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FLOATING PHOTOVOLTAIC MODELS AND THEIR INFLUENCE ON THE EVAPORATION RATE OF THE COREMAS-MÃE D'ÁGUA COMPLEX (PARAÍBA)

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ABSTRACT
The evolution of technologies aimed at generating clean energy is notable, mainly due to the need to exchange the use of fossil energy for renewable energy. The Brazilian Northeast region is widely studied in the generation of solar energy and an example of this is the city of Coremas, but there are some factors that make the installation of photovoltaic systems unfeasible, such as the high cost, the occupation of large areas of land and the movement of land during execution, which ends up causing a negative environmental impact in that location. In the city of Coremas it is possible to find the Coremas complex - Mãe D'água has an extension strip that can make it possible to exchange the use of the land strip for the water body. The objective of this study was to analyze the technical feasibility and effects on the evaporation of the Coremas - Mãe D'água complex of implementing a floating photovoltaic system. To this end, a suspended floating photovoltaic model was developed, including 8,340 photovoltaic modules that could reduce evaporation by approximately 432,000.00 liters per year, calculated using the Penman Monteith method, taking into account temperature, relative humidity, wind speed and radiation.

KEY WORDS: Solar energy, electricity generation, renewables, water body.

INTRODUCTION

The consequences of growing energy demand, the depletion of fossil fuels, and the emission of greenhouse gases require the development and inclusion of Renewable Energy Sources (RES) around the world (DAI *et al*., 2020). Brazil has a much greater potential for using solar energy than most European countries, even greater than Germany, which is one of the countries that invests the most in solar energy (PEREIRA *et al*., 2017; FERREIRA *et al*., 2018).

Furthermore, a very common problem in several countries is the loss of water through evaporation from free surfaces, such as lakes, reservoirs and lakes (CAZZANIGA *et al*., 2018). One of the solutions generally used is to partially shade the water, and this can be accomplished by implementing a floating photovoltaic system. Shading the water by a system of this size will reduce evaporation from the surface and will also increase the efficiency of the system, as the water will contribute to reducing the temperature of the photovoltaic modules.

The first floating photovoltaic systems were installed in Aichi, Japan, in 2007 (one system) and two in California, United States, in 2008. These systems were focused on research and development, which made it possible to improve the technology. However, the majority of commercially installed projects in the world were installed after 2014 (MITTAL *et al*., 2017; TRAPANI; SANTAFÉ, 2015).

Floating photovoltaic systems have become interesting due to some advantages. For installation, it is not necessary to prepare the ground (ground leveling is often necessary in the traditional system). The floating photovoltaic project also makes it possible to reduce evaporation, limit the growth of algae, and increase the efficiency of the panels, as contact with water reduces the temperature. However, there are difficulties with cleaning, maintenance and installation costs, as it is considered a higher-cost investment (HAAS, 2020).

The Coremas - Mãe D'água water complex is a junction of two dams, where the Coremas dam has a maximum capacity of 744,144,694 m³ of water and the Mãe D'água dam has a capacity of 545,017,499 m³. The two dams are located in the municipality of Coremas (Northeast Brazil), and together they are responsible for supplying 13 municipalities. These two reservoirs have been suffering from the major droughts that have occurred in recent years (AESA, 2021).
Thus, the present study aimed to analyze the technical feasibility and effects on the evaporation of the Coremas - Mãe D'água complex of implementing a system of floating photovoltaic panels.

MATERIAL AND METHODS

Characterization of the study area and identification of meteorological stations

The state of Paraíba, located in the Northeast region of Brazil, has four intermediate geographic regions: João Pessoa, Campina Grande, Souza-Cajazeiras and Patos, the latter being the area chosen for this study, which has a semi-arid climate (IBGE, 2017). According to data presented by the Brazilian Institute of Geography and Statistics (IBGE) in 2020, the state of Paraíba has an area of 56,469 km², made up of 223 municipalities and an estimated population of 4,039,277 people (IBGE, 2020).

The Coremas - Mãe D'água complex is located at coordinates: 6° 59' 57" South, 37° 56' 7" West, and is part of the Piancó River basin. According to data from Google Earth (2022) in December 2022, the Mãe - D'água dam has an area of approximately 16 km², while Coremas has 24 km². These values are approximate as they may vary according to the levels of the dams (Figure 1).

