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Climate impact on combined cycle thermoelectric power plant in hot and humid regions

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ABSTRACT

Thermoelectric power plants have been designed to operate in ISO conditions, similar to the temperate climatic conditions of the northern hemisphere. Thus, some equipment used in tropical regions operated outside the ideal conditions, with high relative humidity and ambient temperature. This ends up impairing its efficiency and maximum generation. This paper presents the analysis of 2020 and 2021 hourly electric generation and climatic conditions data for 2020 from the gas based combined cycle Cuiabá Thermoelectric Power Plant, located in the state of Mato Grosso do Sul, center-west region of Brazil. The main objective is to present and discuss the correlations between meteorological conditions and power generation in the plant. Results show a strong correlation between generation and the wet bulb temperature. They also show that high wind speeds, increase thermal losses and the efficiency of the steam cycle. This paper shows that thermal electric power plants are particularly sensitive to climate conditions in hot and humid regions.

1. Introduction

Thermoelectric power plants (TPP) produce electricity from thermal energy obtained by burning different kinds of fuels, such as natural gas, diesel oil, coal, nuclear, biomass geothermal and solar energy [1,2]. For the specific case of TPPs that use Brayton cycle turbines, the inlet air density and the presence of humidity influence the performance and maximum power obtained by them [3–6]. The reduction in generation from these turbines can vary from 5 to 12% for every 10 °C increase in ambient air temperature [7–9].

The most common way to increase the mass of air propelled by the gas turbines is by cooling the air admitted by them, seeking an increase in air density by dropping its temperature [10,11]. Evaporative coolers are commonly applied for this purpose [12–14]. However, its performance also depends on the weather conditions, presenting good results when the climate is dry and mild. On the other hand, in rainy and hot seasons, typical of tropical regions, its performance drops considerably, causing the turbines not to reach their maximum power generation potential [7,12–15]. Deng et al. [7] and Jaber et al. [9] investigated the electric power generation in combined cycle power plants that use different techniques for cooling the intake air of the gas turbines. Among the different techniques that use evaporative methods, the authors report that the use of evaporative cooling increases the performance of these plants by 2–15%. However, fogging cooling achieves more significant improvement ranging from 3 to 22%. Both techniques are negatively affected when the wet bulb temperature of the intake air is high, restricting the absorption of moisture in the evaporative cooling process.

TPPs that work with the Rankine cycle (steam turbines), the weather conditions influence the cooling towers' efficiency to remove the latent

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heat from the steam cycle (heat of phase transformation) [16]. For dry-type towers (Heller type), the high air temperature hinders the heat exchange process and consequently its efficiency, however, the wind speed can also cause a reduction in performance by causing aerodynamic effects that cause an unbalance in the air intake in these towers [17,18]. As for the wet-type towers, which use the same physical principle as the evaporative coolers, their performance is directly linked to the wet bulb temperature, showing a performance degradation when this is high [16,19,20]. The effect of wind in natural draft wet-type towers reduces its performance. It means that in strong winds the temperature reduction in the cooling water is smaller compared to days without wind [21,22]. On the other hand, the damaging effect of wind speed is less noticeable for wet towers that use forced ventilation [23,24]. Studies that investigate strategies to increase the efficiency of thermoelectric power plants can be seen in Refs. [25–30]. TPPs that use the Bryton cycle and for those that use the Rankine cycle, or even for those that use the combined cycle (Bryton and Rankine cycle), the meteorological conditions of high humidity and temperature have a negative impact on their performance, either by directly influencing the conditions of the intake air of the gas turbines or by hindering the evaporative processes that may exist in both generation cycles.

Given this scenario, this article presents a case study of the behavior of the maximum electric generation obtained by the Cuiabá TPP, located in the city of Cuiabá, state of Mato Grosso, in Brazil, a region with a predominantly hot and humid climate, however, with relative humidity presenting large oscillations throughout the year. Similar studies have investigated the impact of the climate on the efficiency of thermoelectric power plants in the literature [31–33]. However, none have investigated this with real observed data in a tropical region with high humidity and temperatures, such as in Cuiabá, Brazil. This study aims to investigate the relationship between different meteorological factors and the behavior of and existing natural gas combined cycle power plant. The results can provide a reference for investigating solutions to improve the performance of TPPs in tropical regions, seeking an increase in the maximum generation power and fewer oscillations due to weather conditions.

2. Methodology

The methodology implemented was divided into three main stages. The first stage presents the Cuiabá TPP, detailing its combined cycle and main equipment. The second step consists of obtaining and processing meteorological and generation data obtained hourly for the years 2020 and 2021. The third and last step presents the results and conclusions about the behavior of the plant's generation systems in relation to meteorological variables.

