INCREASING OCCURRENCE OF EXTREME WEATHER EVENTS AND EVIDENCE OF THE VULNERABILITY OF ENERGY PLANTS IN SOUTHERN BRAZIL

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ABSTRACT
The work aims to analyze and assess the vulnerabilities - of areas, regions, environments, structures and populations - to disasters and losses as a result of extreme events, associated with climate change. The study is restricted to the territory of the state of Rio Grande do Sul (RS) and, in particular, its renewable electricity generation infrastructure, focusing on the defining characteristics of the potential use of hydro, wind and solar resources. Methodologically, a historical/analytical review of the sequence of implementation and consolidation of the production infrastructure of the three energy matrices is made, as well as the frequency and intensity with which extreme events began to occur. As a result, it is proven how much these energy infrastructures, more and more present in RS, and indicated from the perspective of available technologies and under the cost-benefit screen, have been presenting vulnerabilities to recent extreme weather phenomena. Some recommendations are presented by way of conclusion, with the consideration of the variables "climate change/extreme events" in the planning and implementation processes of these facilities, aiming at reducing losses of all kinds.

Keywords: Climate change. Extreme events. Energy infrastructure. Renewable energies. Vulnerabilities.

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INTRODUCTION

Some regions are characterized by having natural conditions conducive to energy generation on a commercial scale from different sources and, in the case under analysis, the focus is directed, in particular, to those considered renewable and sustainable: hydraulic, wind and solar photovoltaic. In this privileged situation, in the case of Brazil, the state of Rio Grande do Sul can be considered in particular.

For hydroelectric plants, in principle, waterfalls or rapids, present in river valleys, canals, gorges and *canyons* with regular water volumes throughout the year, are fundamental factors. The geographical characteristics in these places favour the exploitation of the identified potential. In the case of wind farms, favorable factors include the disposition/presence of mountain ranges, plateau edges or other elevations of the terrain, as well as extensive coastal/coastal areas, with the incidence of winds at high and constant speeds. In addition, the absence of obstacles that interfere with the passage of winds also contributes to the wind potential of these regions. With regard to the exploration of solar energy, especially in so-called centralized photovoltaic parks, the possible use is feasible, even if in a preliminary analysis, with solar clarity and/or incidence available for at least eight hours a day throughout the four seasons. Other local characteristics that must be considered are the extensive free/open areas for the installation of structures with photovoltaic panels, without the interference of high elements/obstacles that produce shadows.

In this context, the present work aimed to analyze and assess the vulnerabilities of areas, regions, environments, structures and populations to disasters and losses resulting from extreme events associated with climate change. The state of Rio Grande do Sul was selected as the study area.

THEORETICAL FRAMEWORK

In hydrological terms, RS can be considered as one of the Brazilian states best provided with surface water resources, and has three large collecting hydrographic basins (also called hydrographic regions): i) the basin or hydrographic region of the Uruguay River (comprises around 57% of the state's surface); ii) the Guaíba basin or hydrographic region (with approximately 30% of the state's area); and, iii) the coastal basin or hydrographic region (covers 13% of the state territory). These three large basins (Figure 1), with regard to the management of water resources, are currently subdivided into 25 basin committees, created between 1988 and 2012 (Rio Grande do Sul, 2022).

The creation and operation of these committees arose as a result of the application of Law No. 9,433, of January 8, 1997, which instituted the National Water Resources Policy (PNRH). Among the six foundations established by this Law, item IV stands out, and determines that "the management of water resources must always provide for the multiple use of water" (BRASIL, 1997).

Figure 1. Three major basins or hydrographic regions of Rio Grande do Sul

Source: SEMA, 2002.

It is worth noting that prior to the enactment of the PNRH, in 1997, the so-called "Water Code" was in force, instituted by Federal Decree No. 24,643, of July 10, 1934. This code was the first Brazilian legislation that contemplated the discipline of the use of water in Brazil and prioritized, fundamentally, the generation of electricity as a priority use of water resources.

