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Technical Potential of Floating Photovoltaic Systems on Artificial Water Bodies in Brazil

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Abstract

Floating photovoltaic systems (FPVs) are an emerging technology where photovoltaic solar panels are placed on the water surface. They are cost-competitive compared to ground-mounted solar farms and provide some additional and unique properties including reduced evaporation of the water from the reservoir, mitigating algae growth; higher efficiency of electricity generation compared to common PV systems because of the cooling effects of water and preventing land-use conflicts. Despite the growing interest in this technology and the opportunities that it could create, there is no systematic assessment of the technical potential of FPVs in Brazil. This work is the first study on the technical potential of FPVs in artificial water bodies applied to Brazil at country and state levels. The country's potential for this purpose was determined based on two criteria: selecting only artificial/man-made water bodies and excluding protected areas. The QGIS software was used to locate water bodies and cross georeferenced meteorological data. The results show that even if FPVs cover only 1% of the identified suitable areas this technology can produce energy equivalent to almost 12.5% of the current national electricity generation and correspond to approximately 16% of Brazil's electricity consumption.

Keywords: Floating photovoltaic system; potential capacity; renewable energy; artificial water bodies.

ANA – National Water Agency (*Agência Nacional de Águas*)
EPE – Research Energy Company – (*Empresa de Pesquisa Energética)*
FPVs – Floating photovoltaic systems
HDPE - High-density polyethylene
HPP - Hydroelectric power plant
IBGE – Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística*)
INMET - Brazilian National Institute of Meteorology (*Instituto Nacional de Meteorologia*)
INPE - Brazilian Institute for Space Research (*Instituto Nacional de Pesquisas Espaciais)*
Isc – Short Circuit Current
NOCT - Nominal Operating Cell Temperature
ONS -National System Operator
Pmax – Maximum potency
PNAD - Continuous Brazilian Household Sample Survey
PV – Photovoltaic
SHP - Small hydropower
TMY- Typical meteorological year
USA – United States of America
UV – Ultraviolet
Voc – Voltage of open-circuit

1. Introduction

Floating photovoltaic systems (FPVs) installations are now present in more than 60 countries, which have reached a cumulative capacity of approximately 2.6 GWp until August 2020 [1]. Compared to common/ground-mounted photovoltaic systems, FPVs are a cost-competitive technology and provide unique energy and non-energy benefits, which stem from the nature of this technology and placing the PV panels on the water surface. These advantages range from efficiency and power production gains, avoiding land-use conflicts, integration with hydroelectric plants, lower site preparation costs, water evaporation reduction, algae growing inhibition, to use of degraded areas such as depleted mine lakes and lower environmental impacts [2–8]. Because of lower ambient temperatures and the cooling effect of water, in addition to higher wind speeds, the FPVs energy yield is higher compared to the common PV systems [9]. FPVs also absorb solar radiation and reduce the airflow on the water surface, leading to less water evaporation which is crucial in water-scarce areas [10,11]. FPVs could also be deployed on the reservoir of hydroelectric dams to complement the existing infrastructures and improve the energy output. This would create a more reliable and diverse energy supply, particularly when less annual precipitation affects the electricity generation by hydroelectric dams [5,12–14].

While countries that have deployed or are planning to install FPVs consider different socio-technical benefits that this technology provides, nevertheless their primary reason for investment in FPVs might be different. For example in South Korea, it’s a viable option because of the land scarcity and population density [15]. The same is for Japan in addition to other concerns including frequent earthquakes and land-use conflicts e.g., between expanding residential areas, agricultural activities, or deploying renewables [16]. China has deployed FPVs as an opportunity to mitigate the social impacts of its energy transition from coal to renewable and revitalize degraded areas. Deploying the largest FPV on the collapsed coal mines in Anhui is a prime example [4]. In Jordan, FPVs were tested and showed positive results in the improvement of reservoir water quality reducing dissolved nutrients like nitrate and chlorophyll-a, mitigating algae proliferation and generation of harmful chemicals, which leads to minimizing water treatment costs [17].

In arid and semi-arid regions, countries like Australia, Spain, Iran, the US, Chile, India, and Jordan, where water evaporation is high and water scarcity is a major challenge deployment of FPVs has been considered for reducing water evaporation from man-made or natural water bodies [8,12,17–23]. A study conducted on the potential use of FPVs in 146 hydropower reservoirs across different African countries showed a potential reduction of 734 million m^3/year in evaporation with only 1% coverage. Moreover, this would improve electricity generation through hydropower systems by about 58% [14]. Because of such benefits, installing FPVs is accelerating globally as seen in Figure 1.

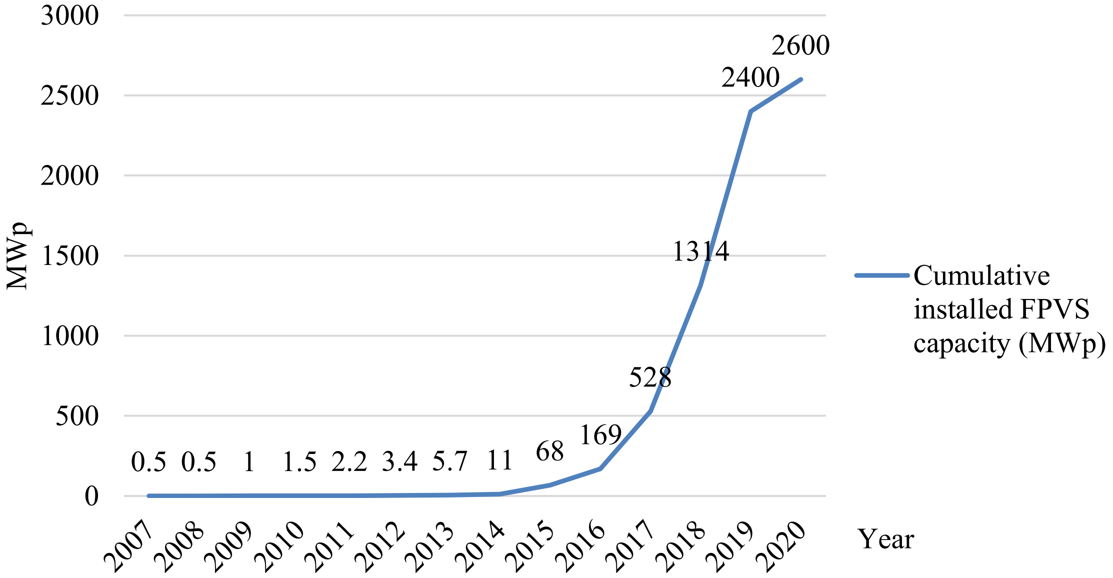

Figure 1: Total capacity of FPVs installed worldwide. Authors' compilation based on [1,24,25] [1]

Considering the technical potential of this technology, evaluating its technical potential and the need for supporting policies is of growing interest and there are emerging studies that cover such topics. Kim et al., (2019), for example, evaluated the FPVs applicability and potential of covering 10% of 3401 reservoirs in Korea [15]. The study used the typical meteorological year (TMY) data and topographical information to predict the irradiance distribution. They also considered a water depth database to select suitable reservoirs to install FPVs, and the findings suggested a potential production of 2932 GWh per year [15].

