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Floating PV power generation to balance Brazil's electric system: A sustainable C-free power generation program

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***Keywords*— Hybrid power generation, Sustainable power generation, Floating Power Plants, C-free energy, Energy Security.**

***Abstract*— *The increase of greenhouse gases (GHG) in the atmosphere forces the power industry to reduce the use of fossils fuels, aiming a Carbon-free energy production. Wind and Solar power plants have been deployed to reduce GHG emissions. However, these technologies occupy big land extensions on a utility-scale. This suggests the use of open water surfaces to install large photovoltaic (PV) floating plants. In this paper, a country-size hydro-solar power generation model is proposed. PV is more predictable than wind power, which already enters the grid without dispatch. This research intends to evaluate if Hydroelectric Power Plants' (HPP) reservoirs can host, near their dams, PV Floating Power Plants (PV-FPP) sized to meet the hydro capacity. Then, use the synergy of hydro and solar sources to run a hybrid generation model. To achieve this goal, we established the state-of-the-art of floating PV generation in Brazil and the world from academic and technical literature. We identified and described the solar characteristics, calculate the PV potential, and simulate a hydro-solar model. This resulted that Brazil can replace its 2020 fossil thermal generation using 50% of the proposed hydro-solar model potential. This model on all country's HEPP can add 84.5 TWh/year to the electric system.*

I. INTRODUCTION

- *Background*

At the start of the XXI century, the world faces significant energy challenges. Energy demand grows all over the world, as the population growth increases the use of air conditioners (refrigeration and heating), appliances, communication technologies, electric cars, and much other electric equipment. Additionally, changes in consumer habits, stemming from new technologies and new mentalities, are diversifying the profile of energy consumption, which is boosting the electricity consumption *per capita* ([1], [2], [3]). Electricity is one of the driving forces of the economic development of society [4].

Brazil has a well-balanced source system to supply its energy demand. 48.4% of Brazilian energy comes from non-fossil sources. When considering only electricity this number reaches 84.8% [5].

Despite having a well-diversified electrical matrix, based on hydroelectricity, this source represented 65% of all power plants as shown in Fig.1 [6], to supply its population for the coming years, Brazil needs to expand its power generation and electrical infrastructure capacity.

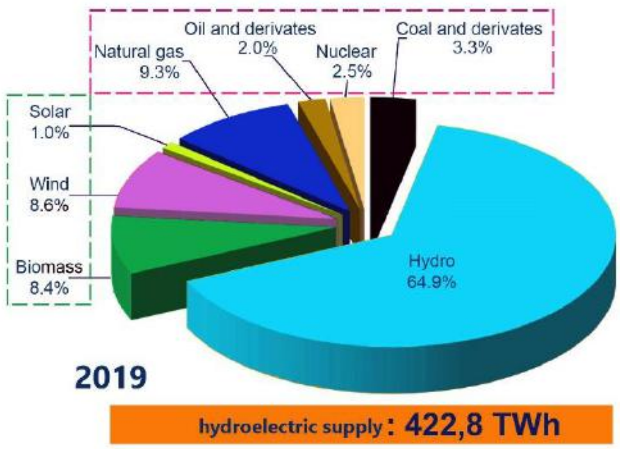

Fig.1: Electric power by source (Adapted from EPE-BEN 2021)

The growth of the demand can not be followed by new HPP, which will drive an increase in the share of thermal power plants (TPP). According to the Geographic Information Database (SINDAT), Brazil's Hydro-Electric Power Plants (HPP) current installed capacity is 101,862 *MW*. Alongside, Brazil imports 7,000 MW from Paraguay (generated by the Itaipu Bi-National HPP), counting with a total hydropower capacity of 108 *GW*.

The higher instantaneous demand of 90,525 *MW* was recorded in 2019, January 31st at 15:30. This means that HPP installed capacity already exceeds the maximum demand. Under optimal conditions, Brazil could have 100% of the electricity generated by a non-polluting, renewable source. The country's electricity consumption in 2019 totaled 536 *TWh* [7].

Despite the small consumption decrease in 2020 (530 *TWh*), due to the SARS COVID19 pandemic, the economic normalization points to an increase in power consumption. Looking forward, the foreseen consumption for 2030 varies from 680 to 812 *TWh* depending on economic scenarios [8].

Far away from the consumption centers, some new hydroelectric dams projects are being developed in the north region (Amazon). This region is considered an extremely high priority for conservation and the environment license process is very sensible. The HPP will not go along with the demand increase.

To cover the large extension of its territory Brazil implemented a 127,000 *km* power transmission base-grid (138 *kV* to 750 *kV*) as shown in Fig.2

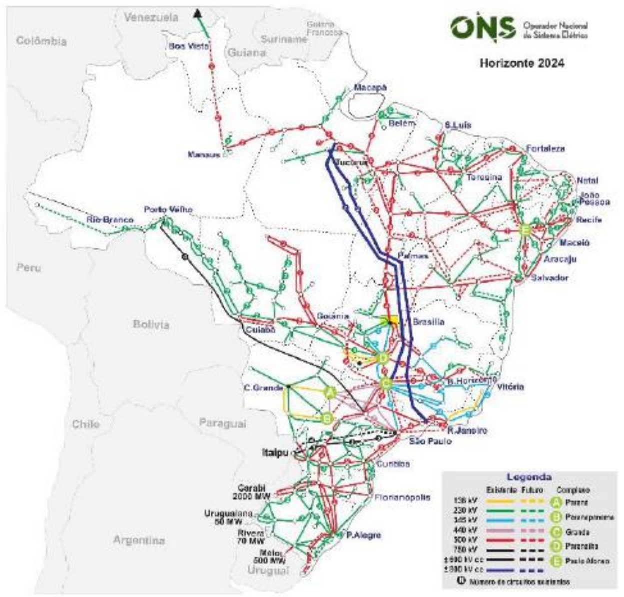

Fig.2: The Brazilian power transmission network (Source: ONS)

This transmission network, the National Integrated System (SIN), with the additional recent 9,500 *km*-600 *kV*, and 9,200 *km*-800 *kV* High Voltage Direct Current (HVDC) lines[1], drives the power to the consumption centers, balancing seasonality and climate effects on hydropower production in the north and the south. This network must be expanded to 184,000 *km* to meet the foreseen demands of 2025 [9]. However, if the new power generation will be near consumption centers, this expansion will be less costly.

Thus renewable energy sources, like wind and solar, are evaluated to attend growth of electricity demand and reduce transmission lines expansion needs. A rising number of small and medium-sized distributed systems, domestic and industrial, are expected to be increasingly present in countries with high rates of solar radiation all year round, including Brazil.

- *The problem*

HPP are dependent on water storage in their reservoirs. Drought periods directly affect their ability to run at nominal capacity ([10], [11], [12]). The current HPP generation does not cover power demand. Lost hydro-power production must be replaced with other resources to meet demand [10]. Restrictions of the HPP require the activation, and dispatch, of TPP [13]. The historical water storage level in HPP reservoirs since 1931 is shown in Fig.3 [14]. Drought periods are highlighted.