Since 1930 (over more than 90 years), when the first Hydroelectric Power Plant (HPP) in Rio Grande do Sul was inaugurated, in São Leopoldo, more than 130 other dams have also been built, specifically intended for the production of hydroelectricity. Many of these hydroelectric dams are located in rivers that make up basins and sub-basins that flow into the Guaíba, in the greater metropolitan region of Porto Alegre. Most of the springs of the rivers that form this basin are located on the Plateau and run along the slopes of the Serra Geral, in formations of embedded valleys, with steps and waterfalls, characteristics that confer great energy potential.

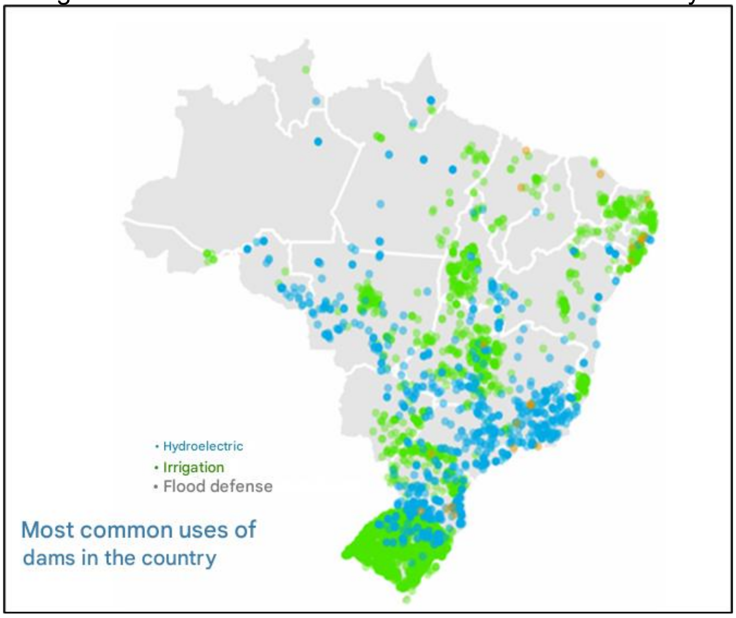
Such potential was explored with the construction of the dams mentioned above, with the main purpose of generating electricity. However, the priority established decades ago, over the years, has highlighted significant weaknesses in critical moments of natural disasters, correlated with the practice, then accepted, of relegating other uses, such as permanent defense against floods, to the background.

Although hydroelectric dams are also subject to compliance with Law 12.334/2010, which established the National Dam Safety Policy and requires their contribution to the flood control effort at the most critical moments, most of those located in Rio Grande do Sul were designed for the generation of electricity. In this sense, changing their function to the priority of "flood defense" would require radical changes in the daily operation of these structures throughout the year.

In addition, in view of the fragility and potential losses caused by extreme weather events in RS, it is noteworthy that the Guaíba hydrographic basin, although it covers 30% of the state's territory, concentrates two-thirds of the population and is responsible for 90% of the state's GDP.

Figure 2, extracted from the Dam Safety Report published in 2019 by the National Water and Basic Sanitation Agency – ANA, one of the summary maps presents "The most common uses of dams in the country". In the territory of Rio Grande Sul, it is noteworthy that there is only one dam with priority use for "Flood Defense" (on the Uruguay River, in the north of the state), which contrasts with the predominance of dams intended primarily for "Hydroelectric Plants" and "Irrigation" (National Water and Basic Sanitation Agency, 2019).