2.1. *The combined cycle of Cuiabá TPP*

Cuiabá TPP is a thermal power plant that operates a combined cycle using natural gas as fuel. Fig. 1-a presents a simplified diagram of the main systems of the plant. In the combined cycle of Cuiabá TPP, the process starts by filtering and cooling the air in evaporative coolers before the air is admitted by two gas turbines, GT10 and GT11. The clean and cooled air is drawn through the gas turbine compressors and then mixed with natural gas and burned in the combustion chambers of each

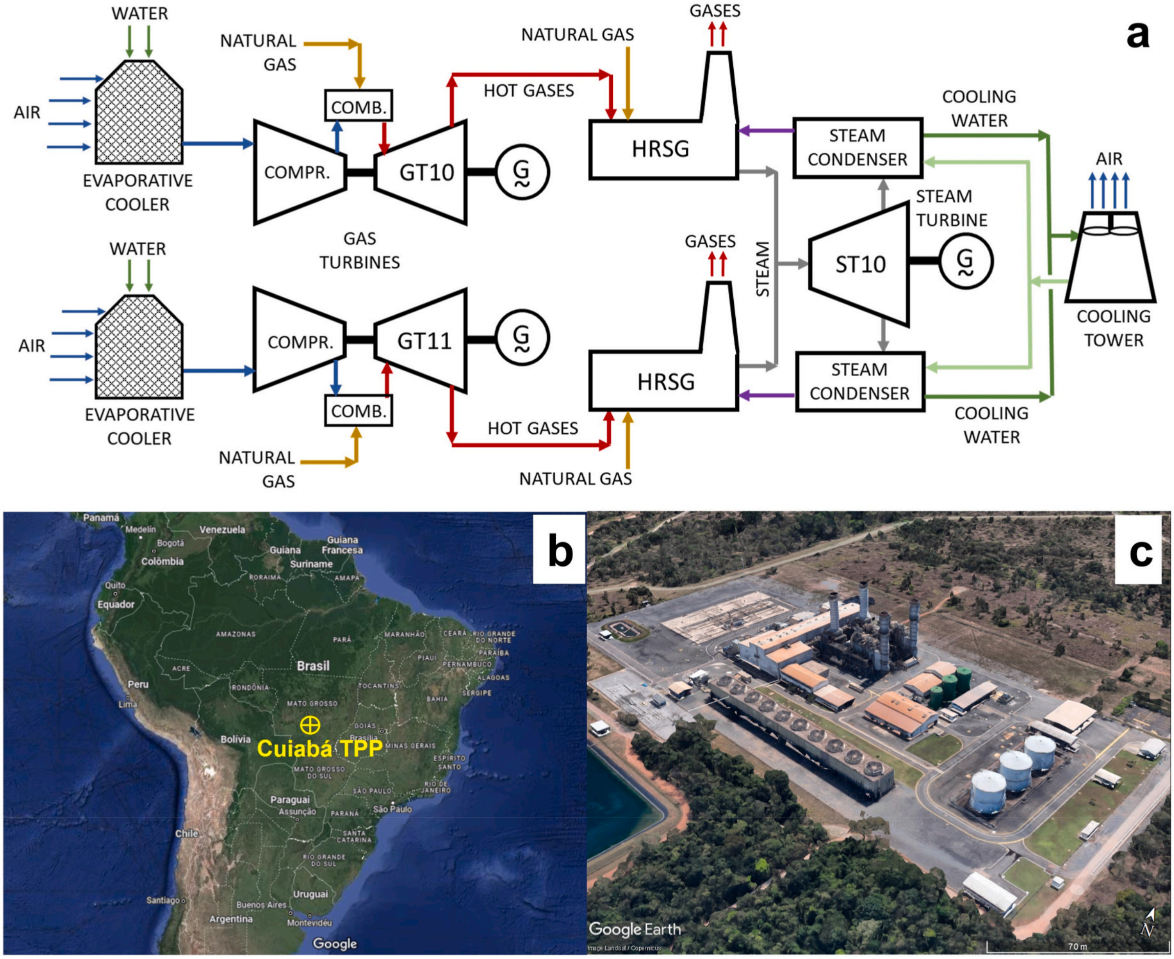

Fig. 1. Overview of Cuiabá TPP: a - simplified diagram of the combined cycle; b - location of Cuiabá TPP in Brazil; c - aerial view.

turbine. The hot gas, after passing through the turbines, is directed to two heat recovery boilers - HRSG (Heat Recovery Steam Generator) existing at the exit of each of them. Part of the energy contained in these hot gases is recovered in steam generation. After passing through several stages existing in these boilers, is directed to a steam turbine, ST10, being fed by both HRSGs. After the steam expansion in the turbine, it is directed to two condenser modules, positioned on both sides of the turbine, where it is condensed and returns to the HRSGs. A cooling tower, composed of 10 cooling modules with independent fans, ensures latent heat removal from the condensation process.

This plant was designed to operate with a combined cycle, with a nominal electric power generation capacity of 480 MW using natural gas as fuel. In operation with only one gas turbine and the steam turbine, the minimum net generation is 135 MW, and the maximum net generation is 240 MW. In operation with the two gas turbines and the steam turbine, the minimum net generation is 300 MW, and the maximum net generation is 480 MW. The predicted efficiency of this plant is 55.99%, considering clean and new generating units, in the base condition, with an ambient temperature of 25.6 °C and relative humidity of 73.2%. Fig. 1-b shows the location of Cuiabá TPP in Brazil, an Fig. 1-c an aerial view of the plant.