[1] http://www.ons.org.br/paginas/sobre-o-sin/o-sistema-em-numeros

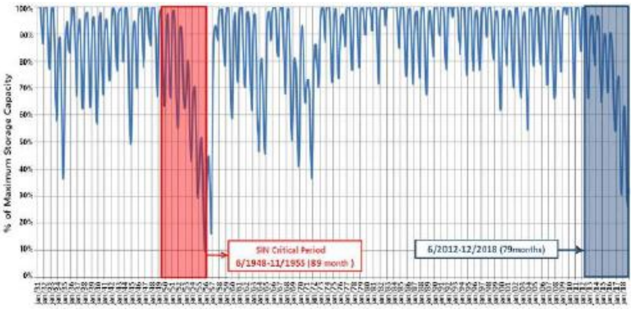

Fig.3: Water storage capacity

(Adapted from ONS-PEN 2019)

The current drought period is still ongoing. The Southeast/Midwest regions hold 70% of the country's water storage capacity. This region's storage capacity reached an even more critical level (less than 26%) during 2021. The historical (minimum water storage average ever recorded) is 19% [15].

The water storage levels on December 31th, 2021 were the highest since 2017 due to the exceptional rains, but still below 55% in every region and the country's average was only 33% [16]:

Region	Storage
North	54.67%
Northeast	52.33%
Southeast/Midwest	25.58%
South	42.79%

The global warming scenario points to prolonged and severe drought periods ([17], [18], [12], [19], [20]), which will increase the share of TPP. Even replacing solid and liquid fuels with natural gas (which is cleaner) TPP will emit GHG. For instance, unburned methane slip is 28 times more harmful than CO_2 ([22], [23], [24], [25], [26], [27]). Glasgow Climate Change Conference (COP-26, 2021) resolutions pointed to the need to combat methane emissions but did not establish numerical goals.

The average GHG emissions per *MWh* is about 690 *kg* in Germany [28] and 710 *kg* in the USA [29]. Low-quality coal firing produces up to 1,400 *kg/MWh*.

In Brazil, due to less efficient gas cleaning devices, this amount is higher, but there is a leak of datum, so the same average value is considered.

In light of this scenario, and the global claim to reduce GHG emissions [30], a new model is required for power generation. This new model should use the available renewable energy sources.

- *Objectives*

The Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change, at its 21st session in Paris in December 2015 (COP21) [30], called for the transition to an energy system with net-zero carbon emissions by around 2050. As a first step of the transition to a C-free program, the hybrid power generation model will be designed to reach 100% of hydro capacity without non-renewable sources. Transmission network issues and restrictions are not considered.

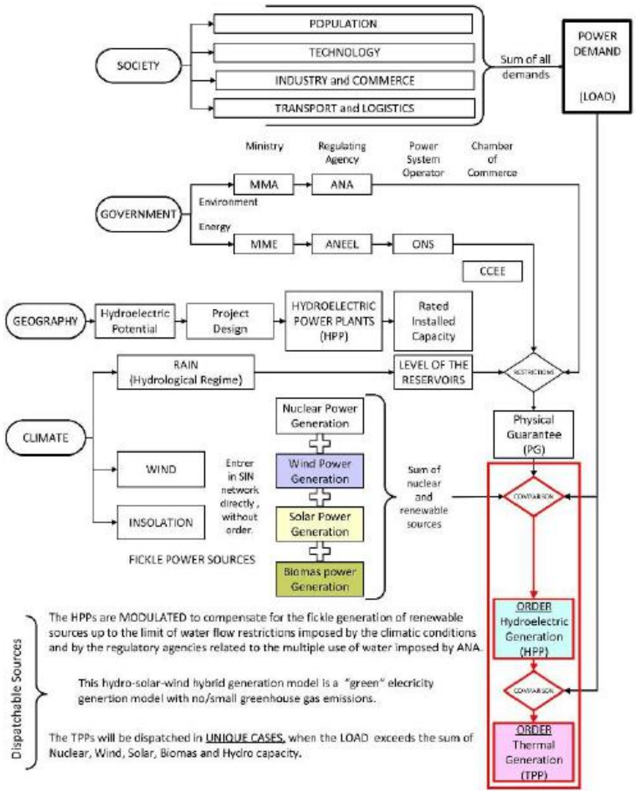

Fig.4: C-free power generation flowchart

We suppose that the power grid will grow, step-by-step, following the country's power demand growth. Then, the hybrid generation capacity will increase to meet the grid size. The flowchart in Fig.4 represents the proposed power generation model.

This article presents the result of research on the feasibility of changing the currently used hydrothermal model by a new hydro-wind-solar model using PV-FPP on HPP waters, focused only on the power generation of Brazil's existing electrical system. To find out and analyze possible issues related to this transition, and propose answers to them, the below steps were performed:

i. identification of the consumption peaks and periods in which they occur;
ii. identification of the power generation by source;
iii. identification of the HPP and the water restrictions in Brazil ;
iv. review of the state-of-the-art of Wind and PV power generation;
v. review the geophysical characteristics of Brazil and their suitability for using renewable energy sources for power generation;
vi. identification of Wind and PV potential;
vii. simulation of the hydro-wind-solar model behavior and its potential to reduce the need to use other energy sources to meet Brazil's electric system (SEB) demand.

A working hypothesis is that non-dispatchable sources (wind and solar) have priority in power-grid supply. Dispatchable sources will balance the power to demand. The HPP will be modulated to supply power, up to their restriction limit, and the TPP will only be dispatched under exceptional, specific and unforeseen conditions.

This approach can aid the actions of the National Electric System Operator (ONS) to ensure operational flexibility for the entire electric system, adequate electromechanical inertia, environmental sustainability, and storage capacity, drastically reducing GHG emissions.

II. METHOD

To achieve this objective, first, the governmental, industrial and academic literature was reviewed to establish the "state of the art" of wind and solar-PV energy generation in Brazil and worldwide. Second, the authors focused on Brazil's geophysical condition and the existing electrical power generation and transmission infrastructure. We assumed the two working hypotheses described hereafter:

1. Non-dispatching energy sources (Wind and Solar) have priority to feed the grid. Hydro will balance to demand.

$$E_{Total} = (E_W + E_{PV}) + \wedge_{(E_W+E_{PV})}^{D} E_H \text{ ; Where } D = \text{Demand} \quad (1)$$

Note: E_W and E_{PV} are fickle, and so is D.

This equation can also be written as:

$$E_H = (D + E_{Lost}) - E_N - E_{Bio} - \underbrace{(E_W + E_{FV})}_{fickle} \quad (2)$$

Where: D is thee demanded load and E_{Lost} is the energy lost in the transmission network (SIN).

2. Photovoltaic power plants (PVPP) will be designed to a peak power equivalent to the rated power of the HPP, not to exceed transmission lines capacity. W. Fang et al. (2017) also recommend this criterion [31].

$$Max. P_{PV} = P_H \leq Grid\ Capacity \quad (3)$$

Once the country's energy demand and generation were investigated, the contribution of renewable energies was evaluated with a focus on PV generation, terrestrial and floating. The method consists of six steps:

1. Determining the area to be covered by the photovoltaic arrays S_{PV} to meet the working hypotheses in each installation, this surface is also called "Solar Area". S_{PV} is obtained from Eq. (4) where $Max.P_{PV}$ is the peak power of PVPP, and μ_{PV} is the power density.

$$S_{PV} = \frac{Max.P_{PV}}{\mu_{PV}} \quad (4)$$

Note: Even though PV-FPP has a power density larger than on-land PVPP and occupies less area, in this article the same power density was considered. The parameter $\mu_{PV} = 1\,MW/10{,}000\,m^2$ [32] is a conservative value ([33], [34], [35], [36]).

