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POTENTIAL OF FLOATING PHOTOVOLTAIC PLANT IN A TROPICAL RESERVOIR IN BRAZIL

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ABSTRACT

The increasing global demand for electricity has been causing a significant increase in the search for low-impact alternative sources, with solar photovoltaic being pointed out as among the most feasible ones. However, photovoltaic power plants require large ground areas, which represent a major constraint. If the panels are installed on water bodies, this restriction may be avoided. In this work, simulation was performed to assess the potential of floating photovoltaic power generation in the tropical Gavião reservoir, located in the Northeast of Brazil. A payback analysis indicated that the investment for construction of the system is fully recovered in 8 years, and that water losses due to evaporation can be reduced by approximately 2.6 x 10^6 m³/year, enough to supply roughly 50.000 persons.

Key words: Renewable energy; floating photovoltaic plant; surface reservoir.

1. INTRODUCTION

Installation of photovoltaic (PV) plants has faced a rapid increase globally in the last few years, and in the end of 2018 the global PV exceeded an installed capacity of approximately 500 GW, with major developments in Europe (Germany, Italy, England, France), Asia (China, Japan, India), USA, and an estimated additional 500 GW of PV capacity is projected to be installed by 2022–2023 (Haegel et al. 2019). This trend was driven by the search for low-impact energy sources and the reduction of PV system costs, which reached nearly 1.5 US$/Wp in 2016 (Feldman et al. 2014; Chung et al. 2015).

According to Jannuzzi and Melo (2013), PV systems have become an interesting option in Brazil due to the combination of high residential tariffs (0.17 - 0.39 US$/kWh), an enormous availability of solar irradiance and an international price reduction of photovoltaic modules (23 US$/W in 1980 – 1.5 US$/W in 2012). Specifically in Brazil, the deployment costs of photovoltaic solutions tend to annually decrease in the range of 3.3 – 6.5% until 2030 (Pinto et al. 2016).

Tropical countries benefit from high and nearly constant solar radiation throughout the seasons and offer good conditions for PV power plants (Martins and Pereira 2011). Particularly in Brazil, the Northeast region presents the highest solar incidence in the country, with an annual variation of 4.7 to 6.1 kWh/m².day (Pereira et al. 2017) and abundant sunlight, about 2800 hours per year (Araújo and Piedra 2009).

These features have favored investments in the local photovoltaic power generation in Brazil. However, the traditional installation of panels on the ground demands large areas, conflicting with other land uses like constructions, agriculture, livestock and generating negative effects on the landscape (Grilli et al. 2017). On the other hand, large water bodies are available in various parts of the country, and Sahu and Shahabuddin (2015) argue that using them as basis for floating PV panels reduces the need for land acquisition and preparation, operating costs, and can improve power generation.

A typical PV module usually converts 5 to 20% of the incident solar energy into electricity at an ideal operating temperature. If the optimum operation temperature is surpassed, the exceeding incident solar radiation is converted in heat, which significantly increases the temperature of the PV, decreasing the panel energy generation at a rate of 0.4 to 0.65% per degree exceeding of the ideal temperature (Gotmare and Prayagi 2014; Shan et al. 2014; Dash and Gupta 2015; Rahman et al. 2015). In floating PV plants, proximity of the panels to the water surface promotes a cooling effect, reducing the overheating and increasing between 5 and 22% the power generated by the modules (Rosa-Clot et al. 2010; Mckay 2013; Bahaidarah et al. 2013; Choi 2014; Sacramento et al. 2013; Majid et al. 2014; Abdulgafar et al. 2014; Sacramento et al. 2015).

The positive effects of cooling on the floating PV panels suggest that higher renewable reliabilities can be achieved at a lower levelized cost of electricity compared to ground-based PV systems (Campana et al. 2019). Song and Choi (2016) in mine pit lake, Korea, verified in the economic analysis over a 20-year lifespan of the floating PV panels, the payback period for the 1-MW facility was calculated to be 12 years, lower when compared with traditional on-ground system. Rosa-Clot et al. (2017) estimate that the payback time for floating PV plant should range between 3 and 4 years with a cost of 0.1 US$/ kWh. Sahu et al. (2016) calculated a payback of 1 MW floating PV plant is 5 years, based in a life time of 25 – 30 years of the floating system. From this perspective, the payback time will depend roughly on the installation cost, operation cost, plant life time and price of the energy generated by the floating PV panels.

The major features of reservoir dynamics are: water input as direct rainfall and runoff in the contributing catchment; water output as evaporation, overspill, withdraw and seepage; energy input as radiation; energy output as reflection; and heat exchange. Santafé et al. (2014) argue that floating PV improves the overall water-energy balance in the water bodies: natural reservoirs receive high rates of solar radiation, causing intense evaporation losses and heat exchange with the surface and the reservoir bed. With the installation of floating solar panels on the aquatic environment, evaporation is reduced due to the shading effect and electric generation is improved due to avoidance of the panels' overheating, resulting in higher availability of water and energy.

Since the first commercial floating PV plant was built in California in 2008 (Trapani and Santafé, 2015) a total of 22 photovoltaic power plants were built in the world by the end of 2014, with the capacity changing from 0.5 kW to 1157 kW. At the end of 2016, the world floating PV installed capacity was more than 94 MWp. Japan represented 60% of the world installed capacity with 56 MWp, followed by China (20 MWp), United Kingdom (10 MWp) and South Korea (6 MWp) (Solar Asset Management, 2019). In 2018, the floating PV capacity reached 211 MWp, only considering the top 70 floating PV installations worldwide (Solarplaza, 2019).

Brazil is one of the main global hydropower producers, ranked second in the world, with this type of electricity generation providing 4,923 MW (Martins et al. 2013). In the

Brazilian Northeast, over 30.000 reservoirs have been constructed since the 19th century to support the local water supply (SIRH/Ce, 2015). This high-density reservoir network has losses by evaporation exceeding 2000 mm per annum (Araújo and Gonzalez Piedra, 2009; Sacramento et al., 2015; Leão et al., 2016; Pereira et al., 2019). Using hydropower lakes or the high-density reservoir network for floating PV has potential to increase power generation in big cities and in remote areas of Brazilian Northeast as well reduce evaporation, keeping higher water availability in remote regions.

In this study, a simulation was performed to assess the potential of power generation from a floating photovoltaic plant in the tropical Gavião reservoir (storage capacity of 2.7×10^7 m³), located in the Northeast of Brazil. The study region is characterized by water scarcity, which led to the construction of a dense reservoir network (Pereira et al. 2019) with more than 5500 surface reservoirs in the 149,000 km² Federal State of Ceará and, thus, presents high potential for floating photovoltaic systems. The main goals of the present work were to assess the economic feasibility of the floating system based on a payback analysis and comparison with a traditional on-ground system, as well as to estimate the reduction of water loss due to evaporation.