2.2. Meteorological data

The Cuiabá TPP does not have a weather station, so the meteorological data used in the following analyses were extracted from the weather station of the 13th Motorized Infantry Brigade, located approximately 14 km away from the plant. Hourly data were obtained for the years 2020 and 2021 for ambient temperature, relative humidity, atmospheric pressure, wind speed, and precipitation. The wet bulb temperatures were calculated using the EES (Engineering Equation Solver) software, providing the ambient temperature, relative humidity, and atmospheric pressure as input data. The EES provides the wet bulb temperature based on the Carrier and Mollier diagrams.

2.3. Generation data of Cuiabá TPP

For the analysis of the influence of weather conditions on the operation of the TPP, individual hourly data of the gross electric power of the three existing generation systems were extracted from its control, that is, data for the two gas turbines (GT10 and GT11) and the steam turbine (ST10). In addition, it was also obtained the total generation of the combined cycle and its efficiency, expressed by the heat rate parameter, which shows the ratio between the amount of thermal energy consumed (by natural gas burning) and the gross electric generation. Thus, the heat rate is expressed by MMBTU/MWh.

2.4. Data processing

Cuiabá TPP can operate at different generation thresholds. For the study presented in this article, which aims to evaluate the impact of weather conditions on the maximum generation of this plant, the generation data were initially filtered based on a minimum power cut-off. Thus, values above the cut-off power were initially understood to be the maximum power achieved by these generation systems. For the gas turbines (GT10 and GT11), a gross cut-off power of 296 MW was used, considering the sum of their powers due to these turbines being identical. For the steam turbine, the gross cut-off power applied was 154 MW. In the graph presented in Fig. 2, it is possible to visualize the power levels of these systems throughout the years 2020 and 2021, and the cut-off lines applied.

Due to the combined cycle characteristics, the gas turbines can be at their maximum generation capacity without necessarily the steam turbine being in the same condition due to its starting process. Thus, the second filter implemented only considers the hourly data when both generation systems (gas and steam) are at maximum generation, with power above the cut-off lines.

Then the data was plotted and visually evaluated. Data from the beginning and end of the peak operation of these systems, i.e., the ramps of power increase or decrease, were manually excluded after analysis. Besides this, certain moments where the auxiliary burners of the recovery boilers were not activated, either by technical problems or by generation strategies, where it is possible to observe a step in the maximum power obtained by the steam turbine, it also had its hourly data eliminated for not representing the maximum power generation of the plant, where the presence of power oscillations perceives the influences of the weather conditions.

3. Results and discussions

In the combined cycle of Cuiabá TPP is expected the maximum power generation achieved by the steam turbine follows the maximum

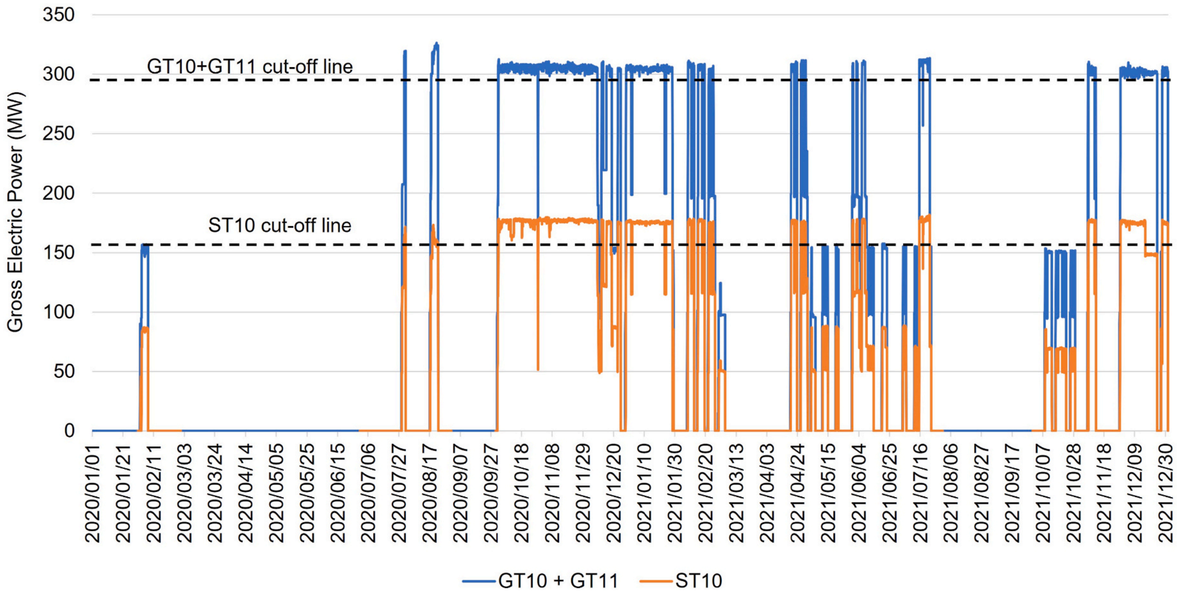

Fig. 2. Gross electric power of the gas and steam turbines over the years 2020 and 2021.

generation of the gas turbines. In other words, if the weather condition increase power generation of the gas turbine, the steam turbine should also increase generation. The graphs in Fig. 3 show the behavior of the maximum powers achieved by these turbines working simultaneously and the influence of the weather conditions through a color scale divided into four value ranges. The wet bulb temperature proved to be the most relevant for the variations in the maximum power generation, evidenced by the color scales ordering in the scatter plot of Fig. 3-a. So, this parameter was used as a base in further analyses. The graphic in Fig. 3-c evaluates the influence of ambient temperature on the electric power obtained by the gas and steam turbines simultaneously. It is possible to observe a color ordering similar to Fig. 3-a, however, the highest power for steam turbine (>180 MW) occurs at high ambient temperatures (>30 °C) but with extremely low relative humidity (<30%), as can be seen in Fig. 3-d, which means at low wet bulb temperature provided by the low humidity. It is an indication that higher ambient temperatures contribute to the performance of the steam cycle, justifiable by providing lower thermal losses.

