

Opportunities and Barriers to Renewable Energy Expansion in Brazil in the Context of Energy Transition and Climate Change Mitigation

Oportunidades y Barreras para la expansión de las Energías Renovables en Brasil en el contexto de la transición energética y la mitigación del cambio climático

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Abstract

The present work aims to establish, characterization, and analyze the associations between the probable impacts of climate change on the primary sources of renewable energy in Brazil and the country's Nationally Determined Contributions (NDC) under the Paris Agreement. Based on a systematic review of the literature and analysis of preliminary data on the Brazilian energy system, analysis of documents such as peer-reviewed scientific manuscripts published in Brazil and abroad, as well as reports published by the Brazilian government and international energy agencies. Due to the intense emission of Greenhouse Gases (GHG) in the production and consumption of energy in the global energy matrix, the analysis of mitigation measures, such as a higher use of renewable energy sources, has become an essential tool in tackling climate change. In the case of Brazil, this context has become increasingly relevant due to the increasing share of fossil sources in the country over the past decade. In addition, this is due to the increasing activations of thermoelectric plants (based on coal, Diesel and natural gas). Hydroelectric, solar, and wind plants tend to reduce the emission of GHG related to the electricity generation in Brazil. Furthermore, electricity generation based on biofuels can be considered in Brazil, a strategy less affected by climate change. The results of this study can assist in the decision-making process of the energy planning in Brazil, serving as an intellectual subsidy for public and private stakeholders, with the point of considering the energy-planning sector widely and necessarily connected with the socio-environmental policies in the country.

Keywords – Brazilian energy matrix, Climate change, NDC, Paris Agreement, Renewable energy.

Resumen

El presente trabajo tiene como objetivo establecer, caracterizar y analizar las relaciones entre los impactos probables del cambio climático en el contexto de las fuentes primarias de energía renovable en Brasil vis-à-vis las NDC del país bajo el Acuerdo de París. Basado en una revisión sistemática de la literatura y el análisis de datos preliminares sobre el sistema energético brasileño, análisis de documentos como manuscritos científicos arbitrados publicados en Brasil y en el exterior; además, de informes publicados por el gobierno brasileño y agencias internacionales de energía. Debido a la intensa emisión de GEI en la producción y consumo de energía en la matriz energética mundial, el análisis de medidas de mitigación, como el uso de fuentes de energía limpias y renovables, se convierten en herramientas fundamentales en la lucha contra el cambio climático, especialmente dada la creciente participación de fuentes fósiles en el país durante la última década. Las plantas hidroeléctricas y aquellas plantas basadas en energía solar y eólica tienden a registrar una reducción en sus potenciales intrínsecos para la generación de electricidad en Brasil; sin embargo, los dos últimos aún pueden usarse a gran escala hasta al menos finales de siglo. En cambio, la generación de electricidad a partir de biocombustibles debería ser la fuente renovable, en general, potencialmente menos afectada por el cambio climático. Este estudio tiene base teórica suficiente para ayudar en la toma de decisiones, sirviendo como un subsidio intelectual para que los gestores públicos y privados que actúan en la planificación del área energética puedan diseñar e implementar políticas socioambientales en Brasil.

Palabras clave – Acuerdo de París, Cambio climático, Energías renovables, Matriz energética brasileña, NDC.

1. INTRODUCTION

For the most part, science assesses that the GHG emitted by human activities, mainly carbon dioxide (CO₂) due to the major volume of its emissions, are the main reason for a sharply perceptible increase in the average temperature of the earth's surface. This increase reached a little more than 1 °C since the predawn industrial period. If the current pattern of continuous growth of GHG emissions continues, warming of another 0.5 °C is estimated by 2052 [1]. In addition, an increase in the level of the oceans due to the melting of glaciers and the thermal expansion of the water itself, a greater frequency of extreme natural events, and a change in the rainfall cycle are still predicted.

Climate change caused by human actions, the consequences of which are already felt in the present, must be sustained for centuries and millennia, necessitating global mitigation efforts [1]. In this context, it is emphasized that the production, conversion, and consumption of energy are responsible worldwide for about 60% of greenhouse gas emissions, being individually the sector that grew the most and, consequently, the one that has been the most polluted since 1970. This outstanding participation of the energy sector in global GHG emissions can, to a large extent, be explained by population growth, an increase in per capita income, and industrial production in a way that correlates with growing consumption of fossil energy, particularly oil, mineral coal and natural gas [2].

The notion that human actions in pursuit of development harm the environment was already widely debated in the scientific community at the same time, in the mid-70s. However, this debate only got real space on the government's agenda around the world with the Convention of the United Nations Framework Convention on Climate Change (UNFCCC in Rio de Janeiro in 1992. At the time, it was found that the model and pace of economic growth, adopted until then, by the developed and developing countries, could not continue, as there would be serious consequences for all forms of life on the planet. Then 175 countries signed and ratified the agreement with the aim of stabilizing GHG emissions and mitigating more harmful human interference in the climate [3]. Countries should share the costs of reducing greenhouse gas emissions; however, the most developed countries had the obligation to spearhead these actions because they were, in theory, the most responsible for the problem and had the greatest economic capacity to act [4].

