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ANALYSIS OF THERMAL POWER PLANTS COOLING SYSTEM IN REGARD OF WATER RESTRICTION

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Abstract. *Brazil is one the countries with the largest use of renewable energy on its electrical energy matrix worldwide, mainly due to its high use of hydropower plants to generate electrical energy. However, environmental restrictions have increased over past years, limiting the construction of new hydropower plants, mainly those with accumulation reservoirs. Thereby, to increase the generating capacity of electricity generation, the participation of wind power, coal, natural gas thermal power plants, and combined cycle power plants have expanded. Knowing that most of the Brazilian thermal power plants use the wet cooling system, a decrease in water availability can cause interruptions or shut down in the operation of the plant. The water scarcity is caused, mainly by climate changes that can result in water stress, such as the water crisis of 2014-2015, and a region with water stress is more vulnerable to face instability in the electrical generation by thermal power plants. Therefore, this paper analyses the Brazilian thermal power plants operation susceptibility in different regions, with regard water restriction.*

Keywords: *cooling system, thermal power plants, cooling towers, water use*.

1. INTRODUCTION

The electrical energy productions use water regardless the source it comes from, either directly (such as the hydraulic turbine movement, steam production for the steam turbine, cooling systems) or indirectly (such as fire system prevention, water supply for employees) (Macknick, *et al.*, 2012). Likewise, the water restrictions have limited the electrical power production, which has impacts on energy and security.

Water constraints have happened on a global scale, and hydropower generation has already been affected directly, as it has occurred in Brazil in 2015, where four million of people were affected by electric power rationing, and India in 2012, where a blackout lasted two days and affected 600 million people (Roehrkasten, *et al.*, 2016). In both Brazil and India, the electrical demand has raised, and specifically, in Brazil, the demand has increased due to high temperatures that led to the large use of air conditioning.

Nuclear and coal are also affected by water restrictions just as hydropower generation, in which they had to operate at reduced load or even had to pause the operation because of water restrictions. These restrictions have happened all over the world, and climate changes are expected to aggravate the water dispute because it the forecast is to increase temperature, increase in the frequency and severity of droughts, reduce in rainfall.

Together with water restrictions, the demand for water has grown, and by 2050, more than 40% of the world population will be living in areas with severe water stress (Roehrkasten, *et al.*, 2015). In Brazil, the water crisis increases the participation of thermal power plants in the electrical generation mix, in which the thermal generation reached peaked of operation during this crisis. Yet, because these power plants also use water in a generation, the water constraints may affect the operation of the plants. Therefore, this paper consists in a diagnostic about the vulnerability of thermal power plants operation regarding water availability.

2. BRAZILIAN THERMAL POWER PLANTS

The Brazilian electrical energy matrix has a large usage of renewable energy, in which 64.1% refers to hydropower plant (MME-SPE/N3E, 2017). However, the participation of hydropower plants in the generating capacity for electrical power generation has decreased since 1990, due environmental restrictions that aim to protect the native forest, the riverine communities and Indian lands.

Between 2000 and 2012, 42 hydropower projects were approved and among that, only 10 projects were storage hydropower, which represents 6.7% of the generating capacity. The other projects were run-of-river hydropower, which indicates that these are gradually replacing the storage hydropower (Tancredi and Abbud, 2013). Therefore consequence of that, the energy stored has decreased, which increases the vulnerability of the system, especially during water scarcity periods.

Throughout the severe water scarcity that occurred between 2000 and 2001, it was necessary to use thermal power plant generation as an emergency program, to complement the electrical energy demand. During this period it was adopted the electrical power rationing and, also happened several events of blackouts, which led the government to create programs to stimulate the use of renewable energy. The Alternative Energy Sources Incentive Program *(Programa de Incentivo às Fontes Alternativas de Energia Elétrica, PROINFA)* was created in 2002 with the objective to increase the diversity in electrical energy matrix, through project implementations of wind power, biomass power, and small hydropower.

The generating capacity evolution between 2002 and 2016 is shown in Fig. 1, in which is considered only the sources with representative participation in electrical energy matrix. The participation of wind power had the highest growth in comparison with the other sources, especially from 2010.