2. Simulate the hypothetical PV-FPP power output, using formulas to stipulatethe radiation hourly profile ($\overline{H}$) in the summer, and the resulting PV powergeneration (P_{PV}). Eq.(5), based on the Rayleigh formula (which is used for wind speed simulation), was adapted for the photovoltaic generation and used to simulate the P_{PV} from sunrise during seven hours. Sunrise (h_0) was considered to be at 8 a.m. h_0 is the start simulation time.

$$P_{PV}(h)_{h_0}^{(h_0+7)} = K \times \frac{2 \times (h-h_0)}{c^2} \times exp\left[-\frac{(h-h_0)}{c}\right]^2 \quad (5)$$

Where: h is the hour, c=6, and K is a coefficient to obtain the results in P.U. (we used: K=1.15× $\overline{H}$).

After seven hours, PPV was adapted to decreasing luminosity using the Eq.(6):

$$P_{PV}(h)_{(h_0+8)}^{(h_0+12)} = \frac{P_{PV}(h-1)}{2^{(h-(h_0+7))}} \quad (6)$$

During the night, PPV is considered null (Eq.(7)).

$$P_{PV}(h)_{(h_0+13)}^{(24)} = P_{PV}(h)_{(0)}^{(h_0)} = 0 \quad (7)$$

3. Modulate HPP power to the local established value as per Eq.(1). HPP modulation results in non-turbocharged water, which can be temporally stored upstream of the HPP. This extra water is considered as a "virtual battery" [37]. The virtual battery may be used for additional hydroelectric power according to the HPP's convenience; during low/no irradiation times, or contribute to the reservoir's level restoration during drought periods. HPP's turbocharging should

respect the environmental impacts of the river's water flow, so the authorized daily flow should not exceed the restrictions established by the authorities.

4. Obtain the expected annual energy generation for each PVPP (E_{PV}) from Eq.(8), where $\overline{H}$ is the annual average of the nearby measured daily solar radiation (in kWh/m^2.day), η_{PV} is the nominal efficiency of the PV panels and PR is the performance ratio of the PVPP [2].

$$E_{PV} = 365 \times \overline{H} \times \eta_{PV} \times PR \times S_{PV} \quad (8)$$

After calculation of the energy to be generated by the PV arrays, the hybrid system was compared to the HPP alone. Doing this for each HPP individually and then results were aggregated to get a country image to assess whether this model can replace the current hydrothermal model, avoiding the use of TPP.

5. For the floating installations, check if the reservoir can host PV-FPP of thissize. Floating installations will be placed near HEEP dams on the reservoir's surface. The percentage of coverage *C(%)* is obtained from Eq.(9), where (S_R) is the reservoir's total surface.

$$C(\%) = 100 \times \frac{S_{PV}}{S_R} \quad (9)$$

III. POWER DEMAND

The Brazilian Ministry of Mines and Energy (MME) found that the temperature is what most influences power consumer habits during the day [38]. As the heat is more intense in the late morning and early afternoon, peaks in electricity consumption are currently recorded in this period and during the summer [39].

Fig.5 shows the electrical load curves of the highest consumption day in the winter (upper), and in the summer (lower), from 2000 to 2015, indicating the official rush time [40]. From 2016 this data is collected by ONS and published in a daily online report on its website [41].

The current power consumption peak have been occurring in the summer between noon and 4 p.m., and not more during the historical rush time from 6 pm to 9 p.m. Maximum recorded power demand in Brazil occurred in 2019, January 30th, at 3 p.m., and the value was 90,525 MW [42]. Over the last 20 years, power consumption has increased by 86% in rush time, and 105% in the afternoon new-peak time, surpassing the traditional rush-time peak during the summer. Maximum evening consumption is currently even lower than the 9 a.m. demand.

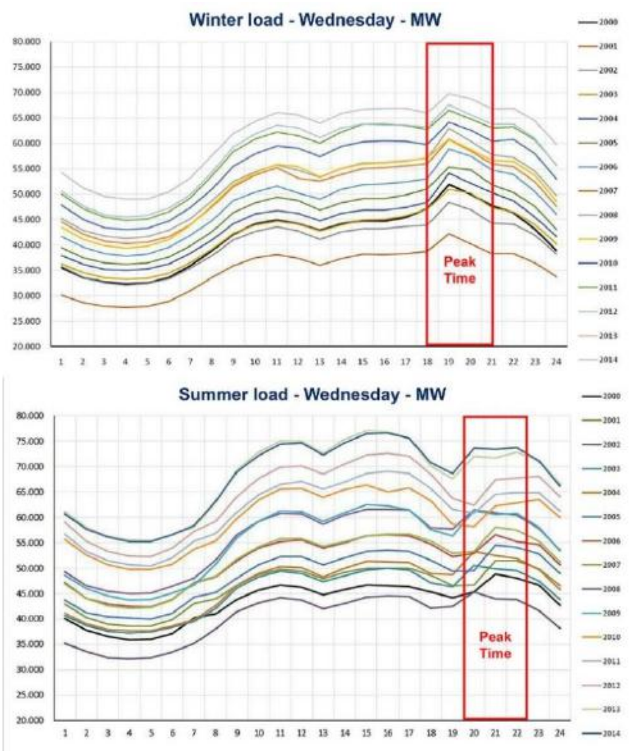

Fig.5: Load curves - 2000 to 2015

(Adapted from EPE, 2015)

The new peak time coincides with the highest daytime radiance, pointing to the solar source as an alternative option to mitigate the peak demand [43].

IV. POWER GENERATION

Distributed Generation (DG)

In Brazil, distributed power generation is defined in Article 14 of Law Nº 5.163/2004. The net-metering concept and consumption compensation were established in the country in 2012. Brazil's National Electric Agency (ANEEL) is responsible for regulating the SEB.

Net-metering was made official by the ANEEL's Normative Resolution (REN) Nº 482/2012 and was updated through REN Nº 687/2015 [44]. This regulation was updated again by Law Nº 14.300 from January, 6th 2022.

Two DG categories are regulated as follows:

- micro-generation: electric power system, with an installed capacity less than or equal to 75 *kW*.
- mini-generation: electric power system with an installed capacity greater than 75 *kW* and less than or equal to 3 *MW* when not dispatchable, and to 5 *MW* when dispatchable.

[2] A typical Crystalline Si - PV panel has a power density of 150 *W/m*^{2}

Micro-, and mini-, distributed generation systems (MMDG) are in a significant expansion all over Brazil. Scenarios for the next 10 years forecast 16.8 to 35.8 *GW*, as shown in Fig.6 [45], depending on electricity price, political issues, and taxation.

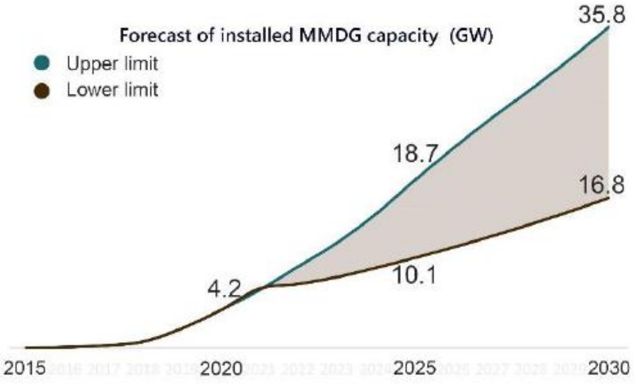

Fig.6: MMDG expansion

(Adapted from PDE2020)

MMDG are characterized as the production of electricity for own consumption. They promote power auto-supply and reduce the load on the SIN transmission lines and the associated losses. In 2019 MMDG contributed with 2.0 *TWh* to overall energy consumption [46]. It was expected to double the PV energy production in two years and overtake 4.0 *TWh* in 2021. Solar PV energy is the fastest-growing energy source, reaching the installed capacity of 9.0 *GW* in February 2022, from more than 817,000 grid-connected active installations (99.9% of it - PV) [47]. More than 1,000,000 consumers are receiving electricity credits through net metering.