In this way, the countries that made up the UNFCCC created the Conference of the Parties (COP) in 1995. The COP is the most important international body on Climate Change, whose annual meetings were responsible for the creation of the Kyoto Protocol in 1997 (during COP 3, in the city of Kyoto, Japan). The central objective of this Protocol was that the 37 industrialized countries plus the European Community adopt

a reduction of their greenhouse gas emissions by at least 5.5% (on average) compared to 1990 levels by 2012 [5]. Among other developments of this agreement, in 2015, during the 21st Conference of the Parties (COP 21) in France, the Paris Agreement also emerged, whose ultimate objective was to strengthen and continue the GHG mitigation efforts initiated by the Kyoto Protocol. As the main goal of the new document, it was decided to limit global warming to a maximum of 2 °C in 2100 compared to the pre-industrial period, preferably limiting it to 1.5 °C. This ultimate objective is related to further intensifying the responses of countries to the dangers of climate change [6].

Brazil has committed to emitting until 2025 a 37% lower rate of GHG emissions compared to 2005 levels; and, in 2030, it aims to achieve a 43% reduction in emissions compared to the same year. To achieve these goals, the Brazilian government designed the NDC of Brazil to include an 18% increase in sustainable bioenergy in the energy matrix as the main objective. In addition, the Brazilian NDC considers that, in 2030, 45% of the energy matrix will be composed of renewable energy [3]; [7].

In such a context, the present work is focused on understanding the likely worsening of climate change. This theme becomes even more important due to the relative absence of studies focused on the national scale, seeking to fill this knowledge gap. The main hypotheses that drove the research were the wide variation between the effects of climate change according to the renewable energy source analyzed; the generation of energy by hydroelectric plants in a state of greater vulnerability; and the adaptability of agriculture as a key to the success of biomass throughout the current 21st century.

2. OBJECTIVES

The primary goal of this work is to establish, characterize, and analyze the relationships between the likely impacts of climate change in the context of Brazil's main renewable energy sources (hydroelectric, sugarcane biomass, wind, and solar). In addition, such analysis considers, centrally, the country's NDC (National Determined Contributions) under the Paris Agreement—that is, considering the commitments made to the United Nations in favor of mitigating GHG emissions. In this way, the present study analyzes this problem from a panoramic view, by which the wide scope is recognized.

3. METHODOLOGY

The methodology approach underpinning the present work is based on a systematic review of the literature. It is opportune to highlight that this methodology is a type of research

focused on a well-defined question, which aims to identify, select, assess, and synthesize the relevant available evidence. Moreover, it was adopted for critical analysis. Therefore, the data collection method was based on deep consultation and analysis of the most recent National Energy Balance elaborated by the Energy Research Company for the base year 2020 [8]. The analysis of documents, such as scientific manuscripts, master's dissertations, and doctoral theses, was obtained from the Web of Science, Scielo, and Science Direct.

Also consulted were documents published by the Brazilian government and by international agencies focused on the topic of energy, such as IEA (International Energy Agency) and IRENA (International Renewable Energy Agency). These data sources allowed the characterization and analysis of possible changes in the participation and efficiency of renewable sources in Brazil, as well as the projections made for the energy matrix until the year of 2030 by the Ministry of Mines and Energy (MME) presented in the Ten-Year Plan of ENERGY (PDE, for the acronym in Portuguese). After that, it was compared to the results and the analyses derived with the projections inherent in the most recent Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), that is, the Sixth Assessment Report (AR6).

This methodological route showed more consistency in the difficulties in conducting field research due to the COVID-19 Pandemic, in contrast to the data and results of various studies and reports, and a genuinely usual methodology pertaining to the topic of energy planning.

A series of semi-structured interviews were also carried out with Brazilian specialists in renewable energy, energy planning, and climate change, aiming to deepen and qualify the analyses under the aegis of energy planning inherent to the work. The questionnaires contained nine questions from different specific areas but kept the focus on energy planning. The interviewee was given the option of answering only questions of interest or all of them. The questionnaire was sent to 15 experts, and the answers were used as an extra guideline for the project. Moreover, among the topics covered were: (1) The importance of the transition from the energy matrix to one less carbon-intensive; (2) The energy vulnerabilities that Brazil may face in the next 20-30 years; (3) The mitigating policies employed by the country in tackling climate change; (4) Renewable energies that should be better exploited and the obstacles to doing so; and (5) The future of the oil industry in Brazil.

It is important to highlight that quantitatively, this sample of 15 stakeholders interviewed, of course, is not typically representative, especially from the perspective of the statistical sample. However, from the qualitative perspective, even in the context of semi-structured interviews, it was possible to use the answers as the basis for the generation of critical analyses. After all, the interviewees are the most cited (in international publications) Brazilian scientists working in the area of energy planning.

As a way of understanding the scenario in a more diverse and panoramic way, the questionnaires were sent to key actors in the country's energy sector, from both academia, the private sector, and the public sector. In this way, it was possible to gather information from professionals working at the World Resources Institute (WRI) Brazil, the German Cooperation for Sustainable Development (GIZ), and university professors. Among his backgrounds were Master's and Doctoral degrees in energy, a Doctorate in Transport Engineering with a focus on sustainability, a Doctorate in Energy Planning; and a Ph.D. in Engineering. The anonymity of the interviewees was agreed upon as a strategy to ensure greater freedom of opinion and expression, in addition to the possibility of receiving a greater number of answered interviews.