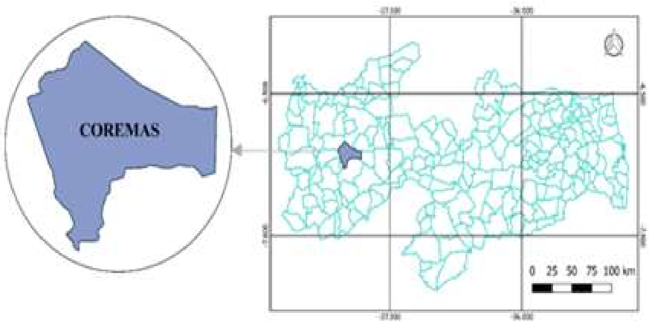

Figure 1: Location of the Municipality of Coremas in the state of Paraiba (Brazil).
Source: PEREIRA *et al.* (2020)

The study area has a semi-arid tropical climate, which is characterized by dry landscapes, high temperatures, accompanied by low annual thermal variability and rainfall irregularities, in addition to being a region marked by long periods of drought (CAVALCANTI *et al*., 2009; MENDONÇA; DANNI-OLIVEIRA, 2007). The Coremas Mãe D'água complex also supplies water to other locations besides the city of Coremas, with a route that goes from the state of Paraíba to Rio Grande do Norte.

To find the region's rainfall indices, rainfall data obtained through the digital files of the Executive Water Management Agency of the state of Paraíba (AESA - PB), from the municipalities of Pombal, São José da Lagoa Tapada and Coremas, during the years 2011 to 2021, to obtain a 10-year sample, having a more recent view of precipitation levels for the city. Records show that between 2014 and 2019 the two reservoirs suffered from low levels, which greatly affected the surrounding cities, since even though the city of Coremas is the largest beneficiary of water from the complex, 13 municipalities still receive water from the complex and need this supply for daily use.

The network of rainfall monitoring stations in Paraíba is relatively old, dating back to the early 1910s and quite dense, covering all of its 223 municipalities. However, successive crises and the scrapping of the network meant that some stations had their data collection interrupted (BECKER *et al*., 2011).

Total horizontal solar irradiation of the Coremas – Mãe D'água complex

To calculate solar irradiation, data provided by the SunData software was used, which is intended for calculating the monthly average daily solar irradiation using data from the 2nd Edition of the Brazilian Solar Energy Atlas in 2017 (CRESESB, 2018).

Floating photovoltaic model with anchored modules

For this study, the floating system was simulated with modules anchored to a tubular buoyancy system. This model was chosen because it reduces the temperature of the models, as they allow good ventilation and cooling. The photovoltaic solar module so that it had a good percentage of efficiency and was easily found on the market, thus meeting the needs of the project, which is why the MFV HO-MO-156-600W was chosen, which is manufactured by Belenus LTDA (Monocrystalline Half Cell Module–600 W).

When choosing the module, it is also necessary to choose an inverter that meets the needs of the project and is easily found on the market, which is why the selected module was the Sungrow brand inverter model SG125HV with 1500VDC.

Technical sizing of the system

The project was designed for 5 MW. Thus, a sequence of steps was defined that enabled the sizing of the entire system so that it was possible to define all the parts, quantities and angulations necessary for an efficient system (VILLALVA, 2012). To estimate the real area, the modeling software AUTOCAD 2020 (Autodesk) was used. To make the project viable, a substation is needed to carry out the protection, control, transmission and distribution of high-power energy from the floating photovoltaic system to the consumer unit.

As investment in photovoltaic energy has increased a lot over the last few years, the company specializing in energy generation with a focus on photovoltaic plants, the Rio Alto group, made an investment in a substation, which can also be used to collect and distribute the 5 MW analyzed. in this project, this avoids the need to design and execute a sheltered substation, which would be built exclusively for this project, thus reducing the cost of the work. Figure 2 shows the location of the substation in the city of Coremas.

Figure 2: Location of the Coremas Substation – CHESF.
Source: Google Earth (2023)

For better visualization, Figure 3 shows the straight-line distance between the substation present in the region and the access to the Coremas – Mãe D'água complex through the city of Coremas.

Figure 3: Distance between the Coremas – Mãe D'água complex and the Coremas Substation – CHESF.
Source: Google Earth (2023)

Considering the distance in a straight line, from the COREMAS - CHESF substation to the Coremas dam, it reaches 882.39 m. This distance may allow the feasibility of using this suspension in the project analyzed here.