The combined cycle behavior was evaluated in graphic (a) in Figs. 4 and 5 as function of wet bulb temperature and associated with wind speed and ambient temperature. Looking only the influence of wet bulb temperature, a reduction of 6 °C in the can represent an increase of 15 MW in electric power generation. However, temperatures below 16 °C cause a stagnation in the power gain, possibly because the generation systems reach their maximum limits in a plateau of approximately 493 MW. The isolated analysis of electric power from gas turbines was performed in graphic (b) in Figs. 4 and 5. The wet bulb temperature presents a similar influence, with gains on the order of 12 MW for a 6 °C reduction in temperature, reaching a maximum generation plateau of around 312 MW for temperatures below 16 °C. In graphic (c) in Figs. 4 and 5, it is possible to notice a generation gain of about 3 MW for the steam turbine considering the same 6 °C of wet bulb temperature reduction. However, it is possible to observe two power generation plateaus below 16 °C, one with power around 177 MW and the other with 180 MW, discussed below. As for the behavior of the heat rate, evaluated in graphic (d) in Figs. 4 and 5 also as a function of the wet bulb temperature, the tendency of improvement in the efficiency of the combined cycle (reduction of heat rate) with the reduction of this temperature is clear.

The associative influence of wet bulb temperature and wind speed in the maximum electric powers of combined cycle, gas turbines, steam turbine, and the heat rate, was evaluated in Fig. 4. It can be seen the lowest generation powers occurred at high wet bulb temperatures (>24 °C) and frequently under winds above 1.5 m/s. In Fig. 4-c, which analyzes the behavior of the steam turbine electric power, the wind speed appears to be the possible cause of the presence of two power plateaus. A greater occurrence of stronger winds (above 1.5 m/s) in the lower plateau, and light winds in the higher plateau. Thus, the increase in electric power when the winds are light is justified by the reduction of thermal losses in the steam system. The influence of this meteorological variable was evaluated in an isolated way in the graphs of Fig. 7 discussed forward. For the heat rate, evaluates in Fig. 4-d, a clear behavior associated with wind speed is not observed.

The associative influence of wet bulb temperature and ambient temperature in the maximum electric powers of combined cycle, gas turbine and steam turbine, and in the heat rate, was evaluated in Fig. 5. The color scales show a strong influence of this meteorological factor in all parameters. The highest values of electric powers are reached when the ambient temperature is equals 20 °C or below, and the lowest values of heat rate (or the highest combined cycle efficiency) are also reached in the same range of ambient temperature.

Since in the combined cycle, the Rankine cycle recovers the energy from the gas turbines, only assessing the behavior of the maximum electric power of the steam turbine by meteorological factors can lead to a false interpretation. Thus, if a colder ambient temperature contributes to increasing the gas turbine's power, the hot gases flow rate also