4. CLIMATE CHANGE, ELECTRIC POWER GENERATION, AND RENEWABLE SOURCES

4.1 Climate Change and Its Likely Impacts

The climate change process is no stranger to the planet, as it has undergone drastic variations in its environmental characteristics over the course of 4.6 billion years [1]; [9]. However, with the constant increase in anthropogenic GHG emissions, greatly aggravated since the Industrial Revolution, we have intensified this phenomenon on earth, causing the average temperature in the air and oceans to rise. GHG envelop the planet and absorb part of the infrared radiation reflected by the earth's surface, making it impossible for part of this energy to escape into space, superheating the earth as a direct consequence. It is worth remembering that the greenhouse effect is a natural phenomenon and necessary for the preservation of life on Earth, as it keeps the planet warm and habitable by allowing part of the solar radiation reflected back into space to be absorbed by the Earth [1]; [9]. It is the accumulation of GHG in the atmosphere that causes further energy retention and, consequently, the increase in the average of the surface temperature of Earth, which needs to be controlled – to avoid, for example, many deleterious consequences related to the climate extreme events. The main gases that contribute to this effect are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). It is important to note that CO₂ emissions are the primary cause of global warming until the end of the current century, not because of their ability to absorb energy, but because their gross amount is much greater than that of other GHG [10].

With the increasing warming of the atmosphere, which has been experiencing a decade warmer than the previous one since 1983, and the ocean accumulating more and more energy through increasing thermal expansion and melting of the polar ice caps, some points on the planet are already about 2.5 °C warmer than observed in the early 20th century. According to the IPCC, this is the case of Brazil, which throughout the length of the coast bathed by the South Atlantic presented growth above 2 °C, demonstrating the current deleterious effects of climate change [10].

In addition, the climate modeling published by the Ministry of Science, Technology, and Innovation (MCTI in Portuguese) states that extreme natural phenomena should occur and intensify in Brazilian territory by the end of this century. This is because the South Atlantic Convergence Zone (SACZ), responsible for most of the rainfall during the summer season in part of the country, tends to lose strength and reduce the number of its occurrences in this period. Because of this phenomenon, a reduction in rainfall is expected by 2100, mainly in the Midwest and Southeast regions of Brazil, where the deficit can reach up to 4 mm per day, a number similar to the drought recorded in the summer of 2014. This drought devastated the metropolitan region of São Paulo and imposed water cuts on the population. On the other hand, it is necessary to emphasize that the projections also indicate an increase in precipitation for the South Region, mainly in the state of Rio Grande do Sul, since an area of greater cloudiness should form during the summer over Paraguay, Uruguay, and part of Argentina, in addition to the Brazilian South [11].

Among the main possible impacts of these climate changes in Brazil, in addition to the synergy with other factors such as land-use change and natural effects like El Niño (potentially intensified), it is expected that there will be desertification in the Northeastern Semiarid Region and savannization of part of the Amazon, causing drastic losses of biodiversity [12]. This is due to the increase in temperature that should increase evapotranspiration, reducing the amount of water present in the soil available for plants [13]. It should be noted that the semi-arid and the Amazon represent two biomes that, during the last decades, have already suffered from the advance of the agricultural frontier in their native forests.

Due to the large spatial-temporal differences in the distribution of rainfall and long periods of drought, in addition to the already existing social vulnerability, the Brazilian Northeast can be placed as the portion of the country most affected by the action of climate change [11]; [14]. The existing vulnerability added to the temperature increase predicted by the IPCC, around 1.5 °C to 3 °C, should cause severe changes in the social, economic, and environmental spheres.

4.2 The Possible Impacts on Electricity Generation from Renewable Energy Sources in Brazil

The models developed by the MCTI [11] conclude that the water balance (BH) in all the country's hydrographic basins is negative (a worsening of the water deficit) in the scenario stipulated until 2100, with the exception of those located in the South region. Between 2011 and 2040, scenarios of an abrupt fall of BH are presented in all basins, in relation to the previous period (1961-1990) of the modeling. Such a phenomenon is expected mainly in the maximum values of BH and even in the basins that must have gained in the water balance until 2100. In the rest, where a drop is expected, there is a slight recovery

in the following period between 2041 and 2070, and again a drop for the last window, between 2071 and 2100.

This means that the Amazon River Basin, responsible for about 17% of total electricity production in 2018 [15], will have a reduction in production during this period. There are similar decrease prospects for the São Francisco River Basin, where average BH values reach zero and minimums are the worst in the country [11]. The work by Schaeffer et al. [16] points out that this region can register a drop of 23.4% in the A2 scenario (high emission) and of 26.4% in the B2 scenario (lower emission), corresponding to a drop in electricity production of about 7.7% by the year 2100 [16]. This situation may be worrying for two main reasons: the possibility of increasing regional water stress, which has been increasing; and the lower hydroelectric potential of plants located in the basin. This means that this region, which is already considered semi-arid, tends to have even more severe droughts until 2100 [16]; [17].

