Renewable and Sustainable Energy Reviews 135 (2021) 110082

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Floating PV system as an alternative pathway to the amazon dam underproduction ☆

Samer Sulaeman *, Erik Brown, Raul Quispe-Abad, Norbert Müller

Department of Mechanical Engineering, Michigan State University, East Lansing, MI, 48823, USA

ARTICLE INFO

Keywords:
Floating PV
System adequacy
Hydropower
Reliability
Brazil

ABSTRACT

With increasing electric demand and the continued underproduction of existing dams and the environmental and social concerns of traditional hydropower dam expansion in the Amazon region, alternative power sources are needed to meet future power needs. Recently, large-scale deployment of photovoltaic (PV) systems has gained more interest globally, mainly because of the improved technology and rapid price decrease. Although solar power in Brazil makes up a small percentage of its generation mix, large-scale deployment could potentially be one of the promising solutions for offsetting dams' underproduction. This work evaluates the benefits of adding floating PV (FPV) systems on system adequacy. FPV systems are integrated alongside existing dams to enhance the existing power sources and provide an alternative pathway to meet the increasing power demand without the need for more dams. System adequacy is evaluated with the current production of dams and the required capacities of FPV systems to compensate for the current underproduction of dams. Furthermore, the correlation between PV output and system load is evaluated, and the environmental and social concerns associated with dam expansion in the Amazon basin are briefly discussed. The results indicate that the investment toward installing FPV systems on the dams' reservoirs leads to a significant improvement to the overall system reliability, minimize load curtailment, and could potentially add more flexibility to the operator to dispatch power generated by hydropower plants during peak demands.

1. Introduction

One of the numerous, and perhaps most transformative, changes that the power grid is undergoing is the inclusion of renewable energy resources. In recent years, the penetration of grid-level renewable resources such as wind power and photovoltaic (PV) systems has tremendously increased due to political, environmental, and economical incentives. The rapid investment toward increasing the penetration level of renewable energy sources has become one of the possible solutions to reduce greenhouse gas emissions, among other social-environmental issues related to electric power production. By aiming to replace the need for fossil-fueled generators, the rapid investment toward installing large wind and PV farms, and hydropower plants (dams) have increased in the recent years, largely because of the believed benefit over fossil fuel generation systems in regards to: environmental concerns, global warming awareness, and economic incentives. Wind power, PV systems, and hydropower plants have received more attention especially in regions where the output power of these sources is potentially high. In the US, the projection of wind power and PV system penetration level is expected to reach 35% and 19% respectively by 2050 [1]. In other countries such as Brazil about 68% of the electrical energy is currently coming from large dams, while the contribution of other energy sources is around 32% [2]. However, the Brazilian government is planning to build more dams to meet the future increased power demand [2]. On the other hand, many environmental and social concerns associated with hydropower plants expansion in the Amazon region are still of concern, some of these concerns have already been studied and extensively addressed in the literature [3–8]. However, the utilization of an additionally balanced mix of energy sources may potentially provide an alternative pathway to avoid the environmental and social impact of dam expansion in Brazil while meeting the increasing power demand.

One of the promising applications of a generation mix that has gained attention recently is the integration of FPV systems on the reservoir of dams. China has already aggregated as much as 150 MW of

☆ This work is supported by the National Science Foundation (grant number 1639115) through INFEWS/T3 project: Rethinking Dams: Innovative Hydropower Solutions to Achieve Sustainable Food and Energy Production and Sustainable Communities.

* Corresponding author.
E-mail addresses: samersul@msu.edu (S. Sulaeman), brown722@msu.edu (E. Brown), quispeab@msu.edu (R. Quispe-Abad), mueller@egr.msu.edu (N. Müller).

https://doi.org/10.1016/j.rser.2020.110082
Received 24 July 2019; Received in revised form 7 July 2020; Accepted 9 July 2020
Available online 6 September 2020