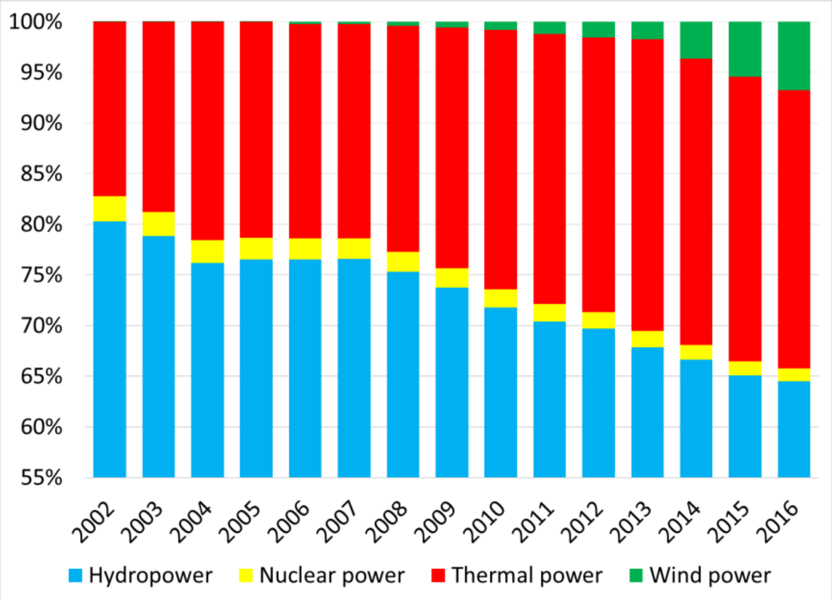


Figure 1. Generating Capacity evolution between 2002 and 2010.
Source: Modify from from EPE (2015a).

Despite the expressive growth, the participation of wind power generation only became relevant in 2014, because even though the wind farms were installed, the electrical grid was not connected with transmission lines. On the other hand, the thermal generation has increased gradually its participation in the electrical energy matrix, as is shown in Fig. 2, which considers only the relevant sources in the electrical energy matrix. During the 2014-2015 water crisis, the participation of thermal generation was 23% of the total electricity generated.

Figure 2. Electricity generation by sources between 2002 and 2016.
Source: Modify from ONS (2017).

The 10-year Energy Plan 2024 shows that the participation of thermal plant plants in the generating capacity will decrease from 14.8% to 14.3%, even though Fig. 1 and 2 show that the participation of thermal generation has increased over the last years. The projection for 2024 indicates a growth of 10 GW in generating capacity, indicating the construction of new thermal power plants, as is shown in Table 1.

Table 1. Generating Capacity evolution in the electrical energy matrix between 2014 and 2024 (EPE, 2015b).

Brazil electrical generation by type	**December/2014**	**December/2024**
Hydropower	90 GW (67.6%)	117 GW (56.7%)
Nuclear power	2 GW (1.5%)	3 GW (14.3%)
Thermal power	20 GW (14.8%)	30 GW (14.3%)
Biomass power	11 GW (8.3%)	18 GW (8.7%)
Small hydropower	5 GW (4.1%)	8 GW (3.8%)
Wind power	5 GW (3.7%)	24 GW (11.6%)

The participation increase of thermal generation in the Brazilian electrical energy matrix is directly linked with the water availability on reservoir storage of hydropower plants. In comparison with hydropower plants, the advantages of the thermal power plant are the speed of construction, operation readiness, the proximity of energy consumers and lower water consume. However, the fuel price and the carbon dioxide emission are disadvantages of the energy use.

In Brazil, the Brazilian National Interconnected System *(Sistema Interligado Nacional, SIN)* is responsible for the public service of electrical energy generation and transmission, with exception of the state of Roraima. The SIN has the objective to assure the electrical energy demand with the minimal operational cost so that hydropower plants are preferable to be put to operate because of its low operational cost.

However, when hydropower generation is not enough to supply electrical energy demand, the thermal power plants are put to operate. The thermal power plants operation in Brazil is intermittent and, its determination is based on the following variables: the water level in hydroelectric reservoirs, the rain forecast, the thermal power plants fuel and operational cost.

Presently, according to Generation Information Bank *(Banco de Informações de Geração, BIG)* da ANEEL *(Agência Nacional de Energia Elétrica)* (2017), there are 2928 thermal power stations operating, 33 stations under construction and 177 stations are on project. In this database is only consider the stations with permission to operate given by ANEEL (ANEEL, 2017).

The electrical energy generated in Brazil has two destinations, whatever is its source of generatino: it can be used by the company that owns the plant or it can commercialize on the electrical energy market. The self-producers *(Autoprodutores, APE)* can be a physical person, a legal person, or a consortium, in which the electrical energy production aims its own consumption. The surplus energy can commercialize with ANEEL authorization.