Spencer et al. (2019) have assessed the US technical potential for PV systems on man-made water bodies and shown that more than 24,000 reservoirs are suitable for installing such systems representing 27% of the total number of man-made water bodies or 12% of the total surface area. Only man-made reservoirs, with a water depth bigger than 2 meters and contiguous transmission in a distance less than 80 km were studied in this research and reservoirs with purposes like recreation, tailings, navigation, fish and wildlife pound, and water surface areas with less than 4,000m² were excluded [3]. The results show a potential of 2116 GW of FPVs capacity representing about 10% of the current electricity generation of the USA [3].

Acharya and Devraj (2019) and have estimated that the surface area available for FPVs in India is about 18,000 km² with a potential capacity of 280 GW. In Brazil, Santos et al. (2019) calculated the power generated by FPVs using 10% of the area of the reservoirs of the four largest hydroelectric power plants in the country. According to the results, the Balbina hydroelectric plant has a FPVs energy generation potential of 47,910 GWh annually, which corresponds to about sixty folds increase in the plant's actual electricity generation.

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[1] The value for 2020 is the cumulative capacity up until August 2020.

The *Sobradinho* and *Tucuruí* plants present the potential of 112,632 GWh/year and 59,906 GWh/year respectively - four and two times the plant's annual electricity generation. In the case of the *Itaipu* plant, the potential energy generation in its reservoir is almost 29 TWh/year but does not surpass the actual hydroelectric generation levels.

Although this is not the first study that evaluates FPVs installation potential, this work differentiates itself from other studies in presenting a methodology explicitly applied to Brazil in a country-level analysis for the first time. The approach of this research can be reproduced for other countries when information about local water bodies and climatic conditions are available. Brazil has a promising potential for FPVs installation due to the variety and quantity of water bodies in its territory. There are close to 241,000 water bodies in Brazil cataloged by the National Water Agency (ANA, 2020), including hydroelectric reservoirs, lakes, lagoons, weirs, dams, rivers, basins, among others. Also, Brazil presents high levels of global irradiance, especially in the Northeast region [28].

Hence, this work proposes to evaluate the Brazilian FPVs technical potential considering the utilization of 1% of the surface of all the available artificial water bodies in the country. The article addresses the following research questions:

1) What is the FPVs' technical potential for each Brazilian waterbody type?
2) Which Brazilian regions and states offer the highest potential for FPVs installation?

The methods section characterizes, maps, and accounts for the water bodies found in Brazil followed by technical descriptions of characteristics of the adopted FPVs model. Then this article presents the databases and equations used to calculate the technical potential of installing FPVs and the potential for electricity generation if 1% of the water body surfaces is covered by floating solar.

2. Methods

As defined in this study, the technical potential represents the achievable energy generation and installed capacity of technology. It depends on the availability of resources, system performance, and environmental constraints. One of the benefits of assessing technical potential is that it provides an upper-boundary estimate of the technology's development in a certain region [29]. Figure 2 presents the steps considered to estimate the FPVs technical potential in Brazil.

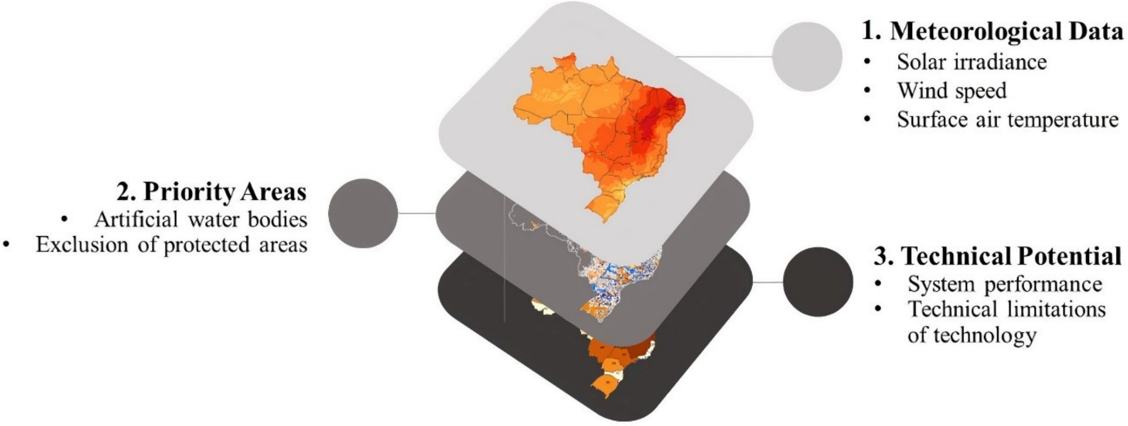


Figure 2: Study process to assess the Technical Potential of FVPs in Brazil

The first step of the methodology was the research of spatial meteorological data in Brazilian databases. The main inputs for calculating PV systems energy generation were solar irradiance, wind speed, and surface air temperature. The second step counted with selecting the most suitable areas for FPVs implementation, producing a data set of the water bodies suitable for PV development. Only artificial water bodies were selected, and protected areas were excluded from the analysis.

Finally, a state-level annual FPVs energy generation and installed capacity was obtained using a group of mathematical equations and assumptions for the FPVs system configuration and performance (step 3). The equations adopted step 1 and step 2 data as inputs. All steps utilized the open-sourced geoprocessing tool QGIS to filter, join, analyze the data, and visualize the results.