2. FLOATING PHOTOVOLTAIC SYSTEMS

Floating photovoltaic power plants are composed of several pieces that can be described as 6 components: pontoon; mooring system; solar module; connectors and cables; power converter; power transmission. Pontoon is the floating component with buoyancy enough to float by itself as well as with a heavy load (Rosa-Clot et al. 2010; Santafé et al. 2014), usually formed by a combination of multiple plastic hollow floats. The floats are typically made of a high density poly-ethylene, known for its tensile strength, maintenance free, ultraviolet and corrosion resistance (Sahu et al. 2016). There are different types of floating structure as floating platform (pontoons) (Ferrer-Gisbert et al, 2013), floating PV module support structure (Sahu et al. 2016), articulated metal couplings between pontoons (metal chains or cables linking the pontoons together, allowing vertical and horizontal displacements as well as gyrations) (Trapani and Santafé, 2015), flexible couplings (rubber or MDPE straps) allowing the pontoons to move so the system can adapt to different water levels (Trapani and Santafé, 2015), ropes (polyester and nylon nautical ropes) (Santafé et al. 2014) and rigid anchoring system that anchors the floating cover (Santafé et al. 2014).

The mooring system is a permanent structure to which the system may be secured. In the case of a floating PV panels, the mooring system keeps the PV array in the same position and prevents them from turning or going away (Sharma et al. 2015). The installation of an anchorage system can be challenging and expensive in deep waters.

Solar photovoltaic modules, where the radiation is converted into electricity, have been composed of crystalline solar PV panels in the floating solar systems. However, Sahu et al. (2016) argue that specifically fabricated more resistant modules, such as polymer, will be needed as more projects are installed on salty water surfaces.

Connectors and cables are used to transport electricity from the floating PV array to the land, where the power can be fed to the grid or stored in batteries. In floating systems, the cables have to be properly coated with waterproof material and periodically maintained. The energy generated from floating PV system are converted in a central inverter (power converter) from direct current to alternating current. The energy is then sent through power transmission (power pole and power transmission cables). Figure 1 presents all components required for a floating PV system.

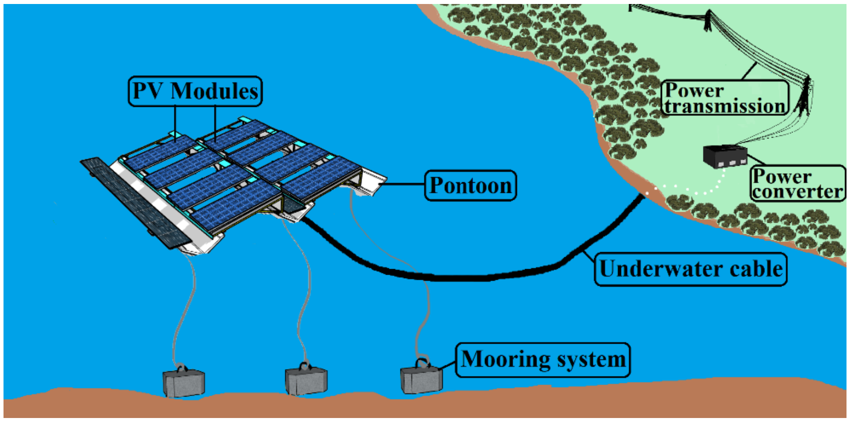

Figure 1: Floating PV components

2.1. Progress of floating photovoltaic plants

Floating PV systems were initially proposed in Aichi, Japan in 2007, on a plant with 20 kW capacity (Trapani and Santafé, 2015; Rosa-Clot and Tina 2017) after which many systems of varying scales have been built around the world. Trapani and Santafé (2015) made a historical review of the main floating PV plants in the period of 2007-2013 and Sahu et al. (2016) extended it to the year 2016, showing how this technique evolved in terms of modeling and implantation.

The first floating PV system was built in 2007 with fixed angles and a simple design, but precisely moored to avoid movement of the panels. Choi et al. (2014) indicate the reduced weight and the rather less mechanically strong floating structure as the main advantage of this system.

Flexible PV thin film was initiated in 2010, this concept being proposed to increase the reliability, without significantly affecting the electrical performance of the system. Trapani and Millar (2014) designed a thin film flexible floating PV array and compared its performance with ground PV system. They reported an average of 5% improvement in electrical yield due to cooling effect of water.

In 2011 a concentrating light floating PV system was proposed, consisting of reflectors positioned in V shape with the panels located between them, inclined by a small angle (about 2°), and oriented in line with the sun radiation (Cazzaniga et al. 2012). The geometrical concentration ratio depends on the reflector angle and on the correct alignment with solar radiation. Cazzaniga et al. (2018) state that the real gain due to the concentration light is low, but taking into account also the cooling effect of panels, it can reach between 60 and 70% more than operational efficiency than on-ground systems, depending on the latitude and on clear sky conditions.

Recent advances in this field came with floating PV tracking system, able to track the sun azimuth. Other materials have also been used, like the Fiber Reinforced Polymeric plastic member as round rotary material for the panels, which was found to be more durable and stable steel and aluminum (Choi and Lee 2014). Floating tracking cooling concentrating system promotes 60 to 70% more energy yield than a fixed floating PV plant (Ueda et al. 2008). Cazzaniga et al. (2012) verified that 25% gain in efficiency is obtained by using vertical axis tracking system.

Anhui Province (China) is currently the city with largest floating PV system in the world, with a potential of 40 MWp (Solar Asset Management, 2018). As of end of 2018, the global cumulative installed capacity of floating solar exceeded 1.3 gigawatt-peak (GWp) (World Bank Group et al. 2019). In 2016, the first floating PV plant in Brazil was inaugurated in Balbina reservoir, consisting of the first floating system installed on a hydroelectric power plant lake. The panels cover an area of 60 m², with a potential of 5 kWp, and are considered as a pilot project for the deployment of floating PV in the country (Galdino and Olivieri, 2017).

In 2016, another floating PV installation was put in operation in Brazil, with 25 kWp, occupying approximately 500 m² in the reservoir of the hydropower plant of Porto Primavera (São Paulo, Southeast region of Brazil) (Secretaria de Energia e Mineração de São Paulo, 2016). Another floating PV system is already in operation in Cristalina, with a potential of about 304 kWp, being the second largest floating array in Brazil (Sunlution, 2017).

The more recent floating system in Brazil was implemented in 2019 in São Francisco River in Bahia, Brazil, where the Companhia Hidrelétrica do São Francisco (CHESF) installed a floating PV plant with 3,792 panels, stretching on a total area of 11 thousand m² and a generation power of 1 MWp, being the largest floating PV system in the country (CHESF, 2019). According to CHESF, this is the first study on the installation of a floating PV plant on hydroelectric lakes (CHESF, 2019). CHESF also expected to install and generate 1.25 MWp of floating PV energy at the Boa Esperança reservoir, in Piauí state, to be installed in 2020 (CHESF, 2019).