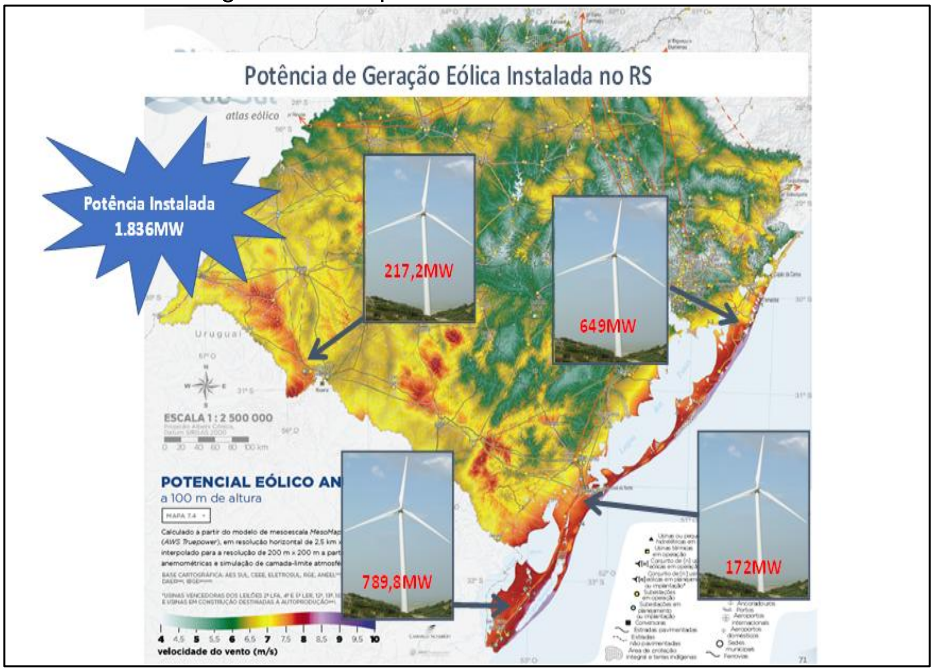
Figure 2. The most common uses of dams in the country



Source: National Water and Basic Sanitation Agency – ANA, Dam Safety Report, 2019.

As for the state's wind energy reserves, research and inventories of the generation potential proved the feasibility of their use, as highlighted in Figure 3. Since 2006, when the first wind turbine towers were installed in Osório - RS, several other wind farms/complexes have emerged in the state, currently totaling more than 80 in operation (Rio Grande do Sul, 2014).