Centralized Generation

Alongside the MMDG, the additional large utility-scale hydro, thermal, wind, and solar power plants will be required to attend to the country's energy demand. Utility-scale plants are centralized power generation systems.

- *Nuclear*

The nuclear complex of Angra dos Reis is located in Rio de Janeiro, Southeast Brazil. It consists of two reactors, Angra I and II, with a net output of 1.9 *GW* connected to SIN's power grid shown in Fig.2. From 2015 to 2020 nuclear power plants (NPP) generated more than 14 *TWh* every year. Maximum generation occurred in 2019 - 19.1 *TWh*. In 2021 nuclear power plants (NPP) generated 13.2 *TWh*.

Angra III, construction ongoing, will increase the nuclear capacity to 3.3 *GW*. This is the slowest growing power industry in Brazil. In addition to those already mentioned, there are no plans to build new facilities.

- *Wind*

Onshore wind power generation is predominant in the Northeast (85%) and South regions. These 2 regions have different climates and different wind regime behavior. There are 789 wind power plants (WPP) in operation, totaling more than 10,000 wind turbines, with a total capacity of 21 *GW* [48].

Fig.7: Wind power plant

(Source: diariodonordeste.com.br)

Brazil occupies the 7th position in the 2021 - Onshore Ranking of the Global Energy Council (GWEC) and is the third country that installed the most wind systems in 2020 [49].

- *Solar*

Utility-scale concentrated solar power plants (CSPP), for commercial use, are not yet installed in Brazil. These systems use mirrors or lenses to concentrate a large area of sunlight onto a receiver. The concentrated light is converted to heat a working fluid that drives a turbine connected to an electrical power generator.

Photovoltaics directly converts sunlight to electricity. There are 5,144 PVPP in operation with a total capacity of 4.6 *GWp*. Another 94 are being erected to increase capacity to 8.4 *GWp* [48].

Fig.8: São Gonçalo Solar Park

(Source: ecodebate.com.br)

Fast-growing industry, in 2015 PVPP generated 21 *MWh* to the overall energy supply; in 2021: 6.9 *TWh*.

The largest PVPP in Brazil is São Gonçalo Solar Park - PI, with an installed capacity of 475 *MWp*, in operation since January 2020. Fig.8 is a partial view of this solar installation.

Table 1 lists the bigger operating PVPP installed in Brazil nowadays:

Table 1: PVPP in Brazil

PVPP	Localization	State	Area (ha)	Capacity (MWp)
São Gonçalo Power Plant	São G. do Gurguéia	PI	2.000	475
Pirapora Power Plant	Pirapora	MG	1.500	321
Nova Olinda Power Plant	Ribeira do Piauí	PI	1.350	292
Ituverava Solar Park	Tabocas do Brejo Velho	BA	1.350	292
Lapa Solar Complex	Bom Jesus da Lapa	BA	700	158
Juazeiro	Juazeiro Central PV	BA	700	156
Guaimbê PVPP	Guaimbê	SP	700	50
Apodi PVPP	Quixeré	CE	600	132
Paracatu	Paracatu Solar Park	MG	600	132
	Total		**9.500**	**2.008**

Land occupancy by PVPP is 3 to 5 *ha/MWp*. Large utility-scale PVPP will require big areas. The utility-scale solar generation comes with a sizable land requirement, depending on the topography of the available site. Densely populated regions, with the highest power demand (Southeastern Brazil), do not have adequate land for these installations, thus they should be located far from the consumption centers.

- *Thermal*

TPP uses fuel combustion to produce heat, then converted to mechanical energy, then converted to electricity.

There are 3,103 TPP in operation with a total capacity of 46 *GW*. Another 58 are under erection, and 68 more will start erection works soon [48].

From 2015 to 2020 TPP were ordered to generate in every year 60 to 70 *TWh* to complement the power generation when other sources did not match the demand.

TPP were responsible for 21.6% of the overall energy supply in 2019 as shown in Table 2 [48].

Table 2: TPP per fuel type

Thermal 2020	Energy (TWh)	%	% of total electricity
Biomass	56,167	43%	9,0%
Natural gas	53,464	41%	8,6%
Coal and Derivatives	11,946	9%	1,9%
Oil derivates	7,745	6%	1,2%
Subtotal	129,322	100%	20,8%

(Adapted from EPE-BEN 2021)

Burning fuels have a substantial carbon footprint. The fuel used can be coal, heavy oils, diesel, gas, or biomass. All of them emit atmospheric pollutants like GHG and particulate matter during the combustion process.

Currently, energy-related GHG emissions, mainly from fossil fuel combustion for heat supply, electricity generation, and transport, account for around 70% of total emissions including carbon dioxide, methane, and some traces of nitrous oxide.

TPP are not eco-friendly facilities. Energy production released to the atmosphere 27.7% of the overall country's CO_2 emissions in 2020, totaling 384,279,528 *tons* [50].

- *Hydro*

The Brazilian hydroelectric long-term potential is 176 *GW*; currently, 108 *GW* are operational. The available inventoried potential is 68 *GW*. Out of these, 52 *GW* are for HPP bigger than 30 *MW* projects and the other 16 *GW* are for small hydroelectric power plants (SHPP) [51] which have special regulations by paragraph §3 of Article 10 of REN Nº 687/2015 [44]. There are 426 SHPP already in operation.

Itaipu is a bi-national 14 *GW* power plant owned by Brazil and Paraguay (Fig.9). Although not the largest installed capacity in the world, it holds the record of the highest annual energy production. It serves as the major load peaking and frequency regulation power plant in Brazil's power grid.

Fig.9: HPP Itaipu-Binational

According to ANEEL's Power Generation Database (SIGA) [48] besides Itaipu, there are 218 operating HPP in Brazil. From those, 164 HPP contribute to SIN; 72 have reservoirs and 88 are run-of-the-river HPP.

The power plants, grouped by hydrographic basins, are shown in the SIN's HPP Schematic Diagram - Horizonte 2021-2025 [52], which is not available in English. This diagram clearly shows the HPP sequences that benefit, in cascade, from the same water flow [52]. The level of any reservoir, and the flow restrictions, affect the operation of all downstream power plants.

HPP are able to increase power output to maximum plant capacity within minutes of starting [10]. They can be adjusted to balance the grid's power demand. The National Operator of the Electric System (ONS) operates the country's power system by dispatching HPP and TPP according to forecasts of reservoirs levels and economic criteria.

- *Offshore*

Brazil has a 7,367 *km* oceanic coast [53]. Brazil's offshore wind-fields map, indicating the average wind speeds, divided by bathymetric bands, is shown in Fig.11 [51].

Gross evaluation of Brazil's offshore wind power potential point to be 6,150 *TWh/year* [51]. This tremendous potential is not yet explored. Despite having a strong synergy with Oil & Gas Upstream technology, offshore wind power plants projects are just starting and are dependent on a complex, and partially undefined, licensing process.

Until January 2021, Brazil had only 6 projects for offshore wind farms with environmental licensing underway at The Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), [54]: Caucaia~Parazinho-Iparana (310 *MW*)-CE, Asa Branca I (400 *MW*)-CE, Pilot Plant-RN (5 *MW*), Jangada (3 *GW*)-CE, Maravilha (3 *GW*)-RJ and, Aguas Claras (3 *GW*)-RS. Altogether, these projects have a power capacity of circa 10 *GW*, all of which are in the preliminary licensing phase.