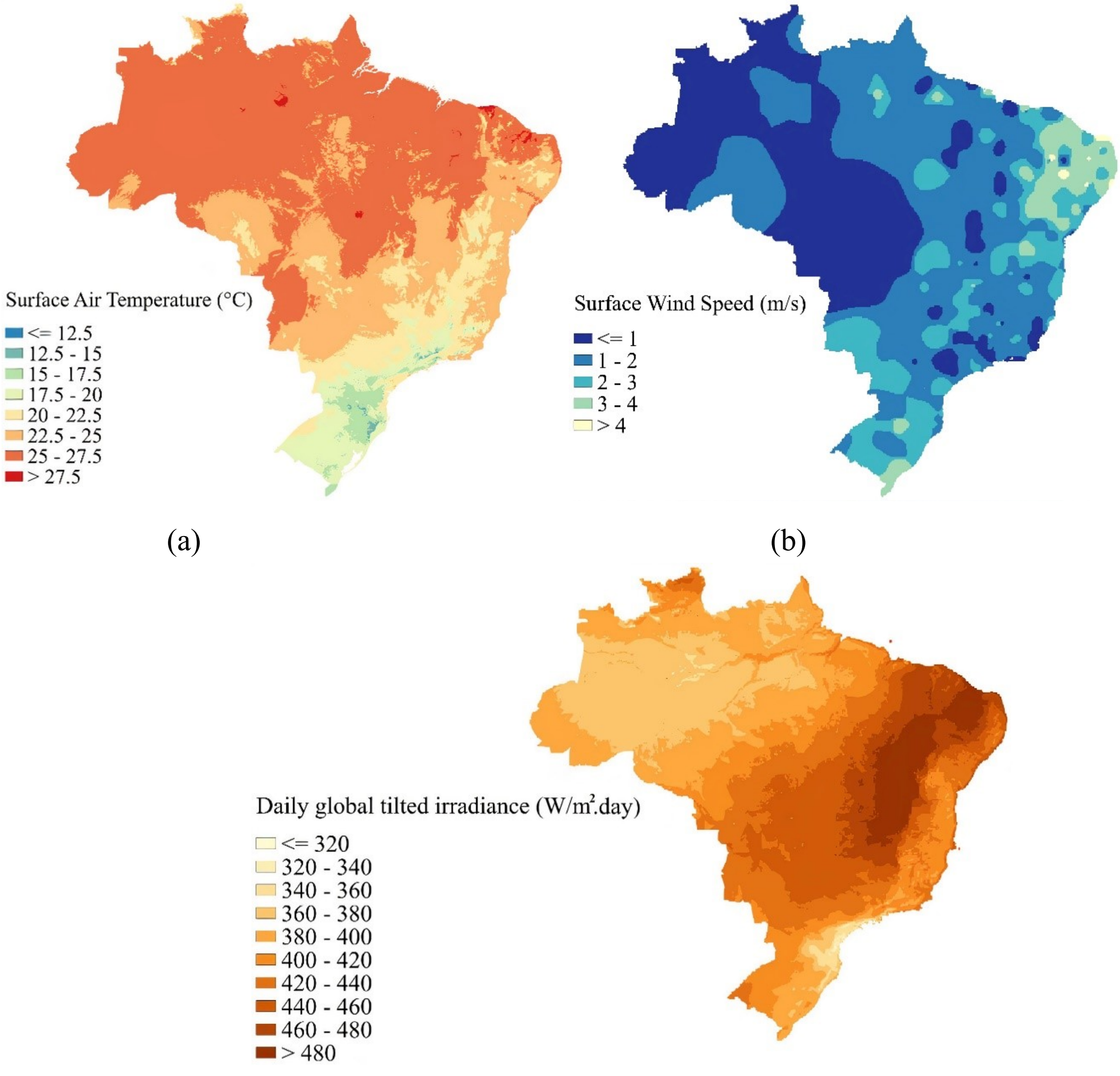
Note that the estimates do not consider the local market constraints, current or future technology costs, and relevant policies as a technical potential. Also, this paper does not capture the availability of grid infrastructure or possible future technology improvements, which might affect the level of energy generated.

2.1 Meteorological data

The use of geoprocessing tools permits the crossing of several features for making smarter decisions based on geographic visualization, allowing spatial planning, creation, and comparison of scenarios, editing, and data analysis, in addition to transforming tables of attributes in cartographic data. This paper differs from other studies which commonly consider only solar resources, disregarding that the real operating efficiency of PV modules is very susceptible to temperature [30–33]. Simioni & Schaeffer (2019) [33] approached the importance of adopting georeferenced weather data besides radiation to make a more effective solar potential evaluation for continental extensions like Brazilian territory. Therefore, this work applies a similar methodology used by Simioni & Schaeffer (2019), using QGIS geoprocessing software to cross-reference meteorological data that influence the solar generation and thus apply this information into a mathematic model to obtain the differentiation of technical potentials of floating PV systems for each location in Brazil [33]. The mathematical model applied in this article is detailed in section 2.3.2.

Three meteorological input variables which affect solar PV power are considered in this study: average daily global tilted solar irradiance throughout the year (W m^{-2} day^{-1}), average annual wind speed (m s^{-1}), and average annual surface air temperature (° C). Average daily global tilted irradiance throughout the year is derived from average daily global tilted irradiation, obtained from the Brazilian Atlas of Solar Energy [28]. This research is based on considering 4,380 hours of sunshine hours within a year, or half the annual number of hours, which results in a yearly average of 12 hours of daylight each day [34].

Average annual surface air temperature data were obtained from the AMBDATA database of the Brazilian National Institute for Space Research (INPE) [35]. The average annual surface wind speed was calculated based on surface wind speed data, between 2013 and 2017, collected from 245 weather stations within the country installed by the Brazilian National Institute of Meteorology (INMET) [36]. Different layers for each weather database were created in QGIS for data crossing and spatial visualization. The meteorological layers and their classification are shown in Figure 3.



(a) (b)

(c)

Figure 3: Meteorological input variables used in this paper: (a) annual average surface air temperature (° C); (b) annual average surface wind speed (m s^{-1}); and (c) daily average global tilted irradiance throughout the year (W m^{-2} day^{-1}).

The highest levels of global tilted irradiance are registered in the Northeast region, with daily averages higher than 485 W m^{-2}, while the lowest values of irradiance are in the easternmost parts of the South region. The annual average surface air temperature is higher in the North region. Finally, the highest levels of surface wind speed are found in the Northeast region, with annual averages above 3 m s^{-1}.

2.2 Priority areas selection

Georeferenced data from the Brazilian Water Agency [37] for the selection of the priority areas. The selected database contains 240,899 water bodies classified according to type (weir, dam[2], stream, channel, river, basin, cava, dike, reservoir, tank, small hydropower (SHP), hydroelectric power plant (HPP)[3], lake, and lagoon), origin (natural or artificial), ownership (Federal or State), and main use (human watering, animal watering, irrigation, balneary, recreation, hydroelectric and aquaculture).

For the proper site selection, a data spreadsheet software and QGIS were used to filter the artificial water bodies. The option to consider only artificial water bodies is due to the following assumptions:

- Artificial water bodies usually have existing infrastructure and road access for the management and installation of solar equipment [3].
- Natural water bodies tend to have greater environmental concerns [38]
- Most of the existing investments in FPVs, globally, are located on artificial reservoirs [26].

Protected areas and indigenous lands were also excluded from the analysis because different restrictions and rules can be applied depending on the characteristics of the area [39]. Therefore, specific studies would be needed to evaluate the viability of FPVs installation in these areas, which is not the focus of this article.

Table 1 shows the total surface area and the number of artificial water bodies divided by category. Derived from this data, Figure 4 shows the location of each type of waterbody in the Brazilian regional map.

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[2] Although some literatures define construction differences between dam and weir [53], in Brazilian case both could be used as synonymous, generally referring to river dams for the purpose of supplying water to cities, agricultural areas and industries.