The reason that Brazil wants to install the floating PV plants on hydropower reservoir is because this is one of the best places to install floating panels, these two energy sources can operate in a complementary mode. Still, when a large-scale floating PV plant is combined with a hydropower station, it is possible to store the generated electricity without make huge changes in the hydropower facilities and using the existing energy transmission infrastructure at hydropower sites (Maués, 2019).

2.2. Modelling floating photovoltaic systems

Simulations of power yield from PV plants require a large amount of input data, such as solar irradiation, local weather conditions and technical parameters of the planned system (Huld et al 2010a; Huld et al 2010b). Recent advances regarding software availability and technical developments have made modelling one of the most widely used and accepted tools in PV system analysis. An increasing number of modelling software products is observed, including cheaper and user-friendly software (Verma et al 2008).

However, modeling floating PV systems is currently a major challenge. There is not specific software to make this kind of simulation, therefore, some authors create them own program routine or adapted PV software for floating PV results. Sacramento et al. (2015) analysed the use of cooled floating PV panels in a fraction of the area occupied by three reservoirs in the Brazilian semi-arid region. Comparing with conventional ground-mounted PV modules, an average operational efficiency increases of 12.5% was measured for floating PV modules. Then, in a second phase, simulations were made in PVSyst software for three reservoirs. However, in this program there is no option to simulate a floating PV plant, therefore, an increase of 12.5% was considered to the model output value, representing the measured efficiency gain of floating PV panels in Brazilian semi-arid region.

Silvério et al. (2018) used the same procedure for a technically and economically sizing floating PV plants. The simulation was performed in PVSyst, focused on the hydroelectric plant of the São Francisco River basin. The authors added 7% to the output value, a procedure similar to that adopted in this study. This additional efficiency gain was a conservative value based in the experiments of Ueda et al. (2012), Choi (2014) and Sacramento et al. (2015).

Song and Choi (2016), to model floating PV systems, used the software System Advisor Model (SAM), however the current version of SAM has no separate feature for floating PV systems. Therefore, relying on the experimental results of a study by Choi (2014), according to which a floating PV system yielded 11% greater power output than a terrestrial counterpart. After the standard simulation in SAM, Song and Choi (2016) added 11% to the model output value, representing a better operational efficiency for these panels being on water. Silva and Souza (2017) also used SAM to model the potential of a floating PV system on a part of the lake Bologna, Brazil. Their results demonstrated that the annual energy production with 112 panels of 250 Wp each one would generate 38,000 kWh. This energy is able to supply the water treatment station in the region of the water body and could be higher if the additional efficiency generated by the cooling effect of the water on the floating PV panels had been considered.

Kougias et al. (2016) developed an algorithm that examines the degree of time complementarity between small hydropower stations and adjacent solar PV systems. The algorithm examines possible alterations on the PV system installation that increase the complementarity, with minor compromises in the total solar energy output. The methodology has been tested in a case study and the outcome indicated that a compromise of 10% in the solar energy output (90% threshold) may result in a significant increase of the complementarity (66.4%).

Liu et al. (2017) developed a 3-D model of a polysilicon PV to examine the temperature differences between a floating PV system and a normal terrestrial system in order to verify the cooling effects of water. Based on the cooling effects, this study then analyzed the influence of the cooling effects on the power generation efficiency of the floating PV system.

Louise (2017) evaluates and optimizes energy solutions using floating PV systems for a shrimp farm cultivation in Thailand, where the technical, environmental and economic aspects were included. The optimizations have been done in the open source model OptiCE, where an algorithm has been used to maximize the renewable reliability and minimize the levelized costs of electricity. In order to find the optimal renewable solution for the investigated shrimp farm, four scenarios have been compared considering different PV system combinations. The simulated results showed how the scenarios considering floating PV system generated a higher reliability than the scenarios considering ground-mounted PV system.

Recently, Campana et al. (2019) developed a dynamic techno-economic simulation and optimization model, evaluating PV and wind based hybrid energy systems, off-grid and on-grid PV based hybrid energy systems, ground mounted and floating PV based hybrid energy systems, and floating and floating-tracking PV based hybrid energy systems.

2.3. Impacts expected from floating photovoltaic plants

The main benefits of floating photovoltaic plants, if compared to traditional on-ground ones, are the higher efficiency of power generation, the reduction in evaporation losses and avoidance of costs with land acquisition.

Evaporation from the water body promotes cooling of the photovoltaic panels, keeping the system’s temperature lower and increasing the system efficiency in terms of power generation (Santafé et al. 2013; Trapani and Santafé 2015; Santafé, 2014; Majid et al. 2014; Abdulgafar et al. 2014; Sahu et al 2016; Sacramento et al. 2015).

Reduction of evaporation losses from the reservoir is due to the shading effect, decreasing the solar radiation and aerodynamic effects on the surface of the water body, resulting in higher water availability (Trapani and Santafé, 2015; Melvin, 2015; Sahu et al. 2016; Silva and Souza, 2017; Taboada et al. 2017). Floating solar panels may reduce evaporation of natural water bodies by up to 33%, and up to 50% in built-up reservoirs (Santafé et al. 2013; Choi, 2014; Rosa-clot et al. 2017). From a water food-energy nexus perspective, floating PV systems can be combined in the aquaculture, generating aquavoltaics, synergies for dual use of reservoir area for solar PV electricity supporting pumps used in aquaculture (Pringle et al. 2017).

Construction of a traditional on-ground PV plant is considered the most impactful phase of the project due to deforestation, loss of natural habitat, soil compaction, intermittent noise pollution, emission of air pollutants, particular matter, waste generation (solid and effluent), accidental spillage of vehicle lubricants and oils, stress on local roads and infrastructure, flow alteration, sedimentation, displacement of aquatic biota, and contaminant runoff (Grippo et al. 2015; Silva and Branco, 2018; Silva et al. 2019). Deforestation to install on-ground PV might also enhance sediment load in the surrounding lakes causing siltation and depletion of water resources (i.e. turbidity and eutrophication) (Silva et al. 2019). There are studies pointing out changes in the local temperature due to vegetation removal and albedo increase (Silva et al. 2019). Placing PV panels on water bodies avoids the acquisition of land (Mckay, 2013; Sahu et al. 2016; Galdino and Olivieri 2017; Pearce et al. 2017) and the associated cost and negative environmental impacts. Furthermore, land can be occupied by other use types, such as constructions, agriculture, livestock, tourism, preservation, among others.

Additionally, lower interference of dust or residues on the photovoltaic panels have been reported. Generally, areas with high potential for PV plants are located in arid or semi-arid zones, with large amount of dust. When residues accumulate on panels installed on the ground, daily energy production can be reduced by 4 to 7%, reaching up to 20% if there are long periods without rain or the panels not being washed (Mani and Pillai 2010; Turney and Fthenakis 2011; Touati et al. 2012; Zorrilla-Casanova et al. 2013; sahu et al. 2016; fountoukis et al. 2018). Floating systems are less susceptible to this problem, as the dust falling on water is kept by it, keeping the surface of the panel cleaner and allowing a more efficient power generation.