Wind farms' feasibility depends on sea depth and waves shape in every local.

Offshore wind power potential is estimated according to the distance from the shore as follows: 0-10 *km*=57 *GW*; 10-50 *km*=202 *GW*; 50-100 *km*=255 *GW* and, 100-200 *km*=1,266 *GW* [55].

Oceanic solar farms are still under research, not yet technically developed. Several issues like corrosion, wave profiles and mooring challenge are still being studied.

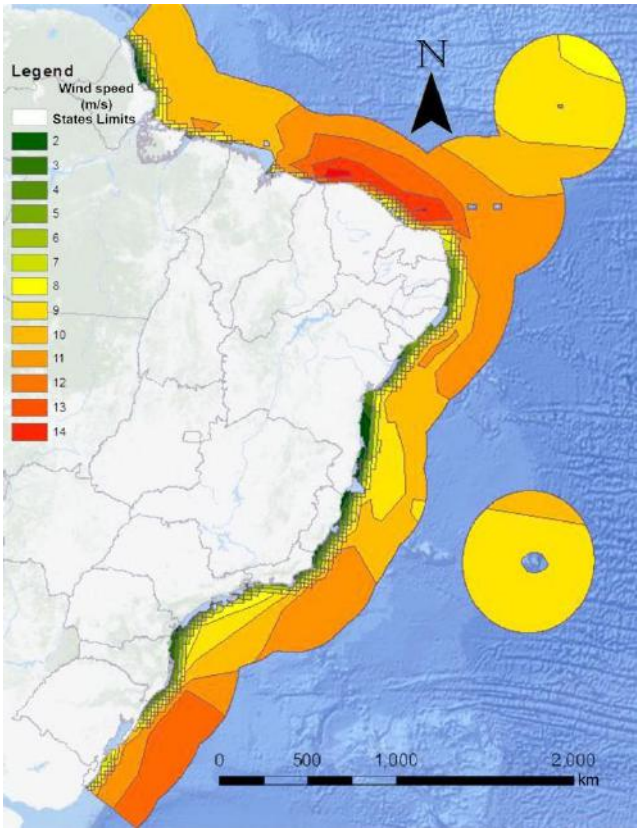

Fig.10: Offshore wind fields

(Adapted from EPE,2018)

V. GEOPHYSICAL CHARACTERISTICS

Brazil is a country with continental dimensions located in South America. Its territorial extension is 8.5 million km^2 [56] most of it in the tropical and subtropical range, between the Ecuador Line and the Tropic of Capricorn. The extreme points of the Brazilian territory are shown in Table 3.

Table 3: Brazil's extreme limits

	Point	Place	State	Border	Latitude	Longitude
NORTH	Sestentrional	Ailã river Source	RO	Guiana	05° 16'19" N	60° 12'45" W
SOUTH	Meridional	Arroio Chuí	RS	Uruguay	33° 45'07" S	53° 23'50" W
EAST	Oriental	Ponta do Seixas	PB	Ocean	07° 09'18" S	34° 47'34" W
WEST	Occidental	Moa river Source	AC	Peru	07° 32'09" S	73° 59'26" W

Distance North-South: 4,395 km ; Distance East-West: 4,320 km

Southeastern Brazil has an area of 924,000 km^2 and a population of 85 million inhabitants [56], 40% of the population consumes 60% of the country's electricity [57]. This is the most power-demanding region ([46], [56]) and has the highest population concentration. Actions to increase energy generation in this region can reduce losses and the need to expand the energy transmission infrastructure.

Rain forests and large rivers mostly cover the North Region. In this region, population concentration is low, and the infrastructure is poor. The exceptional wind conditions along the Northeast seashore attract private equity investments in WPP. Most of the new WPP are being erected in this region. The South Region also has very good wind conditions, however with a smaller potential.

- *Wind*

Wind speeds over 7 *m/s* at 50-150 *m* above ground enable WPP to generate power at commercial conditions. Along the Northeast Brazilian seashore, excellent wind conditions encouraged the installation of the main wind farms in the country. The South region has completely different wind behavior, much more turbulent and variable.

WPP are already providing 10% of the country's power. Fig.11 shows the existing wind farms and typical wind speeds at 50 *m* height, pointing to the potential of WPP.

Seasonality records show that winter months (June to September) have more wind generation than summer months (December to March) in Brazil ([57], [58]). Wind production decreases as air is hotter, peak production often occurs at night time, between midnight and 5 a.m. On an hourly scale, typical wind profiles are dependent on local conditions.

The new CEPEL's Wind Atlas (2017) shows local profiles covering all of Brazil's territory [59]. On a sub-hourly scale, wind power production is absolutely random and not predictable [60].

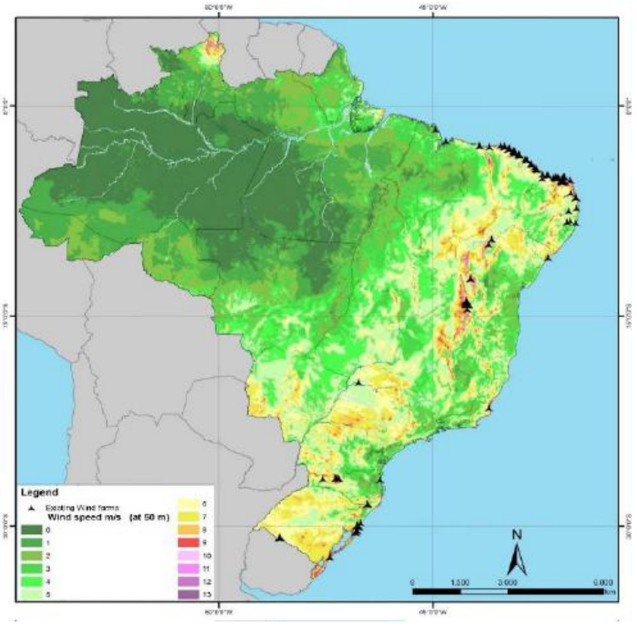

Fig.11: Wind speeds
(Adapted from EPE,2018)

Considering several premises and restrictions, Brazil's potential for onshore WPP is estimated at the order of 143 *GW* (able to produce 272 *TWh/year*), 50% of it in the Northeast region ([51], [59]).

Compared to other power sources, the wind is inconstant. Very fast variations of direction, intensity, and turbulence are unpredictable. Not dispatchable, wind power enters the grid once it is generated, those why other sources must complete demand. The hydro-wind-solar model considers wind power as a second layer; a variable layer just over the base of nuclear power.

- *Solar*

The average annual solar radiance is high and relatively close in intensity in the different climatic regions of Brazil as shown in Fig.12

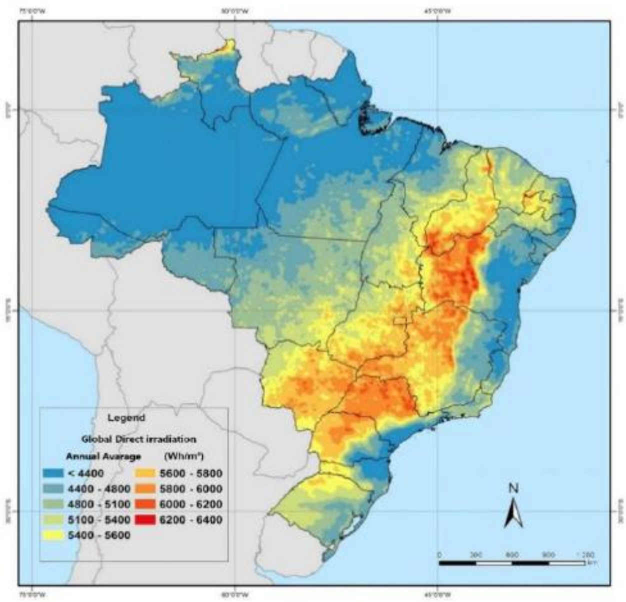

Fig.12: Solar radiation
(Adapted from EPE, 2018)

The 700 *km* width diagonal band, from Northeast Brazil to Paraguay, has excellent conditions to promote PVPP, including Midwest and Southeast regions where population and power demand is concentrated. A country of continental extension like Brazil has room for large solar power plants; however, urban agglomerations and fertile (arable) land should not host large PV plants.

