population activity recovery in disasters	Resilient Cities and Structures	2
(Liu and Bai, 2023)	Daily Variation and Regional Differences in Wind Power Output during Heat and Cold Wave Days in China	International Transactions on Electrical Energy Systems	2
(Liu et al., 2022)	A sequentially preventive model enhancing power system resilience against extreme-weather-triggered failures	Renewable and Sustainable Energy Reviews	29
(Shahbazi et al., 2021)	Effects of resilience-oriented design on distribution networks operation planning	Electric Power Systems Research	71
(Ramanan et al., 2024)	Design study on the parameters influencing the performance of floating solar PV	Renewable Energy	17
(Vugrin et al., 2017)	Resilience metrics for the electric power system: A performance-based approach	*Sandia National Laboratories*	189

erosion surrounding their ground-mounted arrays. Taiwan, frequently impacted by typhoons, has found that even systems enduring multiple storms demonstrate declining performance. Hurricanes and tornadoes have been shown to have effects on solar PV systems that go beyond normal damage. These effects include damage to structures, power outages, loss of efficiency, debris hitting modules, inverter and electrical system failures, damage to ground-mounted and floating systems, disruption of grid-tied systems, scouring and erosion of ground-mounted systems, and long-term performance problems. This indicates that previous studies, including Panteli et al., regarding the resilience of renewable energy systems (solar PV) against hurricanes and storms are limited (Panteli et al., 2017). This may result from the heightened influence of extreme weather phenomena on solar photovoltaic installations. Panteli et al. present a comprehensive framework for power grid resilience (Panteli et al., 2017); however, the present study is more pertinent to solar energy research, concentrating on the impact of hurricanes and high winds, including tornadoes, on the structural integrity of solar PV systems. The present study offers targeted insights and solutions to enhance the durability and reliability of solar installations against climate-induced weather events that have overwhelmed traditional solar PV systems in Puerto Rico, Yalanda, Jebi, Mangkhurt, Patricia, and Taiwan. Given the detrimental effects of climate-induced weather events on solar PV systems, there is an urgent need for more resilient, durable, and reliable solar installations. Kumar et al. looked at important ways to increase the amount of energy a discontinuous GPS-tracking solar PV system produces by changing its orientation on the fly based on GPS and real-time weather data (Kumar et al., 2024). This paper's primary contribution is the creation of an adaptive control system that enhances the energy output of solar PV modules by dynamically modifying their orientation based on real-time data.

Kumar et al. present a distinctive energy augmentation technique for solar PV systems amid standard weather variations (Kumar et al., 2024); nonetheless, the present study is more adept at addressing practical challenges posed by hurricanes and strong winds. This article provides essential insights into ensuring the durability and safety of solar PV systems under severe weather conditions in response to the increasing demand for resilient solar infrastructure due to climate change. A separate initiative, directed by Brás et al. (2023), aims to quantify energy production losses, identify the most vulnerable energy sources, and offer strategic insights into the resilience of Europe's power grid against increasing weather extremes. This research is focused on the essential problems regarding the resilience of solar PV systems to storms and high winds. It provides crucial insights into the future of solar energy infrastructure, especially in susceptible coastal and inland regions. There were other studies, like those by Bošnjaković et al. (2023b), Castro et al. (2023), Gilletly et al. (2023), Hanif et al. (2023), and S. Wang et al. (2023), that looked at the history of extreme weather events and how they affected power generation reliability and performance in places like Germany (Rieger et al., 2017), the United Arab Emirates (Hachicha et al., 2019), Nigeria (Chanchangi et al., 2021), Canada (Ismail and Alabdrabalnabi, 2014), and Europe (Brás et al., 2023). This study builds upon its base and expands the logic to encompass the effects of extreme weather, notably on solar PV, practical structural insights, timeliness and climate relevance, as well as specific recommendations for resilience. This research specifically targets solar photovoltaic (PV) systems, a rapidly expanding renewable energy source, distinguishing it from other studies, like Brás et al. (2023), that analyze the effects of extreme weather on various energy systems (wind, hydro, nuclear, etc.). It addresses a significant gap in knowledge regarding the impact of hurricanes and high winds on solar PV installations, as illustrated in Fig. 6. Moreover, although the current research often examines energy efficiency losses or power outages resulting from weather events, there is a scarcity of studies that focus on the physical damage (Panteli et al., 2017) and relocation of solar PV systems (Brás et al., 2023). This study gives clear structural engineering solutions, like mounting that doesn't bend in the wind, that can be used right away in places that are prone to hurricanes. This makes the results very useful and practical (see Fig. 6). This paper integrates real-world case studies with targeted engineering solutions (e.g., reinforcing tracking systems, adjusting tilt angles) to safeguard solar PV systems against hurricane-force winds, in contrast to many papers that offer only theoretical models or simulations of weather impacts (Kumar et al., 2024). This enhances its applicability for politicians, solar farm developers, and engineers.

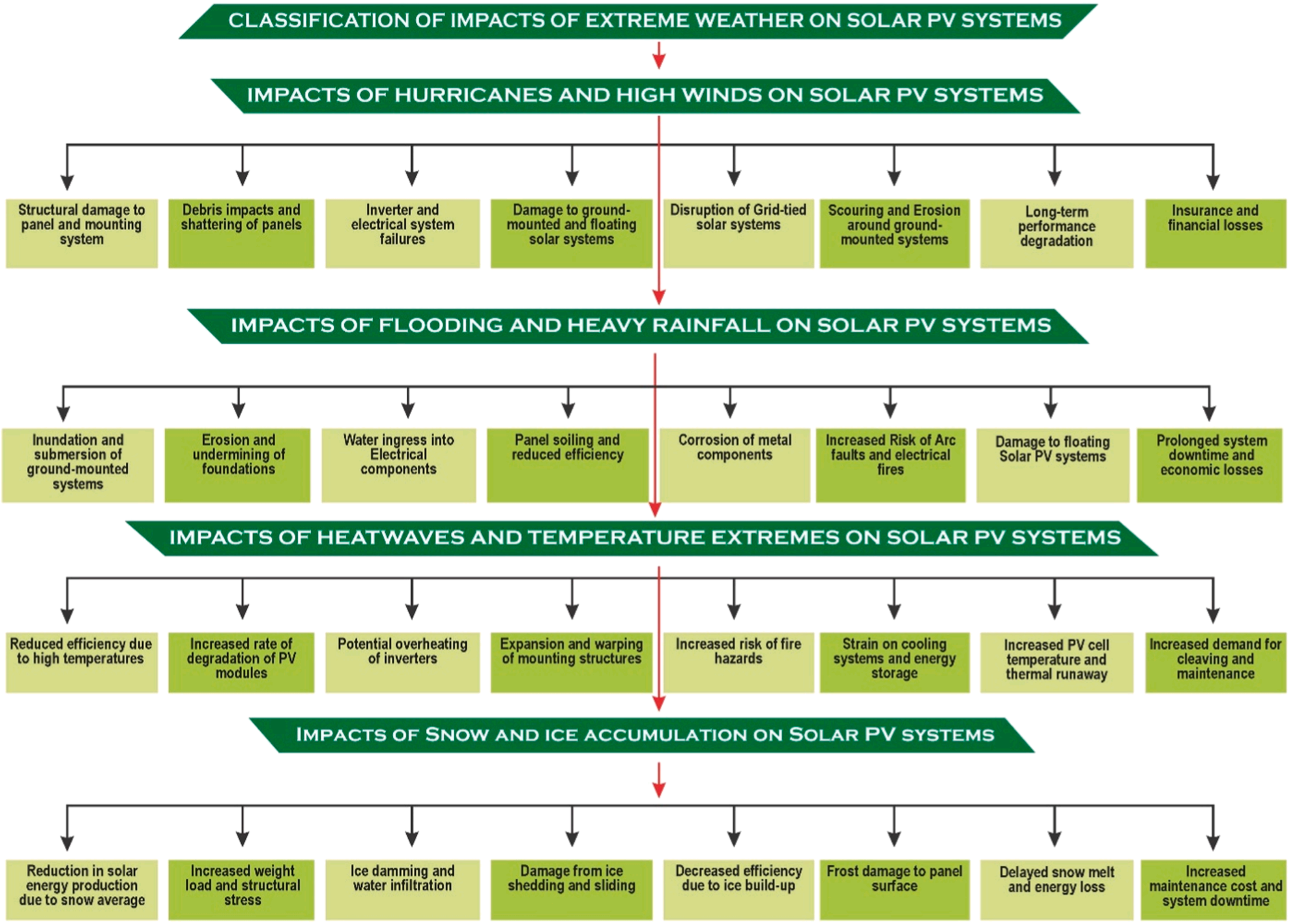

Fig. 7. Impacts of Extreme Weather Conditions on Solar PV Systems: A Comprehensive Classification.

4. Synthesis of findings and framework development

4.1. Classifications based on impacts, innovative technologies, adaptation strategies, and policy and regulation framework

4.1.1. Classification of impacts of extreme weather conditions on solar PV systems

Section 2 (methodology) reveals that most authors emphasized the impact of harsh weather conditions on solar PV installations. This is additionally categorized into four classifications: (1) Effects of storms and strong winds on solar photovoltaic systems; (2) effects of flooding threats and associated safety issues; (3) effects of heatwaves and extreme temperatures on solar photovoltaic systems; and (4) effects of snow and ice build-up on solar photovoltaic systems, as depicted in Fig. 7. The impact of storms and high winds on solar PV system classification assesses the structural integrity of solar panels and mounting systems, together with the potential for debris impact. The study examines the efficacy of different installation techniques in mitigating damage from severe wind events. The category of flooding dangers and safety concerns examines the impact of flooding on the electrical components of solar PV systems, including inverters and wiring, which may provide possible safety hazards. Research examines methods for safeguarding solar PV systems from water damage and providing proper drainage to prevent system failure. The effects of heatwaves and temperature extremes on solar PV system classification examine how elevated temperatures can diminish solar panel efficiency and even lead to overheating, hence reducing energy output. Research investigates methods to cool solar photovoltaic systems to ensure optimal performance during heatwaves and extreme temperature events. The impact of snow and ice accumulation on solar PV system classification examines how winter weather conditions may diminish solar panel productivity by obstructing sunlight absorption due to coverage by snow or ice. Researchers are examining solutions, including tilt angles and heating systems, to prevent snow and ice accumulation on solar PV systems, ensuring continuous energy output in cold environments.

Aly and Rone (2023), Marqusee et al. (2021), and Zhu et al. (2021) have all conducted research into the effects of storms and strong winds on the classification of solar PV systems. This section highlights delicate themes that the previously mentioned authors did not fully explore. The writers of this study classified this division into eight subclasses according to the impact of storms and high winds on different aspects of PV systems. Fig. 7 shows a number of problems, such as equipment breaking down over time, panels breaking because of debris hitting them, inverter and electrical system problems, damage to ground-mounted and floating solar installations, problems with grid-tied solar systems, structural damage to panels and mounting systems, financial losses, and insurance claims. The classification of structural damage to panel and mounting systems examines how severe winds and storms can physically compromise solar panels and their supporting structures. Impact from debris and the fracturing of panels can lead to expensive repairs and replacements, diminishing the overall efficiency and reliability of the photovoltaic system. The classification of electrical system and inverter failures examines how issues with these components might lead to diminished energy output and potential safety hazards. The classification of damage to ground-mounted and floating solar systems examines how environmental factors, including flooding, soil erosion, and vandalism, can inflict physical harm on solar panels and their supporting structures. The categorization of grid-tied solar systems is compromised, examining the impact of power outages, electrical issues, and grid failures on the operation of grid-connected solar photovoltaic systems. The examination of scouring and erosion related to ground-mounted systems classification investigates how external factors, including wind, rain, and soil erosion, may influence the stability and performance of ground-mounted solar PV systems. The classifications for long-term performance degradation analyze the different factors by which inverter efficiency, system maintenance, and module deterioration can affect the overall performance of a solar PV system over time. The classification of insurance and financial losses examines how owners of solar PV systems may incur financial losses due to unforeseen events such as extreme weather, theft, or equipment malfunction. Owners of solar PV systems can enhance their return on investment and ensure long-term performance by understanding these categories and implementing preventative strategies.

The second category of the impacts of flooding and heavy rainfall on solar PV systems is illustrated in Fig. 7, which depicts the consequences of flooding hazards and safety issues. This section further categorized the categorization into eight sub-classes according to their impacts on various photovoltaic system characteristics. These include ground-mounted photovoltaic systems flooding and being flooded, foundation erosion and undermining, water getting into electrical parts, panels getting dirty and losing their efficiency, metal parts rusting, the risk of electrical fires and arc faults rising, damage to floating solar photovoltaic systems, long system outages, and financial losses. The categorization of submersion and inundation of ground-mounted solar systems examines how these events might lead to equipment damage, short circuits, and potential safety hazards for maintenance personnel. The classification of foundation degradation and erosion examines how these issues may compromise the structural integrity of the system, leading to instability and potential collapse. Moreover, water infiltration into electrical components may lead to equipment malfunction and short circuits, jeopardizing user safety and diminishing system performance. The classifications of panel soiling and diminished efficiency examine the effects of dirt and debris accumulation on solar panels, which can adversely affect energy production, leading to reduced output (Nwokolo and Ogbulezie, 2018a) and compromised system performance (Nwokolo and Ogbulezie, 2018b). The classification of metal corrosion examines how exposure to harsh environmental conditions can lead to rust and the degradation of structural elements, threatening the overall integrity and longevity of the system. The presentation entitled "Increased Risk of Arc Faults and Electrical Fires" examines how inadequate maintenance practices and faulty wiring can lead to electrical issues that elevate the risk of dangerous arc faults and fires inside the system. The categorization of damage to floating solar photovoltaic systems examines how improper installation and inadequate maintenance can result in structural degradation and diminished solar panel efficiency, ultimately impacting the system's overall performance (Nwokolo et al., 2022b). The issue of extended system downtime and financial repercussions examines how prolonged system inactivity, either from unforeseen failures or maintenance issues, can lead to significant economic losses for organizations and individuals reliant on the system for energy production or cost savings. Moreover, the necessity for costly replacements or repairs during periods of inactivity may exacerbate financial limitations and diminish productivity.

The third classification is also depicted in Fig. 7, titled "Impacts of Heatwaves and Temperature Extremes on Solar PV Systems." Due to the effects of heatwaves and other temperature extremes on various PV system components, this section introduced eight sub-classes to the classification. Some of these problems are higher risk of accidents, stress on cooling systems and energy storage, high temperatures in PV cells and thermal runaway, faster degradation of PV modules, the possibility of inverters overheating, mounting structures expanding and warping, and more work needing to be done on them and less efficiency because of the high temperatures. This classification of diminished efficiency due to elevated temperatures examines how high temperatures can adversely affect the operation of solar systems, leading to reduced energy output and overall efficiency. The accelerated deterioration rate of PV module classification examines its potential to shorten module lifespan, hence impacting the system's overall return on investment and increasing maintenance expenses (Nwokolo et al., 2022a). Moreover, potential inverter overheating may lead to diminished efficiency and additional faults, further compromising the performance of the PV system. The evolving and complex categories of mounting structures examine how these issues could compromise the structural integrity of the PV system, endangering public safety and requiring increased maintenance frequency. The elevated risk of hazards associated with solar PV system classification examines how these safety concerns may result in penalties from regulatory bodies and legal responsibilities for the system's operator or owner. This essay examines the stress on cooling systems and the categorization of energy storage. It underscores the importance of these components in maintaining optimal performance of the PV system, since any stress on them may lead to diminished efficiency and potential system failure. The categorization of thermal runaway and increased photovoltaic cell temperature examines how these issues may lead to diminished energy production and potentially perilous situations, including explosions or fires (Hassan et al., 2022). The increasing necessity for clearing and maintenance classification underscores the significance of preserving this aspect to ensure the longevity and efficiency of the PV system, as inadequate maintenance may result in diminished performance and heightened safety risks.