FPV systems at many flooded mining sites and connected to the national grid [9,10]. Other countries such as Japan already have installed close to 23 MW of FPV systems; while countries such as Canada, Singapore and India contribute to a small amount of worldwide installation of PV system alongside hydropower plants [9,10]. In the US, despite the fact that investment toward implementing FPV system is limited, a study by Spencer et al. [11] shows that the investment of FPV systems on man-made water bodies could potentially produce up to 10% of current national power supply. In Brazil, where most of the electrical energy is currently coming from large dams, installing FPV systems on the reservoirs of hydropower plants is still in its early stages. Recently, FPV pilot projects were announced by the Brazilian government for the reservoirs of the hydroelectric power plants Balbina (State of Amazonas) and Sobradinho (State of Bahia) [12]. Although the main goal of these pilot projects is to evaluate the performance of FPV systems under different climatic conditions, the current experiences with the installed FPV systems worldwide reveal some advantages of hybrid system deployment, especially on reservoirs of dams. Such a hybrid system already offers a higher power dispatch flexibility that PV power provides especially during high demand times (i.e., day time when the output of PV system is potentially high), and adding more flexibility to the operator to dispatch power generated by hydropower plants as such to be used during night and early morning hours [9,10].

In the literature, several authors have evaluated possible scenarios that can be implemented to minimize the environmental and social impacts associated with reservoirs in the Amazon basin as a result of building new large hydropower plants. In Ref. [13], the authors evaluated the Brazilian electric network expansion considering replacing large dams with wind power plants. The authors' findings suggest that wind power has limited potential as the investment toward more wind power installation increases. With the limited deployment of PV systems in Brazil, several authors have also discussed the potential electrical benefits of PV systems in both grid-connected and off-grid applications, as well as the potential social and environmental benefits, especially in rural and off-grid communities. In Ref. [14–16], the authors have evaluated the transmission expansion and location-based marginal price along with other issues such as energy import/export between Brazil and neighboring countries. Others [17–19] have evaluated the deployment of PV systems in the rural areas where the main grid is too far away to allow for economically-feasible expansion.

Large-scale deployment of PV systems in Brazil also has been investigated with regards to grid-connected and building-integrated systems and their potential benefits to the electric grid [20–22]. In Ref. [23], a literature review of FPV system configuration, application, and its impact on water evaporation and CO2 reduction have been discussed. It has been concluded that using the FPV system has a high potential of reducing CO2 emissions and water evaporation. In Ref. [24], a sustainable hydro-solar model is proposed as an alternative to the current model of power production in Brazil [25]. evaluates different FPV technologies and their performance, and the authors conclude that the FPV system performance is mainly dependent upon the technology used and the location of the PV system. Another benefit is that the deployment of FPV could also lead to more favorable policies towards future consideration of large-scale deployment of PV systems in Brazil [26]. also has shown that a hybrid FPV-hydropower system improves the energy efficiency of the hydropower plant. In Ref. [27], the electrical and economic benefits of installing a FPV system on the tropical Gavião reservoir in Northeast Brazil have been evaluated. The authors have concluded that it is economically viable, besides the environmental benefits. Further [28], examines the environmental and socio-economic impacts of large-scale deployment of photovoltaic systems in Brazil. In Ref. [29], a case study on the hydroelectric plants of the São Francisco River basin has been presented, wherein the technical and economical procedures for sizing the FPV system and the coordination with hydroelectric plant operation have been evaluated. Besides the environmental gain, the results also indicate installing FPV could potentially increase the hydroelectric plant production flexibility by 76% and the capacity factor by 17.3% on average.