Control of algae growth has also been pointed out as a potential benefit from floating PV systems due to reduced photosynthesis (Alam and Ohgaki 2001; Sahu et al. 2016; Galdino and Olivieri 2017). Maestre-Valero (2011) conducted an experiment covering a reservoir with suspended shade cloth aim to minimize evaporation and observed reduction of algal blooms, saving the cost of algaecides as well as reducing filtration costs for drip irrigation.

Main drawbacks resulting from on-water photovoltaic plants are related to implantation and maintenance costs. Although avoiding the acquisition or rental of land, floating photovoltaic plants even now consist of new technology and present high costs, increasing the initial investments when compared to on-ground plants (Trapani and Millar 2013; Trapani et al. 2013; Ferrer-Gisbert et al. 2013; Santafé et al. 2013). Furthermore, maintenance of PV systems on water is more difficult and costlier, as a boat is required to access and work on the panels (Choi, 2014; Sahu et al. 2016).

The floating structures of on-water PV systems are in direct contact with water and may have a shorter life cycle due to corrosion in the metal structures or accelerated decomposition if the support is made of plastic. To avoid such damages, floats made by inert material in contact with water, like stainless steel, glass or aluminum, have been recommended (Ferrer-Gisbert et al. 2013; Sahu et al. 2016; Cazzaniga et al. 2017), which also increases the costs.

Another disadvantage of floating PV system is the reduction of the photic zone in the lake, as the solar panels prevent solar rays penetration in the water, reducing the gas exchange in the water body-atmosphere interface, which may affect the local fauna and flora (Sahu et al. 2016; Pearce et al. 2017). Fishing and boat transportation activity may also be affected depending on the selected site (Trapani et al. 2013; Trapani and Santafé, 2015; Sahu et al. 2016).

To mitigate some of the negative impacts, it is recommended the floating system to be installed in a portion of the water body and to be movable, facilitating to change the position of the system over the lake, guaranteeing sunlight in much of the reservoir (Mckay, 2013; Cazzaniga et al. 2017). If the floating system needs to cover a large portion of the reservoir surface, due to high energy demand, LED lamps can be installed below the photovoltaic panels and oxygen and other gases can be pumped into the water, which demands power, on the other hand (Pearce et al. 2017).

3. MATERIAL AND METHODS

Performance of the floating photovoltaic system in terms of power generation and its contribution to reduce evaporation losses are assessed from the technical and financial aspects, as illustrated in Figure 2 and detailed below.

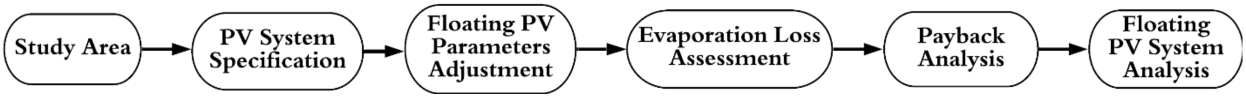

Figure 2: Flowchart of the methodological approach

3.1. Study area

This study was conducted in the tropical Gavião reservoir, located in the northeast region of Brazil, Federal State of Ceará (Figure 3). The Gavião reservoir has storage capacity of 2.7 x 10^7 m³ and integrates the water supply system of the Metropolitan Region of Fortaleza (MRF), with high demand of power (6,000 MWh/year) and water (just over 200,000,000 m³/year) (IPECE, 2017). The reservoir proximity to a region with high power and water demand favors the installation of floating photovoltaic panels.

In addition to its contributing catchment, Gavião is artificially provided with water by the "Eixão das Águas", a water transboundary system from the Castanhão reservoir, with storage capacity of 6.1 x 10^9 m³ capacity. Gavião reservoir presents a predominantly rural catchment and preserved riparian vegetation with native trees, like *Licania tomentosa* (popular name Oiti), *Copernicia prunifera* (popular name Carnaúba), *Combretum laxum* (popular name Mufumbo), *Ziziphus joazeiro* (popular name Juazeiro). Suppression of this vegetation to install on-ground PV would impact the hydrology of the Gavião catchment and the natural habitat of local animals (foxes, birds, insects and agoutis). Currently, Gavião serves as a water reservoir to the water treatment plant (WTP Gavião) that supplies the MRF, not presenting other uses (as fishing, recreation or navigation) by the native people.

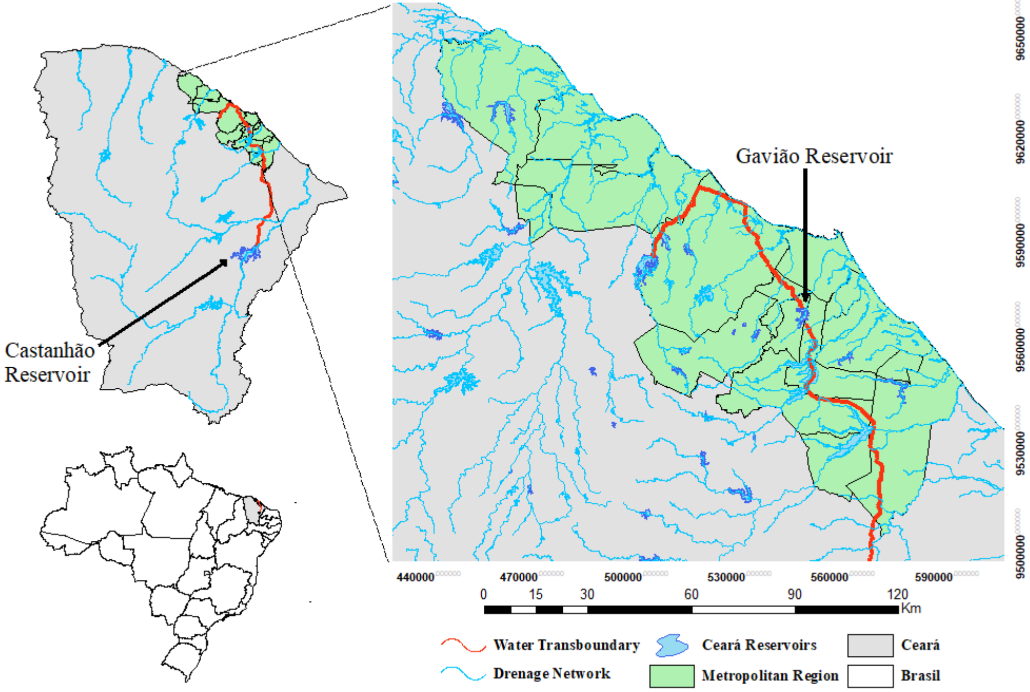

Figure 3: Location map of the Gavião reservoir and the Metropolitan Region of Fortaleza

3.2. Simulation of power generation

We perform a simulation using PVsyst software (version 6.68), applying the methodology presented by Mermoud and Wittmer (2014) to quantify the potential of photovoltaic power generation by floating solar panels in the Gavião reservoir. PVsyst is widely used for modelling of photovoltaic power plants, because it has a meteorological database encompassing the study area and considers the various losses on power generation (Table 1) (Mermoud, 2012; Mermoud and Lejeune, 2010; Wittmer et al. 2015), which is crucial for accuracy of the simulations. Understanding the amount of energy produced by the PV panels is essential for the electrical system management. Thus, an accurate modeling of the generation losses is key to analyzing future scenarios.