Fig. 7 presents the fourth classification, titled Consequences of Snow and Ice Accumulation on the Solar PV System. This section included eight sub-classes to the classification, determined by the impact of snow and ice accumulation on different PV system components. Elevated weight load and structural stress, ice damming and water infiltration, damage from ice shedding and sliding, reduced efficiency owing to ice accumulation, frost damage to panel surfaces, delayed snowmelt and energy loss, as well as heightened maintenance costs and system downtime are among these issues. A decrease in solar energy generation due to snow accumulation. The decrease in solar energy output due to snow cover classification examines how snow accumulation on photovoltaic systems might impede sunlight access to the panels, hence diminishing energy production and efficiency. The implications of snow accumulation on roof weight, potentially leading to structural damage or collapse if improperly managed, are addressed in the classes on increasing weight load and structural stress (Obiwulu et al., 2022). Moreover, the melting and subsequent refreezing of snow on the roof may lead to ice damming and water infiltration, potentially causing leaks and water damage within the structure. The classification of damage from ice shedding and sliding examines the potential harm to adjacent property and the safety risks posed to individuals below by falling snow and ice particles from roofs. The diminished deficit due to ice accumulation classification examines how ice formation on the roof can lead to increased heating costs and decreased energy efficiency, as the ice serves as an insulating barrier, preventing heat from escaping the building (Obiwulu et al., 2020a). The categorization of frost damage to panel surfaces examines the mechanisms by which frost can deteriorate these surfaces, leading to costly repairs or replacements (Obiwulu et al., 2020b). The category concerning delayed snowmelt and energy loss examines how ice accumulation-induced delayed snowmelt can cause water infiltration into the building, leading to further damage and potentially the proliferation of mold. Moreover, heating systems may experience increased strain due to energy loss from the insulating layer of ice, leading to elevated energy expenditures and consumption. The necessity for the periodic removal of ice and snow accumulation can lead to increased maintenance expenses and system inactivity, adversely affecting overall production and efficiency. This is examined thoroughly

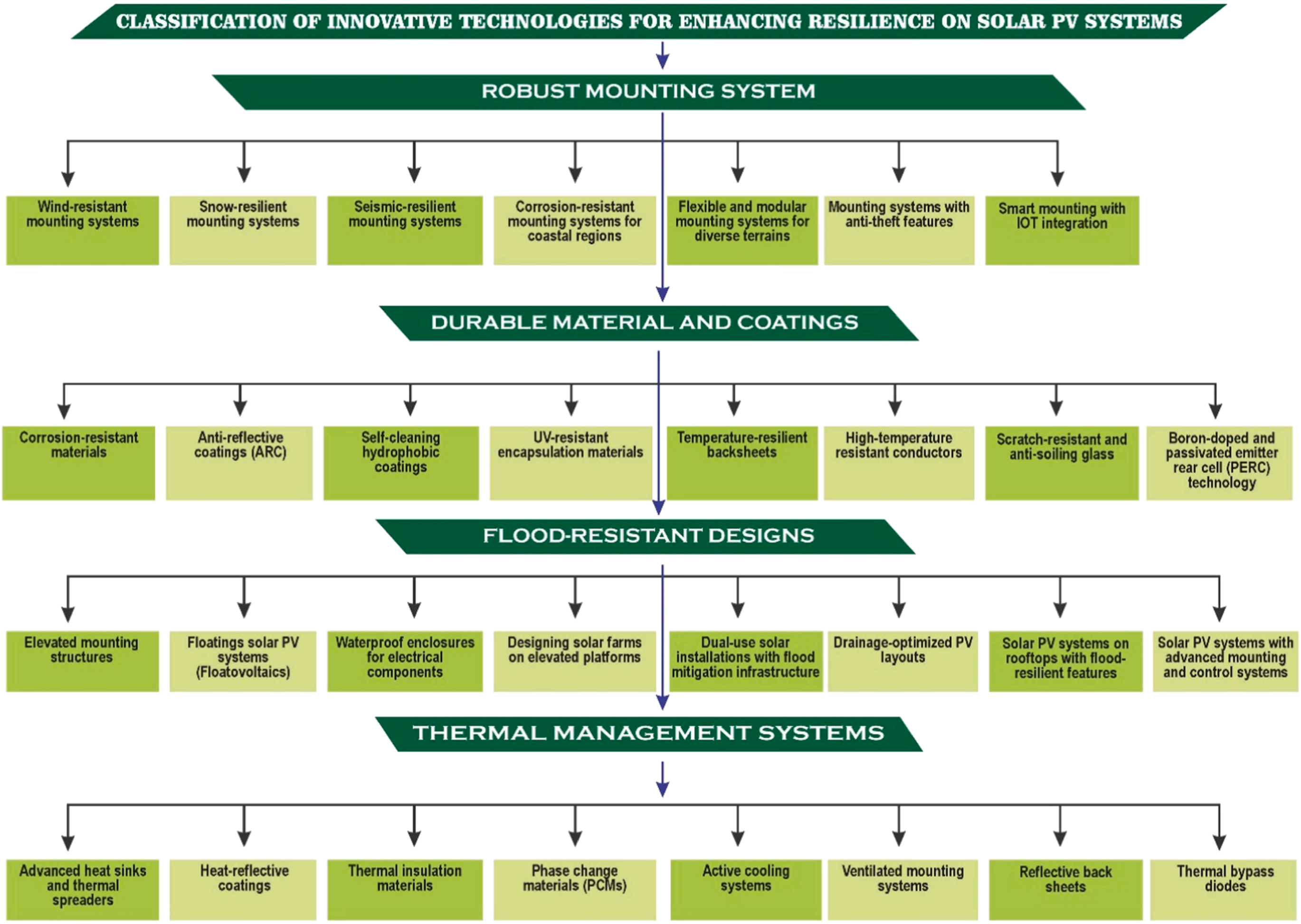

Fig. 8. Classification of Resilience-Enhancing Technologies for Solar PV Systems.

in the categorization of elevated maintenance expenses and system outages.

4.1.2. Classification of innovative technologies for enhancing resilience on solar PV systems

The authors developed a paradigm grounded in current research employing advanced technology to enhance resilience in solar PV systems worldwide, derived from the synthesis of data from the systematic review. The authors categorized the list of ground-breaking technologies into four main sectors for enhanced reader accessibility. Fig. 8 illustrates the following components: (1) robust mounting techniques; (2) durable materials and coatings; (3) flood-resistant configurations; and (4) thermal management technologies. Durable materials and coatings focus on prolonging the lifespan of solar panels, while robust mounting solutions emphasize the importance of secure installation methods to withstand severe weather conditions. Additionally, systems are protected from water damage by flood-resistant designs, while thermal management systems facilitate temperature regulation for optimal performance. This methodology provides a comprehensive assessment of resilience-enhancing technologies in solar PV systems to assist academics and practitioners in boosting system performance and reliability.

Seven grades constituted the subclassification of the robust mounting systems classified. These include mounting systems that are resilient to wind, snow, seismic activity, and corrosion in coastal regions; flexible and modular mounting systems; mounting systems equipped with anti-theft mechanisms; and intelligent mounting systems that interface with the Internet of Things. To ensure optimal performance and longevity of solar panel installations, each category of mounting options is designed to address specific challenges and climatic conditions. These categories provide a comprehensive guide for selecting the optimal mounting option based on project requirements and location.

There exist eight subcategories within the categorization of durable materials and coatings. These comprise the following: (1) corrosion-resistant materials; (2) anti-reflective coatings (ARC); and (3) self-cleaning hydrophobic coatings. Materials for UV-resistant encapsulating temperature-resistant back-sheets; high-temperature-resistant conductors; anti-scratch and anti-soiling glass; and boron-doped passive emitter rear cell (PERC) technology. These classifications are essential as they dictate the endurance and quality of materials utilized throughout various industries, especially in the production of solar panels. Each subtype is crucial for ensuring the efficacy and durability of the final product.

Eight classifications were established based on the subclassification of flood-resistant designs. Some of these are floating solar photovoltaic systems (floatovoltaic), structures for mounting them higher, waterproof covers for electrical parts, solar farms built on raised platforms, dual-use solar installations with infrastructure for preventing flooding, photovoltaic layouts that are best for drainage, rooftop solar photovoltaic systems that won't get damaged by flooding, and complex monitoring and control systems. To ensure that solar PV systems can withstand flooding events and maintain operational efficiency, each category offers tailored solutions. The solar industry can more adeptly address the challenges posed by climate change and severe weather events through the adoption of flood-resistant systems.

The categorization of thermal management systems was subdivided into eight classes. Examples include phase change materials (PCMs),

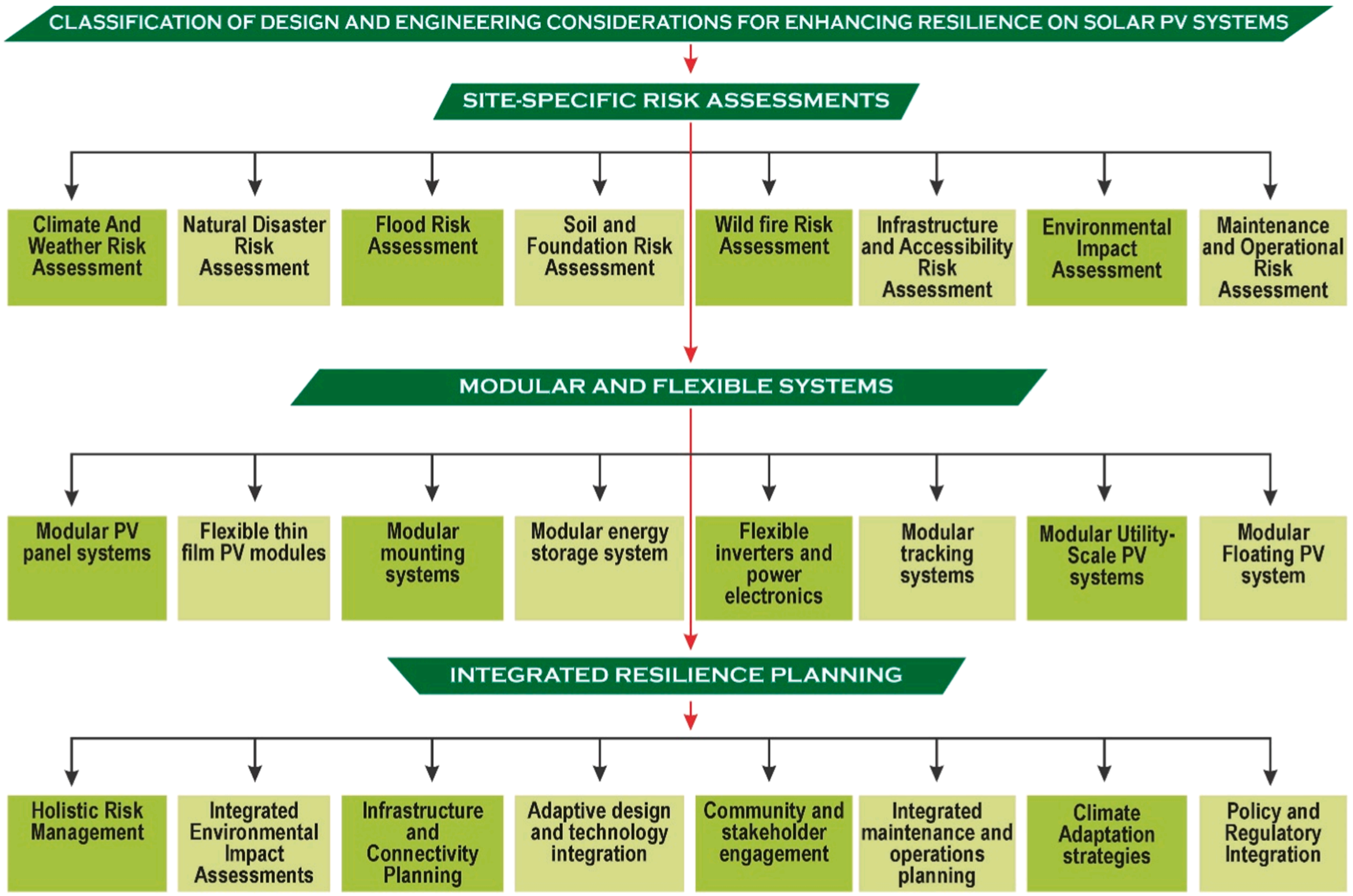

Fig. 9. Classification of design and engineering consideration for enhancing resilience on solar PV systems.

heat-reflective coatings, enhanced heat sinks and thermal spreaders, thermal insulation materials, active cooling systems, vented mounting systems, reflective back sheets, and thermal bypass diodes. To ensure maximum effectiveness and longevity, each of these classes serves a specific purpose in controlling the heat that electronic devices produce. Understanding the distinctions within each class enables engineers to make informed choices regarding the best suitable thermal management system for their specific application.

4.1.3. *Classification of design and engineering consideration for enhancing resilience on solar PV systems*

Section 2 (methodology) indicates that the majority of authors concentrated on engineering and design elements to enhance resilience in solar PV systems. This is subdivided into three additional categories: (1) location-specific risk assessment; (2) emergency response and recovery plans; and (3) cohesive resilience planning, as seen in Fig. 9. The classification of the site-specific risk assessment evaluates potential hazards and vulnerabilities inherent to the solar PV system's location, including extreme weather events or physical security threats. Emergency response and recovery plans focus on establishing protocols for the swift and effective management of disruptions, while integrated resilience planning involves comprehensive strategies that meld risk assessment with response actions for enduring sustainability. Collectively, these three components ensure that the solar PV system is prepared for any potential hazards or threats that may occur. The system can sustain its efficacy and efficiency amid challenges by employing integrated resilience planning, mitigating site-specific hazards, and establishing emergency protocols. Marqusee et al. (2021), Aly and Rone (2023), and Zhu et al. (2021) have all conducted studies to improve the robustness of solar photovoltaic systems. The authors emphasize the importance of conducting site-specific risk assessments, developing emergency response and recovery plans, and implementing integrated resilience planning to enhance the reliability of solar PV systems. These studies provide substantial contributions to the development of more resilient solar energy infrastructure through the examination of various design and engineering methodologies.