EVAPORATION CALCULATION METHODS

Evaporation calculation model for free water body

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Do not use abbreviations in the title or heads unless they are unavoidable. In the present study, the Penman model (1948) was used as a basis, which even after so many years of its creation is still widely used. To reach the result, the method uses data on solar radiation, minimum and maximum temperature, wind speed and relative air humidity (Equation 1).

$$E_L = 86{,}4 \frac{\Delta}{\Delta+\gamma}\frac{R_n - G}{\lambda\rho} + \frac{\gamma}{\Delta+\lambda} 0{,}26(0{,}5 + 0{,}54\mu_2)(e_S - e_a) \qquad \text{Equation (1)}$$

where,
EL - evaporation in the reservoir, mm/d;
Δ - slope of the saturation vapor pressure versus temperature curve, Pa/ºC;
γ - psychrometric coefficient, Pa/ºC;
Rn - net radiation, W/m²;
G – Heat stored in the watercourse, W/m²;
λ – Latent heat of vaporization, MJ/kg;
ρ - water density, kg/m³;
u2 - wind speed measured 2m above the surface, m/s;
es - vapor saturation pressure for air temperature, mbar;
ea - current vapor pressure, mbar.

The vapor saturation pressure for air temperature es is given by the Tetens Equation (Equation 2).

$$e_s = 6{,}108e^{(\frac{17{,}27T_a}{Ta+237{,}3})} \qquad \text{Equation (2)}$$

where,
Ta – Average air temperature, °C.
The current vapor pressure e_a is calculated by Equation 3.

$$e_a = \frac{RHe_s}{100} \qquad \text{Equation (3)}$$

where,
RH – Relative humidity, %;

The slope of the vapor saturation pressure curve Δ is calculated by Equation 4.

$$\Delta = \frac{4{,}098 \times 10^5 \times e_s}{(T_a + 237{,}3)^2} \qquad \text{Equation (4)}$$

The latent heat of vaporization is defined by Equation 5.

$$\lambda = 2{,}501 - 0{,}002361T_a \qquad \text{Equation (5)}$$

The psychrometric coefficient is defined by Equation 6.

$$\gamma = 0{,}0016286\frac{P_{atm}}{\lambda}$$ Equation (6)

where,
Patm – atmospheric pressure in mbar;

The wind speed at a height of 2 m can be defined from the speed at any height by Equation 7.

$$u_2 = u_z\frac{4{,}87}{(ln67{,}8z - 5{,}42)}$$ Equation (6)

where,
uz – wind speed at height z, m/s;
z – height of the speed measurement, m;

Evaporation calculation model for covered water bodies (suspended type)

For suspended systems, to arrive at the equation used, it was necessary to consider that the diffuse component of solar radiation can reach the water body below the module due to the spacing between the model series. Thus, the net radiation balance is given by the diffuse component, which considers short waves and long waves, and which will have C=0.3, which corresponds to the completely cloudy condition (BONTEMPO *et al.*, 2020). This made it possible to arrive to Equations 8 and 9.

$$SW_{nB,C} = R_{dif} - \alpha R_{dif}$$ Equation (8)

where,
SW - Short Waves;
Rdif - Diffuse radiation;
α - Albedo or reflection coefficient.

$$Lw_{nB,C} = \sigma T_W^4(0{,}56 - 0{,}0092\sqrt{e_a})(0{,}1 + 0{,}9 \times 0{,}3)$$ Equation (9)

where,
LW - (from English Long Wave) long waves
σ - Stefan–Boltzmann constant
Tw - Water temperature
ea - current vapor pressure.

The total evaporation rate of reservoirs partially covered by floating photovoltaic systems E_{FVF}(Evaporation with floating photovoltaic system) is given by the sum of the evaporation in the free fraction and the fraction of the covered reservoir. As shown in Equation 10.

$$E_{FVF} = (1 - x)E_{Llivre} + xE_{Coberto}$$ Equation (10)

where,
x is the covered percentage of the reservoir.

Using Equation 1, it was possible to analyze evaporation for 100% of the covered water body, 70%, 50% and 30%, thus being able to have more analysis views.

RESULTS AND DISCUSSION

Technical sizing of a 5 MW floating photovoltaic plant.