The radiation shading (12%) and solar rays incidence (10.5%) reductions are discounted at the local average irradiance during the year, reducing the local potential from 5.58 to 4.32 kWh/m².day. The other losses considered in the region of Gavião are computed in the photovoltaic system operation.

Type	Loss (%)
Shading	12.0%
Solar rays incidence	10.5%
Irradiation rates	1.1%
Temperature	13.7%
Module photovoltaic quality	1.5%
Module array mismatch	1.0%
Cabling resistance	1.1%
Inverter operation	3.0%

Table 1: Losses on the power generation by photovoltaic panels, considered in the PVsyst software

To define the flooded area that can be used for the floating PV panels installation, the dynamics of the reservoir's flooded area was assessed from January 1st, 2004 to December 31st, 2018 and the frequency curve elaborated, expressing the relationship between the flooded area and the frequency with which it is overcome. From this curve, it is possible to obtain the percentage of time in which there is a flooded area available for the installation of the photovoltaic arrangements.

The software Radia Sol 2 is used to find the proper angle of the panels for better power generation in the region (Masutti et al. 2016; Coelho and Oliveira, 2018) according to the location's latitude. For fixed systems, it is recommended that this angle is approximately equal to the local latitude (Strangueto, 2016).

Selection of the PV panel is based on analysis of the most commonly used floating solar panels in the literature review carried out by Trapani and Santafé (2015), associated with the panel existence in the PVsyst database, and to the certification of the Brazilian National Institute of Metrology, Quality and Technology (INMETRO). The panel considered in the simulations for the Gavião reservoir is from supplier Kyocera 245 Wp KD245GX-LPB, following the same standard adopted by Strangueto (2016).

For the power inverter, we consider equipments used in the projects that participated in Strategic Call N°13 of the Brazilian National Electric Energy Agency (ANEEL). According to Lopes (2013), there was a predominance in the choice of inverter manufacturer Ingeteam model Ingecon Sun 500 TL U X208, also adopted by Strangueto (2016), and this equipment was chosen for the simulations in this study, as well. This inverter is certified by INMETRO and is available in the PVsyst database.

The floating system is inspired on the work from Santafé et al. (2013), who made several measurements and obtained the number of photovoltaic panels and installed energy depending on the angle fixed for the Ciel & Terre Hydrelio Float, also considered in this work. This equipment is also manufactured in Brazil, favoring its acquisition and maintenance.

3.3. Adjusting simulation parameters to floating PV system

The PVsyst software used in the simulations has no tool to distinguish floating photovoltaic systems from on-ground installations in the simulations. Therefore, the experimental results found by Sacramento et al. (2013) and Sacramento et al. (2015) were used as a reference for the computation of the additional power generation by the floating system due to the reduction of the panels' temperature. The percentages of improvement found by Sacramento et al. (2013) and Sacramento et al. (2015) for a reservoir also located in the Brazilian state of Ceará, approximately 180 km south of the Gavião reservoir, were admitted as representative for the region and adopted in this study.

A fixed percentage improvement for the simulated photovoltaic power generation was considered, and three scenarios were simulated: pessimistic, with 8.1% improvement; an optimistic scenario with 14.5% improvement (Sacramento et al. 2015) and; a third condition with 11.3% improvement on power generation, representing an average between the pessimistic and optimistic scenarios.

3.4. Estimation of the impact on the evaporation losses

For evaporation quantification in the reservoir under study, the Penman (1948) equation was used, which involves two theoretical considerations, mass transfer and radiant energy balance (Leão et al. 2013), as defined by the following equation:

$$E = \frac{\frac{\Delta}{\gamma L} R_l + E_a}{\frac{\Delta}{\gamma} + 1}, \tag{1}$$

where E is the evaporation from the reservoir (mm/day); Δ is the tangent to the vapor saturation pressure curve (kPa/ºC); γ is the psychrometric constant; R_l is the balance of radiation cal/(cm^2.day) and; Ea is the evaporation power of the air in the shade (mm/day). To calculate the variables of the Penman equation, the method described by Allen et al. (1998) was used.

However, the installation of the photovoltaic panels on the reservoir generates a reduction in the water body evaporation, which was quantified according to the results of the experiment conducted by Melvin (2015). This study was carried out in Singapore, in a reservoir located near the equator line and with similar climatic characteristics to the state of Ceará. At the end of the experiment, Melvin (2015) found average reduction of water evaporation of 30%, a percentage used as reference in this study.

To convert the non-evaporated water layer (mm) into volume (m^3), it was considered that the area of the floating system is constant in time, as the Gavião reservoir did not show great variation in the flooded during the period studied. Therefore, the potentially non-evaporated water volume (m^3/year) was obtained by the product of the avoided evaporated water layer (m/year) by the area of the floating system (m^2).

3.5. Payback analysis

The project budget (solar panels, inverters, floats, cabling, installation, maintenance, and annual operation) was estimated through a request for a company specialized in floating PV projects. According to Ludwig (2017), the current quotation for floating photovoltaic plants in Brazil is US$ 1533.75/KWp. For floating panels maintenance, Ludwig (2017) affirms that most of the maintenance are in the inverters, with costs in the range of 6.15 to 9.50 US$/kWp. In this study, it was considered 9.50 US$/kWp as a more conservative value. For installation of panels on the ground, the value is currently US$ 1380.35/KWp (Portal Solar, 2016). For ground installations, 0.5% of the project total value is admitted for maintenance (Elysia Energia Solar, 2017).

Adopting the abovementioned costs for on-water and on-ground PV plants, a payback analysis was carried out for both systems. The online platform Sun-Earth Tools was used in the analysis with incorporation of important features not considered by that tool, such as monetary inflation, interest for bank loans and annual investment income.

The parameters required to calculate the payback period in this online tool are: the initial total cost of the system, annual maintenance expense, nominal power (kWp), energy production in one year (Kwh/year), average tariff charged per kW and the decay average percentage in the electrical production of photovoltaic panels, adopted as 0.75% per year (Branker et al. 2011).

An interest rate was applied to the initial investment, by adopting the average rate of the Special Settlement and Custody System (SELIC) for the period from 2000 to 2018. Such procedure was admitted as representative of the interest rate used in the Brazilian interbank market for financing, and was incorporated into the loan value until the entire initial investment was paid.