4.1.4. *Classification of operation strategies for resilience for enhancing on solar PV systems*

Recent technological advancements and a greater understanding of the benefits of renewable energy sources have led to a significant increase in support for strategies to increase the resilience of solar PV systems. Using strategies like adding microgrids, energy storage solutions, and predictive maintenance can make solar PV systems more reliable and efficient, making them less likely to break down because of things like bad weather or power outages. The authors consider it essential to critically analyze operational techniques for resilience to enhance solar PV systems, aiming to get a comprehensive understanding of how these systems may endure diverse obstacles and maintain reliable energy generation. By assessing various operational strategies and pinpointing potential vulnerabilities, stakeholders can make educated decisions to enhance the efficiency and durability of solar PV systems under fluctuating environmental circumstances. Drawing from the synthesis of data in the systematic review, the authors formulated a framework grounded in ongoing research focused on operational measures to bolster resilience in solar PV systems globally. To enhance accessibility for readers, the operational methods described by the authors were classified into three principal categories: (1) routine maintenance and inspections, (2) emergency response and recovery plans, and (3) smart grid integration, as seen in Fig. 10. The classification of

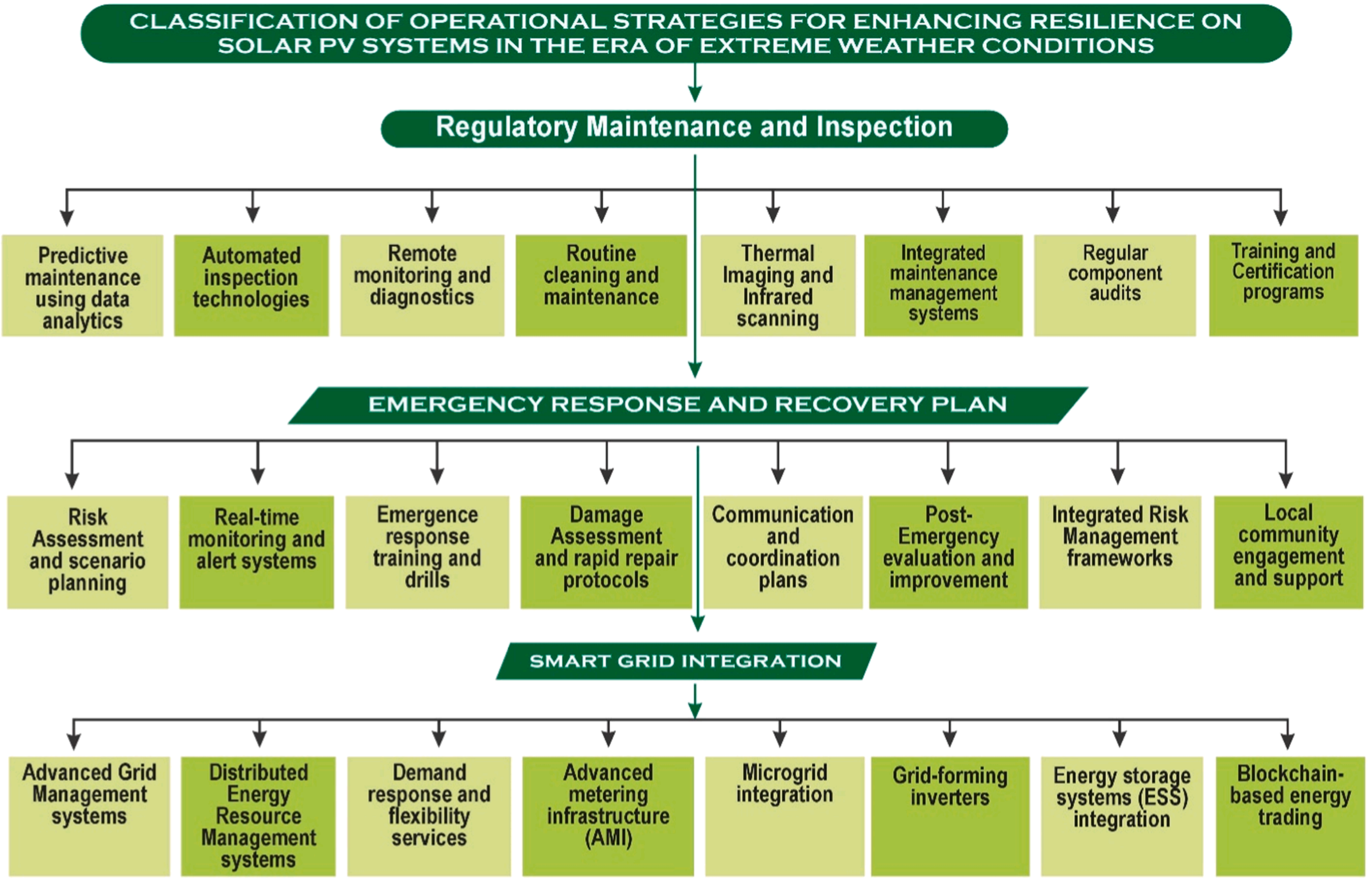

Fig. 10. Classification of Operation strategies for resilience for enhancing on solar PV systems.

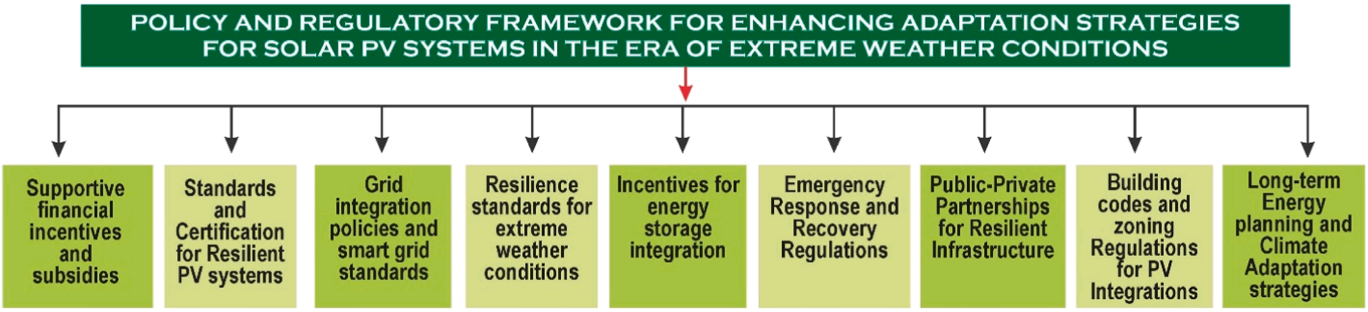

Fig. 11. Classification of policy and regulation framework for resilience for enhancing on solar PV systems.

regular maintenance and inspections examines how frequent evaluations and proactive upkeep can avert potential problems and guarantee optimal performance of solar PV systems. Emergency response and recovery plans emphasize readiness for unforeseen occurrences like natural catastrophes or equipment malfunctions, whereas smart grid integration investigates the enhancement of overall system resilience and efficiency through the connection of solar PV installations to the broader electrical grid. These three classifications together enhance the dependability and efficacy of solar PV systems, assuring the continuous provision of clean energy in a sustainable manner. Implementing these techniques will enhance solar energy systems' capacity to address difficulties and optimize their advantages for the environment and consumers.

4.1.5. Classification of policy and regulation framework for resilience for enhancing on solar PV systems

This section categorizes legislative and regulatory frameworks for resilience to enhance the sustainability and efficacy of solar PV systems in renewable energy efforts. By explicitly delineating roles and responsibilities, instituting clear norms, and implementing procedures for monitoring and assessment, policymakers can foster a conducive climate for the expansion of solar PV systems. Moreover, integrating stakeholder feedback and consistently revising laws to align with technological progress will guarantee that the regulatory framework stays pertinent and responsive to the industry's evolving requirements. Numerous countries, regions, and scientific communities have established policy and regulatory frameworks to increase the resilience of solar PV systems; however, there is still room for improvement in streamlining procedures, lowering administrative barriers, and increasing transparency to further encourage the global proliferation of solar PV systems.

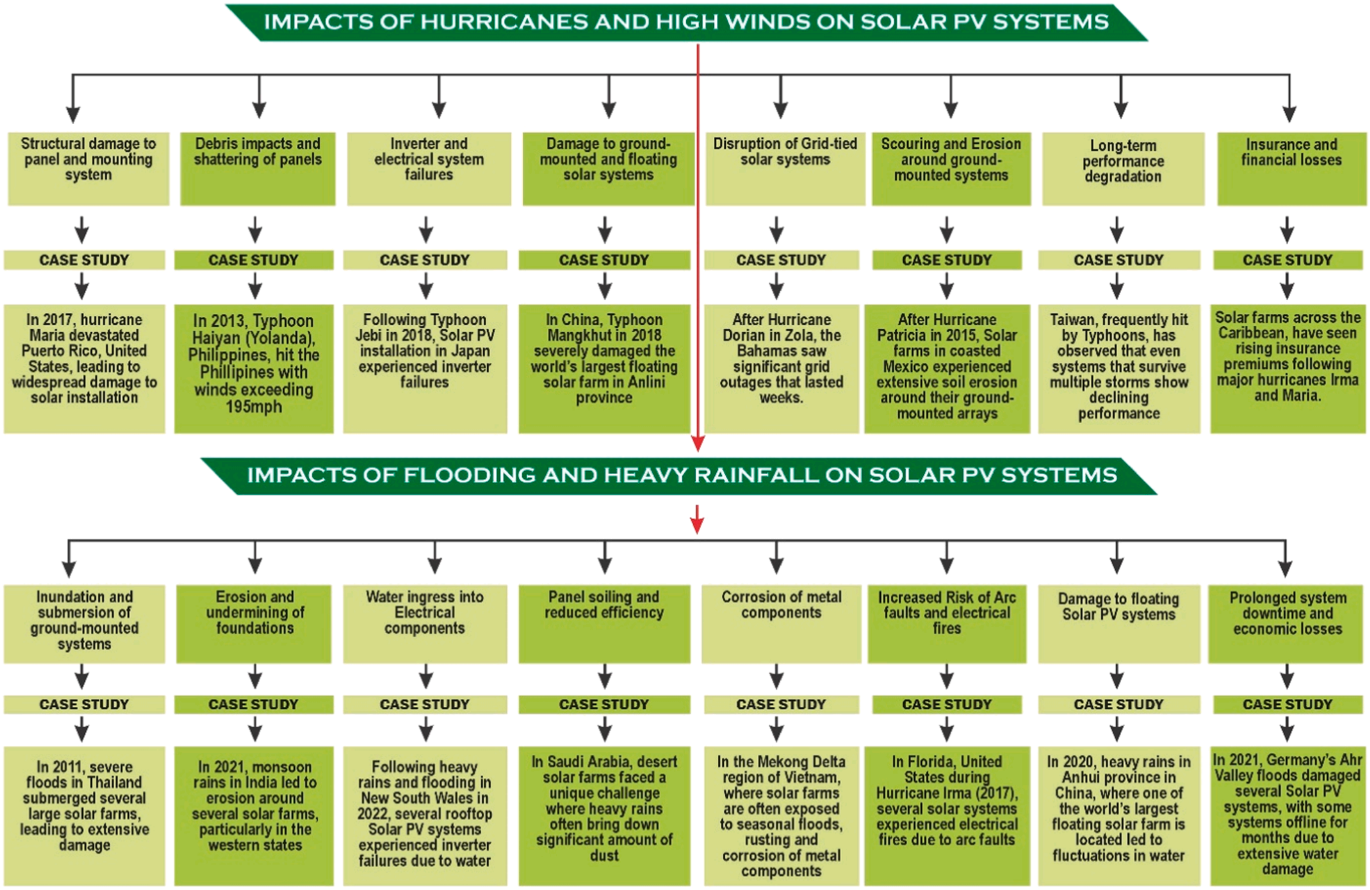

Fig. 12. Impacts of hurricanes and high winds on solar PV systems.

Policymakers can enhance the effectiveness of their initiatives in advancing sustainable energy practices by studying successful models and consistently improving regulations through feedback and data analysis. Consequently, by an analysis of various policy and regulatory frameworks derived from the literature study, the writers broadened the perspective to furnish a detailed guide for policymakers aiming to execute effective strategies for the extensive adoption of solar photovoltaic systems. By implementing best practices and innovative strategies, policymakers can foster a more favorable climate for the expansion of renewable energy sources and promote a more sustainable future for all. The author categorizes these policy factors into nine distinct groupings to furnish a systematic framework for policymakers in formulating their policies. Organizing the policies in this manner facilitates the comparison and analysis of various strategies for boosting solar PV uptake. This classification method can enhance the decision-making process and facilitate the effective implementation of renewable energy regulations.

The authors categorized the legal and regulatory system into eight primary areas for enhanced reader accessibility. (1) Financial incentives and subsidies that encourage support, (2) standards and certifications for robust photovoltaic systems, (3) policies for grid integration and intelligent grid standards, (4) resilience standards for extreme weather conditions, (5) incentives for energy storage integration, (6) regulations for emergency response and recovery, (7) public-private partnerships focused on resilient infrastructure, (8) building codes and zoning regulations for photovoltaic integration, and (9) long-term energy planning and strategies for climate adaptation as depicted in Fig. 11. The categorization of financial incentives and subsidies analyzes how monetary support promotes the implementation of resilient solar systems, while standards and certification ensure that these systems are designed to withstand unfavourable weather conditions. The categorization of grid integration policies and smart grid standards analyzes the potential enhancements in system resilience and efficiency resulting from the integration of solar systems and the use of smart grid technology. The resilience standards for extreme weather conditions and incentives for energy storage integration classifications assess how the integration of energy storage systems improves the resilience of photovoltaic systems during severe weather events by providing backup power and reducing reliance on the grid. Additionally, these categories analyze how financial incentives may encourage the integration of energy storage technologies to enhance system stability and performance. The resilience standards for extreme weather classification assess the contribution of energy storage systems to enhancing the resilience of photovoltaic (PV) systems during severe weather events, while the incentives for energy storage integration highlight how financial incentives can facilitate the adoption of these technologies to enhance system reliability and performance. The categorization of emergency response and recovery rules analyzes the execution of guidelines to enable a swift response and efficient recovery during severe weather events, hence improving system resilience. Moreover, examining the viability of public-private partnerships for funding and implementing energy storage devices could substantially enhance system resilience during disasters. The categorization of building codes and zoning rules for photovoltaic integration analyzes the enhancement of these codes and regulations to promote the installation of solar photovoltaic systems into existing structures, hence improving sustainability and energy efficiency. The categorization of long-term energy planning and climate adaptation strategies investigates how these methods might aid communities in preparing for and mitigating the impacts of climate change on their energy infrastructures. By incorporating renewable energy sources and energy efficiency measures into these policies, communities can reduce their carbon footprint and improve their resilience to forthcoming

Table 3
Innovative Technologies for Robust Mounting Systems for solar PV systems.