[3] SHP in this case is encompassing Small Hydroelectric Plants (with reservoirs of up to three square kilometers and installed capacity from 1 to 30 MW) and Hydraulic Generating Plants (plants with a capacity of up to 1 MW) [54]. All water bodies destined to generate electricity that do not fit in these cases are considered Hydroelectric Power Plants (HPP).

Table 1: Type, quantity, and the total surface area of Brazilian artificial water bodies

Type	**Quantity**	**Area (km²)**
Weir/Dam	9,162	6,539
Stream/Channel/River	318	180
Basin/Cava/Dike/Reservoir/Tank	121	32
SHP	761	705
HPP	200	33,140
Lake/Lagoon	364	133
Without classification	163,600	4,774
Total	**174,526**	**45,502**

Source: Constructed by authors based on [37]

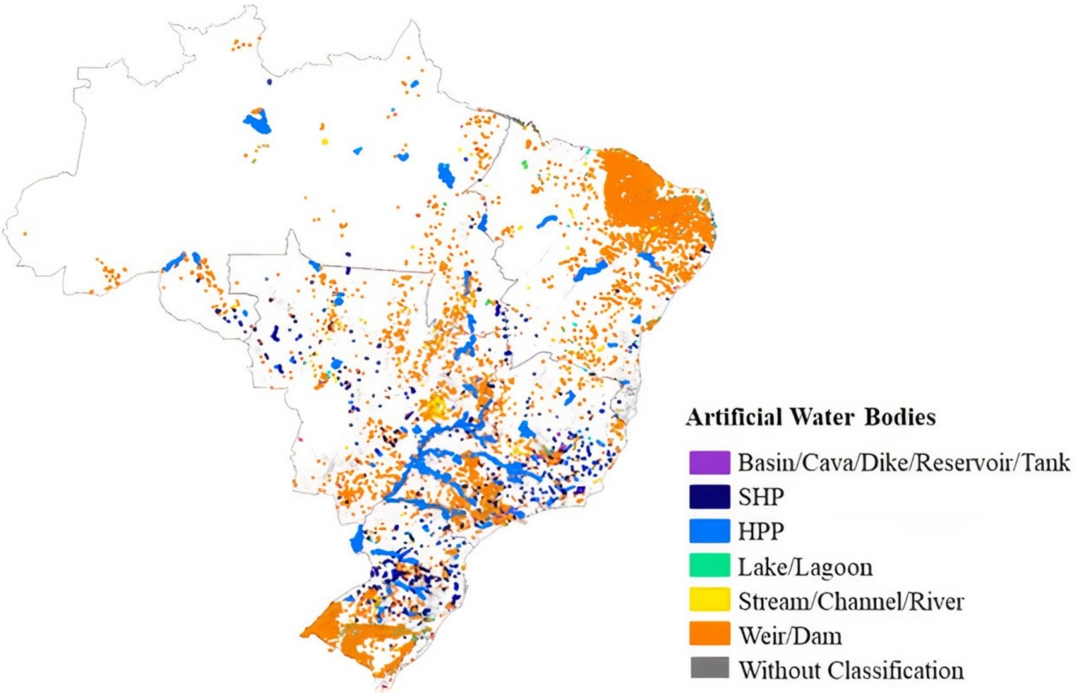

Figure 4: Type and location of artificial water bodies. Elaborated based on ANA database [37].

Because of their large reservoirs, the hydroelectric plants represent 73% of the total surface area. Considering this, hybrid systems of FPVs and hydropower plants provide a unique opportunity for the country, bringing benefits such as mitigating electricity supply variability by adding additional capacity of clean energy generation, diversifying the energy supply, making it more reliable, and utilizing the existing energy transmission infrastructures.

Figure 4 also states the representativeness of weirs and dams in the Northeast region that is a consequence of public policies, which encouraged the construction of water reservoirs and rainwater cisterns to address the region's water supply issues in the semiarid [40]. Therefore, the Northeast region could benefit from installing floating photovoltaic systems as a strategy to mitigate water scarcity by reducing the evaporation rate on water bodies.

From obtaining the total surface value of the reservoirs, a percentage of surface use with FPV systems can be considered. Rosa-Clot and Tina (2018) [41] suggested the following maximum percentage of reservoir coverage with FPVs: 90% to 95% for Industrial basins (sandpit, mines, cooling basins, wastewater treatment basins, etc.) [41]; 5% for Hydroelectric basins; 0% to 5% for natural lakes, and 10% or more for Sea surfaces (low depth sea, branches, lagoons, and offshore systems) [42]. Thus, the adoption of this present work to cover all water bodies with only 1% was an arbitrary and conservative proportion of real available surfaces that could be used for FPVs. This cover percentage is a simplification that has the intention to show the potentiality of installed capacity and energy generation of FPVs with a little part of the available surface of water bodies. In addition, the 1% cover value was adopted because the linear relation, permits that the results of potential generation of FPVs could be multiplied by any cover factor of reservoir surface that is intended to implement the system.

2.3. Technical potential calculation

2.3.1. Technical characteristics of proposed FPVs

With the main areas identified, the installed capacity and the annual electricity generation for each waterbody were calculated, considering floating PV system characteristics and local climate conditions. The general layout of an FPVs system is similar to a land-based PV system, except it is located on top of a floating platform with a rigid anchoring and mooring system [43].

The technical characteristics of modules and inverters determine how much power per area could be generated by floating solar systems. In this study was adopted an FPVs module based on the equipment of the national company Sungrow. The floating system is composed of high-density polyethylene (HDPE), resistant to UV radiation and tolerant to temperatures from 40 °C to 85 °C. It presents wave resistance anti-fatigue, has a 25-year lifecycle, and is adjustable for different angles [44].

In a previous study, Lopes et al. [11] suggested that for floating solar systems a composition of 25 PV modules per string and 125 strings covers 10,512 m² (or 1.05 ha) of water surface and creates a capacity of 1 MWp. This article considers the same approach here and assumes that each MWp FPV covers approximately 10,512 m². Some of the technical characteristics of the module and floating area are presented in Table 2:

Table 2: Technical characteristics of PV module and floating area [45]

Characteristic	Value
Module capacity (Wp)	320
Nominal efficiency (%)	16.49
Temperature coefficient Pmax (%/°C)	-0.43
Temperature coefficient Voc (%/°C)	-0.34
Temperature coefficient Isc (%/°C)	-0.065
Nominal Operating Cell Temperature (NOCT)	45±2
Panel capacity density (m²/MWp)	6,062.5
Floating capacity density (m²/MWp) (CD_F)	10,512

Characteristic	Value
Module area (m^2/unit)	1.94

2.3.2. Mathematical model for solar PV installed capacity and electricity generation

The estimation of the technical potential of the FPVs in Brazil was based on the conservative assumption of 1% of each artificial water body area, as mentioned before. These results can be reliably extrapolated for higher surface area coverages if needed.