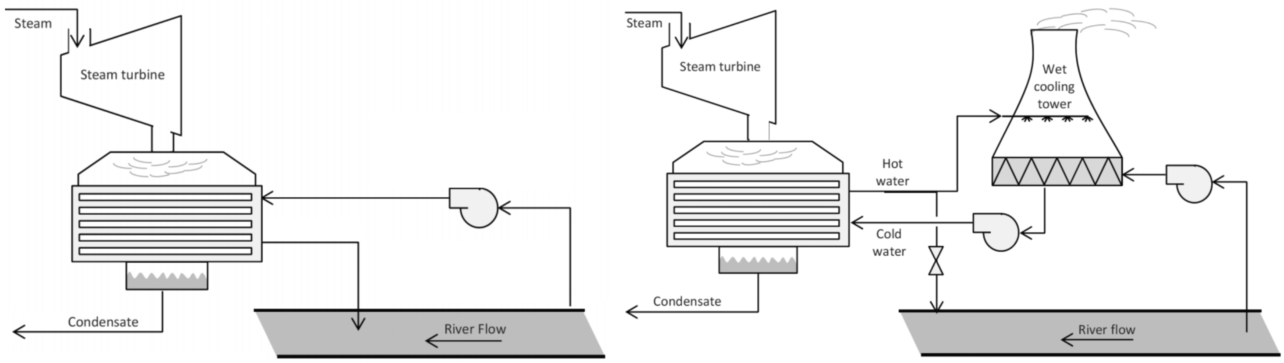
The independent energy producers *(Produtores independentes de energia, PIE)* are agents that produce electrical energy to commercialize it, and the generation is the responsibility of the producer. The public authority may delegate the provision of public services through a public service concession *(Serviço público, SP)*, which can be given to a legal people or a consortium (ANEEL, 2012; ANEEL, 2015).

2.1 Thermal power plant cooling system

The water usage in a thermal power plant can be classified as use or consume. Water use is a situation when there is a return of the water withdrawal to its source and water consume is characterized by the non-return of the water to the source. The operation of coal and natural gas with combined cycle power plant utilizes water for steam production and cooling system.

The cooling system is a set of accessories and equipment in charge of cooling and condensing the steam that was expanded in the turbine and, after that, to transfer the heat to the ambient as efficient as possible, without compromise the efficiency and safety of the plant. To do so, it is used a heat exchanger (condenser) to cool the steam and transfer the rejected heat to the water or to the air, depending on the working fluid of the condenser.

The cooling water from the condenser can be discharged directly into the environment (once through system), shown in Fig. 3 (a) or it can be cooled and return to the cooling system (closed system), shown in Fig. 3 (b). The once-through system is more efficient than the closed system because the cooling water that returns to the system with a temperature higher than the ambient water temperature.



(a) (b)

Figure 3. Cooling systems (a) once-through system; (b) wet closed system
Source: Modified from International Atomic Energy Agency (2012)

Besides, the water consumption of the once-through system is lower than the one of the closed system, with an evaporation rate by 0.5% to 2% (EPRI, 2013). The closed system is classified as wet (cooling pound, mechanical or natural cooling towers) or dry (air-cooled condenser or dry cooling tower). Once through system and wet cooling tower are the most popular cooling system in EUA (DOE, 2014).

The huge amount of water used by thermal power plants using once-through cooling system is one of the main incentives to convert it the system for closed system. In the USA, the EPA (Environmental Protection Agency) established the Clean Water Act, in 1973. In section 316 (b) it was determined that thermal power plant should use the best technology available to minimize environmental impacts associated with the cooling system type (Madden, *et al.*, 2013). In Brazil, the Resolution CONAMA n. 430 (Brasil, 2011) regulates the wastewater discharge, in which is determined that the maximum discharged temperature is 40 °C and the temperature gradient cannot exceed 3 °C in the mixture zone.

Cooling towers are classified in natural or mechanical, and these can be classified in forced or induced. The towers are more efficient in heat transfer than the cooling ponds or dry cooling system. Besides, they have a lower withdrawal rate (about 97% lower than once through system) (Harvey, 2008), but they have a higher water consumption (about 83% of total water consumption of the power plant) (Elcok, 2011). Besides, the closed system affects the power plant operation, causing a reduction in overall efficiency by 2% to 5% (World Nuclear Association, 2017).