Classification	Key Features and Technologies	Examples and Use Cases	Source
Wind-Resistant Mounting Systems	Aerodynamic designs, wind-tunnel-tested brackets, and pre-stressed steel cable systems to reduce wind load on modules.	**DAS Solar:** Flexible cable-net structures with advanced wind resistance, proven effective in Typhoon-prone areas.	PV Tech (https://www.pv-tech.org/)
Snow-Resilient Mounting Systems	High-tilt frames, frameless modules, snow-phobic coatings, and vertical orientations for snow shedding and load reduction.	**IEA PVPS Recommendations:** Frameless systems with high tilt angles mitigate snow accumulation and shading impacts in snowy regions like Northern Europe and Japan.	IEA-PVPS (https://iea-pvps.org/)
Seismic-Resilient Mounting Systems	Flexible joints, high damping racking systems, and earthquake-resilient trackers.	**NEXTracker:** Incorporates advanced pivot designs and seismic isolation features to endure high-magnitude earthquakes in seismic-prone regions like California.	Trina Solar (https://www.trinasolar.com/us)
Corrosion-Resistant Systems for Coastal Areas	Use of anti-corrosion coatings (e.g., galvanized steel) and materials resistant to saline environments.	**Trina Solar's FixOrigin:** Components with anti-corrosion coatings provide long-term reliability in high-salinity coastal regions.	Trina Solar (https://www.trinasolar.com/us)
Flexible and Modular Systems	Modular systems for varied terrains, slope adaptability (up to 30°), and minimized earthworks.	**FixOrigin by Trina Solar:** Highly adaptable fixed-tilt systems reduce installation complexity on uneven terrains with pre-engineered flexibility.	Trina Solar (https://www.trinasolar.com/us)
Mounting Systems with Anti-Theft Features	Integrated locking mechanisms and monitoring solutions using IoT.	**IoT-Enabled Systems:** Real-time alerts for unauthorized access and theft prevention in remote installations.	Industry reports (https://iea-pvps.org/)
Smart Mounting Systems with IoT Integration	Real-time monitoring, predictive maintenance, and automated adjustments based on environmental data.	**Smart PV Solutions:** IoT-integrated mounting frameworks paired with advanced sensors optimize system resilience and energy efficiency.	Trina Solar (https://www.trinasolar.com/us)

climate-related challenges.

4.2. *Impacts of extreme weather events on solar PV systems*

The effects of extreme weather events on solar PV systems are categorized into four primary types: hurricanes and high winds, flooding and heavy rainfall, heatwaves and temperature extremes, and snow and ice build-up. The subsequent sections will examine each of these classes in detail, providing a comprehensive understanding of how each type of extreme weather event may affect solar PV installations. Understanding the distinct risks associated with each category of extreme weather event is essential for developing suitable mitigation strategies for solar PV systems. Stakeholders can gain a clearer comprehension of the risks linked to each category.

4.2.1. *Impacts of hurricanes and high winds on solar PV systems*

Considering the impact of hurricanes and strong winds on solar PV system classification, it is essential to meticulously and analytically evaluate the proposed eight sub-classes depicted in Fig. 12 to comprehensively assess potential vulnerabilities and hazards. By meticulously examining each sub-class, stakeholders can formulate targeted measures to safeguard solar PV installations from damage and ensure their enduring viability throughout harsh weather events.

4.2.1.1. *Structural damage to solar panels and mounting systems: case study of hurricane maria in puerto rico in September 2017*

4.2.1.1.1. Causes of structural damages. This section examines the structural damage to solar modules and installed solar energy systems caused by the extreme weather conditions of Hurricane Maria in Puerto Rico in September 2017. The severe extent of the structural damage can be attributed to category 4 hurricanes with sustained winds of 155 mph (Aros-Vera et al., 2021). This resulted in extensive damage to the island's infrastructure, including solar photovoltaic module systems. Climate-induced extreme events, primarily influenced by hurricanes, intense winds, rainfall, and debris, exposed significant weaknesses in solar PV panels and their mounting systems. The damage serves as a significant case study illustrating the adverse effects of climate-induced extreme circumstances on solar technology, underscoring the necessity for more resilient infrastructures and designs. This section thoroughly delineated the structural damages inflicted on solar panels and mounting systems during Hurricane Maria, analyzing the principal causes, failure processes, and insights gained for enhancing future infrastructure and designs.

(i) **Extreme wind forces**

The damage to solar PV systems and mounting structures in Puerto Rico during Hurricane Maria in 2017 was primarily attributed to the severe wind velocities (Kwasinski, 2018). The intense wind pressures exerted on the solar modules and their mounting frames produced pressure and uplift, potentially stressing the mounting systems beyond their structural design limits. This led to extensive damage and malfunction of solar PV systems around the island, underscoring the necessity of adequate design and installation to endure severe weather conditions. In the town of Humacao, multiple solar PV rooftop modules were discovered displaced following the catastrophic storm, with modules detached from their mounting structures due to insufficient anchoring and the intense force of the high winds. The severity was significantly greater in inadequately secured solar PV module systems, which suffered a complete detachment of modules from the fixed rooftop, resulting in substantial losses for the end-users. Wind across solar PV modules can create negative pressure beneath them, resulting in uplift pressures that may dislodge the modules from their mounting systems. Although several modules are rated to endure wind storms up to 140 mph, which is enough for typical storm circumstances (Gargani, 2022), the wind forces of Hurricane Maria surpassed these limits in several instances. This may be ascribed to the distinctive interplay of wind velocity, orientation, and duration during the hurricane, resulting in unparalleled destruction to solar PV systems. Inadequate installation methods or insufficient maintenance may have also played a role in the dislodgment of modules from their mounting structures during the severe weather event. Nonetheless, regardless of the robustness of solar PV mounting systems, over 150 mph may provide a catastrophic threat to the affixed solar panels. Solar PV modules installed on rooftops are susceptible to wind uplift during storms, particularly when the mounting mechanisms are not engineered to endure hurricane-prone conditions, as appears to be the situation in the predominantly mounted town of Humacao.

Table 4
Innovative Technologies for Durable Materials and Coatings in Solar PV Systems.

Category	Description	Examples/Technologies	Advantages	Source
Corrosion-resistant materials	Advanced materials and coatings designed to withstand corrosive environments, especially in coastal or industrial areas.	Marine-grade aluminum, stainless steel, polymeric coatings	Reduces corrosion, enhances lifespan, and ensures long-term efficiency	https://www.pv-magazine.com/
Anti-reflective coatings (ARC)	Thin-film coatings that enhance light absorption by reducing reflection from PV module surfaces.	Nanoparticle coatings with silica and titania; sol-gel synthesis	Improves efficiency by 1–2 %, enhances durability	https://www.pv-magazine.com/
Self-cleaning hydrophobic coatings	Superhydrophobic surfaces that prevent dust, water, and pollutants from adhering to PV panels	SiO_2-based hydrophobic layers; UV-cured nanoparticle suspensions	Reduces maintenance costs, improves energy output by 3–5 %	https://www.pv-magazine.com/
UV-Resistant Encapsulation Materials	Encapsulation films designed to resist degradation due to ultraviolet (UV) radiation exposure	UV-stabilized EVA (ethylene vinyl acetate), TPU-based encapsulants	Extends module lifespan, reduces discoloration and delamination	https://www.pv-magazine.com/
Temperature-resilient backsheets	Multi-layer backsheets that maintain integrity under extreme temperature fluctuations	Fluoropolymer-based backsheets (e.g., PVDF); PET laminates	Prevents cracking and ensures electrical insulation	https://www.pv-magazine.com/
High-temperature resistant conductors	Materials engineered to conduct efficiently under high temperatures, ensuring reliability	Copper-zinc alloys; advanced interconnects (e.g., AgZn coatings)	Minimizes efficiency losses in hot climates	https://www.pv-magazine.com/
Scratch-resistant and anti-soiling glass	Specially treated glass to resist physical wear and soiling, maintaining optical clarity	Chemical vapor deposition (CVD) coatings with silica-titania combinations	Maintains energy output; reduces cleaning frequency and cost	https://www.pv-magazine.com/
PERC Technology (Boron-doped)	Advanced solar cell technology with a passivated emitter rear contact for enhanced efficiency	Boron-doped PERC cells used in commercial and utility-scale applications	Increases module efficiency by ~1 %	Industry whitepapers (https://www.pv-magazine.com/)

(ii) **Frame and structure bending**

In a municipality of Yabucoa, ground-mounted solar farms experienced considerable structural deformation of racking systems, resulting in misalignment of the complete solar cell arrays (Kwasinski et al., 2019). This resulted in a decline in the module's energy production capacity and necessitated costly structural repairs prior to the resumption of power generation. This may be due to the fact that even when panels were not entirely removed, the severe wind uplift pressure from the storm resulted in significant structural deformation of many mounted solar PV systems. The metal frames supporting the modules were distorted, compromising both the efficiency and integrity of the solar PV modules' performance.

(b) Debris impact

Hurricanes and strong winds generate airborne debris that can inflict significant damage on solar photovoltaic modules and mounting systems. Throughout Hurricane Maria, several types of debris, including high-velocity roofing materials and tree branches, resulted in two distinct forms of damage: shattered glass modules and compromised mounting systems. Two categories of debris were seen in Puerto Rico and a solar farm in Guayama (Esteban et al., 2015). The metal beams supporting the solar PV modules at a solar farm in Guayama were discovered to be bent and cracked due to significant debris impact, rendering the entire solar farm system useless until comprehensive repairs were conducted. Additionally, several solar farms in Puerto Rico, including one in Salinas, reported a sizable number of solar PV modules with broken glass due to airborne debris. The protective glass of the solar PV system safeguards the internal solar cells; however, significant debris impact on the glass renders the solar cells more vulnerable to water intrusion, resulting in irreversible damage to the solar PV-mounted systems.

(c) Flooding and water damage

Besides wind uplift and panel displacement, frame and structural bending, shattered glass panels, and damage to the mounting system, Hurricane Maria resulted in extraordinary rainfall and flooding in many regions of Puerto Rico. Ground-mounted solar PV systems are typically not designed for submersion, rendering coastal regions in Puerto Rico particularly susceptible to water damage (Kwasinski, 2018). Ground-mounted solar photovoltaic farms in Loiza were completely inundated by powerful winds, resulting in flooding damaging electrical components. The downtime extended the power outage by several months, and the cost of restoring these components was substantial. A commercial rooftop installation in San Juan saw significant water infiltration due to inadequate waterproofing at the mounting locations. This inflicted significant damage to the building's structure, leading to increased repair costs and an extended restoration period. These examples illustrate the necessity of incorporating waterproofing measures in solar PV installations in coastal regions susceptible to extreme weather events.

4.2.1.1.2. Systemic vulnerabilities exposed. A potential cause of the lethal Hurricane Maria may be linked to a systemic vulnerability in Puerto Rico's solar energy infrastructure. The abnormalities manifested not only in the structural and engineering design of individual solar PV systems but also in the broader context of solar power integration into the island's energy output. Inadequate maintenance and insufficient investment in infrastructure may have exacerbated the solar energy grid's susceptibility during extreme weather events such as hurricanes. Inadequate preparation and cooperation among government agencies and energy providers may have intensified the storm's effects on Puerto Rico's electrical infrastructure. These structural challenges underscore the necessity for extensive reforms in the implementation and management of renewable energy in Puerto Rico. Confronting these difficulties will be essential for establishing a more robust and sustainable energy infrastructure for the island's future.

(a) Grid-Tied Systems without Battery Backup

The excessive dependence on the central power grid can be attributed to grid-connected systems that were devoid of battery backup before Hurricane Maria. Consequently, the overwhelming majority of solar photovoltaic systems in Puerto Rico were integrated into the grid. When the grid collapsed during the hurricane, the entire photovoltaic system became inoperable, despite the modules being undamaged. Integrating battery backup systems into grid-tied solar photovoltaic plants helps mitigate the effects of power disruptions caused by natural disasters. This method would facilitate the storage and utilization of solar energy during outages of the primary power grid.

(b) Inadequate design for extreme weather

The majority of solar installations in Puerto Rico are poorly engineered to withstand the destructive effects of hurricanes and high winds associated with category 4 or 5 storms. In numerous areas, including Ponce and Mayaguez, many photovoltaic systems were installed utilizing standard mounting technologies, such as lightweight aluminum racking systems, which failed under the hurricane's intense wind loads. As a result, Hurricane Maria in 2017 destroyed or severely damaged many solar panels, underscoring the need for more robust and

Table 5

Innovative Technologies for Enhancing Resilience on Solar PV Systems: Flood-Resistant Designs.

Technology	Description	Examples	Source
Elevated Mounting Structures	Structures that raise PV systems above typical flood levels to prevent water damage.	Solar farms in flood-prone regions of Bangladesh utilize elevated platforms.	RatedPower (https://ratedpower.com/)
Floating Solar PV Systems (Floatovoltaic)	PV panels mounted on buoyant platforms, allowing operation on water surfaces while mitigating land use conflicts and managing water level variations.	Omkareshwar Dam Floating Solar (India), Hangzhou Reservoir Floating Solar (China).	RatedPower (https://ratedpower.com/)
Waterproof Enclosures	Specialized casings for electrical components, ensuring protection from water ingress during floods or heavy rain.	Advanced junction boxes with IP68 waterproof ratings in Southeast Asia installations.	DNV (https://www.dnv.com/); PV-Tech (https://www.pv-tech.org/);
Designing Solar Farms on Elevated Platforms	Combining height with land grading to reduce direct water damage and enhance resilience to floods.	Elevated installations in the Netherlands where land reclamation and flood prevention align.	RatedPower (https://ratedpower.com/)
Dual-Use Installations with Flood Mitigation	PV systems integrated with infrastructure like levees or dams to provide both power generation and flood control.	The Saemangeum Floating Solar Project in South Korea incorporates water level regulation.	RatedPower (https://ratedpower.com/)
Drainage-Optimized PV Layouts	Designs incorporating channel systems to manage water flow around ground-mounted PV farms effectively.	Solar parks in Japan integrating rainwater harvesting and drainage systems.	DNV (https://www.dnv.com/)
Rooftop PV Systems with Flood-Resilient Features	Strengthened supports and waterproofing enhancements for rooftop systems to withstand heavy rainfall and minor flooding.	Tropical installations in the Philippines with elevated rooftop arrays.	RatedPower (https://ratedpower.com/)
Advanced Monitoring and Control Systems	IoT-enabled systems that detect and predict weather events, managing energy storage and panel positions to minimize flood risks.	Smart grid-linked PV farms in Taiwan that preemptively shut down during extreme conditions.	PV-Tech (https://www.pv-tech.org/); RatedPower (https://ratedpower.com/)

Table 6

Innovative Technologies for Enhancing Resilience on Solar PV Systems: Thermal Management Systems.

Technology	Description	Examples	Source
Heat-Reflective Coating	Specialized coatings that reduce thermal absorption and improve cooling efficiency.	CoolPV systems incorporating nano-reflective layers to manage heat.	Architectural Digest (https://www.architecturaldigest.com/)
Advanced Heat Sinks and Spreaders	Metal or composite-based structures enhancing heat dissipation to prevent overheating.	Aluminum finned heat sinks in tropical solar farms.	Architectural Digest (https://www.architecturaldigest.com/)
Thermal Insulation Materials	High-performance materials minimizing heat transfer and maintaining optimal temperatures.	Aerogel-based insulation for rooftop installations in extreme climates.	Wired (https://www.wired.com/)
Phase Change Materials (PCMs)	Materials that store thermal energy during temperature peaks, releasing it as temperatures normalize.	PCM-enhanced modules showing 12 % improved performance in India.	Wired (https://www.wired.com/)
Active Cooling Systems	Mechanically driven cooling, such as water or air-based solutions, for efficient thermal management.	Solar farms in deserts using forced air-cooling to extend system life.	Wired (https://www.wired.com/)
Ventilated Mounting Systems	Designs promoting natural airflow around solar panels to reduce operating temperatures.	European solar arrays incorporating elevated designs for ventilation.	Wired (https://www.wired.com/)
Reflective Back Sheets	Materials with enhanced reflectivity reducing backside heat absorption and improving energy efficiency.	Backsheets with high UV and heat resistance installed in the Middle East.	Wired (https://www.wired.com/)

hurricane-resistant solar installation designs in Puerto Rico. Enhanced mounting techniques and robust anchoring methods can prolong the lifespan and improve the performance of solar energy systems in bad weather conditions.

