

Climate Vulnerability in Solar Microgeneration: Analysis of the Impacts of Urban Flooding on Photovoltaic Systems

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The increased frequency of extreme weather events, especially floods, has exposed the vulnerability of photovoltaic microgeneration systems in urban areas. This theoretical, descriptive study analyzed the physical and operational impacts associated with flooding, focusing on three recurring categories in the literature: inverter damage, photovoltaic module failure, and electric shock risk. In addition to financial losses, structural damage was identified, which impacts the safety and resilience of these systems. The results highlighted the importance of preventive measures, such as elevating sensitive components, adopting moisture-resistant materials, and adopting safe shutdown protocols. The conclusion is that, although solar microgeneration is strategic for the energy transition, it directly depends on the adoption of adaptive solutions to mitigate vulnerabilities during extreme hydrometeorological episodes.

Keywords: Photovoltaic Microgeneration. Urban Flooding. Climate Vulnerability. Structural Impacts. Energy Security.

Investing in renewable and alternative energy sources has been considered an important low-impact strategy to reduce greenhouse gas emissions and generate energy efficiency through clean energy, both at the national level and for locations in more remote areas [1-3]. Stimulating investment in distributed generation of photovoltaic solar energy has been considered a priority action to stimulate decarbonization through the diversification of the energy matrix [4]. It was estimated that this would contribute 9% of electricity consumption in Brazil by 2034, generating greater autonomy and minimizing the impact of interruptions in the network [4,5], however, ANEEL data from 2024 already shows that this contribution in 2024 was 10.68%, exceeding the EPE estimate [6].

In this context, microgeneration of photovoltaic energy contributes positively to climate change by enabling the replacement of fossil fuels and the consequent reduction in pollutant gas emissions,

especially in urban centers [7]. Improving the efficiency and stability of these systems, particularly through the integration of climate data, aligns technology with global sustainability and energy transition policies [5]. In a scenario where extreme events affect energy generation, transmission, and consumption, renewable sources, however, are considered quite vulnerable [4]. Therefore, the expansion of photovoltaic installations has also been affected by extreme weather events [7].

The feasibility of implementing these structures must consider the risk of flooding, which can result in damage and structural failures [8]. Floods cause multidimensional effects, and the electricity supply is often affected, generating a cascading effect. Power outages and damage to the electrical grid are reported in the literature as a direct consequence of urban flooding, requiring continuous improvement in the electrical grid infrastructure [9-11].

As discussed, the literature highlights solar photovoltaic energy as a strategic solution in the context of the energy transition, yet it is vulnerable to the effects of the climate crisis. Especially in residential and commercial settings, it requires continuous monitoring of its resilience, safety, and operational stability. Faced with the intensifying

Received on 17 April 2026; revised 28 June 2026.

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J Bioeng. Tech. Health 2026;9(7):698-704
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climate emergency, these technologies will need to adapt to scenarios marked by increasingly frequent extreme events, such as heavy rainfall, flooding, and urban inundation [12,13].

This approach sought to characterize the impacts of floods and severe storms on photovoltaic microgeneration systems through an analytical survey. To guide the analyses, the research question is presented as follows: How can extreme weather events, such as floods and storms, impact the operation and safety of photovoltaic systems installed in urban areas?

Materials and Methods

This study is theoretical in nature and descriptive in approach, focused on analyzing and systematizing information related to the impacts of urban flooding on photovoltaic systems. A comprehensive approach was adopted to address technical, safety, and economic aspects associated with the operation and vulnerability of these systems in the context of extreme hydrometeorological events.

The first step in the study consisted of a literature review to map the scientific literature relevant to the topic. Articles indexed in the Scopus and Web of Science databases were selected, addressing the interfaces between climate change, energy infrastructure, and risks associated with distributed microgeneration. In addition to the academic literature, a documentary analysis of institutional sources was conducted, highlighting technical reports from the Energy Research Company (EPE), which support national electricity sector planning and provide relevant data on the expansion of solar energy in Brazil.

To broaden understanding of the topic, based on applied technical information, digital channels of institutions specializing in electricity sector services and industry associations were consulted. This methodological combination allowed us to construct a well-founded and up-to-date overview of the adverse effects that affect photovoltaic systems during flooding. The methodological choice for this approach highlighted the three

most common types of impacts in the literature for detailed analysis: inverter damage, photovoltaic module damage, and electric shock hazard.

Results

This section discusses the main findings of this study. Figure 1 presents a systematic overview of the three most frequently mentioned types of impacts in the analyzed publications, and Table 1 lists the publications addressing the topic.

Figure 1. Approach to flood impacts on photovoltaic systems in the analyzed publications. Prepared by the authors.



Table 1. Main impacts mentioned in the publications.