The maximum daily average global radiance, around 6.5 kWh/m^2 occurs in the northern region of the state of Bahia. The minimum daily average global solar irradiation, about 4.3 kWh/m^2, occurs in the coastal region of the state of Santa Catarina [61].

Deforestation or the use of areas subject to reforestation to install large-scale PVPP is incongruous with any preservation program [30]. Excluding the Amazon and Pantanal biomes, the remaining area has regions not suitable for those installations. Fig.13 maps the suitable areas for this technology, considering other priority use of the land [51].

To achieve the COP21 goals of reducing GHG emissions, the Brazilian government will adopt policies in several sectors [62]. Brazil intends to ensure 45% of 2030 power generation from renewable sources, including hydroelectric, while the global average is only 13%. Concerning land use, the goal is to restore and reforest 12 million hectares of vegetation in addition to ending illegal deforestation.

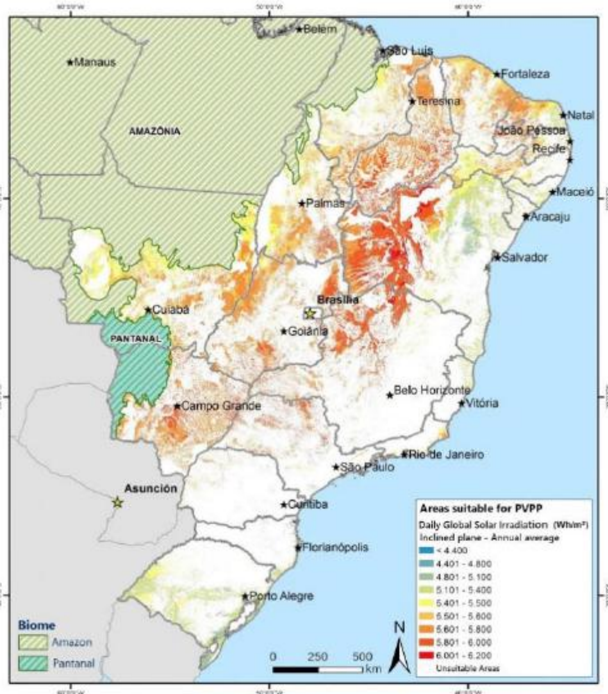

Fig.13: Areas suitable for large-scale PVPP

(Adapted from EPE, 2018)

Hybrid Wind-PV systems connected to the grid, using a common substation, already exist. Those systems using 2 variable sources are non-dispatchable and do not have electrical inertia. The produced power feeds directly into the grid. Fig.14 is an example of such installations.

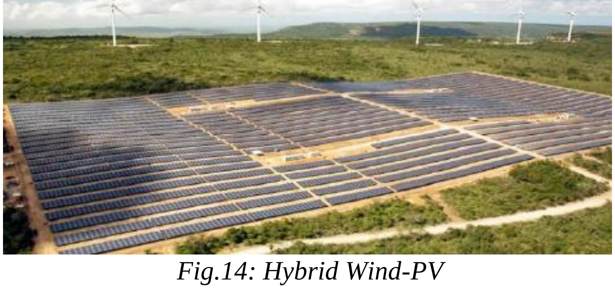

Fig.14: Hybrid Wind-PV

Land occupancy of these power plants is an important issue since they compete with other land destinations such as agriculture or forest preservation.

The use of flooded surfaces, in particular the surfaces of the HPP reservoirs, is a solution that addresses this issue. Using the reservoir's water surface enables a full hybrid hydro-solar model, using one common substation to feed the transmission line. Floating PV outcomes as a technology that is widely used in the conservation of water resources [63]. PV-FPP integration with the existing infrastructure of HPP has vast potential and capability to meet the peak load demand without losing the electrical inertia [64].

- *Water*

Fig.15: Free water surface

(GIS output with IBGE and ANA water databases)

The Brazilian territory contains about 12% of fresh water on the planet. It is an enormous water potential, as shown in Fig.15, capable of providing a volume of water per person 19 times higher than the minimum established by the United Nations (UN) - of 1,700 m^3 per inhabitant per year [65].

Water is considered public property and a limited natural resource, with economic value, and with multiple uses. Drought periods directly affect the availability of this resource.

Despite the abundance, Brazilian water resources are not inexhaustible. Access to water is not the same for everyone. The geographical characteristics of each region and the changes in river flow, which occur due to climatic variations throughout the year, affect the distribution.

The sum of the water surfaces in Brazil is 170,000 km^2 as illustrated in Fig. 16. HPP reservoirs are 22% of all free water surfaces. When the reservoirs are full, they total 38,000 km^2 [33]. These reservoirs can host floating PV systems. These large surfaces of water are wave-less, flat, and without shading. Hydroelectric dam's water surfaces are ideal for PV-FPP to work together with the HPP as a hybrid system.

VI. RESULTS

The following sections discuss the outputs of the hydro-solar model applied to the case of Brazil. First, the analysis of HPP behavior with the same size PVPP under coordinated hybrid operation is discussed. Followed by a study of a case of an existing HPP to demonstrate the feasibility of such a model. Finally, the country size power production environment is analyzed using the hydro-solar model and its potential is established. Then, compared to fossil fuels use by TPP in the current generation model.

- ***Hydro-Solar generation model***

PV Floating Power Plants (PV-FPP) placed near HPP can share the substation e and the grid connection taking advantage of the hydro-solar synergy ([3], [66]). Operation through a shared control room makes managing the hybrid power generation system easier, more reliable and more efficient. Random fluctuations in the solar resource availability on the sub-hourly scale are not considered, as well as demand variability. The PV-FPP will be designed to meet rated HPP capacity at the highest local radiation condition. This design criterion respects the maximum rated capacities of the transmission line and the transformer.

The proposed hydro-solar model is represented in Fig.16. The graph shows the daily power production of the hybrid facility on an hourly scale. The coordinate's axis is in P.U.

Three representative conditions are illustrated.

(a) Base scenario.

Unrestricted condition in which the HPP can turbocharge water to its nominal capacity.

(b) Restrictions scenario allowing only 50% of the rated daily rated water flow.

In addition to the increase in total generation during sunny hours, the reduction in hydroelectric generation during the day and contributes to the formation of a "virtual battery" [37]. This concept refers to damming water upstream from 8 a.m. to 3 p.m. daily. Respecting the daily flow restrictions imposed by the regulatory agencies, dammed water must be used during the same day maintaining average river flow. The HPP will manage the use of the "virtual battery" according to its technical and commercial conveniences.

(c) Restrictions scenario allowing only 50% of the rated daily rated water flow but using the virtual battery in the afternoon and evening time. This generation profile better attends load curves and can represent a significant increase in HPP's operating profit.