An important variable of the equation is floating capacity density (CD_F). It represents the reservoir surface area that is occupied for a given photovoltaic capacity by the floating system. Its value depends on the capacity of the module, how many modules each floating support, and the floating area for a projected PV system. Each floating project model has a different occupancy area per PV capacity unit. The CD_F in this article was obtained based on the following considerations: 1 MWp of PV system contains 3125 PV modules of 320 Wp and one central inverter. The area of the Sungrow floating model needed to sustain 1 MWp of modules and the central inverter is 10,512 m^2.

The power capacity for the proposed system for each waterbody is presented in Equation 1,

$$C_{wb} = 1\% \times \left(\frac{S_{wb}}{CD_F}\right) \qquad \text{Equation 1}$$

Where C_{wb} is the installed capacity of the waterbody (MWp), S_{wb} is the surface area of the waterbody (m^2), CD_F is the capacity density of the FPVs, calculated for the Sungrow equipment as 10,512 m^2/MWp (Table 2).

The solar PV electricity generation can be calculated as a function of climate data, employing equations derived from heat exchange processes between the solar PV module and the environment. This model is used in papers that describe the impacts of meteorological aspects on the operating temperature of modules, which affects their efficiency [30–32,46,47]. One of the main advantages of this model is its compatibility with geographic information systems, required for estimating the FPVs potential in the scale of countries like Brazil efficiently. This methodology can be replicated in every country with georeferenced environmental measurements. Equation 2 shows the average yearly operating temperature of solar PV modules as a function of climate variables.

$$T_c = T + \omega\left(\frac{0{,}32}{8{,}91+2.V}\right).G_T \qquad \text{Equation 2}$$

Where T_c is the average daily operating temperature of a solar PV module (°C), G_T is average daily global tilted irradiance ($W\ m^{-2}\ day^{-1}$), T is average daily surface air temperature (°C) and V is average daily surface wind speed ($m\ s^{-1}$) throughout the year. Equation 2 introduces the variable ω, named mounting coefficient[4], whose value varies

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[4] A mounting coefficient is established for a specific module arrangement. The mounting scheme impacts the heat exchange between modules and the environment, directly affecting their operating temperature. According to Skoplaki et al. (2008), mounting arrangements can be classified in four types: free-standing, flat roof, sloped

according to the arrangement and installation of solar PV modules [32]. In this paper, it is assumed that ω is equal to 1.0, considering that the modules are organized in free-standing arrays [32]. Thus, it is possible to calculate the module efficiency as a function of operating temperature, as shown in Equation 3.

$$\eta_C = \eta_{ref}\left[1 - \beta_{ref}(T_c - T_{ref})\right] \qquad \text{Equation 3}$$

Where η_C is the average annual solar PV module adjusted efficiency, η_{ref} is the standard solar PV module efficiency, β_{ref} is the coefficient of correction of efficiency as a function of temperature (° C^{-1}), T_{ref} is the temperature of reference that varies according to the module technology (° C) and T_c is the average annual operating temperature calculated previously in Equation 3 (° C). It is assumed in this study that the variables depending on the module technology are based on specifications of the Globo Brasil 320 W module (GBR320p). Thus, η_{ref} is equal to 16.49%, β_{ref} is 0.0043 ° C^{-1} and T_{ref} is 25 ° C [48].

Therefore, the solar PV module's electricity generation can be estimated as a function of global tilted irradiation and the module adjusted efficiency estimated in Equation 3. On an annual basis, the electricity generation of solar PV modules is expressed by Equation 4.

$$E_{FPV} = \eta_c .\ G_T . 365 \qquad \text{Equation 4}$$

E_{FPV} is the average annual electricity generation of the solar PV module (Wh m^{-2}), G_T is the average daily global tilted irradiation throughout the year (Wh m^{-2} day^{-1}), η_c is the average annual module adjusted efficiency and 365 is the number of days within a year.

The obtained results are compared with field data collected from solar power facilities with fixed tilted angles connected to the National Interconnected System (SIN), provided by the National System Operator (ONS). As field data from solar power plants are expressed in capacity factors, it is necessary to convert the photovoltaic power output calculated by the mathematical model into a capacity factor for comparison. The average annual capacity factors are then estimated for each site where those solar PV utility-scale facilities are installed. Thereafter, these capacity factors are compared to those observed in five solar PV facilities.

The solar PV facilities, with their average capacity factors reported by ONS in the last 12 months within parenthesis, are: Coremas (23.3%); Mossoró II (28.1%); Paracatu 4 (23.9%); Água Vermelha (24.0%); and Getulina (20.5%)[49]. The average capacity factors calculated through the mathematical model for the sites where the facilities are located are, respectively: 24.1%, 22.9%, 22.7%, 21.5%, and 21.4%. The results obtained from the mathematical model are similar to the observed in SolarGIS, which is a recognized solar resource database, whose capacity factors for the same locations above are, respectively: 20.0%, 19.1%, 19.7%, 19.2%, and 18.8%. The percentual difference of capacity factors from PV facilities and the capacity factors calculated by the model range from -3% to 18%. With the SolarGIS data, this range varies from 8% to 32%. Therefore, the capacity factors of the

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roof and building integrated. Their mounting coefficients are 1.0, 1.2, 1.8 and 2.4, respectively. Higher mounting coefficients lead to higher module operating temperatures.

solar PV facilities are well represented by the capacity factors calculated by the mathematical model.

3. Results and discussion

This section responds to the objective questions about the technical potential of FPVs capacity and generation installed in Brazilian artificial water bodies divided by type and country state. Also, the discussions compare this energy potential of FPVs with the possible number of houses supplied, with the Itaipu's generation (the biggest Brazilian hydroelectric), and with the current electricity Brazilian generation, considering all resources. At the end of the results section, the limitations, and considerations for carrying out the study are presented.

3.1. Technical potential of FPVs by waterbody type

The installed capacity (MWp) and energy generation (GWh/year) of FPVs for each waterbody type are described in Table 3. Also, the percentual FPVs installed capacity potential by type of waterbody is shown in Figure 5.

Table 3: Potential capacity for installing floating solar systems and energy generated from each type of water body in Brazil.