2.2 Water restriction and limitation on thermal power plants

Water stress is defined by European Environment Agency (2017) as the condition in which the amount of water available is not enough to supply the water demand. Therefore, the water stress not necessarily indicate that the region has a history of drought events or even that the decrease in the amount of water volume, but it can also indicate that the demand may be increased in a way that it can be supplied.

Kablouti (2015) says that water restriction on thermal generation can be classified as i) increase in temperature of the water withdrawn by the cooling system; ii) reduction in freshwater availability for the cooling system; iii) increase in water level that can lead to inundation and floods.

The turbine backpressure increases as the temperature of the cooling water increases, which results in less work produced. Consequently, less electrical energy is generated, the overall efficiency is reduced, and the station costs increase. Besides, as the temperature of the water withdrawn increases the temperature of the water discharged approaches or even exceeds the limits of the environmental legislation (Woodruff, *et al.*, 2005).

The consequence is the reduction or, in some cases, the interruption of the thermal power plant operation, as it happened in France, Germany and Spain (Roehrkasten, *et al.*, 2015), India (Patel, 2016), USA, in the states Connecticut and Illinois (Wald, 2012), Vermont, Ohio, Chicago, Alabama (Krier, 2012) Texas (Scanlon, *et al.*, 2013).

The reduction in freshwater available for thermal power plants is caused by the reduction in the river discharge used by the thermal power plant. The reduction can be caused by climate events, such as droughts and rainfall reduction; another cause of water reduction is the increase of water users that can aggravate water conflict. Some examples of thermal power plants that had it operation reduced are found in Índia (Patel, 2016), USA, in the states Texas, Wyoming and Georgia (McCall, *et al.*, 2016) and Australia (Roehrkasten, *et al.*, 2015).

The climate changes are the main responsible for the water level of the oceans, which put at risk the thermal power plants located in coastal areas. In the USA, a great number of stations are located on the east coast, in which at least 13 can be affected by inundation or floods.

In Brazil, climate changes will worse water restriction in almost all regions, because the forecast is high temperatures and rainfall reduction. In Amazon (North Region), it is expected an increase in temperature between 1°C and 1.5°C and a rainfall reduction between 25% and 30% until 2040. In Caatinga (Northeast Region), the forecast is a temperature between 0.5°C and 1°C higher and a decrease between 10% and 20% in precipitation until 2040. In Cerrado (Center West Region), the increase of temperature is between 5°C and 5.5°C and a decrease in rainfall of between 35% and 45% until 2100. In Southeast, it is expected an increase between 0.5°C and 1°C and a reduction of 10% in precipitation. And, different from other regions, in Pampa (South Region) the forecast is an increase between 5% and 10% in precipitation and an increase of 1°C in temperature until 2040 (Alisson, 2013).

Moreover, in addition to the restrictions cited it can be added the water use charge, which is an instrument of water resources management of National Water Resource Policy, established by the National Water Law (Law n. 9433/97), which objective is to incentive the rational water use. The water use charge is a financial charge used to cover water infrastructure, such as the construction of channels (ANA, 2017a). Currently, the charges are done in federal rivers from six basins and in state rivers from the following states: Rio de Janeiro (RJ), São Paulo (SP), Minas Gerais (MG), Paraná (PR), Pará (PA), Ceará (CE), Bahia (BA) and Federal District (DF) (ANA, 2017a; ANA, 2017b;).

3. METHODOLOGY

In this paper, it is considered only the thermal power plants that operate with Rankine Cycle that uses a cooling system and the energy destination is PIE or SP. The APEs were disregard as well the small power plants and the power plants that the cooling system water usage negligible, such as the plants that use alternative fuels.

The data from 39 thermal power plants was compiled from BIG, in which 31 plants are operating, 3 plants are under construction and 5 plants are on project. Classifying the stations by the fuel, they can be divided in 15 uses coal as fuel, 22 natural gas with combined cycle and 2 nuclear power plant.

The power plants locations were determined by BIG as well, and the cooling system and the water source used by each station was determined one by one using Google Earth. The information was confirmed using available data, but in cases that were found a contradiction between the information collected it was adopted the criteria of using the most recent information. Nevertheless, it was not possible to determine the water source of one station (Romulo Almeida I Power Station, located in Bahia).

Among the 39 stations, only the ones that use freshwater were availed by the water vulnerability due to the level of water stress in which the basin is. The determination of the basin condition was done through the interactive map "Water Balance (WB)" that relates the demand and supply of water. This system is available on National System of Water Resources Information *(Sistema Nacional de Recursos Hídricos, SNIRH)*, a system under the management of the National Water Agency *(Agência Nacional de Águas, ANA)*.