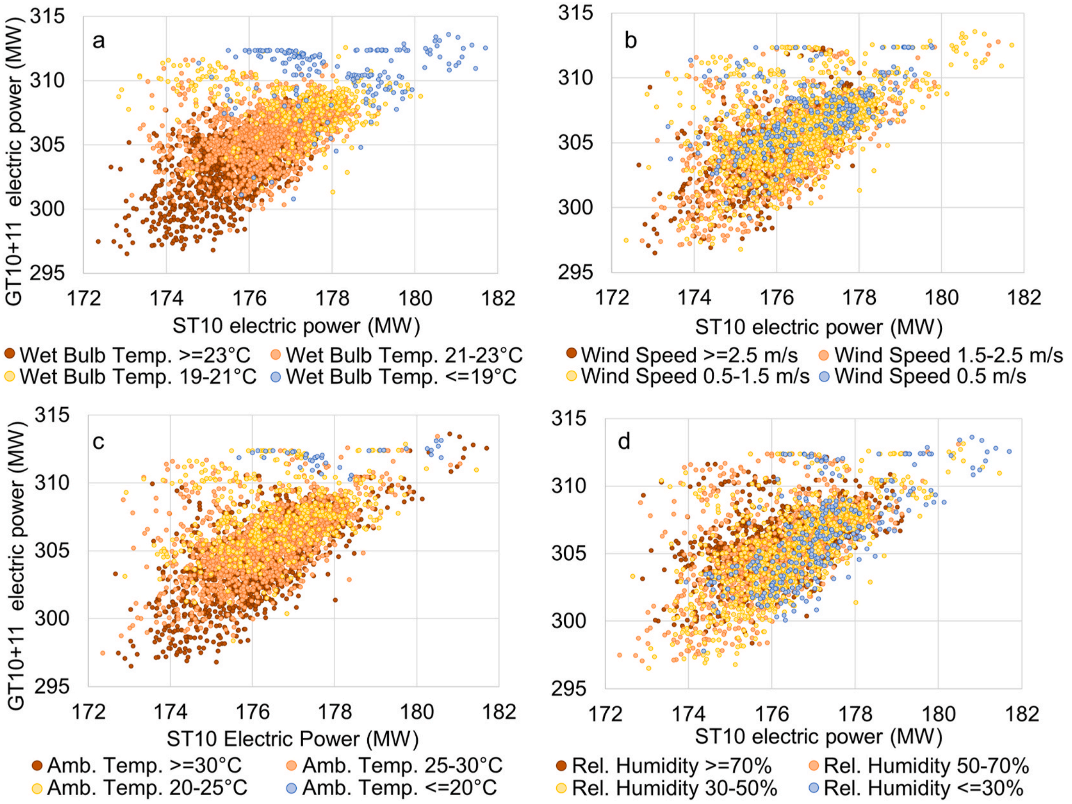

Fig. 3. Electric power of the GT10 and GT11 gas turbines versus the ST10 steam turbine: a - influence of wet bulb temperature; b - influence of wind speed; c - influence of ambient temperature; d - influence of relative humidity.

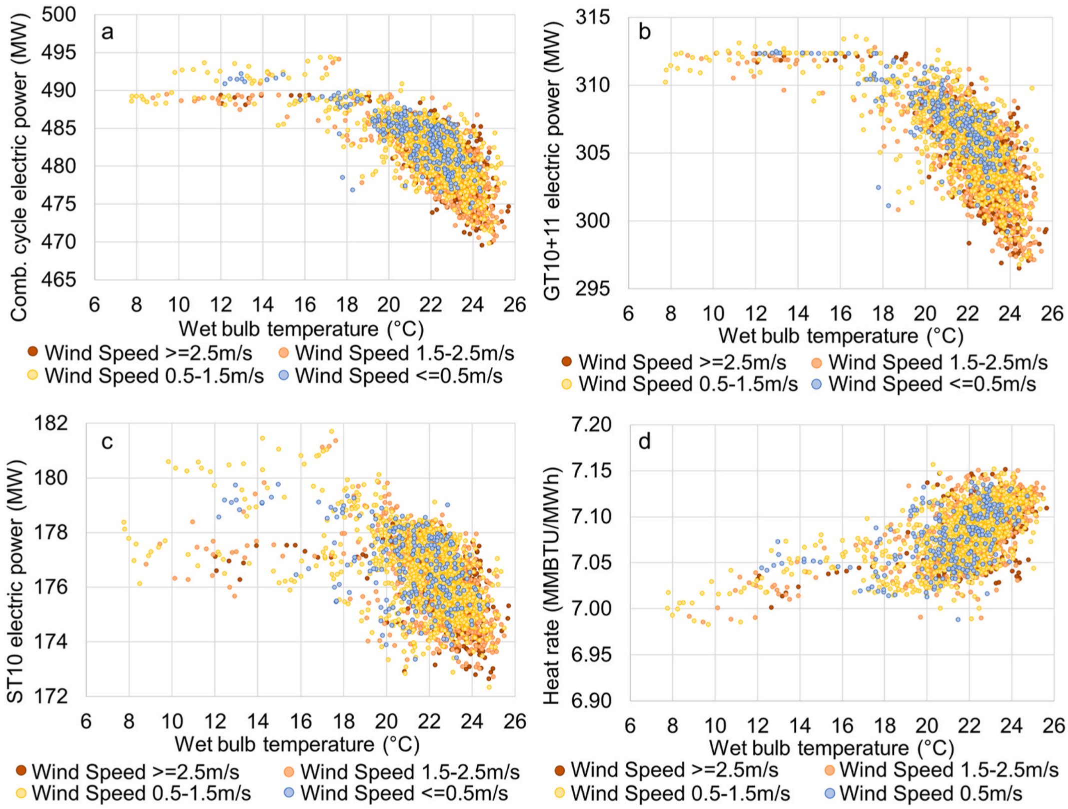

Fig. 4. Influence of wet bulb temperature and wind speed: a – on combined cycle electric power; b – on gas turbines electric power; c – on steam turbine electric power; d – on heat rate.