4.2.1.2. Debris impacts and shattering of panels in extreme weather events: case study of Typhoon Haiyan (Yolanda), 2013

4.2.1.2.1. Causes and mitigation of Debris Impacts and Shattering. The debris from Typhoon Haiyan can be attributed to sustained wind gusts of 195 mph and a storm surge of 20 feet in Tacloban (Hilvano et al., 2016). This led to the devastation of structures using glass windows, unreinforced doors, and lightweight construction materials that incurred substantial damage. Glass panels, especially on skyscrapers, fractured owing to impacts with debris and severe wind pressure. When shattered, debris can infiltrate structures, exacerbating the damage. In Tacloban, floodwaters and winds elevated vehicles, resulting in collisions with structures that damaged walls and external panels. The Category 5 wind speeds of Typhoon Haiyan significantly contributed to the production and velocity of debris, since they were capable of dislodging substantial objects and propelling them over enormous distances. The destruction caused by Typhoon Haiyan can be attributed to inadequate building regulations. These rules did not mandate that structures be engineered to endure the extreme wind velocities of a Category 5 typhoon, leading to extensive destruction. Consequently, numerous structures could not endure the storm's intensity, resulting in their collapse and the generation of further debris. A further cause of debris damage during Typhoon Haiyan is the high population density in areas like Tacloban City, where the storm made landfall. This implied that if one structure was compromised, debris might easily obliterate adjacent structures. This initiated a cascade of devastation. The presence of trees, vegetation, and unsecured outdoor items, including billboards and signage, contributed to the debris load during Typhoon Haiyan, exacerbating damage. This heightened the likelihood that debris would be lifted by strong winds and transported to other areas, causing further harm. Moreover, the absence of efficient waste management systems exacerbated the debris issue, leading to heightened devastation and hindering recovery initiatives in impacted regions.

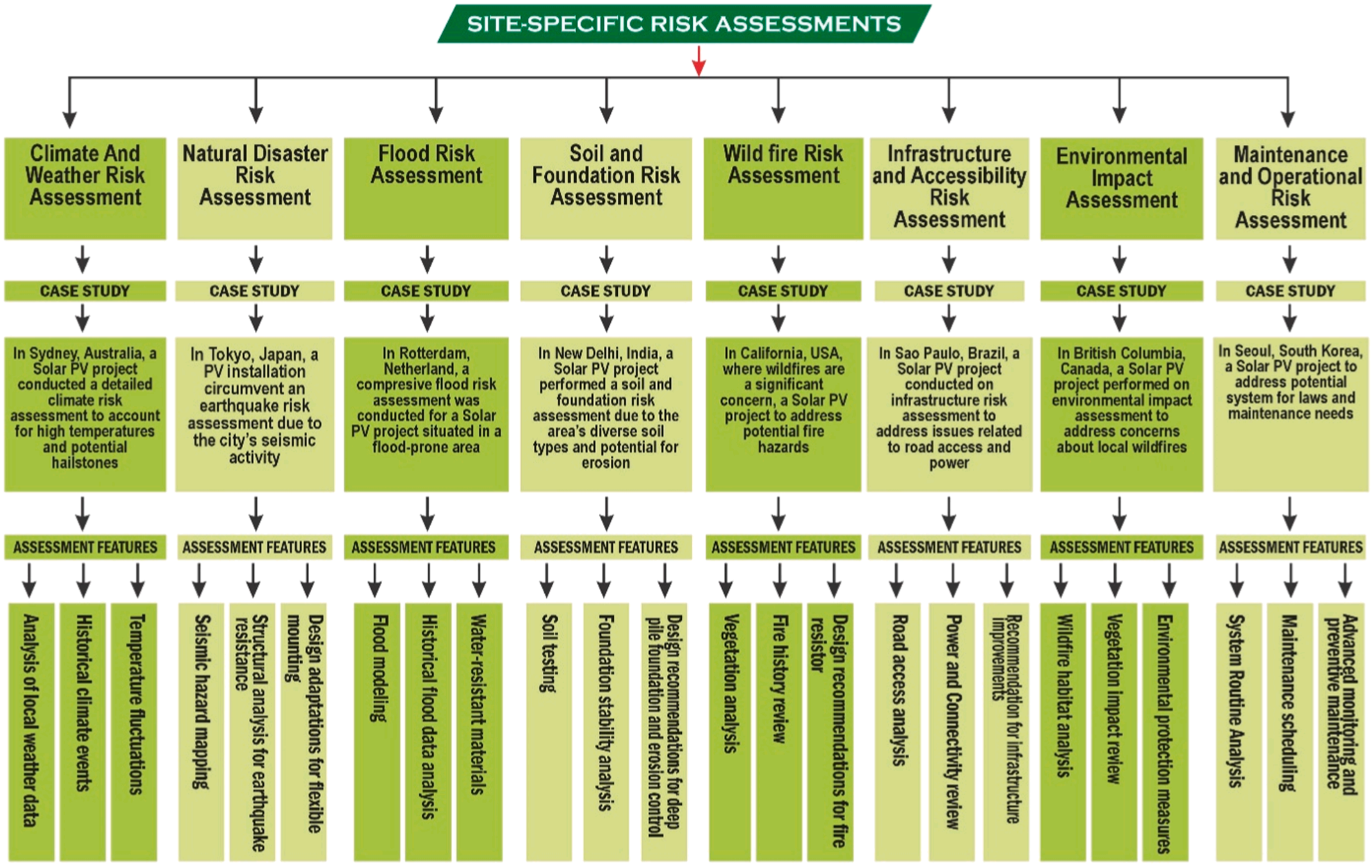

Fig. 13. Site-specific risk assessment for enhancing resilience on solar PV systems.

Utilizing hurricane straps for roof stabilization and reinforcing walls with steel enhances a structure's resistance to high winds. Effective drainage systems, together with regular maintenance of gutters and downspouts, are essential for mitigating floods and water damage during storms. Enhancing construction regulations to require impact-resistant designs, especially in typhoon-prone regions, can mitigate harm from airborne debris. These methods can markedly enhance the resistance of structures to severe weather events, hence increasing occupant safety. Adhering to these architectural regulations and standards may yield long-term financial advantages by reducing the necessity for post-storm repairs and replacements. Moreover, incorporating impact-resistant windows and doors can mitigate damage from airborne debris during a storm. Effective debris management significantly mitigates the dangers and hazards linked to extreme weather occurrences.

Typhoon Haiyan's amalgamation of natural and anthropogenic debris engendered perilous conditions for people in its path. The massive debris not only inflicted immediate destruction but also obstructed post-disaster cleanup and recovery operations. This underscored the importance of employing effective waste management strategies and disaster preparedness protocols in vulnerable areas to mitigate the impacts of future storms. Moreover, it underscored the necessity of synchronizing efforts across governmental bodies, local communities, and international organizations to address debris management in disaster-prone regions. These initiatives should encompass the establishment of efficient debris removal systems, the promotion of recycling and waste reduction, and the provision of public education on proper disposal methods. By addressing these issues proactively, communities can mitigate the enduring adverse impacts of debris collection on the environment and society while simultaneously enhancing their preparedness for and response to future catastrophes.

4.2.1.3. Inverter and electrical system failures of panels: a case study of Typhoon Jebi (2018)

4.2.1.3.1. Causes and mitigation of Inverter and Electrical System Failures of Panels. The breakdowns of Typhoon Jebi's inverter and panel electrical systems can be attributed to six primary factors. These encompass lightning strikes, electrical overloads and surges, wind load and structural damage, water intrusion and flooding, and debris impact (Esteban et al., 2015). Solar panels installed on rooftops or in exposed areas and knocked over by wind serve as an example of these factors by exposing wiring and inverters to the elements and emphasizing the effects of wind loads and structural damage. Flooding and water penetration may increase the risk of system failure by causing short circuits and electrical component corrosion. Inverters and solar panels are susceptible to damage from overloading and electrical surges, especially during extreme weather events such as Typhoon Jebi. The impact of extreme weather events on solar PV systems underscores the necessity for proper installation and maintenance to ensure the resilience of renewable energy infrastructure against climate change. Nevertheless, the subsequent mitigation methods, including enhanced structural engineering, superior waterproofing and enclosures, surge protection systems, and elevated installations, might mitigate the potential harm inflicted by extreme weather events. Routine inspections and maintenance can identify issues before they escalate, ensuring the durability and effectiveness of solar PV systems in adverse environmental circumstances. Moreover, enhanced monitoring systems can provide real-time data on the operation of renewable energy infrastructure, facilitating preventive maintenance and swift repairs. Investing in these preventative measures enables stakeholders to safeguard their assets and promote a more sustainable future.

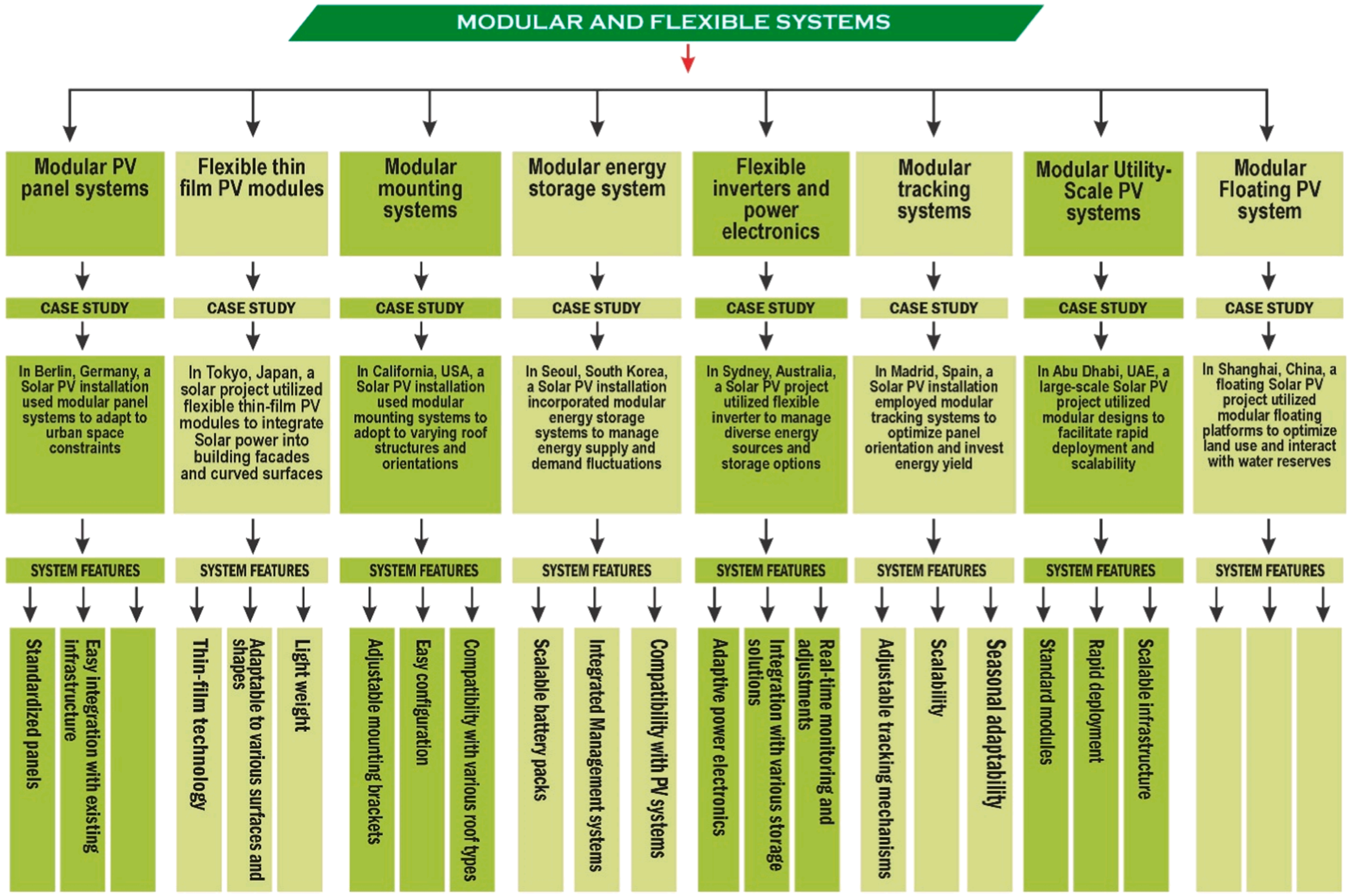

Fig. 14. Modular and flexible systems for enhancing resilience on solar PV systems.

4.2.1.4. *Damage to ground-mounted and floating solar systems due to extreme weather events: Typhoon Mangkhut Case Study (China, 2018)*

4.2.1.4.1. *Causes and mitigation of Inverter and Electrical System Failures of Panels.* Severe weather phenomena, such as Typhoon Mangkhut, can inflict considerable damage on both ground-mounted and floating solar installations, adversely affecting energy generation and safety. In 2018, China suffered significant damage from strong winds and intense rainfall, resulting in the displacement and loss of solar panel systems (Anser et al., 2021). The storm's intensity may result in panels fracturing or becoming dislodged, hence creating possible safety risks. Enhancements in panel mounting technology and installation methodologies are essential to prevent future damage. Enhanced anchoring mechanisms and routine maintenance inspections can guarantee the durability of solar systems during extreme weather events. Chinese officials restored damaged installations by fortifying structures and substituting shattered panels. By drawing lessons from previous experiences and establishing more rigorous design standards, the industry may enhance its preparedness for future extreme weather events and mitigate possible damage. Technological advancements, including wind-resistant panel designs and enhanced installation methods, have been created to improve the resilience of solar systems in regions susceptible to typhoons. By mitigating risks through enhanced technology and installation methodologies, the sector may more effectively safeguard solar installations against natural calamities.

4.2.1.5. *Disruption of grid-tied solar systems due to extreme weather: case study of Hurricane Dorian (Bahamas, 2019).* Hurricanes, like Hurricane Dorian, can severely impair grid-connected solar installations, undermining their electricity generation capacity. The hurricane's intense winds and substantial rains may cause structural damage, undermining renewable energy-producing capabilities and presenting safety hazards owing to exposed electrical components (Ali et al., 2015). To alleviate this influence, stringent design and installation methods are essential, including the use of superior materials, proper panel fastening, and the integration of elements such as tilt mechanisms to diminish wind resistance. Consistent maintenance and inspections are essential to detect potential vulnerabilities prior to their escalation into significant problems.

Stakeholders in the renewable energy sector can formulate plans to bolster the resilience of grid-tied solar systems against future extreme weather events by integrating sophisticated technology such as microgrids and energy storage solutions. Cooperation among politicians, industry specialists, and communities is crucial for the efficient implementation of these measures and for establishing a more resilient energy infrastructure capable of withstanding climate change problems. Analyzing Hurricane Dorian's case study enables stakeholders to formulate solutions that bolster the resilience of grid-tied solar systems against future extreme weather occurrences.