The interactive map uses a methodology developed by the European Environment Agency, the Water Exploitation Index (WEI). The WEI is calculated by "the mean annual total abstractions of freshwater divided by the mean annual freshwater resources" (European Environment Agency, 2016). The region is classified as excellent, when WEI values are lower than 5%; values between 5% and 10% indicate comfortable situation; values between 10% and 20% indicate worrying situation; values between 20% and 40% indicate a critical situation; and values higher than 40% indicate a very critical situation (ANA, 2017c). The regions that are in a worrying situation, critical situation and very critical situation are in water stress condition; therefore, the power plants located in these regions are classified as the at-risk situation.

Figure 4 shows the Brazilian thermal power plants location in the QWB map; the power plants classification was made visually for the water vulnerability. Due to the lack of information available, it was assumed that the data for the thermal power plants analyzed in this paper was obtained from the literature review for each station made by the authors themselves.

Besides, the capacity factor data came from the newsletter Electric Power Generation Generating Capacity of Energy and Mining Minister for the years 2014, 2015 and 2016. In these newsletters, it is listed capacity factor of the ten largest stations for the respective year and the average capacity factor of Brazil; the capacity factor of the stations that were not listed was assumed as the Brazilian average of the year. Lastly, the electrical energy production was calculated using the capacity factor and the generating capacity for each station. For the natural gas power plant, it was calculated only the production of the steam turbine.

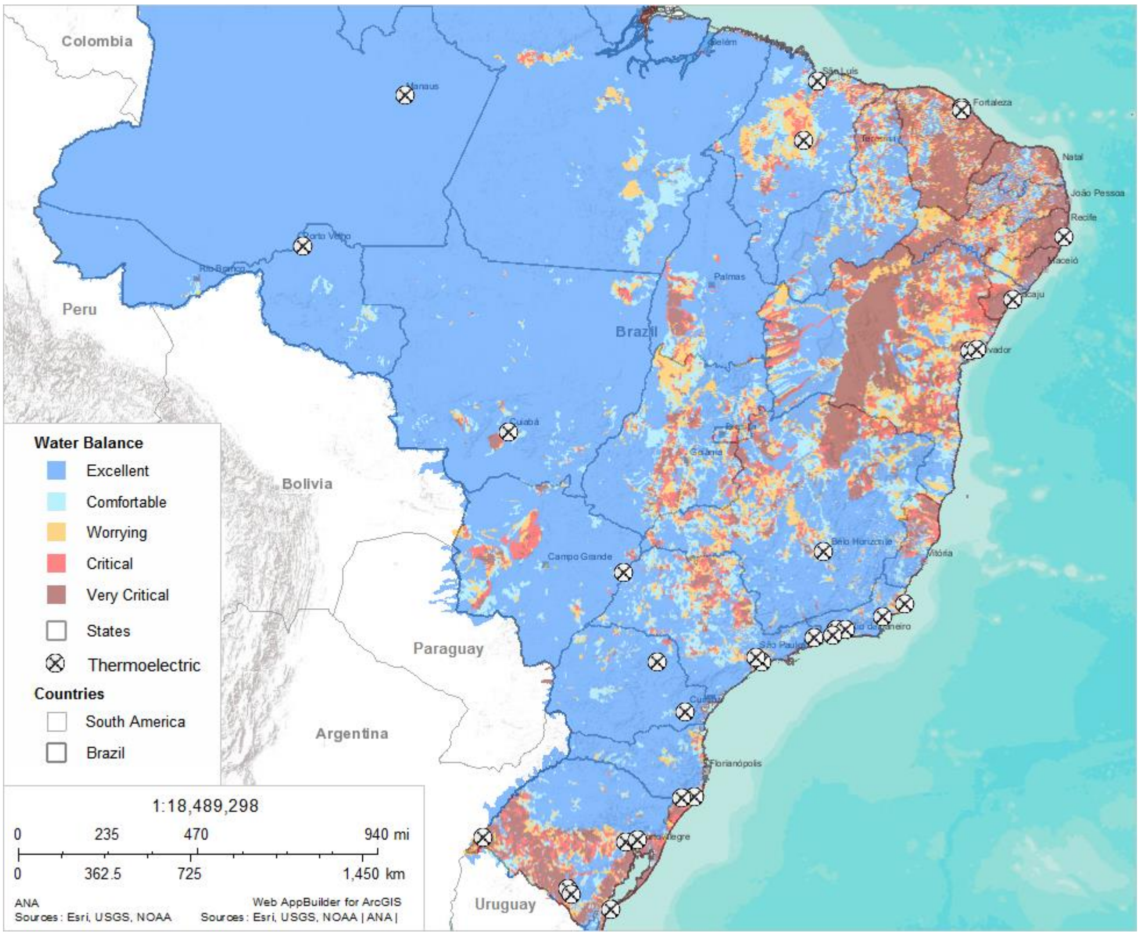
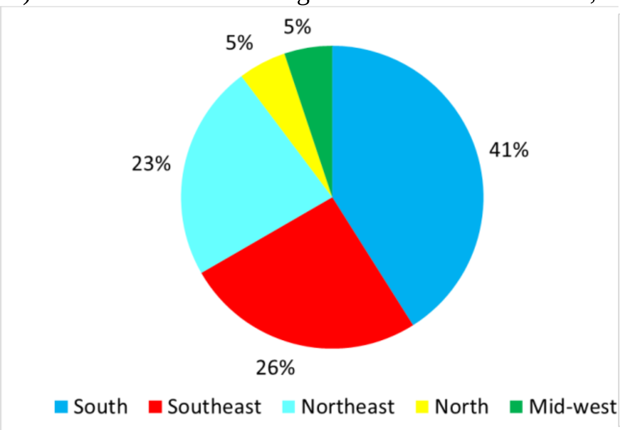