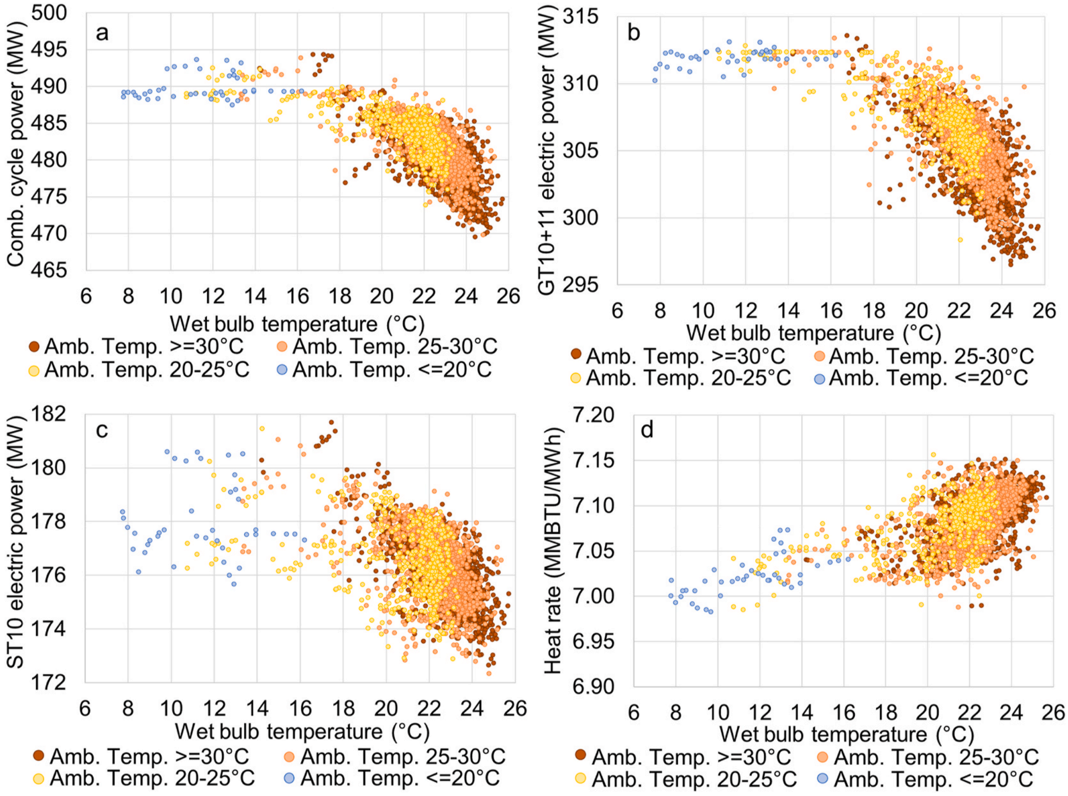

Fig. 5. Influence of wet bulb temperature and ambient temperature: a – on combined cycle electric power; b – on gas turbines electric power; c – on steam turbine electric power; d – on heat rate.

increases from their outputs, as is known. The consequence will also be an increment in the steam turbine power because more thermal energy can be recovered in the HRSG, and more steam is available. On the other hand, if the colder climate does not directly contribute to Rankine cycle generation, the percentage increment in steam turbine power will be smaller compared to the power increment in gas turbines. In other words, assuming this hypothesis, more energy is recovered, but less efficiently. Therefore, a steam turbine generation factor was implemented, called in this paper “Steam Turbine Power Factor” - STPF. This factor shows the ratio between steam and gas turbines power generation to evaluate the proportional power output of the steam turbine.

The STPF factor was plotted as a function of the electric generation of the gas turbines in Fig. 6 provides relevant information about the behavior of the combined cycle. When the gas turbines present high power, the generation factor of the steam turbine is low. That is, the steam turbine reaches a lower proportional power. Again, the wet bulb temperature is the most influential meteorological factor, as shown by the color segregation in Fig. 6-a. However, the interference of the ambient temperature, evaluated in Fig. 6-c, shows similar behavior. Thus, it can be observed that higher temperatures contribute to the steam cycle performance is evaluated by means of the STPF factor and not by the power achieved by the steam turbine. That is, the amount of energy recovered is smaller. However, the recovery process is more efficient.

In all parameters evaluated so far, the wind speed interferes with the results obtained, but less significantly if compared to the main variables analyzed. For example, if the maximum power generation in gas turbines is strongly reduced by high wet bulb temperature, there will be moments of low power for high and light winds if this meteorological factor has a lower impact than wet bulb temperature. An isolated analysis of the main parameters as a function of wind speed should be more appropriate to interpret their influence. The graphs (a)–(d) in Fig. 7 presents the power generation of the gas turbines and steam turbine, heat rate, and STPF factor plotted as a function of wind speed. A trend line was applied in each graph to make it easy to see the point cloud behavior.

For the gas turbines in Fig. 7-a, the wind appears to be a parameter that tends to reduce the maximum power achieved, possibly by acting to hinder (or unbalance) the air suction in the evaporative coolers. The reduction is around 2 MW for a wind speed of 3.0 m/s compared to a day with no wind. In Fig. 7-b it is possible to see the same behavior for the steam turbine. In this case the probable cause is the reduction of the thermal energy available in the exhausts of the gas turbines and the negative effect of the wind on the efficiency of the cooling tower. On the other hand, the analysis by means of the STPF factor shows the inverse in Fig. 7-d, that is, the efficiency of the energy recovered from the steam cycle, when observed by means of the proportional electric power of the steam turbine, increases with the wind speed. One hypothesis of this effect is relative to an increase in the heat rate, as seen in Fig. 7-c, which means that winds tend to reduce the overall efficiency of the plant, especially by reducing the efficiency of the gas turbines. It means that there is more heat available in gas turbines outlet to be recovered per MWh produced by them. For this reason, since the STPF factor looks at the relationship between the electric power output of the steam and gas turbines and does not consider the available heat energy to be recovered in the Rankine cycle, it shows an improvement in this factor if wind speed increases.