The South and Southeast Atlantic Basins, as well as the Uruguay River Basins (another major location responsible for hydroelectric production), will probably have their positive BH and, consequently, high energy generation. In the first, although the maximum values tend to decrease, the minimum and average values increase significantly. In the Uruguay River, where the best prospects are presented, BH should have the highest increase in the country, resulting in increased hydroelectric generation [11].

That said, among the five largest hydroelectric plants in Brazil, only Itaipu, located in Paraná, will have an advantage in the scenario presented since the other four large generators in the country are located in the northern region. It is worth mentioning that a drop in rainfall and, consequently, in the flow of the plants is not necessarily proportional to the decrease in production, since the reservoirs can mitigate this effect, controlling the use of generation. Therefore, part of this loss can be canceled out if the plant is well managed. Even so, it is estimated that the sector will suffer an average drop of 1.0% to 2.2% in its production until 2100 [16].

It should also be noted that the hydroelectric plants based on the "Fio d'água" technology (commonly those with lower production, up to 30 MW, which use a small amount of water) will be more affected than the others. Even though during the summer in the southern hemisphere, their production presents a surplus in the scenarios studied, it would remain in a deficit condition between May and September. This makes the dependence on large plants (above 1000 MW) even greater. That vulnerability combined with the rising energy demand would likely result in the inevitable complement of demand with the use of thermoelectric plants that, despite being less vulnerable to climate change, would increase CO2 emissions in the production of electricity [18].

Part of the literature, such as Whitfield & Cannon [19] and Xu & Singh [20], states that due to the fragility of hydroelectric systems, even small changes in temperature and precipitation, whose significance is often not statistically noticed, can cause variations in energy generation. For this reason, it is extremely important to assume a considerable number of models for climate change before carrying out the planning, as these can come to clash with one another. In this way, there is the possibility of being prepared to adopt management in which the demand can be supplied even with the lower reservoir flow, only having more efficiency in production.

Of comparable importance to the mode of hydroelectric energy production, the production of energy by biomass depends on fertile land and sunlight, two of the factors that exist in abundance in the country. Therefore, biofuels may be the least directly affected by the advance of climate change, especially ethanol production [16]. Crops have shown great adaptation to the most severe climatic conditions during the last decades through genetic changes in plantations and new irrigation techniques, following a similar trend; it is possible that ethanol is little affected by climate change [11].

Schaeffer et al. [16] and De Lucena et al. [17] argue that despite the possible loss of planting territory in part of the country, it will be offset by the emergence of new areas due to climate change. The one by Marin et al. [21] warns of the danger of water stress if the increase in temperature is not accompanied by an increase in precipitation.

With regard to the medium term, it is possible that by the year 2050, there will already be a small increase in the photosynthetic rate of sugarcane and the emergence of new potential areas in places where there were restrictions for cultivation, such as in the south of the country. [10]. For long-term scenarios, Marin et al. [21], which through IPCC projections of an estimated CO₂ concentration of around 720 ppm in the period between 2090 and 2099 and a temperature increase between 1.8 and 3.6 ° C, pointed to significant changes in the behavior of cultivation in the country, as well as important factors that should influence the culture.

This would occur due to the nature of their C₄ metabolism (preference for high irradiation and less need for water), which has a mechanism of concentration of CO₂. This mechanism causes its saturation in the leaves of C₄ plants. Therefore, they would be less affected by the increase in concentration of gas than C₃ plants (more common among plants and perform more photosynthesis in environments with lower solar irradiation). This mechanism would also allow, consequently, the reduction of transpiration when subjected to high concentrations of CO₂, providing greater adaptation to possible future global climate scenarios. The growth of crop photosynthesis is projected to be accompanied by growth in water use efficiency. In fact, this kind of efficiency is essential given the uncertainties about possible changes in hydrological cycles until the end of the 21st century. However, in the same way that the sugarcane crop must react positively to the increase in the concentration of CO₂ in the atmosphere, weeds can also have

a high photosynthetic rate, intensifying the competition between the economic crop and the invader [21].

There is also the possibility of genetic improvement as a way of adapting to a possible future climate of higher temperatures. According to Carvalho and Furtado [22], the country has the technological capacity to respond to the challenges imposed by global warming and climate change. However, there are limitations, such as: the immediacy caused by the need to develop new varieties on the market to reduce the sector's vulnerability to climate and pests; investment and structural difficulties. In the same context, we can mention the need for producer awareness about the significance of climate change and the complexity of the biological structure of the sugarcane plant, whose genetic map still needs to be further explored.

On the other hand, wind energy, despite being considered one of the most important mitigating responses to climate change, is highly vulnerable to its effects and may lose potential in the country, at least in the long term. In general, Brazil uses only a small portion of the wind potential within its borders and has not yet installed any projects for offshore energy generation (outside the continental shelf). As for the impacts of climate change on wind power generation, it was possible to identify a certain convergence between the conclusions obtained by Schaeffer et al. [14=6] and the Ministry of Science, Technology, and Innovation [11]. Both studies point to a slight increase in wind speed, mainly in the Northeast and in parts of the North and Southeast regions, concluding that these areas would still have good climatic conditions and good wind potential. However, the Ministry of Science, Technology, and Innovation warn that without a big leap in cost-benefit efficiency for the use of wind energy, this energy matrix can only be considered as a complement to hydroelectric generation.