Impact	Publications
Damage to inverters	[14, 15, 16, 17, 18]
Damage to photovoltaic modules	[12, 14, 16, 18]
Electric shock hazard	[15, 16, 17, 18]

Damage to Inverters

During urban flooding events, photovoltaic inverters were highlighted as the most vulnerable and frequently damaged components in solar microgeneration systems [14]. These devices are responsible for converting the direct current

generated by solar panels into usable alternating current at 127 or 220 volts [15]. When installed in lower areas of buildings to facilitate access, they become more susceptible to flooding. Although they have an IP65 protection rating, this level was not sufficient to withstand total or even partial submersion [16]. Figure 2 illustrates the condition of an inverter after flooding.

Figure 2. Inverter damaged by flooding.



Contact with water and mud can irreversibly compromise the inverter's internal circuits, generating the risk of immediate short circuits or progressive failures in the medium and long term [16]. Even when flooding occurs partially, preventive replacement of the equipment is recommended, given the impossibility of guaranteeing its integrity and safety after the event [17]. Restarting the system without a thorough inspection and before it has completely dried out not only poses a risk to the electrical safety of the installation, but can also cause overloads in distribution panels and compromise the stability of other system components [18].

The loss of inverters has implications that go beyond simply halting power generation. In many cases, entire systems become inoperable, requiring insurance claims and resulting in significant losses, especially for small businesses that rely on solar energy as a primary or backup power source [16]. Sludge contamination, accelerated corrosion, and

the complexity of replacing damaged equipment exacerbate the vulnerability scenario, highlighting the need for more resilient installation strategies in flood-prone areas, as well as safe shutdown and restart protocols based on thorough technical inspections.

Damage to Photovoltaic Modules

Photovoltaic modules, essential components of solar energy systems, are designed to withstand adverse weather conditions, including heavy rainfall and prolonged exposure to the outdoors. High-quality solar panels typically feature a robust structure consisting of an aluminum frame, tempered glass, and a vacuum-sealed backing, which gives them significant resistance to water penetration [18]. Therefore, even after extreme precipitation events, the modules may be able to remain structurally intact and continue to operate. However, their physical integrity alone does not guarantee full system operation, as damage to electrical wiring, inverters, or the support structure can compromise the entire array [18].

During urban flooding, particularly those with strong currents, modules can be torn from their mounting structures, especially when installed in lower elevations or on ground supports [12,14]. In these situations, there is a risk of the panels being swept away by floodwaters, suffering mechanical damage, or causing accidents by colliding with other objects [14]. Panels mounted at ground level, while also waterproof, are more vulnerable to displacement during floods. In these cases, it is recommended that they be installed in elevated locations and with reinforced anchoring systems to mitigate these risks, as illustrated in Figure 3 [16].

It is worth noting that, even in cases where the modules appear to have suffered no visible damage, a specialized technical assessment must be conducted before any attempt to reconnect the system. Compatibility between the durability of the panels and the resistance limits of the supporting electrical infrastructure, such as cables, connectors, inverters, and metal structures, contributes to

Figure 3. Panels after floods.

ensuring the safety and operational continuity of the photovoltaic system [16,18].

Electric Shock Hazard

During urban flooding events, photovoltaic systems installed in homes or commercial buildings can pose serious risks to the physical safety of occupants and rescue teams. Although solar energy is a clean and promising source, in flooding situations it can be life-threatening due to the possibility of electric shock [17].

The continuous generation of energy by solar panels, even when the grid is disconnected, can be considered an aggravating factor. As long as sunlight is present, the photovoltaic modules will continue to produce voltage, energizing cables, electrical panels, and inverters [17]. Therefore, submerged buildings equipped with solar systems significantly increase the risk of electrocution, especially when in contact with contaminated water or when attempting to access roofs and elevated structures for shelter or rescue, as illustrated in Figure 4 [15].

Given this reality, it is recommended that, upon identifying an imminent risk of flooding, residents turn off the home's main circuit breaker before the water reaches the property [17]. It is also advisable

Figure 4. Properties flooded by flooding.

to cover solar panels with opaque tarps to reduce energy generation and the potential for electric shock [18]. However, these actions should be taken in advance and with caution. Once flooding begins, do not attempt to disconnect photovoltaic equipment, especially if it is wet or submerged, as it remains energized even when the power grid is disconnected [17]. Another important point is to maintain a safe distance from panels, inverters, circuit breakers, and cables, considering that any malfunction can energize the water and result in fatalities [15].

Specialized technical teams are required for both post-event inspections and preventive guidance for the public [18]. These professionals must wear appropriate personal protective equipment (PPE), since even the direct current generated by photovoltaic systems can cause electric shocks [16]. Rescue procedures in flooded areas should also provide for complete isolation of electricity, avoiding operations on roofs equipped with solar panels, where there is a risk of slipping combined with electrical hazards [17]. In all cases, safe conduct seeks to prioritize moving away from the affected areas and awaiting technical evaluation before re-entering flooded buildings that use solar energy.