4.2.1.6. *Scouring and erosion around ground-mounted solar systems due to extreme weather: case study of Hurricane Patricia (Mexico, 2015).* Severe weather phenomena, such as hurricanes, can induce scouring and erosion around ground-mounted solar installations, jeopardizing their stability and efficiency. In 2015, Hurricane Patricia inflicted extensive damage in Mexico, resulting in considerable scouring and erosion at solar farms. Migration tactics encompass appropriate site selection, erosion control measures, and consistent maintenance (Sadiqa et al., 2018). Resilient design elements can mitigate the effects of scouring and erosion. A study conducted by Sadiq showed that new mounting system designs can enhance the robustness of solar farms in coastal areas

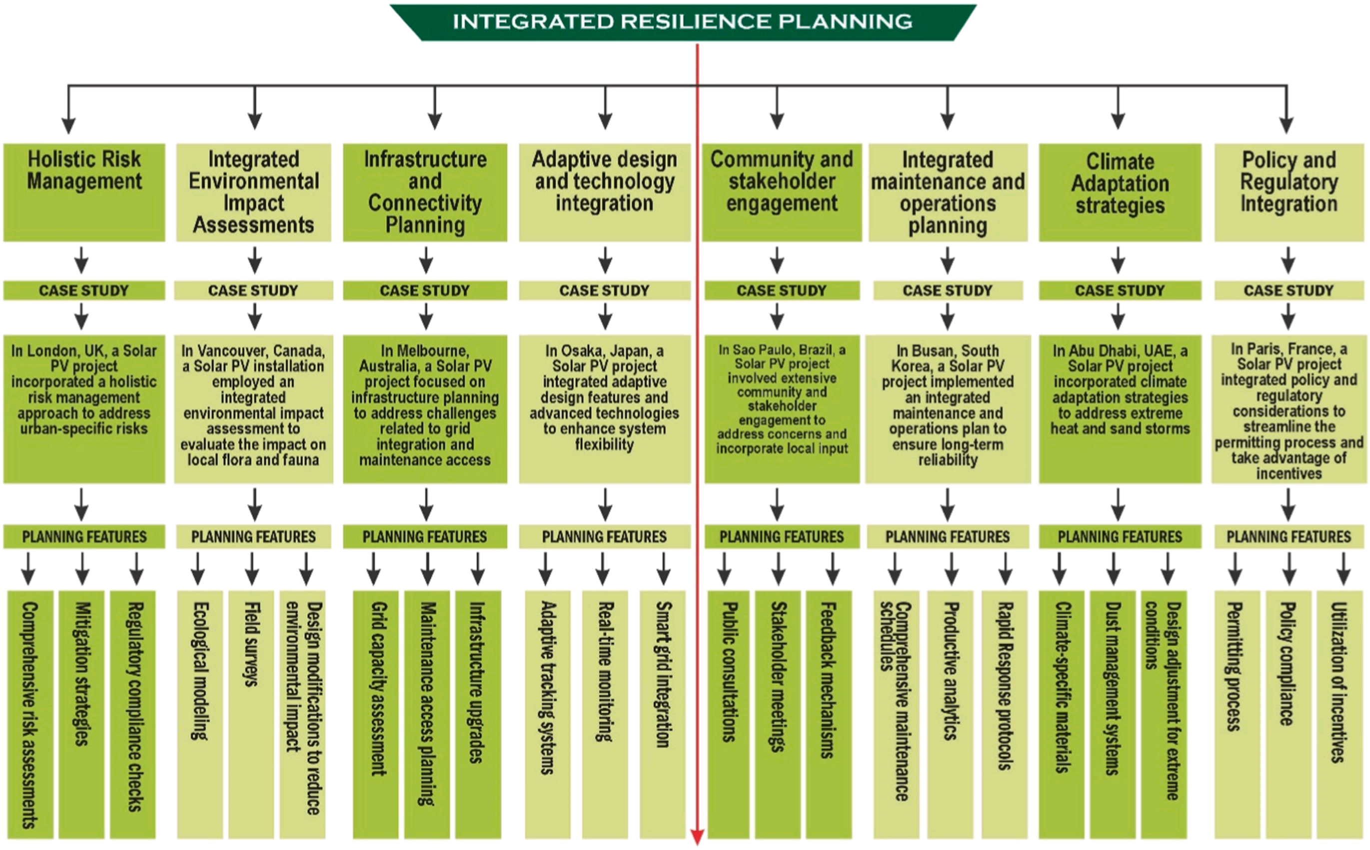

Fig. 15. Integrated resilience planning for enhancing resilience on solar PV systems.

(Sadiqa et al., 2022). Utilizing corrosion- and erosion-resistant materials and engineering structures capable of enduring high winds and substantial rains can markedly diminish the susceptibility of ground-mounted systems to scouring and erosion. Mitigating scouring and erosion around ground-mounted systems is essential for maintaining the long-term efficacy and dependability of solar energy installations in regions susceptible to severe weather conditions. Through the implementation of robust mitigation measures and resilient design elements, solar farms can more effectively endure the effects of hurricanes like Patricia, ensuring the continued provision of clean energy for the foreseeable future.

4.2.1.7. Long-term performance degradation of solar panels due to extreme weather: case study of Typhoons in Taiwan. Severe weather phenomena such as hurricanes can lead to prolonged performance decline of solar panels and their mounting methods. Such incidents may inflict physical harm, leading to diminished efficiency and reduced system longevity. Hurricane Taiwan exemplifies this phenomenon, since its intense gusts and substantial rainfall result in structural damage, leaks, corrosion, and possible electrical complications. Debris from strong winds can undermine the structural integrity of mounting systems, jeopardizing their capacity to securely retain panels. To alleviate this, appropriate installation and maintenance methods are essential. Utilizing premium materials and performing routine inspections and maintenance can enhance longevity and damage resistance. Comprehending the influence of harsh weather phenomena on solar panel performance is essential for maintaining long-term efficiency and efficacy. Owners of solar panels can lessen the likelihood that events like hurricanes will degrade performance by using mitigation strategies and investing in high-quality materials.

4.2.1.8. Insurance and financial losses to solar panels due to extreme weather: case study of Hurricanes Irma and Maria in the Caribbean. Extreme weather phenomena, including hurricanes and tropical storms, have been escalating in both frequency and intensity as a consequence of climate change. These occurrences provide a considerable risk to solar panels and mounting systems in the Caribbean, resulting in substantial damages and financial losses for solar farm proprietors (Gargani, 2022). Insurance firms have reacted to the increased danger by elevating premiums for properties in high-risk regions such as the Dominican Republic and Barbados. Following Hurricanes Irma and Maria in 2017, insurance prices for solar farms in these nations rose substantially. To alleviate these financial losses, solar farm proprietors should invest in more robust mounting systems and adopt enhanced maintenance methods to ensure their systems are more resilient to severe weather occurrences. Furthermore, governments may offer incentives for renewable energy initiatives to mitigate insurance expenses and promote investment in sustainable energy alternatives.

4.3. Innovative technologies for enhancing resilience on solar PV systems

Fig. 8 illustrates the categorization of emerging technologies aimed at augmenting the robustness of solar photovoltaic systems. The four primary classifications—robust mounting systems, durable materials and coatings, flood-resistant designs, and thermal management systems—represent significant innovative technologies being developed globally in response to the effects of extreme weather on local climates and geographic environments, aimed at improving the resilience of solar PV systems. The four groups were then subdivided into several subclasses, as seen in Fig. 8 and detailed in Section 4.1.2. The classification of robust mounting systems encompasses seven sub-classes: wind-resistant, snow-resilient, seismic-resilient, corrosion-resistant for coastal regions, flexible and modular for varied terrains, anti-theft equipped,

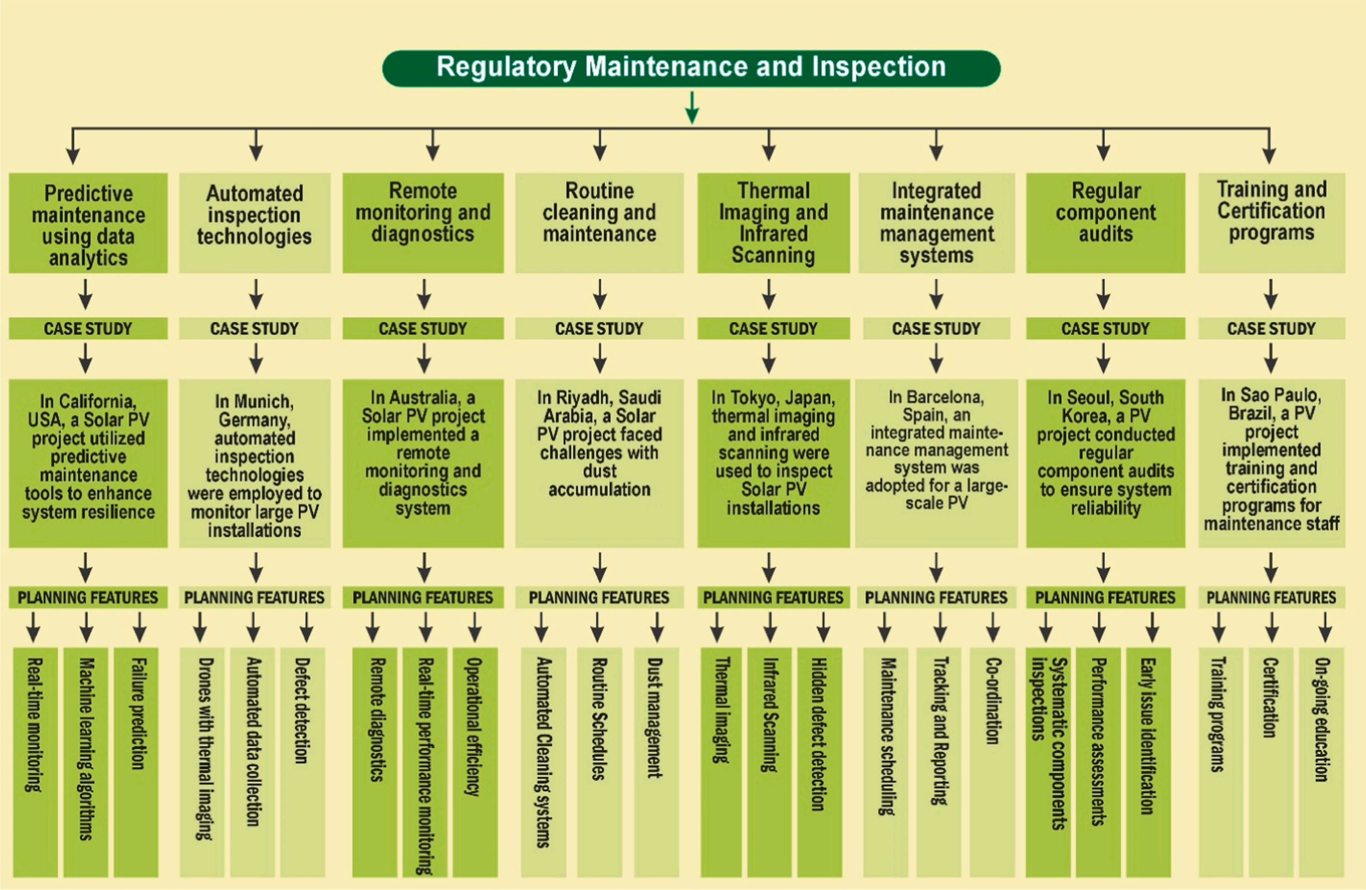

Fig. 16. Regulatory maintenance and inspection for enhancing resilience on solar PV systems.

and smart systems with IoT integration, offering a comprehensive framework for the design of solar PV systems capable of enduring diverse environmental challenges. Each subclass offers unique methods to enhance the system's durability and longevity, hence contributing to its overall resilience. The next sections provide a comprehensive examination of these subclasses. The last three categories of novel technologies for improving resilience in solar PV systems—durable materials and coatings, flooding-resistant designs, and thermal management systems—have been restructured into eight specific subcategories, as illustrated in Fig. 8 and Section 4.1.2. The next sections provide a comprehensive examination of these subclasses. These sub-classes offer an extensive examination of the various strategies that can enhance the durability of solar PV systems in different environmental conditions. Comprehending and implementing these solutions enables stakeholders to make informed judgments regarding the enhancement of their systems' performance and longevity.

Table 3 presents a detailed and novel classification of mounting systems aimed at improving the durability of solar PV systems in adverse weather, providing insights into sophisticated engineering solutions and their applications.

- **Wind-Resistant Mounting Systems:** These systems employ advanced aerodynamic designs, featuring wind-tunnel-validated components and adaptable cable-net structures. DAS Solar's revolutionary technologies efficiently reduce wind loads, even in harsh conditions such as typhoons, guaranteeing steady performance and durability (https://www.pv-tech.org/).
- **Snow-Resilient Mounting Systems:** These configurations feature elevated tilt angles, frameless designs, and snow-repellent coatings to inhibit snow accumulation and minimize shadowing effects. IEA PVPS recommendations underscore their essential function in reducing energy losses in snow-prone areas such as northern Europe (https://iea-pvps.org/).
- **Seismic-Resilient Mounting Systems:** Flexible joints and high-damping constructions allow these systems to withstand seismic shocks. Companies such as NEXTracker utilize pivot-based designs and seismic isolation technology, rendering them appropriate for earthquake-prone regions (https://iea-pvps.org/).
- **Corrosion-Resistant Systems for Coastal Areas:** Anti-corrosion coatings and resilient materials, such as galvanized steel, safeguard these systems from the saltwater conditions prevalent in coastal regions. Trina Solar's FixOrigin system represents this category with its enduring durability in demanding environments (https://www.trinasolar.com/us).
- **Flexible and Modular Mounting Systems:** These systems accommodate various terrains through modular designs that simplify installation. Solutions such as FixOrigin exhibit slope adaptation, reducing labor and earthwork demands while preserving structural integrity (https://www.trinasolar.com/us)
- **Mounting systems equipped with anti-theft features utilize IoT technologies for real-time monitoring and theft deterrence.** Advanced frameworks employ intelligent locks and notifications, especially beneficial for remote or extensive installations (https://iea-pvps.org/).
- **Intelligent Mounting Systems with IoT Integration:** Utilizing IoT-enabled sensors, these systems deliver real-time data to optimize energy output, forecast maintenance requirements, and improve resilience to environmental hazards. These intelligent systems guarantee operating efficiency and durability, representing the