Type of water bodies	Quantity	Area (km²)	Energy (GWh/year)	Installed Capacity (MWp)
Weir/Dam	9,162	6,539	11,876	6,219
Stream/Channel/River	318	180	283	169
Basin/Cava/Dike/Reservoir/Tank	121	32	52	30
Small Hydropower Plant (SHP)	761	705	1,183	671
Hydropower Plant (HPP)	200	33,140	57,384	31,520
Lake/Lagoon	364	133	227	127
Without classification	163,600	4,774	8,372	4,541
Total	**174,526**	**45,502**	**79,377**	**43,276**

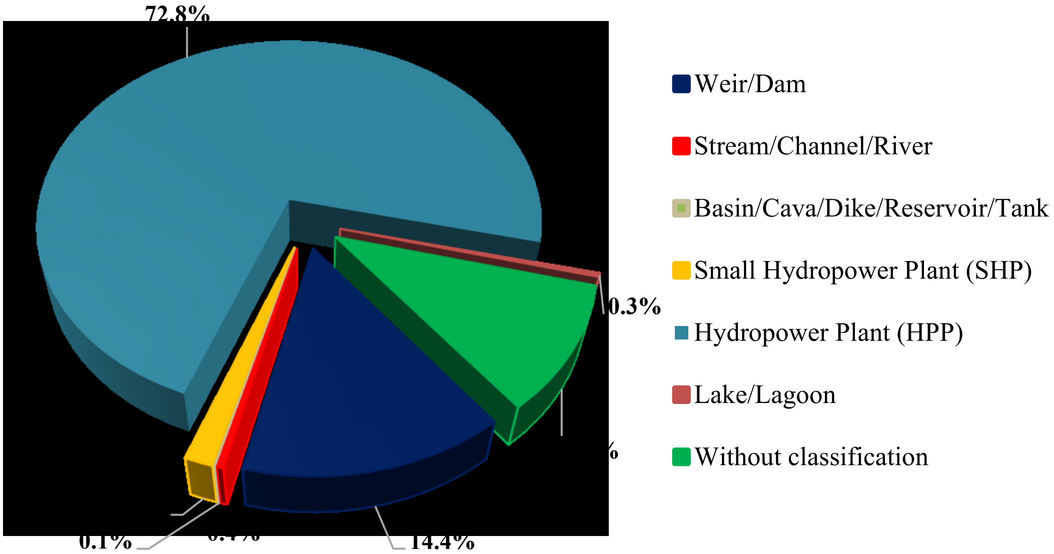

Figure 5: The potential capacity for installing FPVs by the water body type in Brazil.

As shown above, even if only 1% of the surface area of artificial water bodies in Brazil is covered by floating photovoltaic systems it would generate 79,377 GWh/year of electricity with the potential capacity of 43,276 MWp. It is worth noting that approximately 72% of the potential is from hydropower plant reservoirs, for which the FPVs installation capacity and energy generation potentials are 31,520 MWp and 57,384 GWh/year, respectively.

Three indicators were calculated to understand the magnitude of these numbers. The first comparison is related to Brazilian average household consumption, calculated considering the Brazilian residential consumption of 142,781 GWh divided for 73,4 million residences, resulting in 1,945.2 kWh/year per residence, based on the 2020 Statistical Yearbook of electricity [50]. The second comparison is with Itaipu hydroelectric power plant energy generation, the biggest power plant in Brazil with an annual production of around 80,000 GWh/year [51].

Table 4: Comparison of electricity generated by FPVs with Brazilian average household consumption, Itaipu generation, and Brazilian total electricity generation.

Type of water bodies	**Energy (GWh/year)**	**N° of stocked houses⁽¹⁾**	**% Itaipu Generation⁽²⁾**	**% Brazilian Generation⁽³⁾**
Weir/Dam	11,876	6,105,285	14.8%	1.9%
Stream/Channel/River	283	145,486	0.4%	0.05%
Basin/Cava/Dike/Reservoir/Tank	52	26,733	0.1%	0.01%
Small Hydropower Plant (SHP)	1,183	608,167	1.5%	0.19%
Hydropower Plant (HPP)	57,383	29,499,794	71.7%	9.16%
Lake/Lagoon	227	116,698	0.3%	0.04%
Without classification	8,371	4,303,414	10.5%	1.34%
Total	**79,377**	**40,806,601**	**99.2%**	**12.67%**

(1) Considering the Brazilian mean consumption of 1945.2 kWh/year per residence [50].

(2) Considering the Itaipu hydropower plant produces annually around 80,000 GWh [51].

(3) Considering the Brazil electricity generation of 626,324 GWh [50].

The FPVs technical potential is considerably high, corresponding to almost the Itaipu's yearly generation and 12.7% of Brazilian total electricity generation. Furthermore, FPVs generation potential could power nearly 41 million households, which corresponds to 56% of total Brazilian residences - 72.4 million private households according to Continuous National Household Sample Survey (PNAD) 2019 [52]. As stated above, the main potential belongs to hydropower plant reservoirs, which represent 72% of annual Itaipu's generation and 9% of the country's generation.

Assuming a water coverage of 27% as used by Spencer *et al.* [3], the total technical potential would be 2,143 TWh/year, representing 273% of the U.S FPVs power generation potential (786 TWh of electricity per year). It would also correspond to 23 times Itaipu's power generation.

Considering only hybrid PV-hydro systems and a 20% surface occupation, the FPVs Brazilian technical potential represents 11% of the “Close to Shore”[5] scenario global generation (10,616 TWh/year) and 85% of South America technical potential [5].

3.2. Technical potential of FPVs by state and Brazilian region

The power capacity is relatively dispersed by region. Figure 6 shows the special distribution of FPVs potential capacity considering 1% of the surface area.

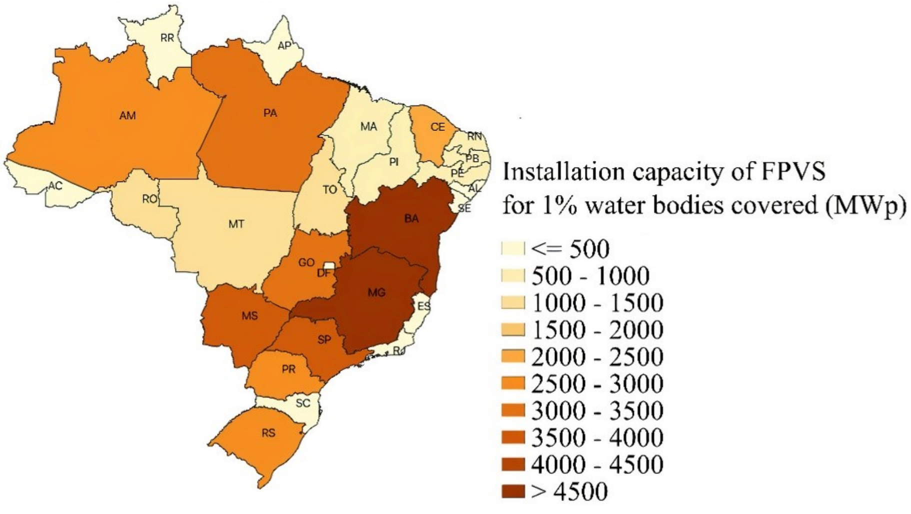

Figure 6: Spatial results of FPVs installed capacity by state (MWp)

The values of FPVs installed capacity for each Brazilian region and state is expressed in Figure 7.

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[5] “Close to shore” is one among three scenarios of minimum distance of shore proposed by Lee et al. [5]. This scenario considers a potential installation of FPVs in a minimum distance about 0 to 50 meters of shore.