Since the increase in wind speeds tends to reduce the maximum power obtained by the plant, as evidenced by the analysis of Fig. 7-a and Fig. 7-b, it is possible to use wind generators as a complementary source of energy in TPPs installed in regions with high wind speed, which allows plants of this type to operate at full load more times a year.

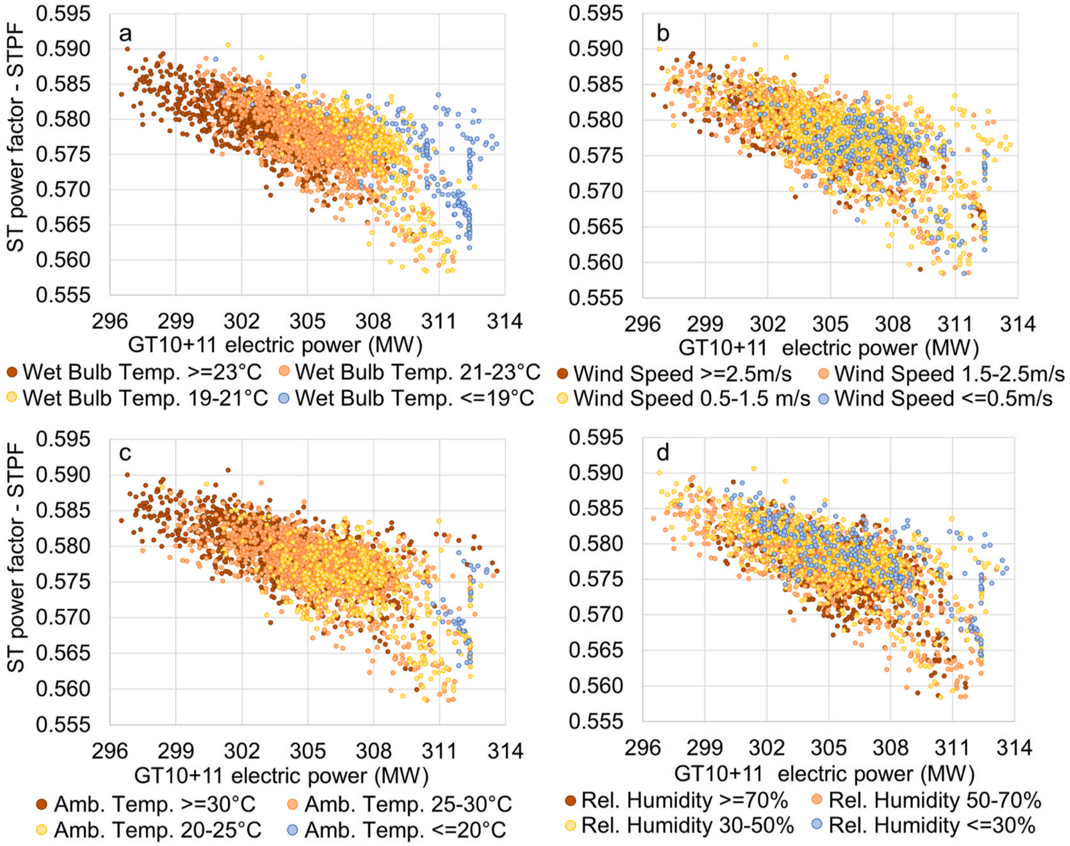

Fig. 6. STPF versus gas turbines electric power: a - influence of wet bulb temperature; b - influence of wind speed; c - influence of ambient temperature; d - influence of relative humidity.