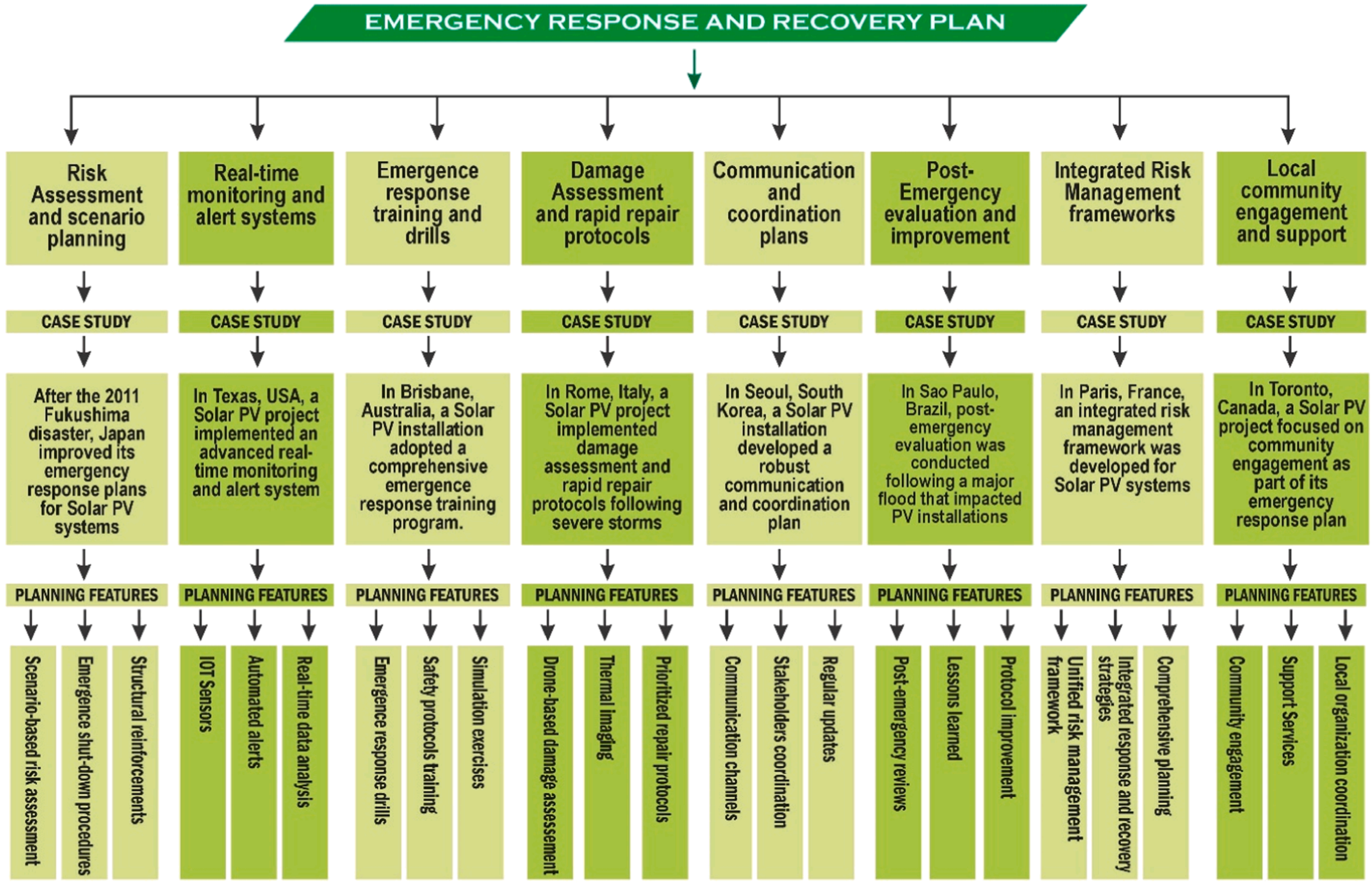

Fig. 17. Emergency response and recovery plan for enhancing resilience on solar PV systems.

future of solar photovoltaic resilience (https://iea-pvps.org/; https://www.trinasolar.com/us).

The technologies outlined not only enhance resilience but also underscore connections with sustainability and intelligent infrastructure. Their incorporation of IoT integration, modular flexibility, and weather-specific enhancements establishes them as essential elements in the progression of renewable energy. Industry analyses and case studies, like those from DAS Solar, Trina Solar, and IEA-PVPS, offer a solid basis for comprehending the practical efficacy of these systems (https://www.pv-tech.org/; https://iea-pvps.org/; https://www.trinasolar.com/us).

These solutions are essential for alleviating the economic and performance effects of harsh weather, hence maintaining sustainable energy production across diverse climates. Their academic significance encompasses areas including climate resilience engineering, renewable energy technologies, and smart grid integration.

4.3.1. *Durable materials and coatings*

Table 4 presents innovative technologies for durable materials and coatings in solar PV systems delineates cutting-edge innovations that tackle difficulties related to extreme weather, environmental degradation, and operational inefficiencies. These solutions are essential for guaranteeing the longevity, dependability, and energy output of solar PV systems across various situations. The following is a comprehensive academic analysis of the table:

- Materials Resistant to Corrosion: Corrosion resistance is essential for solar photovoltaic systems situated in coastal, industrial, or high-humidity environments. The utilization of marine-grade aluminum, stainless steel, and polymeric coatings guarantees durability by inhibiting structural deterioration. Advancements in coating technologies, including chemical vapor deposition (CVD), have enhanced resistance to salt and industrial contaminants (https://www.pv-magazine.com/).
- Anti-Reflective Coatings (ARC): Thin-film anti-reflective coatings diminish light reflection, hence improving the energy absorption efficiency of solar modules. Recent advancements in silica-titania nanoparticle coatings enhance light transmission and durability. Research indicates a steady efficiency improvement of 1–2 %, rendering ARC an essential attribute for high-performance solar modules (https://www.pv-magazine.com/).
- Autonomous Hydrophobic Coatings: Dust, moisture, and contaminants diminish the performance of photovoltaic modules, especially in arid and high-dust areas. Superhydrophobic coatings utilize nanotechnology to produce self-cleaning surfaces, decreasing cleaning expenses and water consumption by 50–70 %. This technology has exhibited enhancements in energy output ranging from 3 % to 5 %, as evidenced by field applications in India and other arid regions (https://www.pv-magazine.com/)
- UV-Resistant Encapsulation Substances: Extended UV exposure can deteriorate encapsulants, resulting in discolouration and delamination. UV-stabilized EVA (ethylene vinyl acetate) and TPU (thermoplastic polyurethane) encapsulants mitigate these effects, substantially prolonging module longevity. These materials guarantee system integrity in areas with elevated solar irradiance (https://www.pv-magazine.com/)
- Temperature-Resilient Backsheets: Solar photovoltaic modules undergo thermal cycling as a result of temperature variations. Multi-layer backsheets composed of fluoropolymers (e.g., PVDF) retain flexibility and insulating characteristics, inhibiting cracking and safeguarding electrical performance. These solutions are particularly

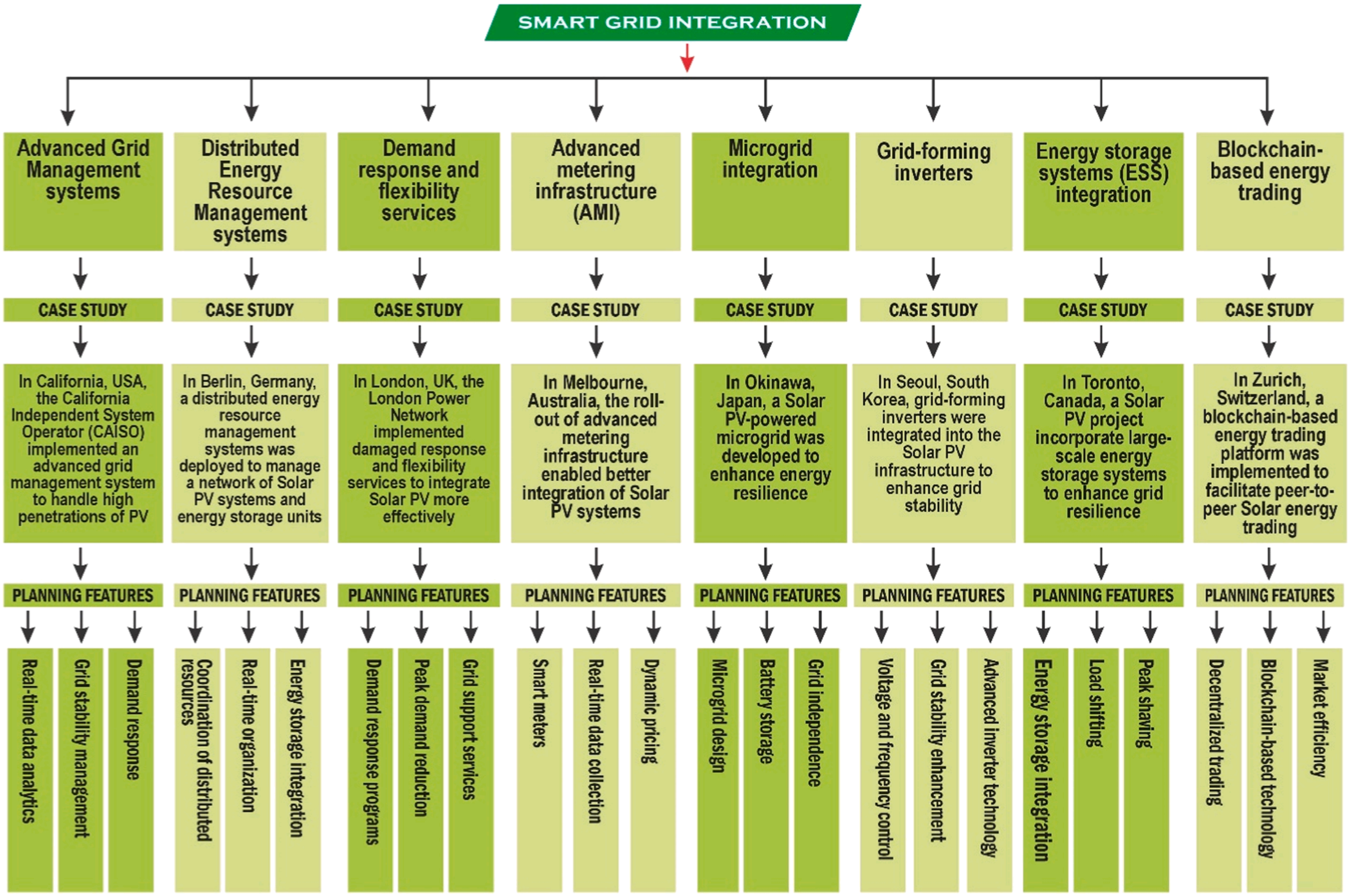

Fig. 18. Smart grid integration for enhancing resilience on solar PV systems.

essential in environments characterized by significant temperature fluctuations (https://www.pv-magazine.com/).

- High-Temperature Resistant Conductors: Excessive heat can diminish conductivity, resulting in energy losses. Copper-zinc alloys and sophisticated connection materials have shown to be dependable options, sustaining efficiency in elevated temperatures. Their function in alleviating thermal degradation is crucial for photovoltaic systems in tropical areas (https://www.pv-magazine.com/).
- Scratch-Resistant and Anti-Soiling Glass: Photovoltaic module glass frequently encounters abrasion and contamination, especially in arid regions. CVD-applied coatings that include silica and titania provide scratch resistance and reduce soiling effects, preserving optical clarity. These coatings diminish maintenance expenses and prolong module longevity by reducing wear and tear (https://www.pv-magazine.com/).
- PERC Technology (Boron-Doped): PERC (Passivated Emitter and Rear Contact) technology boosts light absorption and minimizes recombination losses, hence increasing module efficiency by around 1 %. Boron doping enhances resistance to light-induced degradation (LID) and potential-induced degradation (PID), hence ensuring reliable performance in extensive applications (https://www.pv-magazine.com/).

These technologies represent the integration of materials science, nanotechnology, and engineering to tackle the operational issues of solar photovoltaic systems in extreme weather circumstances. The industry is establishing new standards for durability and efficiency through the integration of superior coatings, durable materials, and innovative solar cell technologies. Case studies, including field trials in India and findings from prominent research institutions, substantiate the practical efficacy of these innovations (https://www.pv-magazine.com/). This synthesis highlights the pivotal significance of durable materials and coatings in promoting the global deployment of robust and efficient solar energy systems.

4.3.2. *Flood-resistant designs*

Table 5 presents advanced flood-resilience techniques for solar PV systems, featuring technological advances that incorporate elevation, hydrodynamic modifications, and intelligent controls. Floating solar has become prominent because of its effective land utilization and the natural cooling effects of water bodies, which can enhance system efficiency. Elevated constructions are crucial for flood-prone areas, while waterproof enclosures protect delicate electrical components. Dual-use designs incorporating levees and dams exemplify a novel integration of infrastructure and energy production, hence augmenting resilience to severe weather conditions.

4.3.3. *Thermal management systems*

Table 6 presents unique solutions for the thermal management of solar photovoltaic systems. Thermal control is essential for sustaining energy efficiency and prolonging panel lifespan, especially in areas with elevated sun irradiation. Technologies such as phase change materials and reflecting backsheets enhance passive cooling tactics, whereas active systems offer precise solutions for severe situations. These advances augment energy production while diminishing operational strain (https://www.wired.com/; https://www.architecturaldigest.com/).

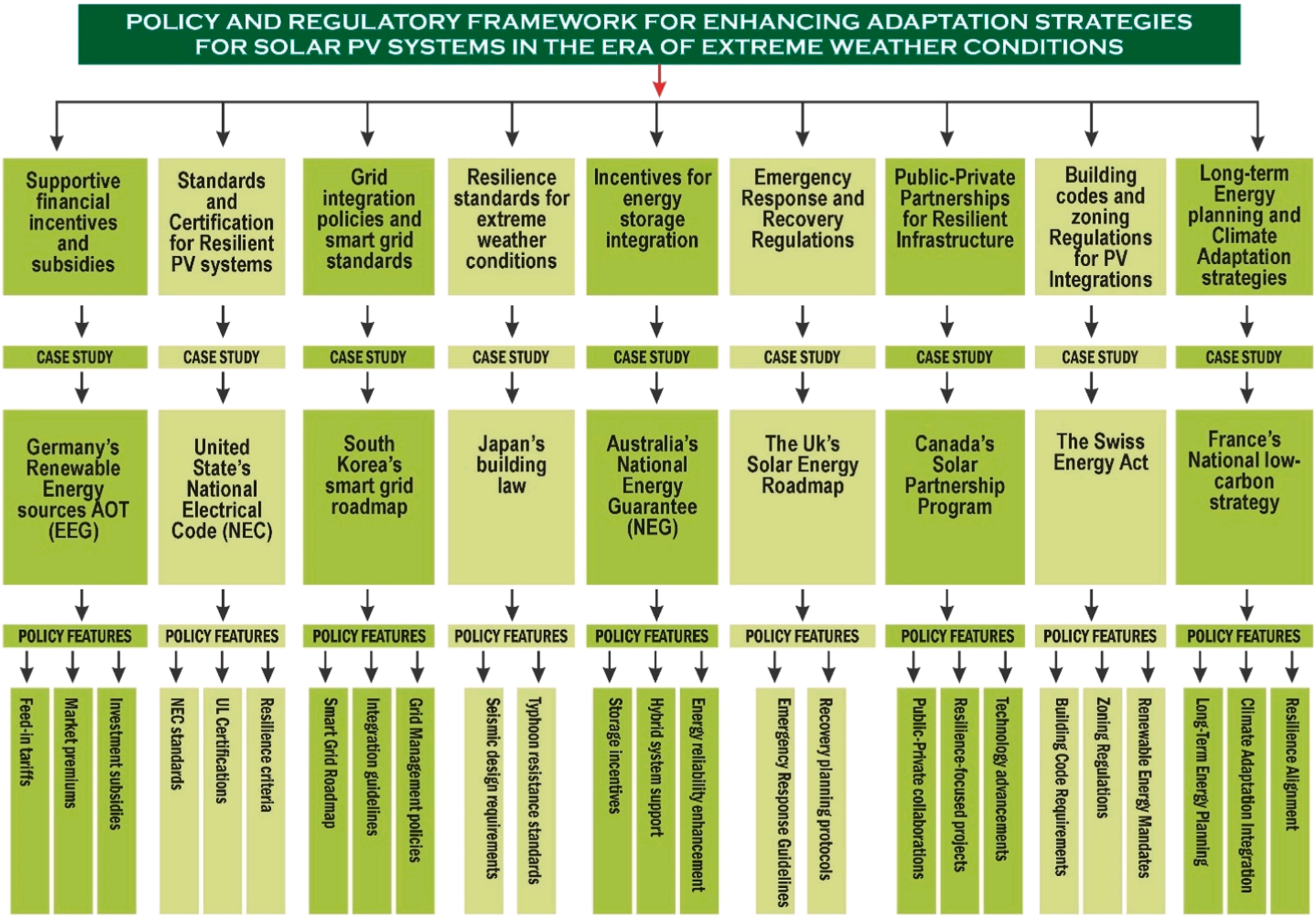

Fig. 19. Policy and regulatory framework for enhancing adaptation strategies on solar PV systems in the era of extreme weather conditions.