Discussion

Although solar modules are structurally designed to withstand high winds and continuous exposure to the elements, components such as inverters, charge

controllers, and batteries remain highly susceptible to damage from flooding, especially when installed in low-lying areas or areas lacking adequate protection against water ingress [17]. Exposing these devices to moisture, mud, or submersion can seriously compromise their operation, cause short circuits, and result in irreversible damage to the system.

Structural and electrical damage to photovoltaic systems can vary depending on the type of architecture adopted. In general, systems fall into three categories: those with string inverters, microinverters, or batteries. All of these models, even the most advanced, can suffer operational interruptions or permanent damage in flooding situations [17]. In particular, hybrid systems that integrate solar panels and storage batteries are vulnerable to loss of functionality when critical electronic components are exposed to water or mud, with additional risks of short circuits and contamination from solid waste [17]. If the neighborhood power grid is damaged by flooding, users with battery systems and inverters with islanding capabilities can still rely on their own generation, as long as the equipment is preserved [18].

Rooftop installations offer a relative advantage, as they elevate the photovoltaic modules above the water level in flood scenarios. However, this does not guarantee the integrity of the system as a whole. Falling trees, strong winds, and structural collapses can affect the panels even in elevated locations. Furthermore, the connection between the solar system and the utility meter, typically located on ground level, remains at risk of flooding and accidental energization [18].

In emergency situations, it is necessary to reinforce safety guidelines. After the partial or total submersion of buildings equipped with solar systems, residents and rescue teams should not, under any circumstances, attempt to disconnect or tamper with electrical connections, inverters, panels, or panels, as there is a high risk of electric shock even with the grid deactivated [17]. The appropriate response involves isolating the area, awaiting specialized inspection, and, when

necessary, replacing damaged components to ensure safety and the reliable restoration of solar energy generation.

More broadly, this situation has repercussions, especially in the scale of the financial impacts resulting from flooding on photovoltaic systems.

A survey revealed that between May and July 2024, approximately 52% (n=92/176) of claims compensated by an insurer specializing in the sector, these losses were directly linked to flooding and inundation, totaling over one million reais in compensation payments. That year, the state of Rio Grande do Sul was the most impacted by extreme weather events, accounting for approximately 32% of registered claims and 22% of the total compensation paid [13].

Despite the state's high installed capacity—approximately 2.7 gigawatts, corresponding to 9.6% of the country's self-generation—with over 302,000 connections distributed across its 497 municipalities. Only 30% of the facilities affected by the floods had some type of insurance, and only 10% of these policies specifically covered flood damage [13, 14]. This scenario exposes the financial vulnerability of thousands of users, particularly small businesses and households that invested in solar systems without considering the risks associated with extreme weather events.

Conclusion

The increased recurrence of urban flooding associated with extreme weather conditions requires the implementation of preventive guidelines and appropriate technical procedures for the installation and management of photovoltaic systems in flood-prone urban areas.

Mitigation of structural and electrical impacts begins at the planning stage, with the identification of risk zones and the selection of elevated locations for the installation of inverters and sensitive components, significantly reducing vulnerability.

Based on the sources consulted, preference is given to equipment with an IP65 protection rating or higher, along with the use of watertight

connections, anti-corrosive materials, and technical seals suitable for moisture. Reinforced anchoring of support structures and photovoltaic modules is another suggested measure, especially in areas subject to strong currents or winds. For ground-based installations, adopting robust drainage solutions, technical elevation of inverters, and monitoring systems increases the resilience of systems to flooding. The use of sealed batteries and their positioning above historical flood levels were also reported as desirable interventions.

In terms of electrical safety, the installation of residual current circuit breakers and automatic reconnection systems is recommended, in addition to periodic maintenance with preventive inspection of equipment performance. In situations of meteorological alert or imminent risk, safe and preventive shutdown of the system must be carried out in advance. After a flood event, technical cleaning and thorough inspection are essential before any reconnection. Ensuring qualified technical support is available for emergencies contributes to the safe and efficient resumption of system operations.

From an economic perspective, the importance of purchasing insurance with specific coverage for extreme weather events was highlighted, as well as a detailed review of contractual conditions with suppliers and installers. Because this represents an emerging topic, the prospect of more in-depth approaches is anticipated, through research applied to specific territorial realities, encompassing socio-environmental and climate aspects. Public policies and adaptation measures, especially in the context of the state of Bahia, represent promising avenues for future research seeking solutions capable of improving the stability and operational safety of photovoltaic systems in extreme weather scenarios.

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