The mentioned work, elaborated by Schaeffer et al. [16], also found very similar conclusions regarding the growth of wind potential in the Northeast, also highlighting that the country's wind potential, in general, should fall in the coming years, reaching up to 60% of production loss in 2100. Given that even with a possible occurrence of stronger winds in the interior of Brazil, as is also shown in the MCTI document [11], the speed would not reach a minimum of 6 m/s for the generation of wind energy. The study highlights the uncertainty of how climate change can affect biomes and vegetation, which is of great importance in wind speeds due to the friction it causes and its effect in locally mitigating the temperature, which in turn can generate consequent changes in pressure.

Another work whose results should be highlighted is that of De Jong et al. [23], being the most recent of those analyzed for the case of wind energy. In this study, it was possible to identify, in two of the analyzed models, a great increase in wind speed in the northern portion of the Northeast Region of Brazil especially in the state of Maranhão (with about 40%, reaching 8.4 m/s). In addition, in the Southeast Region, notably in the

interior Minas Gerais, as well as in all of Rio de Janeiro and Santa Catarina (about 30% increase, reaching 7.8 m/s). This growth in wind speed in the Southeast and Northeast of the country was also present outside the continental shelf, making the generation of electricity by the offshore wind modal gain more strength in the region. Such an advance would allow better use of the country's wind potential in the distant future.

Pryor and Barthelmie [24] provide a more general analysis of the likely impacts of climate change on wind energy. The main impacts highlighted, which can be applied to an analysis based on Brazil, were: variation in wind potential, greater occurrence of periods with winds above the generation capacity of the wind turbines, the occurrence of sudden gusts of air, and also variation in the density of the wind. However, after analyzing projections for the country, only the variation in wind potential was widely explored both by reviewed articles and by this work, with potential growth, or at least the maintenance of the current one, being the most likely scenario. The article in question also highlights the work already mentioned by Schaeffer et al. [16], when citing the problems of downscaling practice in the elaboration of models and projection of results. It is pointed out that this methodology may have caused the reduction of wind potential predicted in the work to be overestimated given that it was estimated via models adapted to a smaller scale use, losing precision in the process [24]. In fact, a 60% drop in the country's potential is much higher than the decrease projected in other regions of the world. This variation can be explained (speculated, in this case) by the overlapping of uncertainties and variability of global climate models, regional climate models, and, still, the use of historical data, possibly distorting the results of the projections.

In general, the projections for the effects of wind energy were the most conflicting among the sources analyzed, so the older works point to a slightly more pessimistic scenario. Due to the most recent and strongly supported data, pointing to a lower drop in wind speed and the question of overlapping uncertainties pointed out by Pryor and Barthelmie [24], the need to expand studies in the area for confirmation or refutation of the projections is clear. The wind energy modal can be considered one of the most complex to estimate future scenarios since, in addition to all the multiple factors that interfere with the wind, it can only be used by wind turbines within a specific speed window when they reach about 6 m/s to 9 m/s.

On the other hand, according to the scenarios designed by the MCTI [11], the intensity of solar radiation should decrease by 4% to 8% by the end of the 21st century, with some oscillations in some periods, however not compromising the generation of solar energy. That is, the period between 2011 and 2040 should have a considerable reduction in relation to the previous period, but with a slight recovery for the window between 2041 and 2070 and another drop, similar to the first,

for the last period between 2071 and 2100.

The most affected region will be the South, where the maximum radiation will reach 5,500 Wh/m², an already expected effect due to the high latitude and the rains that should be more intense in the region, which is why the hydroelectric sector will probably benefit if this is the case. Uncertain forecasts of increased rainfall at high latitudes came to fruition. The North, Northeast, and part of the Midwest will have the lowest losses, at around 4% by 2100, and will continue to be strategic regions for the use of solar energy. One of the explanations for this reduction effect is the increase in temperature across the country by at least 2° C, due to the decrease in available useful radiation, which negatively interferes with the energy generation capacity of some photovoltaic panels [11].

The work developed by Crook et al. [25], also points to similar results regarding the decrease in the intensity of solar radiation in the country. Although Brazil was not one of the focus countries/regions of the study, through available graphs it is possible to draw up estimates regarding possible changes. The aim of the article was to analyze how projected changes in temperature and insolation over the course of the 21st century will affect photovoltaics (PV) and concentrated solar energy (CSP). The HadGEM1 and HadCM3 models were used under the IPCC SRES A1B Scenario that describes a future world of rapid economic growth with a balanced use of energy generation with fossil and renewable fuels.

Results were obtained for reductions between 0 and 8% of photovoltaic potential and between 15 and 5% of the variation in total insolation over the country for the year 2080. Possible variations in the potential of concentrated solar energy are still present, a technology that has not yet been used significantly in the country, despite the existence of plans for implementation. The main points affected by the variation in insolation in the article were the north of the Northeast region, as well as the south of Brazil, both of which, according to the models' projections, should vary negatively. It is worth noting, however, that even with a 15% reduction in insolation over any part of the country, there would still be an enormous solar potential, so it should not negatively affect expansion plans for the technology [25].