4.4. *Design and engineering considerations for enhancing resilience on solar PV systems*

The classifications section delineates design and engineering concepts for enhancing resilience in solar PV systems into three categories: site-specific risk assessment, modular and flexible systems, and integrated resilience planning. The three primary classes were subsequently categorized into eight subclasses, as seen in Figs. 13–15. Modular and adaptable systems comprise easily changeable or upgradeable components such as inverters, batteries, and mounting structures. Integrated resilience planning incorporates factors such as system redundancy, alternative power sources, and emergency response protocols to guarantee continuous operation during disruptions. The site-specific risk assessment classification examines the impact of diverse threats on individual system components. Integrating the three methodologies may enhance the resilience and recovery of solar energy systems from potential disruptions.

The site-specific risk assessment examined several case study and evaluation components, as depicted in Fig. 13. The eight sub-classes encompass climate and weather risk assessment as well as maintenance and operational risk assessment, featuring case studies from Sydney, Australia, to Seoul, South Korea, along with assessment characteristics unique to each sub-class, as illustrated in Fig. 13. Fig. 13 illustrates how diverse manifestations of catastrophic weather events yield methodologies that contribute to distinct risk assessment attributes employed by various nations. These case studies offer valuable insights into regional methodologies for risk assessment concerning extreme weather occurrences. By analyzing the distinct attributes of each subclass, researchers can enhance their comprehension of the many strategies employed globally to mitigate climate-related hazards.

For instance, in addressing the natural earthquake risk in Tokyo, Japan, due to extreme weather events, risk assessment components encompass the design of adaptive, flexible mounting structures, structural analysis for seismic resilience, and seismic hazard mapping. Regions susceptible to wildfires, such as California in the United States, prioritize solar PV installations to alleviate potential fire hazards. These installations can mitigate the risk of fire propagation by providing an alternative energy supply that is independent of conventional power lines, which may serve as ignition sources during wildfires. Additionally, employing fire-resistant materials and landscaping techniques can enhance the resilience of buildings in areas susceptible to wildfires. California prioritizes the enforcement of stringent building codes and regulations to mitigate the risk of fire encroaching upon residential zones. Moreover, emergency response planning and community education are essential elements of wildfire readiness and response.

Consequently, utilizing California as a case study, the components of risk assessment encompass fire-resistant design recommendations, an examination of fire history, and a vegetation evaluation. Figs. 13–15 offers a comprehensive overview for energy researchers, stakeholders, and the scientific community, highlighting the essential site-specific risk assessment, modular and adaptable systems, and integrated resilience planning strategies to improve the resilience of solar PV systems across diverse climates, geographic regions, environments, ethnicities, and populations globally. The case study highlights the necessity of considering local regulations and construction standards when performing risk assessments for solar PV installations. By evaluating these factors,

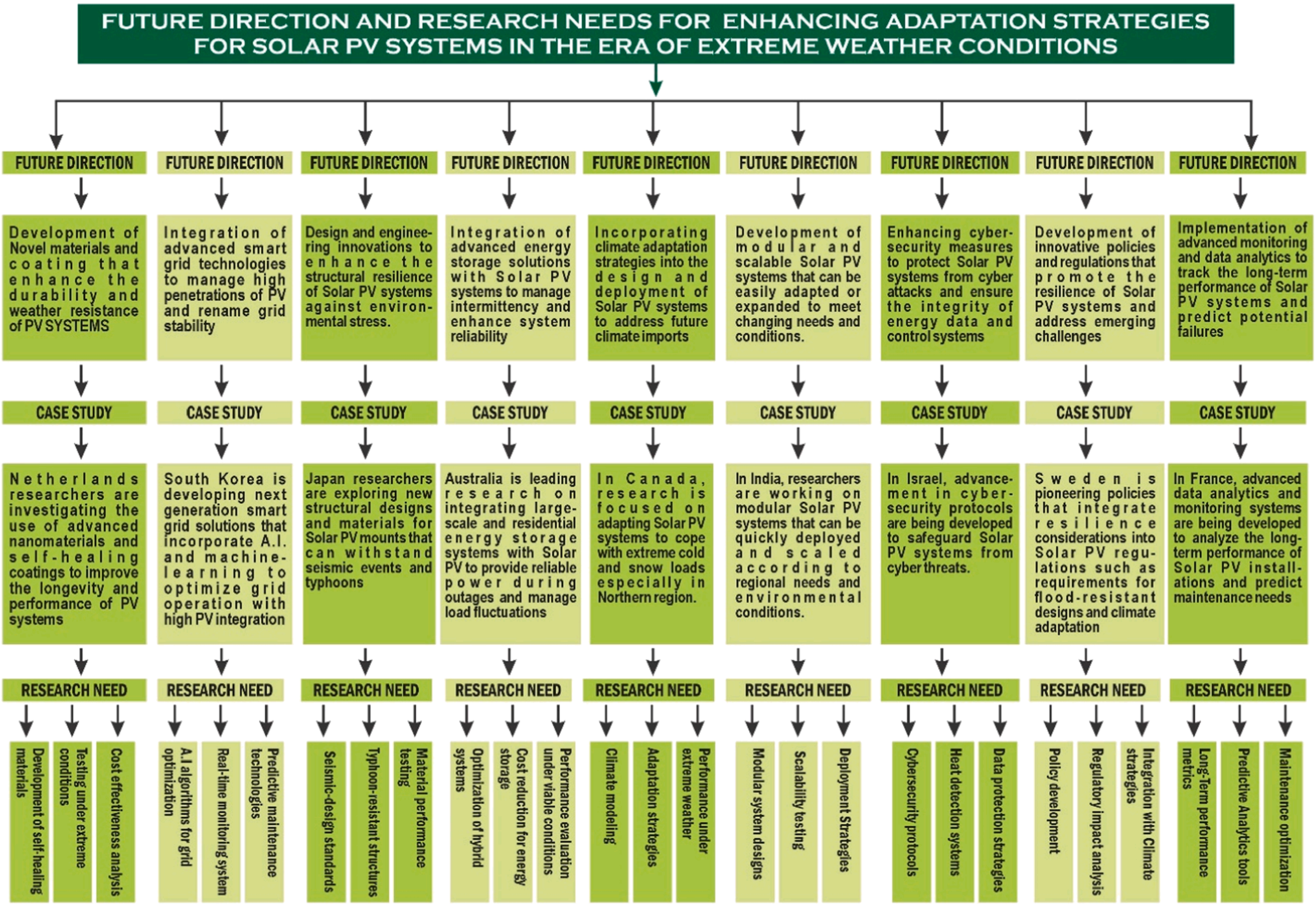

Fig. 20. Future direction and research need for enhancing adaptation strategies on solar PV systems in the era of extreme weather conditions.

stakeholders can more effectively detect and mitigate the risks associated with solar energy installations. Moreover, understanding the social and economic ramifications of solar PV system failures might enhance risk assessment approaches. Incorporating these varied elements in planning and design enables stakeholders to more effectively anticipate and mitigate potential risks associated with solar energy systems.

4.5. Operational strategies for resilience for enhancing on solar PV systems

This study identified three subclasses of operational strategies for enhancing resilience in solar photovoltaic systems: routine maintenance and inspection, an emergency response and recovery plan, and smart grid integration. The three main groupings were further categorized into eight subclasses based on specific case studies, planning components, and occurrences of harsh weather events, utilizing various ethnicities to enhance resilience in photovoltaic systems, as depicted in Figs. 16–18. Regular maintenance and inspection classifications transcend nationalities and their respective practices, which are primarily influenced by technological advancement, population density, economic conditions, and, significantly, the severity of extreme weather events. These characteristics are crucial in determining the preparedness level and response strategies necessary for the maintenance of PV systems in diverse locations. Comprehending these discrepancies enables stakeholders to adjust their maintenance and inspection strategies to effectively mitigate the risks associated with severe weather occurrences.

In Munich, Germany, automated inspection technologies, including drones equipped with thermal imaging, automated data collection, and flaw detection, were employed to oversee large photovoltaic systems, as illustrated in Fig. 16. Fig. 17 illustrates post-disaster assessments conducted after a significant flood that adversely affected photovoltaic installations in Sao Paulo, Brazil, as part of the emergency response and recovery initiatives. Consequently, operational planning elements, including post-emergency assessments, lessons learned, and procedure enhancements, were essential and executed in São Paulo, Brazil, to bolster the resilience of solar PV systems against extreme weather events.

Fig. 18 illustrates the operational blockchain-based energy trading platform developed to facilitate peer-to-peer solar energy trading in Zurich, Switzerland, within the smart grid integration framework. Consequently, operational planning elements such as decentralized trading, blockchain technology, and market efficiency were executed. This illustrates that the platform adeptly employed modern technologies to enable direct trading between energy suppliers and consumers, culminating in a more efficient and sustainable energy distribution system. Moreover, the implementation of blockchain technology guarantees transaction transparency and security, hence fostering trust among participants in the energy trading sector. This indicates that the platform enhances efficiency while also addressing concerns related to data security and trust in the energy market. The application of blockchain technology in energy trading signifies a promising future for decentralized and sustainable energy systems.

4.6. Policy and regulatory framework for enhancing resilience on solar PV systems

Diverse financial incentives and subsidies, standards and certifications for resilient photovoltaic (PV) systems, grid integration policies, and smart grid standards, resilience standards for extreme weather, incentives for energy storage integration, emergency response and recovery regulations, public-private partnerships for resilient infrastructure, building codes and zoning regulations for PV integration, as well as long-term energy planning and climate adaptation strategies, are utilized by various nations, regions, and organizations within this policy and regulatory framework to enhance adaptation strategies for solar PV systems under extreme weather conditions (see Fig. 19). These solutions assure the continued functionality of solar PV systems during extreme weather events, leading to a more robust and sustainable energy infrastructure. Countries implementing these policies and regulations can more effectively prepare for the impacts of climate change while also securing the long-term sustainability of solar energy as an essential element of their energy portfolio.

The policy component illustrated in Fig. 19 is influenced by the national energy policy, the nature of recurrent extreme weather occurrences, and the interests of many organizations across numerous nations. All eight proposed policy and regulation frameworks depicted in Fig. 19 are enacted by various governments and organizations, each exhibiting distinct policy characteristics and classifications. These policies aim to tackle specific regional concerns and priorities, considering the unique needs and conditions of each country. By considering these factors, policymakers can formulate effective strategies to alleviate the impacts of extreme weather events and advance sustainable energy initiatives. Germany's Renewable Energy Source Act (EEG) employs policy mechanisms such as feed-in tariffs, market premiums for financial incentives and subsidies, and investment subsidy classifications; conversely, the United States' national electrical code (NEC) incorporates resilience criteria, UL certifications, and NEC standards for resilient photovoltaic system classifications. South Korea's smart grid initiative utilized grid integration rules and smart grid standards, as illustrated in Fig. 19.

Fig. 19 illustrates the remaining case studies concerning the legislative and regulatory framework aimed at improving adaptation methods for the classification of solar PV systems across diverse industries. The case studies encompass France's national low-carbon strategy, Japan's construction law, Australia's national energy guarantee (NEG), the UK's solar energy roadmap, Canada's solar partnership program, and the Swiss Energy Act. The multiple case studies depicted in Fig. 19 are significantly dependent on each country's specific demands and preferences to formulate appropriate legal and regulatory frameworks that enhance solar photovoltaic system adaptation strategies. These case studies emphasize the significance of including local factors and context when executing such tactics to guarantee favorable outcomes.

Consequently, these strategies may be embraced by solar energy researchers, professionals, stakeholders, and the scientific community across diverse nations or regions to enhance solar PV system adaptation methods under severe weather situations. Collaboration among many stakeholders is essential for the effective implementation of these policies, as it facilitates the interchange of knowledge and resources to tackle shared challenges. The worldwide solar energy community may collaboratively develop innovative ways to enhance the resilience of solar PV systems against evolving climatic patterns.

5. Future directions and research needs

As solar PV systems become increasingly essential to global energy strategies, sustainable development, and net-zero objectives, enhancing their resilience to weather events is imperative across nations, regions, and organizations, as demonstrated in Fig. 20. The future directions encompass advanced materials and durability, improved grid integration and SMT grid technologies, resilient design and structural innovations, energy storage integration and management, climate adaptation and resilience solutions, cybersecurity for solar PV systems, policy and regulatory innovations, and long-term performance monitoring and data analytics classification (Fig. 20), which have informed various research requirements. These future directions are essential for the ongoing advancement and evolution of solar PV systems to tackle challenges such as climate change and energy security. By focusing on these domains, organizations can guarantee that solar energy continues to be a reliable and sustainable power source for the foreseeable future. The specified future goals and their corresponding research requirements predominantly encompass current research issues. As technology advances and new challenges arise, researchers must continually revise and adapt their future trajectories to maintain a competitive edge. By remaining informed and proactive in addressing emerging challenges, the solar PV industry can thrive and contribute to a more sustainable energy future. Through collaboration with experts across several fields and ongoing investment in research and development, the solar energy sector can sustain innovation and enhance efficiency. Moreover, the implementation of robust regulatory frameworks and standards will enhance the safety and dependability of solar energy systems as they become increasingly prevalent.

6. Conclusion

The rising risk of catastrophic weather phenomena underscores the necessity for climate-resilient solar photovoltaic systems. This paper employs case studies and impact evaluations to illustrate the deficiencies of current photovoltaic technology and the pressing necessity for adaptive strategies. Through the adoption of technological advancements, robust design principles, and extensive regulation frameworks, the solar energy sector can mitigate the risks associated with storms, flooding, heatwaves, and snowfall.

Future research should emphasize the advancement of superior materials, predictive instruments, and global standards to ensure the enduring sustainability of solar PV systems in an evolving environment. Transitioning to a renewable energy future necessitates the development of climate-resilient solar PV infrastructure to ensure the reliability and sustainability of solar electricity amid the rising frequency and intensity of extreme weather events.

CRediT authorship contribution statement

Stephen E. Ekwok: Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Peter Andráš:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Anthony E. Akpan:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Anthony Umunnakwe Obiwulu:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Usang Nkanu Onnoghen:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Saad S. Alarifi:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Ahmed M. Eldosouky:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Paul C. Okonkwo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Samuel Chukwujindu Nwokolo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project

administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sunday O. Udo:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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Data availability

https://www.scopus.com/

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