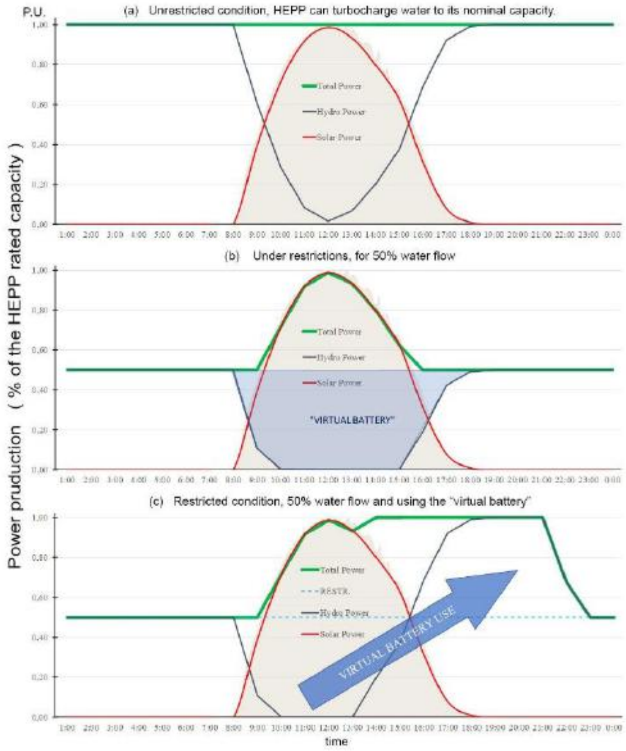

Fig.16: Hydro Solar Model

Item (c) of Fig.16 clearly shows the benefit of the hydro solar model when drought limits the water flow of the HPP. Power generation can increase very significantly without exceeding the daily allowed water flow.

- ***Hydro-Solar model simulation***

A study of the case simulated a hypothetical PV-FPP paired with the existing Porto Primavera HPP in a full hybrid operation model during 2019 [67].

Despite being a run-of-the-river plant, this HPP has a 2,250 km^2 lake. For its formation, the flooded area increased the riverbed 9 times. Its 10.2 *km* length dam is the longest in Brazil. The 16 gates spillway has a flow capacity of 52,800 *m3/s*. The powerhouse has fourteen 110 *MW* turbines and can generate 1,540 *MW*. PV-FPP for the same peak capacity will occupy 15.5 km^2, which is 0.7% of the lake's surface. However, PV-FPP of this size does not yet exist in the world.

The maximum flow is conditioned to allow 24,000 m^3/s in Porto São José heading downstream. The minimum flow rate is 4,600 m^3/s to avoid the formation of marginal downstream lagoons that can trap fish and cause damage to ichthyofauna, and of approximately 5,500 m^3/s between 5 a.m. and midnight, to provide conditions for transverse navigability (ferry crossing) in the port immediately downstream.

Without restrictions, at rated capacity (CF=100%), the HPP Porto Primavera would be able to generate 1,125 *TWh/month*. Recorded data for 2019 shows that the maximum effective generation occurred in January and totaled 0.81 *TWh*, therefore the maximum effective CF was 71%.

The seasonal profile for Porto Primavera's dam location is in Fig.17*: Seasonal irradiation profile*. Using the average daily irradiation measured by 3 stations close to the center of the dam, month by month, PV power was calculated. The yearly average of daily irradiation in this local is 5.0 kWh/m^2.

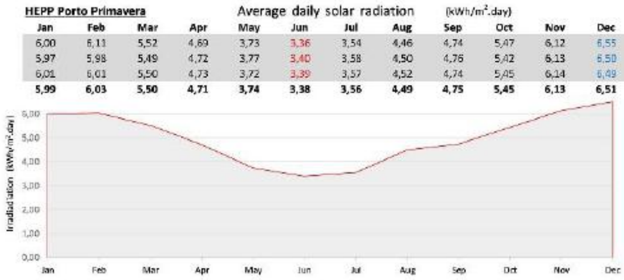

Fig.17: Seasonal irradiation profile

(Adapted from CRESESB)

Table 4 shows the HPP's real power and energy production and simulated energy production of the PV-FPP, demonstrating the hydro-solar model benefits. These results can be observed graphically in Fig.18.

Table 4: 2019 simulated H_S energy production

2019	month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Power	$\overline{MW}$	1,093	990	1,001	962	865	840	837	864	1,051	985	915	1,067
H	TWh	0.81	0.67	0.74	0.69	0.64	0.60	0.62	0.64	0.76	0.73	0.66	0.79
PV	TWh	0.34	0.31	0.32	0.26	0.21	0.19	0.20	0.26	0.26	0.31	0.34	0.37
H_S	TWh	1.16	0.98	1.06	0.95	0.86	0.79	0.83	0.90	1.02	1.04	1.00	1.17

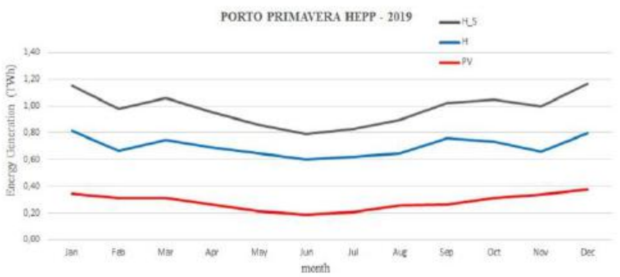

Fig.18: 2019 H_S energy production

When the PV generation is added, the CF (based on the nominal capacity of the HPP) will slightly exceed 100% in the summer (December and January) with a minimum of 73% in July. The annual power generation totaled 8.37 *TWh* with an average CF=62%. The hydro solar model could generate an additional 3.3 *TWh*, increasing the annual electric generation of the hydro + PV set to 11.75 *TWh* for the same water flow. With 40% additional annual generation the gain in the annual 2019 average CF could be 25%, by turbocharging the same volume of water.

- ***The Hydro-Solar Potential***

The World Bank's Energy Sector Management Assistance Program (ESMAP) stated that grid-connected hybrid systems that combine hydroelectric power and floating photovoltaic technologies are still at an early stage of development. It also states that the combination of solar and hydroelectric power dispatch can soften the variability of solar production while making better use of existing transmission assets [68].

- *Itaipu Bi-national*

Itaipu HPP is a run-of-the-river HPP but has a large artificial lake. The flooded area is 1,350 km^2. It is the second world's largest HPP (only the Three Gorges HPP, in China, has a larger installed capacity) and holds the annual electricity production world record: 103.1 *TWh* generated in 2016 [69]. To match its capacity, a gigantic PV-FPP that would cover about 10.5% of the lake is needed (Table 5). This model is able to yearly generate additional l 29 *TWh*.

Table 5: The hydro solar potential of Itaipu

Hydroelectric Power Plant (HPP)	Localization	Rated Capac. (MW)	Flooded Area (km^2)	Solar Area (km^2)	Coverage (%)	PV Annual Energy (TWh)
Itaipu binational	Parana river	14.000	1.350	140	10,4%	29,27

- *Brazil*

Table 6 summarizes Brazil's hydro solar potential by hydrographic basin, except for Itaipu. The implementation of the hydro solar model in all Brazil's HPP it m ay make additional annually 169 *TWh* available to the SIN.

The total TPP generation in 2019 was 135.2 *TWh*. Biomass, which is also a renewable (non-fossil) source of energy, and is used mainly as co-generation, was 52.5 *TWh*.