In this project, a 5 MW plant was designed so that it would be possible to cover a considerable portion of the water body. For this, 8340 modules were used, arranged in 26 series of 321 modules, in addition to 40 inverters with an output power of 125 kW each. According to Villalva (2012), it is not recommended to install modules with an inclination angle of less than 10° to avoid excessive dust accumulation on the modules. As the city of Coremas has latitude: 6° 59' 57" South, longitude: 37° 56' 7" West, the modules will be installed with an inclination of $\alpha = 10°$.

Furthermore, to guarantee circulation and ease of maintenance, a spacing between the series was designed, so that it is approximately 60 cm, allowing a technician to walk around the platform and carry out maintenance and cleaning whenever necessary. With this, the system will occupy 29,180.00 m², approximately 0.75% of the water body, being divided between the Coremas and Mãe D'água dams.

Calculation of the average evaporation of the free water body

Using Equation 1, it was possible to obtain the average monthly evaporation values of the free water mass. Figure 4 shows the evaporation levels in mm/day, using the average daily value for each month of the year.

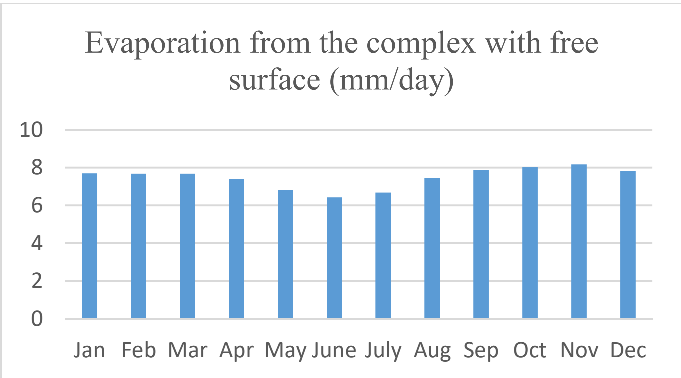

Figure 4: Evaporation from the free water body (mm/day).

The lowest evaporation result occurs in the month of June (6.42 mm/day), while the month with the highest level of evaporation is November, reaching 8.16 mm/day, coinciding with the season of highest temperatures in the region. Analyzing evaporation throughout the year, an average evaporation of 7.47 mm/day can be observed.

Calculation of the average evaporation of the covered water body

Using the suspended type model chosen, the reduction in evaporation in the covered area was between 60.4% and 73.4%, with an average value of 67.9%.
The decrease in evaporation is proportional to the part covered, so considering covering 70% of the Coremas - Mãe D'água complex, in the month with the lowest evaporation rate it would reach 3.12 mm/day, and in the month with the highest evaporation rate, it would reach around 4.77 mm/day.

For 50%, in the month with the lowest evaporation rate, it would reach approximately 4.06 mm/day, in the month with the highest evaporation 5.74 mm/day. With 30%, the values in the month with the lowest evaporation rate would reach 5.0 mm/day, while in the month with the highest evaporation they would reach 6.7 mm/day, considering the average monthly evaporation value, it would reach approximately 5.95 mm/day, so that there would be a reduction of 1.52 mm/day. In a simplified way, it is possible to analyze in Table 1, the evaporation values in mm/day considering the different percentages of coverage by floating photovoltaic systems.

Table 1. Comparative analysis related to evaporation considering different portions of the covered Coremas Mãe D'água complex.

Percent Covered	100 %	70 %	50%	30%	0%
Month with the lowest evaporation	1.71 mm/day	3.12 mm/day	4.06 mm/day	5.0 mm/day	6.42 mm/day
Month with the highest	3.32 mm/day	4.77 mm/day	5.74 mm/day	6.70 mm/day	8.16 mm/day

evaporation rate					
Average evaporation	2.41 mm/day	3.93 mm/day	4.94 mm/day	5.95 mm/day	7.47 mm/day

In Figure 5 is presented the evolution of evaporation according to the level covered, making it clear that the higher the percentage covered, the lower the daily evaporation rate from the water body.