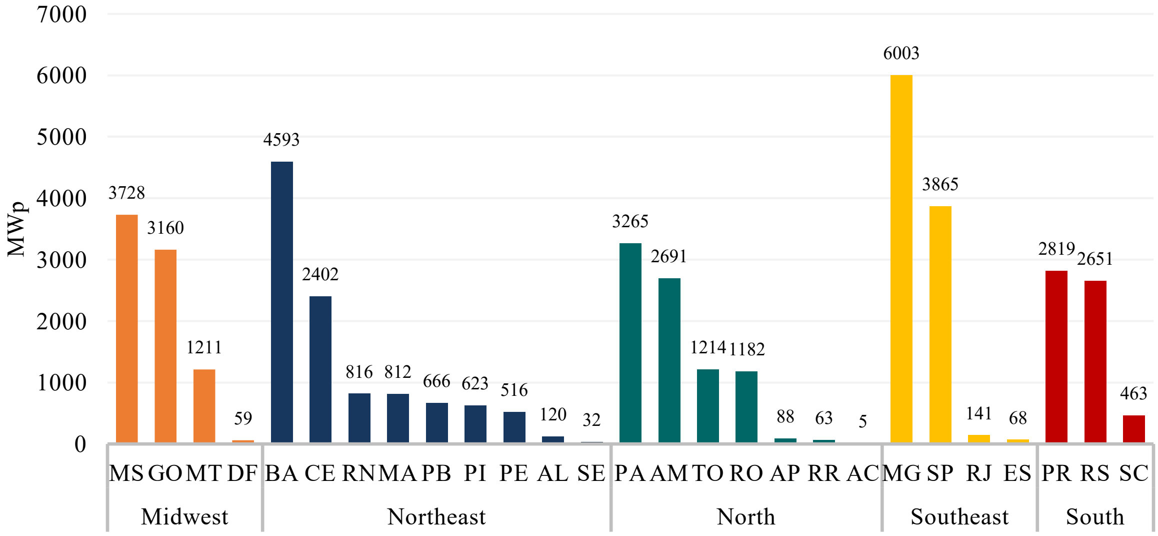

Figure 7: Potential FPVs installed capacity by state and region (MWp).

The power capacity is relatively dispersed by region. The most significant potential is in the Northeast region with 10,580 MWp (24.5%). Further, comes the Southeast with a 10,077 MWp potential (23.3%), followed by the North with 8,508 (19.7%), the Midwest with 8,158 MWp (18.9%), and the South with 5,933 MWp (13.7%).

The Brazilian Southeast is the most populous region with 42% of the country's population (IBGE, 2020). The installation of FPVs in this region could reduce energy transmission losses and the grid infrastructure investments due to the proximity of the consumption center and energy generation.

By crossing the installation potential in each state and region with georeferenced data on radiation, temperature, and wind speed, it was possible to obtain the energy generation potential by location. The result of annual energy generation potential is expressed in Figure 8 and Figure 9.

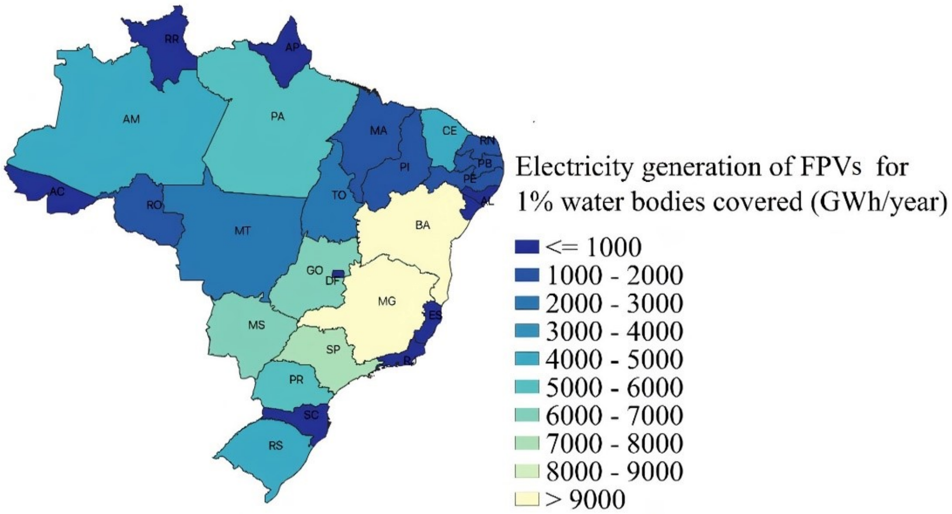

Figure 8: Spatial results of FPVs electricity generation by state (GWh/year)

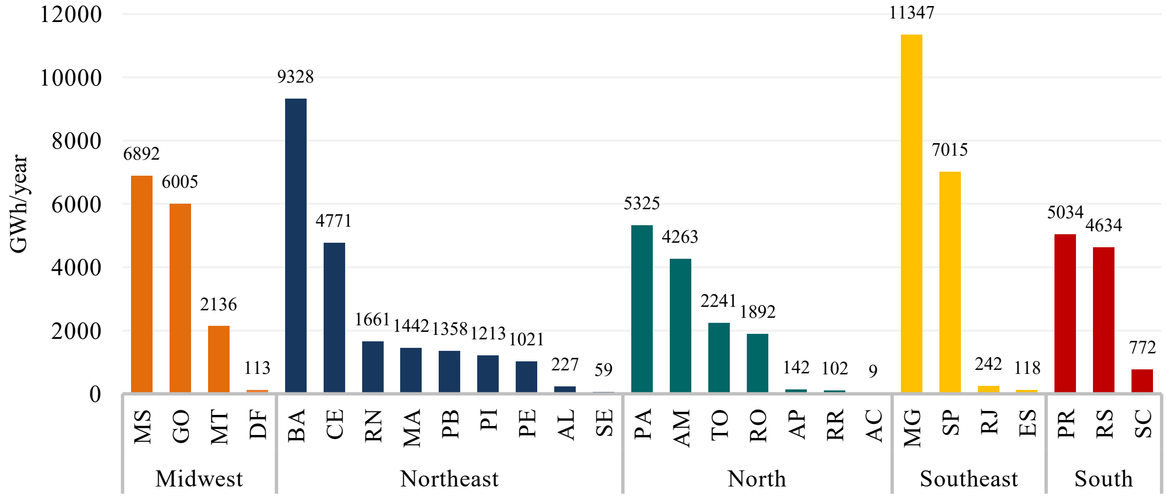

Figure 9: FPVs electricity generation by region and state (GWh/year)

The knowledge of FPVs technical potential by state is relatively important to developing effective incentive policies and the definition of promising locations for FPVs investments in each region. For example, in the Southeast Region, the best generation potential is in *Minas Gerais* state due to the higher insolation and higher quantity of the region's water bodies.

The Northeast region presents the greatest energy generation potential, with 21,080 GWh per year, as it brings together the highest amount of solar radiation and availability of artificial water body surface area in the country. The second greatest energy generation potential is from the Southeast region with 18,721 GWh/year (24%), followed by the Midwest region with 15,146 GWh/year (19%), North region with 13,974 GWh/year (18%). The lowest energy generation potential is from the South region with 10,440 GWh/year (13%), due to reduced surface area and lower solar irradiance.