Thus, it is still expected that Brazil will enter the 22nd century with at least 60% of its territory with average solar radiation of 5,600 Wh/m² day, which makes the use of photovoltaic panels in several regions possible [11]. In the same way that the "Luz para Todos" (Light for All) Program, created by the Ministry of Mines and Energy, installed some photovoltaic systems in the interior of Bahia, which contributed to the state's having the largest amount of solar energy generated in the country [15]; [26].

A more recent study by De Jong et al. [23], presents

contrasting and positive results, with regard to growth, on the total variation of irradiation over the country. This was a workshop focused on Brazil, specifically on the Brazilian Northeast, given its importance for wind and solar expansion. It was based on three models (HadGEM2-ES, MIROC5, and CANESM2), which underwent a downscaling process (scale reduction) to form the Eta Model, and data from INPE. This allowed greater precision in the projections, obtaining a spatial resolution of 20 km and intervals of 3 hours between the years 2006 and 2100, in low and high GHG emission scenarios.

In the publication, it was stated that the country should indeed suffer a loss of solar irradiation, but it would occur significantly only in parts of the northern and southern regions of the country in the high emission scenario. In the entire central region of the state of Amazonas, a drop of up to 3% in solar irradiation was identified, while the rest of the region would present an increase that would vary between 6% and 20%. The Southern Region of Brazil, especially the state of Rio Grande do Sul, would have an irradiation drop of up to 4%. The rest of the national territory either shows an intensification of solar irradiation or, in smaller portions, the maintenance of current conditions [23].

In any case, Brazil still presents ideal conditions for the dissemination of solar energy, mainly due to its geographical location, where its extreme does not reach 35° South latitude, which becomes even more evident since the country is at high latitudes, reaching 52° North [26]. That is, even in southern Brazil, the sun's rays fall less obliquely than in the European country, providing more power for solar energy generation. Few studies address the impacts of climate change on solar resources, especially in South America, and most of these studies are based on global or regional models, negatively affecting the accuracy of the results obtained.

5. DISCUSSION

5.1 Hydroelectrics

Analyzing the hydric balance in the general context of Brazil, a drop in electric energy production in hydroelectric plants is expected, since the deficit area tends to be much larger than that, which presents a surplus scenario, and in terms of production in this sector, BH is a preponderant factor for generation potential [11]. This drop in BH would be more accentuated in the São Francisco River Basin. Moreover, it could extend water scarcity from the social sphere to electricity production, further aggravating the vulnerability of the Brazilian Northeast. Furthermore, it is highlighted in the questionnaire responses that increased precipitation does not necessarily result in increased production capacity since the hydroelectric plant may not have the infrastructure for that level.

Expansion works or even construction of these projects in the southern region should not be a viable solution since the

population density of the states that comprise it is high and the socio-environmental impacts of such activities are strong. However, some of the interviewees agree that there should be close monitoring of this possible energy surplus in the region in the coming years. It should also be noted that the stipulated scenarios, mainly for the long term, are strongly subject to imprecision. For this reason, it is extremely important to use as many climate models as possible. At this point, it is evident that the state of the art in Brazil is limited since no specific case studies for hydrographic basins were found, whereas the international literature, which can better specify the impacts in certain regions.

It is also clear that run-of-river hydroelectric plants are vulnerable. Given the difficulty in approving and installing projects for large hydroelectric plants in the North Region (whose untapped potential inventories are the highest among all regions of the country), small hydroelectric plants, commonly of the run-of-river type, have been adopted as an alternative with less environmental impact, despite the lower production of electricity. The higher vulnerability of these smaller hydroelectric plants, indicated by the literature, demonstrates that the current path adopted by the government may not be sustainable in the long term, requiring further investigations.

5.2. Biofuels

On the other hand, biofuels may be the renewable resource least affected by climate change due to their great ability to adapt to severe climatic conditions already demonstrated in recent years and possible natural expansion of arable land. Whether for the production of ethanol or the use of sugarcane biomass for electricity production, biomass has shown good resilience to possible scenarios of higher concentrations of CO₂ in the atmosphere. Continuous investment in research and development is necessary to ensure the maintenance (and extension) of this resilience, which often ends up being impeded by its high cost. However, it is possible that there will be changes in the crop management system since weeds, pests, and diseases will benefit from the possible increase in atmospheric CO₂. In the same way that the sugarcane crop must react positively to the increase in CO₂ concentration in the atmosphere, weeds can have a high photosynthetic rate, intensifying the competition between the economic crop and the invader [21].

It is worth mentioning the possible emergence of conflicts between fuel production and refined sugar [27]. It is necessary to maintain a balance between the two products given the dynamics of supply and demand in the international market, preventing favoritism of one product over the other. The EPE describes the production of ethanol in the country as dependent on several factors. Among them is the international sugar price, highlighting the need to understand this correlation [8].

Although ethanol is certainly an alternative with lower GHG generation compared to gasoline, it can still cause several environmental problems. An existing obstacle is the higher opportunity cost of land exploration than conservation, encouraging the planting of sugarcane in legal reserve areas, especially in the case of large refineries that, in most cases, own the land and control the product's production chain, making the opportunity cost of not exploring even higher. In other words, the PES instrument for the protection of legal reserves is just enough to cover the profit that would be made on sugarcane (unprocessed material). However, a producer, such as a refinery, for example, would not be adequately compensated by the PES and would leave profit on the final products obtained from sugarcane, as in this case, sugar and ethanol [28].