From the year of total payment of the investment, it was admitted that the balance between revenue and expenditure was converted into savings, to which the average savings interest rate in the period 2000-2017 was applied, thus representing the annual minimum monetary income.

The current energy tariff was considered in the simulations, an annual increase was applied to the tariff as the average readjust observed during the years 1995 to 2014 in Brazil (Nakabayashi, 2015). To the maintenance services during the operation of the system, it was added an annually average monetary inflation obtained in the period of 2000 to 2016.

The process can be summarized in the following equations:

$$GAI = AEG \cdot ASPD \cdot Ta_i \,, \tag{2}$$

$$Ta_i = Ta_{i-1} \cdot AIR \,, \tag{3}$$

$$NAI = GAI - MAC \cdot (1 + MI) \,, \tag{4}$$

$$\text{If } CB_{i-1} < 0; \; CB_i = (CB_{i-1} + NAI) \cdot (1 + SELIC) \,, \tag{5a}$$

$$\text{If } CB_{i-1} \geq 0; \; CB_i = (CB_{i-1} + NAI) \cdot (1 + IS) \,, \tag{5b}$$

where *GAI* is the gross annual income (US$); *AEG* is the annual energy generation (KWh/year); *ASPD* is the annual decay of the solar panels (%); Ta_i and Ta_{i-1} are the energy tariffs (US$/KWh) of the year under simulation and the previous year, respectively; *AIR* is the annual increase rate representing readjust of the tariff (%); *NAI* is the net annual income (US$); *MAC* is the maintenance annual cost (US$); MI is the monetary inflation (%); CB_i and CB_{i-1} are the cash balances (US$) of the year under simulation and the previous year, respectively; $SELIC$ is the special settlement and custody system rate (%); and IS represents the income saving rate (%). In the first year of simulation, $ASPD = 0$, as the equipment is new, and CB_{i-1} is admitted as the negative value of the initial investment to build the system.

4. RESULTS AND DISCUSSIONS

Power generation was simulated with Radia Sol 2 for different possible angles of the floating system installation. The chosen angle of the fixe tilt was 10º for better generation of photovoltaic energy in the Gavião reservoir, which was used for the simulation in PVsyst. According to Strangueto (2016), for the tilt chosen in this study, lower shading will be generated, reducing the losses from the panels and without the need to change the panel’s angulation during the year.

The flooded area frequency curve of the Gavião reservoir (Figure 4a) was used to define the region of the panels’ installation. During the evaluated period, it was observed that the flooded area was nearly constant and never smaller than 5 km², which is very uncommon in the study area, where the reservoirs present high temporal variability of the stored volumes (for instance, reservoirs Castanhão and Orós, Figure 4b and Figure 4c, respectively).

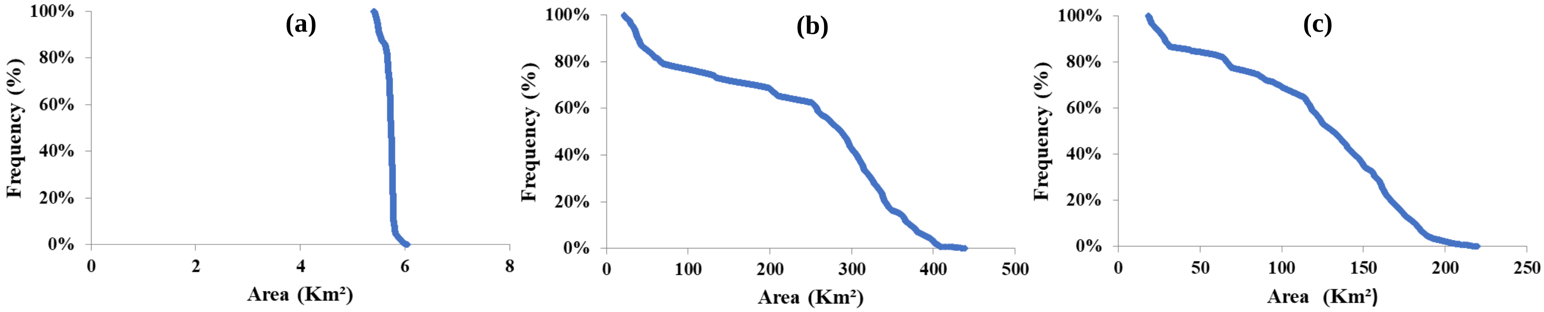

Figure 4: Frequency curves of the flooded areas of the reservoirs Gavião (a), Castanhão (b) and Orós (c) for the period of 2004 to 2018

The relative low variability of the stored volume, and consequently the flooded area in the Gavião reservoir is possible due to the water transfer from the Castanhão reservoir, through a transboundary channel, the “Eixão das Águas”. Based on the frequency curve of flooded areas, it was defined that 81% (5 km²) of the Gavião Reservoir water surface would be suitable for the installation of the floating solar arrangements, as the reservoir never presented a flooded area lower than 5 km² during the analysis period. However, according to Strangueto (2016), for the panel and float used in this work, 34% of the area of implantation should be destined for the spacing between the floats, reserved zone for the technicians’ movement and not having shadows interference between the panels. Thus, 47% (3.3 km²) of the maximum flooded area of the reservoir would be actually occupied by photovoltaic panels.

The PVsyst software was used to simulate the photovoltaic potential in the study region considering the application area of the floating arrangements, resulting in 492 MWp or 773,190 MWh/year for equivalent on-ground plants, requiring 2,008,162 panels. However, assuming that the panels would be installed on the water, a gain on the power generation is expected. Thus, the three scenarios tested would produce: 1) pessimistic, with 8.1% gain and a potential of power generation of 835,820 MWh/year; 2) optimistic, in which 14.5% efficiency gain was considered, generating 885,300 MWh/year; 3) intermediate, with 11.3% efficiency gain, resulting in 860,560 MWh/year. Even for the pessimistic scenario, power generation by a floating PV plant in the Gavião reservoir would be enough to supply 19% of the demand of Fortaleza 4,627,482 MWh/year, IPECE 2017), with roughly 2,600,000 inhabitants.

Umenoki floating PV plant (Japan) has the potential of 7.6 MWp, while Pei County (China) has around 10 MWp. The third largest plant in the world is located in Yamakura (Japan) with the potential of 13.7 MWp. The second one is installed in the same city, Anhui (China) with two plants generating 20 MWp and 40 MWp (Pouran, 2018; Solar Asset Manegement, 2018). Therefore, the Gavião reservoir would have the potential to become the largest floating photovoltaic plant in the world.

Using the Penman (1948) equation, the average potential evaporation for the Gavião reservoir was estimated as 2,124 mm/year. This result was similar to that obtained for the city of Fortaleza (2,450 mm/year) with measurements in a "Class A" tank performed by Aguiar et al. (2003).