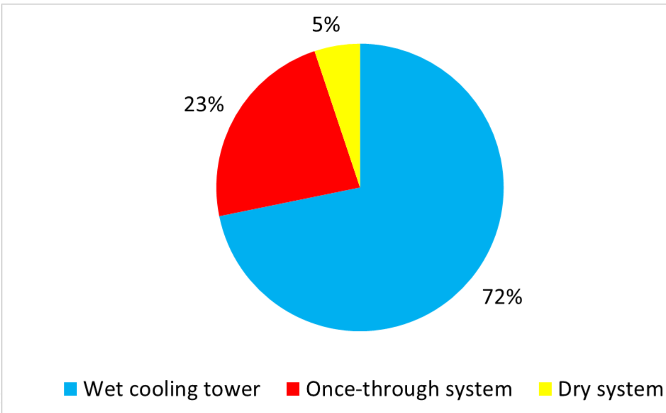
Figure 4. Water Balance (Brazil).
Source: Modify from ANA (2017c).

4. RESULTS

The distribution of the power stations by region is shown in Fig. 5 (a), in which is shown that the South (S) region has the larger number of power plants with the cooling system, followed by the Southeast (SE) region. These two regions concentrated the higher number of electrical energy consumers. In Southeast, in which São Paulo (SP) and Rio de Janeiro (RJ) are the states with the highest number of consumers, both residential and industrial ones.



(a)



(b)

Figure 5. (a) Distribution of the power plants by region; (b) Power plants quantitative classification by the cooling system.
Source: Elaborated by authors.

The cooling system most used in Brazil are the wet cooling tower and once through system, as it is shown in Fig. 5 (b). The water source most used is freshwater, which is 83% of the total because most of the Brazilian stations are not in the coastal area.

Among the operating power plants, 71% started to operate from 2000, which explains the choice for cooling systems that have the best technology available, considering the lower water withdrawn. Considering the plants under construction and the plants on project, only one has once-through cooling system and one uses dry cooling tower, wherein the project was modified after being approved due to economic factors.

Figure 6 shows the quantification of the thermal power plants situation, as they were classified according to Fig. 4. The power plants that use seawater in the cooling system and the plants that use dry system were not considered in this analysis because they are not affected by water restrictions.

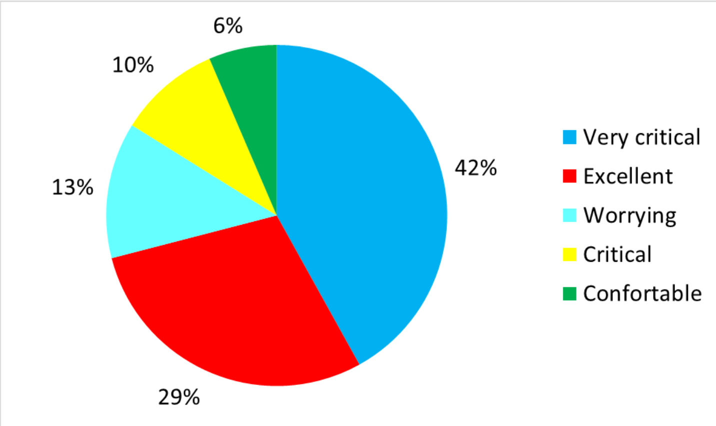


Figure 6. Classification of thermal power plants by WEI.
Source: Elaborated by authors.