Using the information of the 2020 Statistical Yearbook of electricity (EPE, 2020), it was possible to obtain the consumption of each Brazilian state and compare it to the FPVs generation potential. The results are expressed in Figure 10.

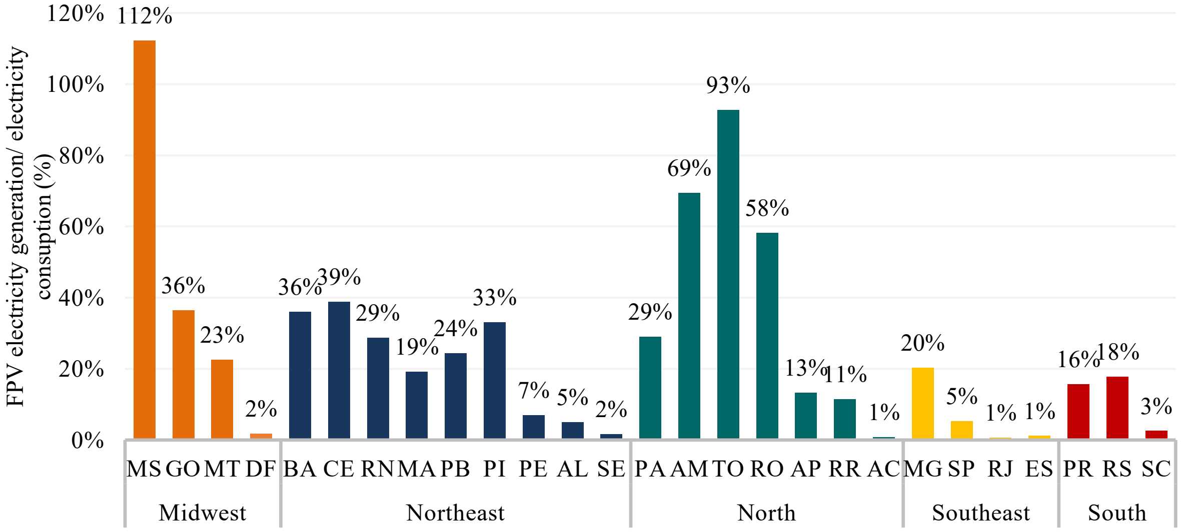

Figure 10: Percentual of electricity consumption (2019) that could be supplied by FPVs generation for each state.

Covering only 1% of the surfaces of the water bodies, it would be possible to meet 39% of electricity consumption in the Midwest region, 25% in the Northeast, 42% in the North, 8% in the Southeast, and 12% in the South region. The state of *Mato Grosso do Sul* (MS) had all its consumption supplied and could still export the energy generated to another state. Tocantins (TO) also presented the potential of much of its consumption to be supplied by FPVs. Brazil could have 16,5% of all electricity consumption supplied covering only 1% of the country's artificial water bodies. Table 5 shows the potential generation of FPVs installation, the energy consumption, and the supply electricity potential by FPVs (%) for each region.

Table 5: Electricity consumption (2019) and FPVs potential generation by region

Region	**Energy generation (TWh/year)**	**Energy consumption 2019 (TWh/year)[1]**	**Supply potential by FPVs (%)**
Midwest	15.1	38.4	39.4%
Northeast	21.1	83.6	25.2%
North	14.0	33.0	42.3%
Southeast	18.7	238.5	7.9%
South	10.4	88.7	11.8%
Total	**79.4**	**482.2**	**16.5%**

[1] Data from EPE (2020)

3.3. Limitations

FPVs are an emerging technology, and limited research, experiments, and analysis are available on their potentials and impacts. In the same way, the resources available for this research were limited for example, while the mathematical model used in this paper is suitable for calculating the national FPVs potential, no specific mounting coefficients for floating photovoltaic systems are available in the literature yet. This paper considers that the mounting arrangements of FPVs are equivalent to free-standing modules, as specified by Skoplaki et al. (2008), and are equal to 1. Also, this work is based on using high-level data, it does not evaluate site-specific limitations that could affect the implementation of FPVs such as the depth of the reservoirs, transmission grid infrastructure, environmental constraints, legal impediments, and road access. This work did not consider the costs, economic conditions, and future technology improvements, as part of the data analysis and calculation used in this study. However, it strived to depict a picture based on realistic assumptions that highlight the potential of FPVs as sustainable, clean, and reliable energy supply to encourage and facilitate further studies including detailed environmental impact analysis for FPV systems.

4. Conclusions

The increasing deployment of floating photovoltaic (FPV) technology across the world has created new possibilities within the renewable energies sector and provided unique opportunities for many countries and markets. Moreover, compared to common/conventional PV applications FPVs have significant socio-technical advantages including a higher efficiency because of the cooling effect of water.

This study evaluates the technical potential of FPVs installation for the Brazil energy sector assuming the utilization of part of the surfaces of artificial water bodies across different regions in the country. The estimation was based on current configurations of existing FPVs systems implemented in other countries by addressing the technical potential. The results show an estimated potential of 43 GWp, even with the conservative consideration of only 1% of coverage adopted in the study. This FPVs potential is equivalent to about 12% of the total electricity generation in Brazil and 16.5% of the national electricity demand. It is also equivalent to the electricity produced annually by the Itaipu binational hydropower plant (the second largest in the world).

However, to determine usable technical potentials, an even more comprehensive assessment will be needed to show how the potential interacts with other perspectives, such as technological, economic, social, operational, environmental, and regulatory. FPVs still have challenges requiring further research and learning for broader adoption, for example, better types of anchoring and mooring, tracking systems, specific operation and maintenance protocols, long-term safety and reliability of electrical equipment, and evaluation of environmental impacts. Economic analysis and additional benefits compared to ground-mounted PV systems could play a crucial role in encouraging investors to consider this technology. This economic analysis includes the value of non-evaporated water, the time and costs required to prepare the installation area, the growth of efficiency of the panels resulting in more energy generated, the decrease of possible costs of water treatment from reducing algal blooms. All these co-benefits related to FPVs are part of the knowledge gap that needs to be addressed to have realistic expectations of the benefits of this technology.

In addition, electricity generation studies are needed to evaluate the extent of generation throughout the day, allowing for better planning of the grid. This is particularly helpful for hybrid hydropower dams that have integrated FPVs on their reservoirs. Such hydro reservoir-based power plants can have the necessary flexibility for balancing the FPVs generation and the grids during low or no irradiation periods, supplying the electrical demand with solar energy during peak irradiation hours.

This study demonstrates the significant role that FPVs can play in responding to the country's energy needs and how Brazil can benefit from this emerging technology. This research also highlights the importance of investment in the research and development of technology in the country, such as the development of the floats, anchoring and mooring components, new techniques for operation and maintenance, and the new configuration of the technology installation.

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