Figure 3. Wind potential in Rio Grande do Sul

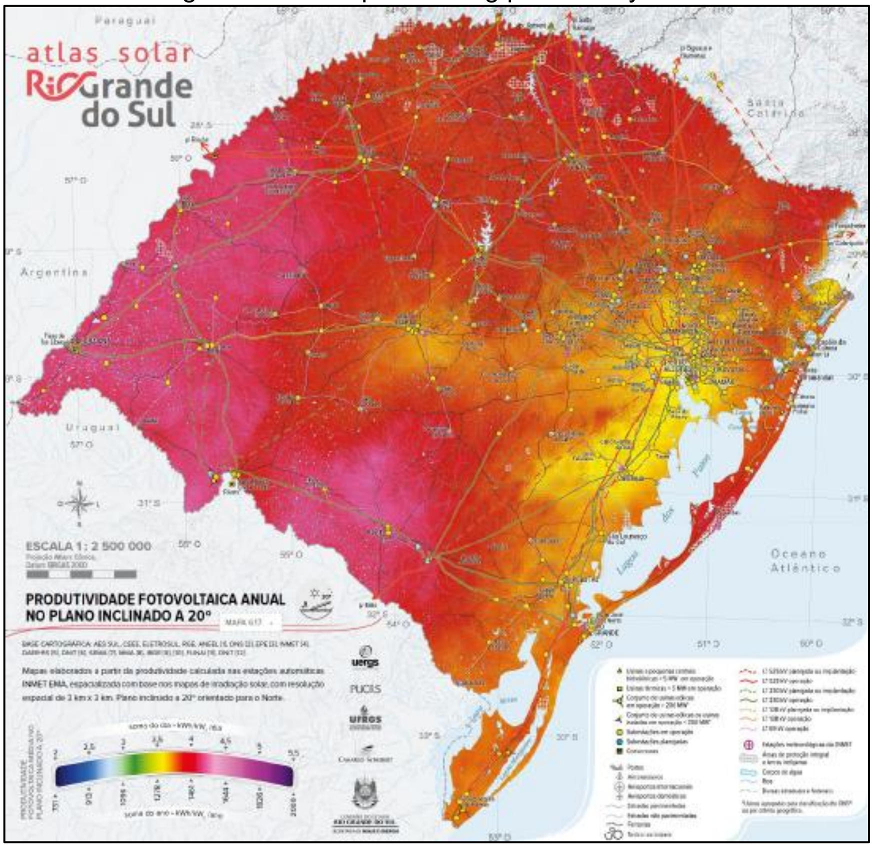


Source: Gaucho Agency for Development and Investment Promotion – AGDI, Wind Atlas: Rio Grande do Sul, 2014.

The aptitude and potential of RS for the use of solar energy through photovoltaic plants, whether in the distributed or centralized modality, in *onshore* and *offshore environments,* have been widely evaluated in several recent studies. These studies showed promising scenarios for the large-scale application of this technology in different regions of the state, as illustrated in Figure 4 (Rio Grande do Sul, 2018).

The production of photovoltaic solar energy in RS began in the 2010s, in a distributed form, with uses in homes, businesses and industries. From 2016 onwards, large centralized plants also emerged. Surveys from March 2023 estimated that there are more than 220 thousand active solar photovoltaic systems in the state.

Figure 4. Annual photovoting productivity in RS



Source: Secretariat of Mines and Energy of Rio Grande do Sul, 2018.

METHODOLOGY

The historical/analytical rescue of the sequence of implementation and consolidation of the production infrastructure of the three energy matrices is carried out and, with a time horizon of the last 40 years, several events/natural disasters associated with the worsening of climate change that have affected the state of Rio Grande do Sul are analyzed. Among such events/natural disasters, those of increasing and more frequent intensity gain relevance, such as: floods, flash floods, bank erosion, windstorms, hailstorms, windstorms accompanied by hailstorms, tornadoes, hurricanes, droughts and landslides.

Based on this list of possible natural disasters, for the purposes of analysis, two groups of events stand out: i) those disasters correlated to rainfall/river dynamics; and ii) those correlated with winds/atmospheric disasters. Thus, in the present study, the disasters associated with "Emergency Situation" or "State of Public Calamity" decrees declared by the municipalities of Rio Grande do Sul and officially approved by the state government/Civil Defense were computed.

RESULTS AND DISCUSSIONS

Based on data cataloged from 1980 to 2020 in the state of Rio Grande do Sul (sometimes with the inclusion of affected areas in the south of the state of Santa Catarina), rainfall/fluvial dynamics led to the official record of 962 disasters/calamities, which included floods, heavy rains, flash floods, floods, and floods. In the case of winds, the official record of 2,424 disasters/calamities was originated, related to windstorms/storms, hailstorms, tornadoes, extratropical cyclones, and hurricanes (Dávila, 2021; Reckziegel, 2007).

Among the most significant disasters/extreme events associated with the winds/atmospheric disasters included in the period analyzed, and considered here, are: 1) tornadoes that occurred in July and December 2003, which struck the municipalities of São Francisco de Paula and Antônio Prado, respectively; 2) Hurricane Catarina, which occurred in March 2004 in the south of the state of Santa Catarina and five municipalities on the north coast of Rio Grande do Sul, with winds of up to 150 km/h; 3) tornado that occurred in August 2005, which hit the municipality of Many Capões, with winds of up to 180 km/h; and, 4) a very intense windstorm that occurred in December 2014, hitting the municipality of Santana do Livramento, with winds of up to 250 km/h, which knocked down eight wind power generation towers, in the Cerro Chato wind farm, belonging to Eletrosul. With regard to the extreme events associated with rainfall/river dynamics that resulted, directly or indirectly, in significant damage to the hydroelectric energy production infrastructure, the focus and object of this study, two remarkable episodes that occurred in 2023 and 2024 gain relevance and stand out, namely:

1) series of nine extratropical cyclones followed by heavy rains/floods that occurred in 2023 (three of them of great intensity in June, July and September), the last of which hit the Taquari River valley hard, with a huge amount of rain and windstorms accompanied by hail, causing floods and many losses, which made this the biggest natural disaster in RS, until then, in more than six decades. In addition to the enormous material losses, this cyclone left a balance of 50 dead and 8 missing (g1 RS, 2023);
2) intense and incessant rains in the final days of April and part of May 2024, as a result of a wide atmospheric blockage over much of the state, causing rapid rises in levels with overflow of the channel in streams, streams, small streams and riverside regions, as well as the rise of the main rivers and, subsequently, causing flooding and flooding in the metropolitan region of Porto Alegre and in a large part of the capital of Rio Grande do Sul itself. In several cities, in the period between April 27 and May 2, it rained from 500 to 700 mm, corresponding to a third of the historical average of precipitation for an entire year, and in many other cities the precipitation was between 300 and 400 mm between May 3 and 5.

This event reached about 78% of the municipalities in Rio Grande do Sul and 336 had the situation of public calamity recognized. The disaster, given the number of people affected (more than 2.3 million people directly affected, 182 victims were confirmed dead and, three months after the most critical moment of the floods, 29 were still missing (Borges, 2024)), devastated communities and damage caused, has been classified by the government of Rio Grande do Sul as the biggest climate catastrophe in the history of the state. Resuming the analysis of the vulnerability of renewable energy generation infrastructure in the face of the occurrence of extreme events associated with climate change, now objectively considering the floods that occurred in RS in late April and early May 2024, it can be seen that the losses and fragilities exposed were enormous. In terms of the vulnerability of the dams that generate electricity, with the high volumes resulting from the rains concentrated in five days, on May 2 there was a rupture of the dam of the 14 de Julho HPP, on the Antas River, between the municipalities of Cotiporã and Bento Gonçalves and, in the following days, with the continuity of the rains, the issuance of emergency alerts from the Civil Defense, with the risk of imminent rupture or the attention of eight other hydroelectric plants (Bugres HPP, Jacuí HPP, Salto Forqueta SHP, Monte Claro HPP, Castro Alves HPP, Dona Francisca HPP, Canastra HPP, Furnas do Segredo SHP). In May 2024, with damage assessments still in progress, the Ministry of Mines and Energy already estimated the damage caused, specifically in the electricity sector, exceeding R$ 1 billion (Borges, 2024). A partial and summarized survey of this climate tragedy, citing official data and published on 08/02/2024, recorded that in the state "44 power generation projects were directly impacted, which affected the safety level of the dams and led to stoppages". On the date of publication, 29 impacted plants already had their operations normalized, but at least 15 power generation plants were still out of operation, due to floods and debris that damaged their structures (Borges, 2024). Part of the plants heavily affected by the floods are expected to return to operation only in 2025 - the situation of the Toca hydroelectric plant, for example, with a forecast to return to operation in February 2025. Located on the Santa Cruz River in São Francisco de Paula, one of the rainiest municipalities in the state, the plant was swallowed by mud on May 2, 2024, paralyzing all its turbines. The situation is similar in the case of the Soledade hydroelectric generation plant, in the Municipality of Fontoura Xavier, which is expected to return only in May 2025. The plant had complete compromise of the civil structure of the engine room, the automation and communication system, the voltage measurement and lifting system and protection of the connection point with the local distributor. In addition, access roads were totally obstructed due to falls of barriers and bridges (Borges, 2024). In terms of the vulnerability of photovoltaic solar energy production systems as a result of heavy rains/floods and floods in late April and early May 2024 in RS, there are also large losses. The state concentrates, according to data from the Brazilian Solar Energy Association – Absolar, almost 10% of all installed power in the country, referring to self-generated solar energy, mainly on rooftops/roofs and land. There are, or were, more than 300 thousand connections in operation, distributed in 497 municipalities. Precise data, Absolar acknowledged, regarding the number of photovoltaic systems that were damaged or lost due to floods, are difficult to total (Neris, 2024). With vast areas that were flooded or covered by mud, with tens of thousands of residents or even companies that were without access to their properties or commercial/industrial establishments for more than a month, it became effectively difficult to accurately measure the impacts on photovoltaic systems collectively in the state.