In Fig. 7 it is shown the distribution by region of the power plants at risk situation, which are 16 stations. These stations correspond to 44.3% of the power among the all the stations analyzed in this paper, in which 65% use natural gas as fuel and 35% use coal. With regard to the situation of the power plant, 65% are in a very critical situation, 15% are in a critical situation and 20% are in a worrying situation; besides, 90% use the wet cooling tower.

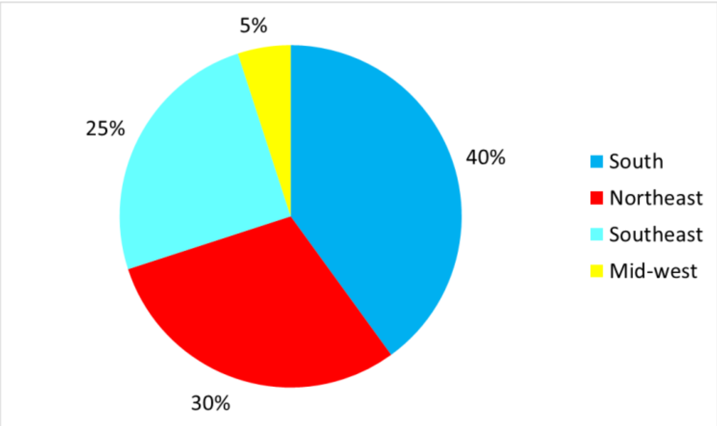


Figure 7. Distribution of the power plants at risk situation by region.
Source: Elaborated by authors.

The average capacity factor of coal power plants was 0.67 in 2014, 0.65 in 2015 and 0.56 in 2016; for natural gas power plants, it was 0.73 in 2014, 0.72 in 2015 and 0.43 in 2016 (MME-SPE/N3E, 2015; 2016; 2017). In years before the water-energy crises, the capacity factor for thermal power plants used to be lower the values presented. Specifically for 2012, the average for coal plants was 0.48 and for natural gas plants, it was 0.47 (MME-SPE/N3E, 2015).

The electrical energy production was calculated using the capacity factor, only for operating stations. In 2014, the generation of the plants analyzed was 39.2% of the total Brazilian thermal power plant production, in 2015 it was 38.8% and in 2016 it was 50.1%. Comparing only the plants at risk situation, the production was 14.1% of the total thermal generation in Brazil in 2014, 14.2% in 2015 and 18.9% in 2016.

5. DISCUSSION

The natural gas with combined cycle power plants uses and consume a lower amount of water than coal power plants (Macknick, *et al.*, 2012). Therefore, the concentration of coal power plants in South region is a potentially problematic scenario because the south of the region is in a critical or very critical situation.

The state of Rio Grande do Sul (RS) has coal reserves, which motivate the construction of power plants in the region. There are three projects of coal power plants for the state, in which two will use a closed system. However, the decision to use cooling tower is already being questioned by environmental non-profitable organizations because they consume a large volume of water and this region where the plants are planned to be constructed are in worrying or very critical situation. An option to decrease the water withdrawn is the substitution of the wet closed system by a dry cooling system

The Sul Catarinense Power Plant (Usitesc) that will be constructed in Santa Catarina (SC) (South region) chose to substitute the wet cooling system by a dry one to avoid the construction of a dam for water withdrawn. Even though the region where the plant will be constructed is not at risk situation, this change will reduce the water consumption in 90% (Nandi, 2006), indicating that it is possible to do it for new plants.

The Northeast region has the second larger number of plants located in regions at risk situation, wherein two plants located at the state Ceará (CE) uses coal as fuel, Pecém I and Pecém II. The cooling tower of these two plants uses freshwater; however, it is important to note that Ceará has adopted the water use charge as an instrument of water resources management since 1996 (Araújo e Campos, 2009).

The water use charge has increased since its implantation and, in addition to this charge, since October 2016 it was established an extra rate, the Emergency Water Charge *(Encargo Hídrico Emergencial)*. The emergency rate is higher than the regular charge, which increased by eight times the Pecém I and Pecém II water costs, which was R$ 1,308 million from the regular charge in September 2016 plus R$ 9,125 million from emergency water charge (Estadão Conteúdo, 2016). Both plants Pecém I and Pecém II have a water consume equivalent to 6% of daily consumption of the state capital, Fortaleza-CE. In 2016, the main reservoir used for water withdrawn by the power plants reached 5% of total capacity (Borges e Warth, 2016).