Therefore, adopting the result obtained by Melvin (2015), which indicates a reduction in the evaporation by 30% in floating photovoltaic systems, an evaporation reduction of 637 mm/year is obtained for Gavião reservoir. However, as only 81% of the water body would be covered by the floating panels and its components, the expected reduction in the evaporation would be 519 mm/year for the entire reservoir, corresponding to a volume of 2,595,000 m³/year that may be saved. The amount of water maintained in the reservoir is enough to supply a population of approximately 50000 persons, considering a per capita consumption of 150 L/hab.day.

Tables 2 and 3 show the financial analysis of the floating and on-ground PV systems, respectively, whereas Figures 4 and 5 represent the payback curves for the two projects. Those results were obtained considering: 1) interest rate (SELIC) of 15.47%; 2) income for savings of 2.66%; 3) annual increase rate of the tariff of 2.70%; 4) the monetary inflation used to estimate the maintenance costs during the period of operation, of 6.64%. The scenario considered for additional panel efficiency on the floating system was the pessimist (8.1% gain), representing a more conservative approach.

Years	Annual energy generation (KWh/Year) - AEG	Energy tariff (US$/KWh) - Tai	Gross annual income (US$) - GAI	Maintenance annual account (Maintance oparation US$ 9.20/KWp) - MAC	Net annual income (US$) - NAI	Cash balances (US$) - CB
1	835,820,000	0.21	179,470,552.15	-4,674,000.00	174,796,552.15	-754,605,000.00
2	829,551,350	0.22	182,933,885.13	-4,973,136.00	177,960,749.13	-693,381,644.37
3	823,329,715	0.23	186,464,051.78	-5,291,416.70	181,172,635.07	-619,475,149.69
4	817,154,742	0.23	190,062,341.81	-5,630,067.37	184,432,274.44	-530,875,680.90
5	811,026,081	0.24	193,730,069.86	-5,990,391.68	187,739,678.17	-425,262,470.56
6	804,943,386	0.25	197,468,575.88	-6,373,776.75	191,094,799.13	-299,955,775.63
7	798,906,310	0.25	201,279,225.72	-6,781,698.46	194,497,527.26	-151,861,406.87
8	792,914,513	0.26	205,163,411.58	-7,215,727.17	197,947,684.41	22,593,317.90
9	786,967,654	0.27	209,122,552.52	-7,677,533.71	201,445,018.81	224,639,318.97
10	781,065,397	0.27	213,158,094.97	-8,168,895.86	204,989,199.11	435,603,923.96
11	775,207,406	0.28	217,271,513.31	-8,691,705.20	208,579,808.11	655,770,796.45
12	769,393,351	0.29	221,464,310.34	-9,247,974.33	212,216,336.01	885,430,635.65
13	763,622,901	0.30	225,738,017.87	-9,839,844.69	215,898,173.18	1,124,881,263.73
14	757,895,729	0.30	230,094,197.27	-10,469,594.75	219,624,602.52	1,374,427,707.87
15	752,211,511	0.31	234,534,440.04	-11,139,648.81	223,394,791.23	1,634,382,276.13
16	746,569,925	0.32	239,060,368.40	-11,852,586.34	227,207,782.06	1,905,064,626.73
17	740,970,650	0.33	243,673,635.85	-12,611,151.86	231,062,483.99	2,186,801,829.79
18	735,413,370	0.34	248,375,927.84	-13,418,265.58	234,957,662.26	2,479,928,420.73
19	729,897,770	0.35	253,168,962.31	-14,277,034.58	238,891,927.73	2,784,786,444.45
20	724,423,537	0.36	258,054,490.36	-15,190,764.79	242,863,725.57	3,101,725,489.45
21	718,990,360	0.37	263,034,296.89	-16,162,973.74	246,871,323.15	3,431,102,710.62

Considering a 0.75% annual decay of the solar panels (ASPD)