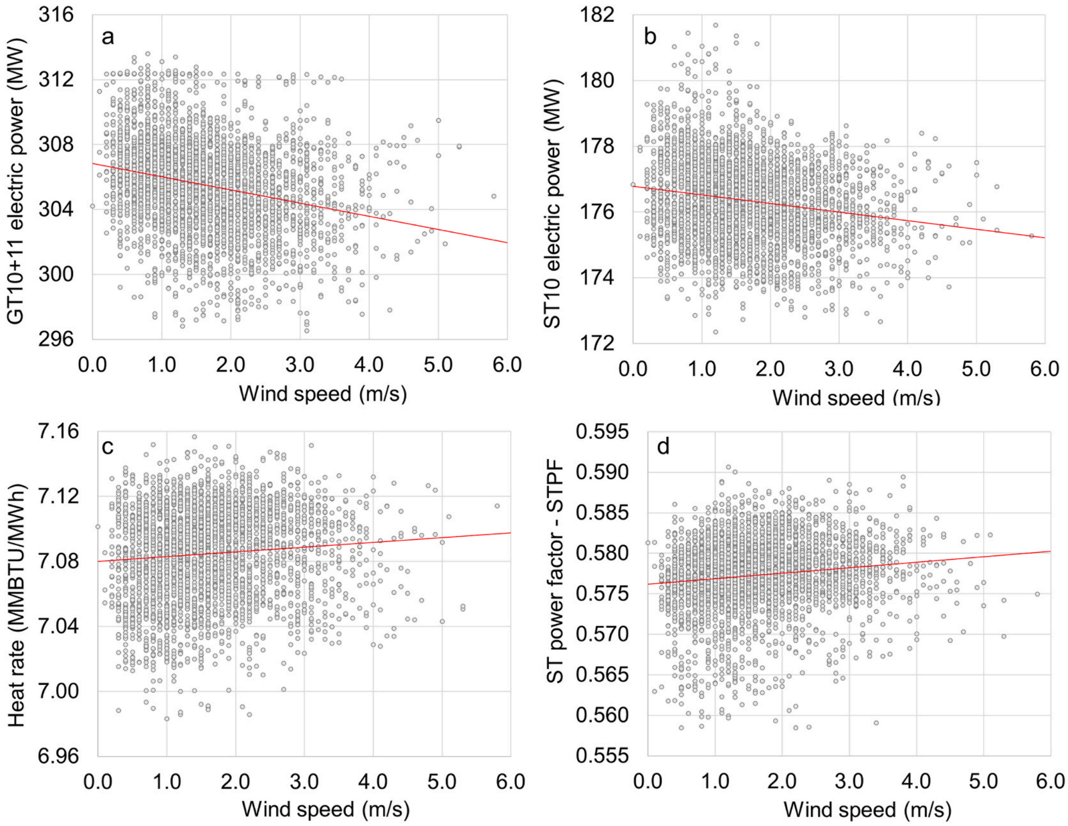

Fig. 7. Influence of wind speed: a - on the electrical power of the gas turbines; b - on the electrical power of the steam turbine; c - on the Heat Rate of the combined cycle; d - on the STPF of the combined cycle.

However, a more appropriate analysis of the influence of wind speed requires a local measurement of this meteorological variable since the values used were obtained 14 km from the Cuiabá TPP. In addition to the distance, the meteorological station is in a non-isolated region like the TPP and the existing buildings in the surroundings may interfere with the wind direction reading, not corresponding exactly to the TPP's wind direction. For the temperature and relative humidity data, the distance does not seem to significantly affect the analyzes carried out, since there is no inconsistency in the results.

Through the results presented, it is evident that the parameter with the greatest impact is the wet bulb temperature, as this meteorological parameter shows the behavior of evaporative coolers in the air inlet of gas turbines. Thus, a more effective way of cooling the air, without depending on the meteorological conditions of the ambient air (temperature and relative humidity) could bring benefits to the plant in moments when the hot and humid climate prevails, impairing the performance of evaporative coolers. In the work of Gareta et al. [34], which compares the use of chillers with 8 MW and 20 MW of cooling power and the evaporative cooler, applied for cooling the air before the turbine compressor in a 395 MW combined cycle TPP in Spain, shows that the benefit of a chiller is the gain of 5–12 MW in electrical power respectively compared to evaporative coolers at the most favorable times for the latter (hot and dry weather), and about 2 MW gain for both sizes of coolers at the worst times in terms of air cooling (cold and wet weather).

The research conducted by Santos an Andrade [35], which evaluates the performance improvement of gas turbines for sites in Brazil using different inlet air cooling techniques, shows an increase in generation ranging from 3.6% to 5.8% for the use of chillers compared with evaporative coolers. However, for the specific case of UTE Cuiabá, this type of solution should be evaluated with caution, since the existing evaporative coolers work well at moments in the year when this plant may be required to dispatch more energy, that is, during dry weather, when hydroelectric plants in Brazil suffer from lack of rainfall.

4. Conclusion

The wet bulb temperature is the meteorological variable that most influences the maximum power achieved by Cuiabá TPP since it shows the tendency of cooling of the evaporative system existing in the air inlet of the gas turbines, which reflects directly on the mass of air admitted by these turbines and the amount of fuel needed for optimal burning. Consequently, this also influences the amount of energy available to be recovered in the steam cycle (Rankine cycle). In general, the reduction of 6 °C in the wet bulb temperature can increase 15 MW in electric power generation.

The wind speed harms the combined cycle electric power generation. However, it appears to increase Rankine cycle efficiency when evaluated by the STPF parameter, possibly by improving airflow above the cooling towers and heat removal, but this is not enough to increase steam turbine electric power, once it impairs its thermal energy input, either by reducing gas turbine power output or by increasing steam pipes thermal losses. However, a more appropriate analysis of the influence of wind speed requires a local measurement of this meteorological variable since the values used were obtained 14 km from the Cuiabá TPP. The conclusion can be summarized with the point below.

- The wet bulb temperature is the meteorological factor with the greatest influence on the maximum generation of TPP Cuiabá.
- The higher the wet bulb temperature, the lower the maximum power achieved by gas turbines.
- The lower the power reached by the gas turbines, the lower the maximum power reached by the steam turbine.
- 6 °C of reduction in the wet bulb temperature represents an increase of 15.0 MW in the maximum power of the TPP, on average.

- 3.0 m/s of wind speed causes a 2.0 MW reduction in the maximum power of the gas turbines compared to days without wind.
- Wind speed also reduces the overall efficiency of TPP Cuiabá, as seen by the tendency for the plant's Heat Rate to increase.
- The STPF factor, created in this study to evaluate the ratio between the maximum powers of steam and gas turbines, tends to increase with wind speed.
- Due to the effects on the steam turbine power output, the influence of meteorological conditions on the thermodynamic conditions of, we propose that future work should deeply investigate the exhaust flue gas exiting the gas turbine.

Declaration of competing interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

In other words, there is no conflict of interest involved in this publication.

Data availability

Data will be made available on request.

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