On the other hand, integrating companies that sell/install these systems in RS, crossing information from their installed plants with flood maps, evaluated approximately the number of damaged installations due to their location in areas covered by flood water. Thus, it was possible to state that there are thousands of systems affected/paralyzed, with losses of inverters, damage to modules/panels, cables and connections, junction/control boxes, and distribution boards. Most of the time, the modules/panels are more resistant to water because they are outdoors, but many were also damaged by materials dragged by the flood, and there are cases of total loss, in which the plant simply disappeared, and everything was washed away, house, plant, everything. Another risk factor that photovoltaic systems located in flooded areas have to do with the safety of consumers, residents or users, to avoid accidents, shocks or losses due to the possibility, depending on the technology of the installations, of the solar modules/panels remaining active, energized as long as/if there is sunshine, even with the system not producing energy (Neris, 2024). Among the large photovoltaic solar installations with significant losses due to floods in Rio Grande do Sul is the Salgado Filho Airport, located at one of the exits of Porto Alegre, and which had its facilities completely flooded, with the water reaching 2.5 m in height.

CONCLUSION

The state of Rio Grande do Sul has been presenting increasing figures in the last four decades with regard to extreme weather events, according to data presented here. The lack of effective preventive and protection measures against these events has also increased the numbers related to human, property and infrastructure losses, evidencing numerous vulnerabilities, among which we focus here on the growing vulnerability of energy uses, in their hydraulic, wind and solar photovoltaic matrices. Several preventive and predictive actions can be implemented, in addition to the traditional physical/structural barriers already employed and which have been shown to be undersized/insufficient and without adequate maintenance/conservation, given the frequency and intensity with which extreme weather events have been impacting RS and, in the study presented here, its infrastructure for the energy use of water resources, wind and solar. Among these possible preventive and predictive actions/recommendations, and considering the available technological resources, the following are listed:

- Expansion and technological updating of continuous and permanent systems of hydrological and hydrometeorological measurements and monitoring, in real time, automated, without dependence on the supply of electricity by conventional means, allowing efficient and effective risk management/decision-making, and the issuance of alerts to the most vulnerable communities;
- Reconfiguration of projects and, if possible, alteration of the operational assumptions of existing hydroelectric plants, in order to contemplate as an equally fundamental priority, the preventive capacity to contain/slow down the sudden increase in flows, flash floods and floods, especially in the already known periods of greater incidence of torrential rains, windstorms followed by storms, cyclones, tornadoes and hurricanes; and
- Preparation, improvement and permanent updating of regional studies that simulate the situations of extreme weather events, based on the analysis of different scenarios of floodable areas, possible "routes/corridors" for the incidence of windstorms and cyclones that cross wind farms and photovoltaic solar energy uses. Such predictive studies are feasible with the use, for example, of Remote Sensing (SR) orbital images, combined with the already established but little disseminated tools of the *Google Earth Engine* (GEE) platform, in which it is possible to analyze, evaluate and make simulations, considering the "collections" of satellite images available on the dates/periods in which the most significant natural disasters occurred in RS, or on close dates, and also to evaluate one or several elements - areas, regions, environments, plantations, productive, road and urban structures, populations and energy infrastructures - that proved to be more vulnerable to extreme events and, in fact, suffered severe damage and destruction, seeking to characterize more frequent routes/patterns of displacement or rivers and drainage basins more susceptible to sudden variations in water levels and flooding.

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