Table 2: Financial analysis of floating photovoltaic system

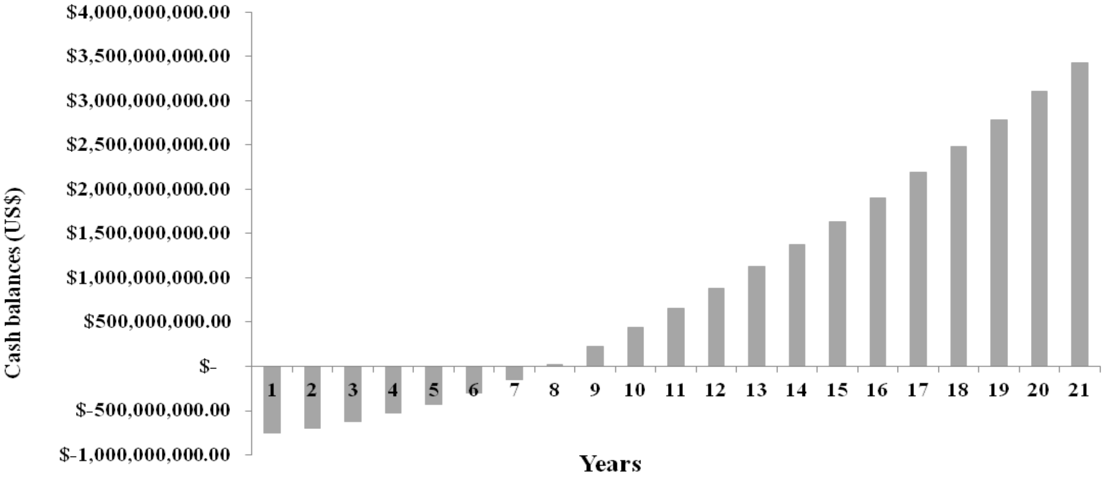

Figure 5: Payback curve of the floating photovoltaic system

Years	Annual energy generation (KWh/Year) - AEG	Energy tariff (US$/KWh) - Tai	Gross annual income (US$) - GAI	Maintenance annual account (Maintance oparation 0.5% of the project total value) - MAC	Net annual income (US$) - NAI	Cash balances (US$) - CB
1	773,190,000.00	0.21	166,022,392.64	-3,395,661.00	162,626,731.64	-679,132,200.00
2	767,391,075.00	0.22	169,226,209.76	-3,612,983.30	165,613,226.46	-618,580,724.88
3	761,635,641.94	0.23	172,491,852.54	-3,844,214.24	168,647,638.31	-545,627,524.72
4	755,923,374.62	0.23	175,820,514.07	-4,090,243.95	171,730,270.12	-458,305,832.67
5	750,253,949.31	0.24	179,213,410.44	-4,352,019.56	174,861,390.88	-354,344,354.10
6	744,627,044.69	0.25	182,671,781.23	-4,630,548.81	178,041,232.41	-231,120,193.27
7	739,042,341.86	0.25	186,196,889.92	-4,926,903.93	181,269,985.99	-85,604,501.18
8	733,499,524.29	0.26	189,790,024.41	-5,242,225.79	184,547,798.62	85,700,281.11
9	727,998,277.86	0.27	193,452,497.40	-5,577,728.24	187,874,769.17	275,854,677.75
10	722,538,290.78	0.27	197,185,646.97	-5,934,702.84	191,250,944.13	474,443,356.31
11	717,119,253.60	0.28	200,990,836.99	-6,314,523.83	194,676,313.17	681,739,862.75
12	711,740,859.20	0.29	204,869,457.67	-6,718,653.35	198,150,804.32	898,024,947.42
13	706,402,802.75	0.30	208,822,926.03	-7,148,647.17	201,674,278.86	1,123,586,689.89
14	701,104,781.73	0.30	212,852,686.45	-7,606,160.58	205,246,525.86	1,358,720,621.70
15	695,846,495.87	0.31	216,960,211.16	-8,092,954.86	208,867,256.30	1,603,729,846.54
16	690,627,647.15	0.32	221,147,000.84	-8,610,903.97	212,536,096.86	1,858,925,157.32
17	685,447,939.80	0.33	225,414,585.09	-9,162,001.83	216,252,583.26	2,124,625,149.76
18	680,307,080.25	0.34	229,764,523.04	-9,748,369.94	220,016,153.10	2,401,156,331.84
19	675,204,777.14	0.35	234,198,403.92	-10,372,265.62	223,826,138.30	2,688,853,228.58
20	670,140,741.32	0.36	238,717,847.62	-11,036,090.62	227,681,757.00	2,988,058,481.46
21	665,114,685.76	0.37	243,324,505.29	-11,742,400.42	231,582,104.87	3,299,122,941.94

Considering a 0.75% annual decay of the solar panels (ASPD)

Table 3: Financial analysis of the photovoltaic system on ground

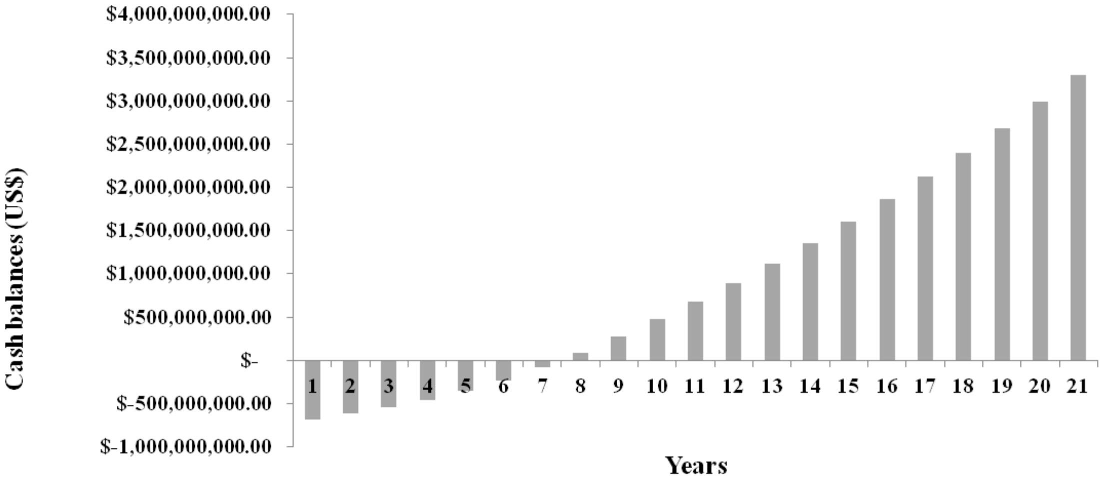

Figure 6: Payback curve of the photovoltaic system on ground

In the simulations (Tables 2 and 3), the floating system is more expensive than the on-ground one, as described by Sudhakar et al. (2016) and Ludwig (2017), resulting in higher investments and higher negative balances in the first years after the system implantation. However, both on-water and on-ground systems would produce positive balances in the eight year, and from the eleventh year, the on-water PV plant produces higher positive balance. Furthermore, if a value is attributed to the non-evaporated water on the floating system, it is possible to reduce its payback time, in addition to the higher water availability in this water-scarce environment.

One must also be aware that acquisition or rental of land and the preparation of the area for the installation of on-ground PV plants was not considered in the simulations. The price of land was not placed in the analysis because it is not fixed like the other items, the cost can be influenced by the attributes that it offers (infrastructure of energy, water, internet, transportation, security, vegetation type, etc.), hampering a precise estimation of land value. Another point that could contribute to a lower payback time of the floating PV system is if the additional costs of land preparation for on-ground PV plants were considered in the financial analysis (Song and Choi, 2016).

Our analysis considered the pessimistic improvement scenario for simulation in the floating PV, in order that amount of energy is expected to be higher than that considered in the study, reducing the payback time for this system. Although some economic factors have not been considered, the payback of the modeled floating PV system in Gavião is in accordance with some results worldwide (Sahu et al. 2016; Rosa-Clot et al. 2017; Song and Choi 2016).

Indeed, infrastructure works that demand large territorial extensions are usually built away from large cities like Fortaleza, with approximately 2,600,000 inhabitants, because of land availability. Therefore, additional costs would enhance the initial investment of an on-ground photovoltaic plant above the value considered in this study, for land acquisition or rental and/or infrastructure to transport the generated electricity, in case the plant would be built farer from the demand center of Fortaleza.

5. CONCLUSION

Simulation of a floating photovoltaic plant in the tropical Gavião reservoir, in northeast Brazil, showed that this type of power generation is a feasible alternative for that region, which is near a large power demand center (the Metropolitan Region of Fortaleza) where land availability is low, which makes the traditional on-ground photovoltaic system more expensive. The potential for power generation in the pessimistic scenario (835,820 MWh/year) is sufficient to supply 19% of the demand of the city of Fortaleza (4,627,482 MWh/year), with approximately 2,600,000 inhabitants.

The area covered by the photovoltaic panels represents 81% of the maximum reservoir flooded area. With the shading caused by the floating system, it was estimated that 2,595,000 m^3/year of water would no longer be evaporated, enough to supply 1.5% of the total demand of Fortaleza.

Both on-ground and floating PV system presented the same payback period, but some elements contributing to the floating system were not considered, like the value of non-evaporated water, the value of acquisition and the preparation land for installation of on-ground PV panels and a better efficient scenario of the floating PV performance (rising the generated energy). Adding these parameters could make difference in both systems, reducing the payback for floating PV and rising for on-ground PV.

The initial project costs of the floating system in the Gavião Reservoir (approximately US$ 755 million) are compatible with the investments planned for the region. For instance, the official document “Fortaleza 2040: Renewable Energy and Energetic Efficiency” estimates, until 2040, private investments of the order of US$ 4 billion.

Despite the positive aspects of the floating photovoltaic system, there are some relevant key issues which need to be studied, such as: i) how to ensure better conditions of installation and operation for the whole floating system; and ii) how the reduction of the photic zone impact on the water quality. These issues will allow a better understanding of the operation and expected consequences of floating PV panels.

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