The company that owns and operates Pecém I and Pecém II started to invest in groundwater withdrawn and desalination projects to mitigate the water restriction (Estadão Conteúdo, 2016). Nonetheless, it is important to note that the power plants are located 6 km from the Pecém Port, so seawater withdrawn is used in the cooling system would be the more economical option. In Porto Itaqui Power Plant, located in Maranhão (Northeast region), a power plant owned by the same company that owns Pecém I and II, it is used seawater in the cooling system after water treatment.

The situation described in Ceará reveals a peculiarity of electrical energy generation in Brazil, in which the use of thermal power plants for long periods is associated directly with the water crisis, as well the water use charge. The reduction in the power plant operation and the possibility of pausing the operating were not only caused by water shortage but also due to economic reasons since the water use charge was not considered an operational cost of the plant.

Furthermore, the replacement of wet cooling system by a dry system has a higher impact on the power plant production in Northeast region than in the South region, due to climatic conditions, such as temperature and humidity. The efficiency penalty can be between 10% and 25% in hot weather (Mills, *et al.*, 2012), which can be prejudicial to electrical energy generation in the state since Pecém I and Pecém II are responsible for 60% of total power consumed in Ceará.

There are a large number of basins that already has water conflicted located in Southeast region, especially in the metropolitan areas of São Paulo and Rio de Janeiro. The power plants analyzed in this paper located in this region uses natural gas as fuel, so the impact of water withdrawn and consume are reduced. Yet, it is important to note that the power plants located in this region have a high capacity factor, which indicates that the water usage is frequent, the contrary of other regions in which the capacity factor have a larger amplitude.

The Mid-West region has only two plants analyzed in this paper, wherein one of them are located in a metropolitan area with the very critical situation. The North region has only two power plants analyzed in this paper and both are in regions with the excellent situation, according to with the water balance.

This region has the larger number of small thermal power plants in Brazil because of it is composed of isolated systems, due to the dense vegetation and lack of infrastructure. These factors encouraged the construction of diesel oil power plants because the speed of construction and favorable logistics of the region to supply this fuel (Grandes Construções, 2011). Still, even though there is a high concentration of power plants, the North region has only a few areas in the critical or very critical situation, so this region is the more suitable for the construction of new thermal power plants.

The electrical energy production by Brazilian thermal power plants reached a maximum peak in 2014 and 2015 due to the water crisis that occurred in this period. Even though there was an increase in power production, the plants did not report interruption or pause in operation due to water restrictions, with the exception of Pecém I and Pecém II. Still, it is important to note that 51% of 39 power plants analyzed in this paper are located in regions at risk situation, in which 20% are under construction or on project.

The forecast due to climate change is, in general, that there will be a reduction in rainfall, which indicates that the interference on thermal power plant operation due to water restriction will become more common. In addition, the increase in temperature will affect the power generation, due to the increase in water temperature used by the cooling system and due to the increase in the electrical energy demand.

6. CONCLUSION

The electrical energy generation in Brazil has been changing due to the growth in power demand, and, in addition, to the transformation in the electrical energy mix. The decrease of storage hydropower has decreased the energy storage capacity, which has increased the necessity of alternative sources to the traditionally used in Brazil, this is, thermal power plants and wind power plants.

Moreover, the water restriction events are becoming frequent, in which the low water availability is a result of climate changes that have been happening all over the world. The rainfall reduction in association with high temperature is one of the main reasons for low storage capacity, which also prevents the recuperation of the water level. Thereby, the operation of thermal power plants of a period longer than the Brazilian usual has happened often, as in the water crisis in 2014-2015. Still, the thermal power plants have not had its operation reduced or paused due water restriction, with the exception of Pecém I and Pecém II.

The water stress has intensified in Brazil, due to the growth in water demand and to climate changes, so that power plants located in regions at risk need to evaluate the possibilities of reduction in water dependency by the cooling system. In this regard, it is necessary to evaluate the best technology to be used (in the case that the power plant is still on project), reevaluate the plant operation and, if it is possible, consider the replacement option for the cooling system. Any change in the cooling system, it can be the complete replacement or only the change in the operation of the power plant, most consider the impacts in electrical energy generation (or, in the plant efficiency), besides the environmental impacts in the region where the plant is located.

7. ACKNOWLEDGEMENTS

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