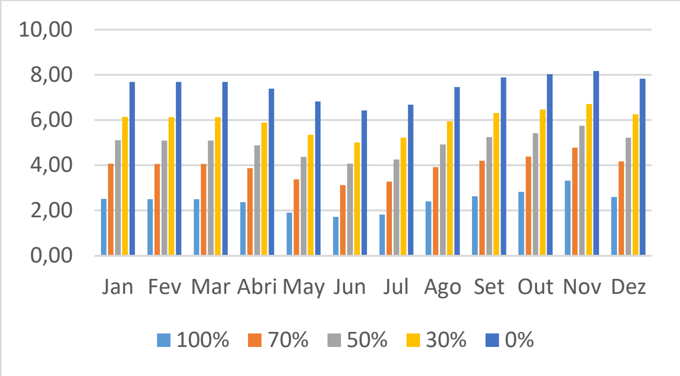

Figure 5: Evaporation rate considering 100%, 70%, 50%, 30% and 0% of the Coremas - Mãe D'água complex covered, considering evaporation values in mm/day.

According to IBGE data, the population of the city of Coremas by the year 2021 was approximately 15,441 inhabitants, and taking NBR 5626 of 2022 as a basis, it is considered that domestic consumption is 150 liters/inhabitant/day. Thus, if 100% of the Coremas – Mãe D'água complex were covered, it would be possible to reduce evaporation by 72,864,000.00 liters per year, which would be equivalent to approximately 31 days' supply. Covering 70% would reduce 50,976,000.00 liters per year, which would be equivalent to a 22-day supply. For a system that covers 50% of the water body, it would be possible to reduce approximately 36,432,000.00 liters per year, which would be equivalent to a 15-day supply. And for 30% it would be possible to reduce approximately 31,888,000.00 liters per year (Table 2).

Table 2. Reductions considering 100%, 70%, 50%, 30% and 0% of the Coremas - Mãe D'água complex covered.

Percentage Covered (%)	Average Evaporation Reduction (mm/day)	Reduction Quantity in Liters (L)	Population of the City of Coremas	Supply Days (days)
100	5.06	72,864,000.00	15.441	31.46
70	3.54	50,976,000.00	15.441	22.01
50	2.53	36,432,000.00	15.441	15.73
30	1.52	21,888,000.00	15.441	9.45

Considering a real model, with 5 MW for the Coremas – Mãe D'água complex it would be possible to cover approximately 0.75% of the complex, so that in the month with the lowest evaporation rate, it would reach approximately 6.38 mm/day, in the month with the highest evaporation 8.12 mm/day, and an average of 7.44 mm/day. In Figure 6 it is possible to see the project positioned at the Coremas Dam, so that it is close to the banks, facilitating arrival for installation and maintenance of the system.

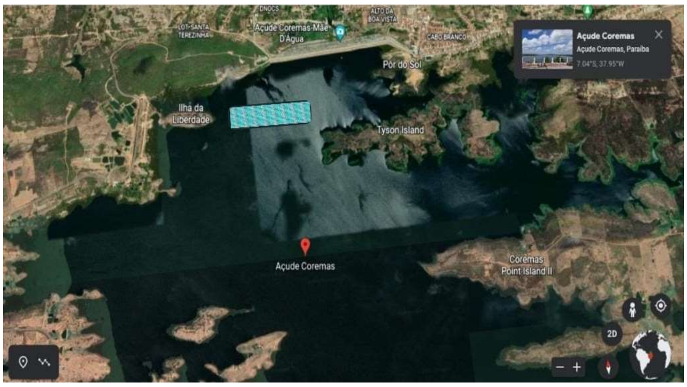

Figure 6: 5 MW project located in the Coremas – Mãe D'água complex.

Taking into account the extension of the project in relation to the complex, it would be possible to reduce approximately 432,000.00 liters per year.

CONCLUSIONS

The region where the city of Coremas is located has levels of solar irradiation suitable for photovoltaic systems. However, in the same proportion this irradiation affects the region's water bodies in relation to evaporation, as is the case of the Coremas – Mãe D'água water body.

Therefore, when analyzing the possibility of implementing a floating photovoltaic system for the Coremas – Mãe D'água complex, it was possible to conclude that by partially covering the complex, it would be possible to significantly reduce evaporation losses, thus using this water to maintain supply for longer periods in cities that depend on the Coremas – Mãe D'água complex directly or indirectly.

In addition, the amount of evaporation reduction is entirely linked to the type of system implemented, and the percentage that will be covered. For this study, seeing a real system, and feasible for investment, it was possible to realize that covering with a 5 MW floating photovoltaic system it would be possible to cover approximately 0.75% of the complex, which would result in a reduction that could be considered negligible. However, that would reduce an amount of approximately 432,000.00 liters of evaporation per year.

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