Thus, while sugarcane biomass has good potential even in a future further impacted by GHG emissions, it is necessary to balance ethanol supplies with the environmental costs of land exploitation (avoiding deforestation of new areas) and with the possible intensification of conflicts with the food sector. Only in this way can biomass be treated as a favorable long-term option.

1.3 Wind and Solar Energy

The results for wind energy, on the other hand, are more uncertain and with little guarantee in the long term, thus making it a less secure option from an energy supply standpoint, even though it is renewable. This is because, in addition to the great uncertainties (greater than in other renewables), this sector can suffer from several synergistic impacts, especially with regard to local temperature and soil cover, as they are important factors for maintaining the winds. Even so, it should continue to be, in the coming years, an important complementary source of energy, especially in the northeast of Brazil during the dry season of the rivers, though this balance may be shaken by climate change in the region. In 2019, wind energy was responsible for 55,986 GWh, representing about 8.6% of the domestic supply of electricity, proving to be important in the Brazilian matrix [8].

Finally, the interviewees and the bibliography are unanimous in concluding that solar energy is the least used Brazilian potential due to the fact that Brazil, being a tropical country with a large part of the territory located in low latitudes and with an interior with little rainfall rate, has strong potential for solar industry advancement. Regulatory obstacles and the price of photovoltaic panels were identified as the main obstacles to expansion. Even though the literature is found to be unanimous in relation to the drop in solar radiation in the country until the end of the 21st century, the capacity to generate energy through this mode will still be strong, at least in the medium term, and should be explored

as an alternative to non-renewable sources. However, for this potential to be translated into a usable product, it is necessary to continue and expand current incentive practices, such as tax reductions, as well as investments in technology, especially as a decentralized alternative for regions where hydroelectricity may lose strength, such as the Brazilian Northeast.

Furthermore, investing in solar energy would be one of the best ways for Brazil to achieve its NDCs under the Paris Agreement. These goals are considered bold for a developing country, whose main commitment is to reduce greenhouse gases by 37% by 2025 compared to 2005. For this, the energy and electricity matrix would undergo a series of changes until 2030, including:

- Expand the supply of renewable energy in the energy matrix to a level between 28% and 33%, in addition to hydroelectric plants;
- Achieve 45% of the supply of renewable energy in the composition of the national energy matrix;
- Increase in electricity generation by hydroelectric plants to 71%;
- Participation of wind, solar, and biomass of at least 22% (combined) in electricity production.

5.4 The Ten-Year Energy Plan and the Role of the Current Federal Government

The most recent Ten Year Energy Plan (PDE), namely the PDE 2029, considered one of the sectoral plans for mitigating climate change, is effective in reaching almost all NDCs for the energy area. However, the participation of hydroelectricity in the generation of centralized electricity draws attention, since, according to the PDE, its percentage of participation in the matrix should decrease, keeping it even further away from the determined contributions. This possibility can be explained in at least two ways. Firstly, the difficulty in approving plans to expand supply for the next decade, which may not confirm such expansion within the next few years. Moreover, the greater use of thermoelectric plants, which are already used as a complement in terms of energy supply, and which may be even more requested [7]. In addition, when analyzing a pre-COVID-19 pandemic scenario, it must be understood that concomitantly with the reduction of polluting gases, Brazil also tries to reduce poverty levels, which makes the goal even more challenging. The increase in the economic power of the country and its population is, in a way, dependent on the growing consumption of energy, which makes the PDE even more relevant.

It is also necessary to emphasize that the current federal

government is not moving towards full compliance with the Brazilian NDC. In fact, the Brazilian government does not express this intention clearly since it has paralyzed the Climate Fund, a program that supports projects related to the reduction of greenhouse gas emissions, which was only resumed after a process in the Federal Supreme Court. In addition, the data shows that although the country has to reduce its net carbon emissions by 17% by 2025 compared to 2019, which is an achievable goal that has already occurred, the country has an increase in 12% of emissions compared to 2015, when it assumed the target. In other words, Brazil is close to achieving this goal in the year the Paris Agreement was ratified (2006) than in 2019 – when the country should have been moving towards the goal, and not the opposite way [29].

6. CONCLUSIONS AND RECOMMENDATIONS

The scientific community, as the most relevant strategy for mitigating climate change, has mostly considered the energy transition. In fact, the International Energy Agency, the International Renewable Energy Agency, and the United Nations Framework Convention on Climate Change have repeatedly pointed out that it is necessary to accelerate the decarbonization of the global economy. In this sense, the aforementioned transition (which consists of the migration of an energy matrix typically composed of fossil fuels - in particular, mineral coal, oil, and natural gas - to an energy matrix centrally composed of renewable energies) must occur based on the concomitant implementation of various actions. In such a context, it is opportune to highlight public policies, scientific and technological development, subsidies to renewable energies, effective involvement of the private sector, environmental education, and behavioral changes, among others. Moreover, it was emphasized that the most viable renewable energies (economically, technically, and environmentally, in particular) are wind and solar. These renewables have been widely incorporated into the energy matrices of developed countries (as is the case of the European Union, Australia, the United States, Japan, etc.), and in the case of many developing countries (such as China, India, Brazil, Chile, etc.).