The balance: 84.7 *TWh* could be obtained from solar power. PV-FPP can produce the double without any GHG emission and not occupying the land.

Using this simulation for power demand data of 2019, January 30th, the highest load even recorded, resulted that all thermal generation could be replaced by a 91 *GW* hydro-wind-solar model as shown in Fig.19.

Table 6: Hydro solar potential – Brazil

Nr.	HYDROGRAPHIC BASIN	Rated Capac. (MW)	Flooded Area (km^2)	Solar Area (km^2)	Coverage (%)	PV Annual Energy (TWh)
1	AMAZON	23.619	4.687	240	5,12%	38,08
2	TOCANTINS-ARAGUAIA	12.935	6.185	130	2,10%	28,21
3	WESTERN ATLANTIC NE	0	0	-		0,00
4	EASTERN ATLANTIC NE	0	0	-		0,00
5	PARNAIBA	237	13	2	18,25%	0,57
6	SÃO FRANCISCO	10.579	6.219	110	1,77%	7,82
7	ATLANTIC EAST	1.072	234	11	4,58%	2,56
8	ATLANTIC SE	2.572	453	25	5,51%	1,08
9	PARANA	35.841	15.211	351	2,31%	77,37
10	PARAGUAY	663	489	70	14,33%	0,86
11	ATLANTIC SOUTH	1.779	411	20	4,87%	1,84
12	URUGUAY	5.755	560	60	10,71%	11,04
	Total in Brazil, except of Itaipu	95.051	34.461	1.019	2,96%	169,43

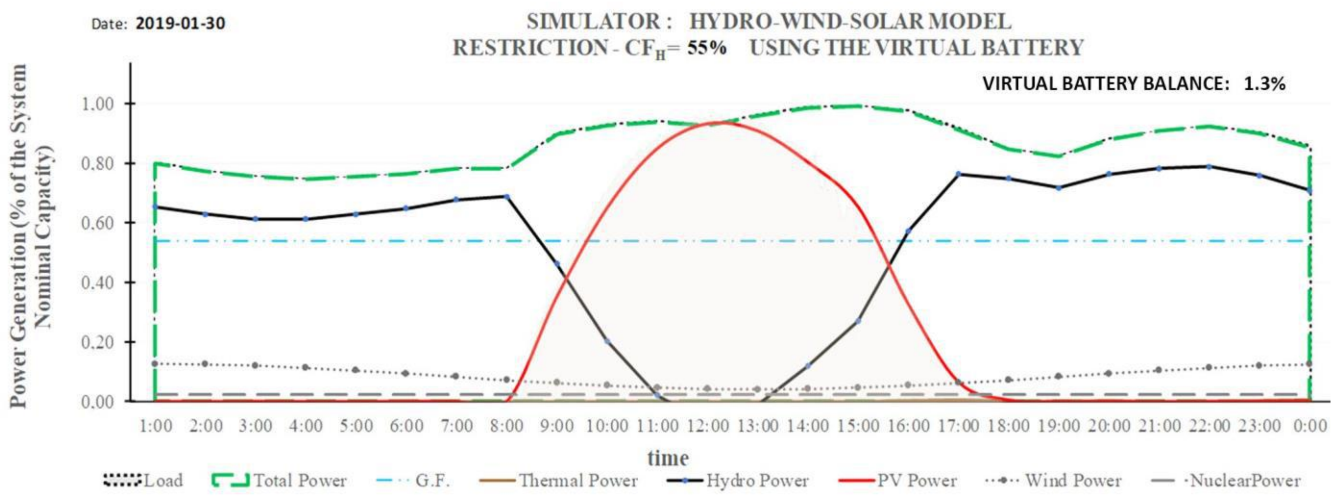

Fig.19: Model simulation for the highest load

This hydro-wind-solar model represents the sum of all the PV-FPP designed to peak power equivalent to the hydroelectric power plants' nominal rates and installed at HPP the dams.

Drought restrictions at that time allowed only 55% of nominal water flow. Real nuclear and wind generation were considered. HPP should be modulated using the water not turbocharged (the "virtual battery") from 8 a.m. to 6 p.m. This simulation resulted that 1.3% of the virtual battery will remain in the reservoir contributing to its storage capacity recovery.

- ***Environmental risks of large scale PV***

Alongside the technical and economic aspects, social and environmental aspects must be considered when planning PV installations.

These aspects encompass visual impacts, facility safety, impacts on tourism and leisure, impacts on water quality, impacts on aquatic flora and animal life, impacts on bird habitats, etc. [3]. PV technology has important environmental risks in two phases:

(a) In the phase of the production of PV panels, which is an energy-intensive technology. The production of elemental silicon is chemical-intensive. More than 500 chemicals are used for imprinting electronic circuits on silicon wafers [70]. 50-80% of GHG emissions arise during the production of the PV panel [71]. Emission levels depend on the type of technology and the source of energy used in manufacturing. China leads silicon PV cells and panels fabrication ([28], [72]),

and,

(b) At the end of its useful life, after 25-30 years of power generation, at the decommissioning of the PVPP, when part is recycled and the remainder disposed of in some landfill [73]. Recycling PV panels at the end of their useful life to reclaim aluminum, glass, and silver, and minimize associated environmental impacts is only starting to gain attention [72].

As there are no evident GHG emissions during power generation. Emissions from solar energy are much lower than those from fossil-fueled generation. Nonetheless, environmental risks and impacts must always be an important consideration [74].

VII. CONCLUSION

Brazil's geographical location, mostly between the Equator Line and the Tropic of Capricorn, greatly favors the use of solar source, mainly PV technology. Brazil can replace its 2019 fossil thermo-electric generation by using 50% of the proposed hydro-solar model potential.

Full implementation of this model, all over the country's HPP, can aggregate new 84.7 *TWh/year* to the SEB. This model can be used by micro- and mini-mills of DG, as well as to SHPP, and even smaller installations. MMDG and self-power-production reduce the grid's load curve. Large-scale PVPP, on land or the water, will help mitigate the afternoon's new peak-time power demand. WPP will attend mainly the night demand.

HPP reservoirs can benefit from PV-FPP installed on their free water surface, supplementing the hydropower with the available PV potential, taking advantage of the existing infrastructure, reducing the need for TPP dispatch, and, without occupying the land.

The proposed hydro-solar model will occupy, on average, only 3% of Brazil's HPP reservoirs with PV-FPP as seen in

The potential to expand the floating PV generation exceeding the HPP capacities is much bigger despite the concerns related to aesthetics, navigation, intrusion on recreational water bodies, and environmental impacts.

In the environmental aspect, by reducing the current 84.7 *TWh* from TPP 50 million tons of Carbon Dioxide can be avoided yearly. The full implantation of the hydro-solar model in all Brazilian HPP will reduce the emission of 200 million *tons* of carbon dioxide into the atmosphere by not dispatching the TPP. By reducing the evaporation on circa 20,000 $m^3/MWp.year$ [75], full implementation of this model all over Brazil will save 1.58 billion cubic meters of water per year.

The suggested model in this article needs to be implemented, tested, and better evaluated, including social and environmental impacts, and other issues that might arise. In the hybrid generation model, Brazil's available HPP compensates for wind and solar inconsistencies and provides the required inertia and stability to the SIN.

This model will allow the operation of the electric system in face of the predicted climate change, mitigating the disadvantages of the current hydro-thermal model, replacing it with a Carbon-free, modern, and sustainable hydro-wind-solar model.

The hydro-solar hybrid generation model can be used to combat global warming all over the world, in places where there are HPP and the radiation conditions allow PV.

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