Based on the development of the present work, it is possible to infer that the country has evident energy vulnerabilities in relation to climate change, especially with regard to the generation of electricity from large hydroelectric plants. This is due to greater evaporation and evapotranspiration, which fall at lower and lower levels of the related reservoirs. In fact, as analyzed in Section 3.2, the models developed by the Brazilian Ministry of Science, Communication, Technology and Innovations (MCTI) conclude that the water balance in all the country's hydrographic basins is negative (a worsening of the water deficit) in the scenario stipulated until 2100, with the exception of those located in the South region. In this context, the Amazon River Basin, which accounts for approximately 17% of total electricity production in 2018, will see a decrease in electricity production during this period. There are similar perspectives of decline also for the São

Francisco River Basin, another very relevant basin in terms of electricity produced in Brazil via large hydroelectric plants.

In general, the average yield of hydroelectric plants installed in the country should not be massively altered, but there are exceptions. The São Francisco River Basin, for example, is one of them insofar as the flow, due to the advance of climate change, would register a drop of 23.4% in the A2 scenario (high emission) and of 26.4% in the B2 scenario (lower emission). These drops, respectively, correspond to a drop in electricity production of about 7.7% by the end of the current 21st century. These numbers highlight the need to plan strategies aimed at technological and economic adaptations in view of the not negligible probability of significant reductions in electricity production and, concomitantly, water scarcity, notably in the Brazilian Northeast.

Even with a probable reduction in insolation over most of the country, due to the evolution of climate change, Brazil would maintain ample and safe potential for the expansion of photovoltaic solar energy. Like solar, wind energy has significant potential not yet used. However, it should suffer impacts of greater magnitude by the end of the current 21st century, with a probable drop of around 60% in the production of electricity. Only the extremities of Brazil would remain as options for expanding the energy supply, especially the coastal region of the North Northeast, where most of the potential should be concentrated, and parts of the South region, with a much lower potential than the north of the Northeast region (but, it should be noted, still not negligible).

Sugarcane biomass, notably due to the traditionally relevant Brazilian production of ethanol, shows great potential economically and technologically. Therefore, this bioenergy, mainly in the Brazilian case, can be considered a viable renewable energy source, even considering global warming. However, as analyzed by the stakeholders interviewed, since investments in the development of even more sustainable and efficient technologies, both in the production and in consumption of ethanol, an analogous situation is also verifiable in the case of biodiesel. It should also be noted that sugarcane biomass has the potential to be improved, in terms of production, due to climate change. Therefore, if the planting of sugarcane is not carried out accompanied by the deforestation of conservation areas, it will be a highly viable option, particularly in the case of Brazil and other countries characterized by typically favorable climatic conditions for planting sugarcane. The aforementioned feasibility is linked to the future of the combustion engine and even to the automobile industry, at least as long as an alternative that causes as many or fewer negative externalities in the context of climate change does not reach the same potential on a scale (which may be the case of electric vehicles, for example).

Therefore, the role of the NDCs assumed by Brazil

until 2030 under the Paris Agreement represents, to a large extent, a fundamental leverage instrument for short and medium-term actions in favor of facing climate change by the country. These are effectively carried out. Thus, in the case of Brazil, as long as public policies that prioritize the mitigation of such changes are outlined and flow within Brazilian society, even in view of the typical intrinsic renewability of the Brazilian energy matrix, the energy transition coupled with the confrontation of global warming is something that we can consider doable. However, if political aspects of a negationist nature are brought into relation to climate change, or even in relation to science and the role of biofuels in the face of this environmental problem of global magnitude, there will be no prioritization in terms of public policies.

Furthermore, Brazil's commitments in the context of the Paris Agreement, that is, the country's NDC in the case of electricity generation, are already included in the most recent Ten Year Energy Plan -PDE 2029-, which compares greater participation of different renewable sources in the composition of the primary energy supply and electricity supply matrices. If the PDE 2029 is complied with, there is a clear trend towards co-benefits for the country. In such a context, it is opportune to highlight an improvement in the country's international image due to the prospect of an eventual return to the leading role formerly exercised within the scope of multilateral efforts led by the United Nations in favor of adaptation and mitigation of climate change. Moreover, there may be a very probable greater attractiveness for international investments in the case of several segments of the national economy, as well as a greater probability of raising funds from abroad to protect the Amazon Rainforest and to reduce fires in this biome and in Pantanal's biome, a tendency to the appreciation of Brazilian commodities that are characterized by sustainable production or that are making efforts in this direction (as in the soybean and coffee sectors, for example), etc.

Finally, it is important to highlight that the process of analyzing projections (or scenarios), which characterizes the present study, involves, by nature, uncertainties and, in a correlated way, a margin of error. Therefore, such projections should not be treated as faithful representations of the future, but they certainly make it possible to take the first steps. Therefore, in this case, towards a more prominent role for Brazil both in the context of the energy transition and in terms of tackling climate change and its deleterious consequences for the human race and, in a realistic and holistic view, for all the biosphere. This, of course, without ignoring the large economic losses that may arise, increasingly, in the face of inaction or even ineffective action against such changes in the Earth's climate. This type of methodological choice, through critical analysis of scenarios, represents an essential tool

in the construction of a more resilient future in the face of the challenges associated with climate change that should intensify in the coming decades.

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