An utilization of mixed generation resources may potentially provide an alternative approach that can be fully implemented and utilized to avoid the environmental and social impact of dam expansion in Brazil while meeting the increased power demand. The work presented here focuses on assessing the contribution of FPV to the adequacy of generating capacity of the Brazilian electric system. The capacities of FPV systems are designed to offset the hydropower dam underproduction and an alternative pathway to large dam expansion is proposed. FPV systems are installed and integrated alongside the existing dams to offset the current underproduction capacities, enhance the existing power sources and provide an alternative pathway to meet the increasing power demand. System adequacy is evaluated by calculating system reliability indices before and after adding FPV systems. Further, the correlation between PV output and system load is evaluated, and the environmental and social concerns associated with dam expansion in the Amazon basin are briefly discussed. This work evaluates the benefits of adding FPV systems on the system adequacy and is not intended for security assessment. The main contributions of this work are: 1) Evaluating the potential contribution of FPV systems to the Brazilian power grid. 2) Investigating the enhancement of the existing power sources by installing FPV on existing reservoirs to provide an alternative pathway to meet the increasing power demand. 3) Evaluating the correlation between FPV output and system load. 4) Evaluating the contribution of large-scale deployment of FPV systems to the system adequacy. System adequacy is evaluated with respect to the current underproduction of dams and the required capacities of FPV systems that are needed to offset the current underproduction of dams. In addition, reliability assessment is used to evaluate the potential benefits for the overall system reliability that result from installing FPV systems on the reservoirs. The adequacy of the generating capacity of the Brazilian electric system is evaluated in several case studies with different scenarios. System reliability improvement, in terms of reliability indices, is also evaluated with and without the addition of FPV systems. Metrics commonly used for reporting bulk power system reliability are utilized in this work: loss of load probability (LOLP), Loss of Energy Expectation (LOEE), expected demand not supplied (EDNS), and loss of load frequency (LOLF). Also, the environmental and social concerns associated with dam expansion in the Amazon basin are briefly discussed.

The remainder of this paper is organized as follows. Section 2 presents an overview of the current power system in Brazil. Section 3 discusses the environmental and social impact of hydropower dam expansion. Section 4 discusses an alternative pathway to dam expansion and the proposed solution. Section 5 describes the adequacy of power system and evaluation of reliability indices. Section 6 presents system modeling. Section 7 provides several case studies, results, and discussions thereof. Section 8 provides concluding remarks.

2. An overview of the current brazilian electric power system

The Operator of the National Electricity System (ONS), which is responsible for the coordination and control of the generation and transmission installations in the National Inter-connected System of Brazil under the supervision and regulation of the National Electric Energy Agency (ANEEL) has listed the current installed power capacities including power capacity expansion needed to meet the increasing demand [30]. These statistics are listed in Table 1.

Currently, the largest power source in the Brazilian power network is the hydropower dams, with an installed capacity exceeds 109 GW and it is projected to increase to 114 GW by the year 2023 [2]. Other resources such as wind and PV power contribute to a smaller percentage comparing with hydroelectric power plants as indicated in Table 1. Currently, solar power contributes to less than 2% of the system total installed capacity, on the other hand, wind contribute to around 9%. However, the projection of PV power in the year 2023 will increase by

Table 1
Current installed power capacities and projection of capacity planning increase by year 2023.

Power source	Installed Capacity (2018) (GW)	Projected Capacity (2023) (GW)	Percentage of Capacity Increase (%)
Hydro	109.1	114.4	4.7
Thermal + Gas	12.8	17.8	27.9
Oil–Diesel	4.6	4.9	5.8
Coal	2.7	3.0	11.4
Biomass	13.7	14.0	2.4
Nuclear	2.0	2.0	0.0
Wind	14.1	17.1	17.7
Solar (PV)	1.8	3.6	50.9
Others	0.8	1.0	22.1
Total	161.5	178.0	9.2

51% while wind power is projected to increase by 17.7%. However, the Brazilian government has recently previewed several pilot-projects on floating PV (FPV), this largely because of the high incidence of solar radiation that powers PV systems [18–20,22]. With the need for more generating capacity expansion, the Brazilian government is planning to expand the existing transmission lines to meet the growing demand, especially with the largest power sources (hydropower dams) being located far away from the major loads. Fig. 1 shows the interconnected system of Brazil as adopted from Ref. [2].

2.1. Underproduction of dams

Dams with reservoirs act as hydraulic batteries that resist high-frequency changes to water levels. The reservoirs, however, can not adjust sufficiently for long-term or severe changes in rainfall or other climatological factors. As a result, dam systems cannot always produce their average rated power when water levels are below an acceptable level to produce the head drop necessary for the installed turbines. Another factor that can affect the ability of the dam system to produce power is economic feasibility; depending on the load on the electric grid system at a given time of the day, it may not be profitable to run the turbines at high load or possibly at all. Water estimations for the Amazon Basin indicate a drying trend in the Southern and Eastern regions,

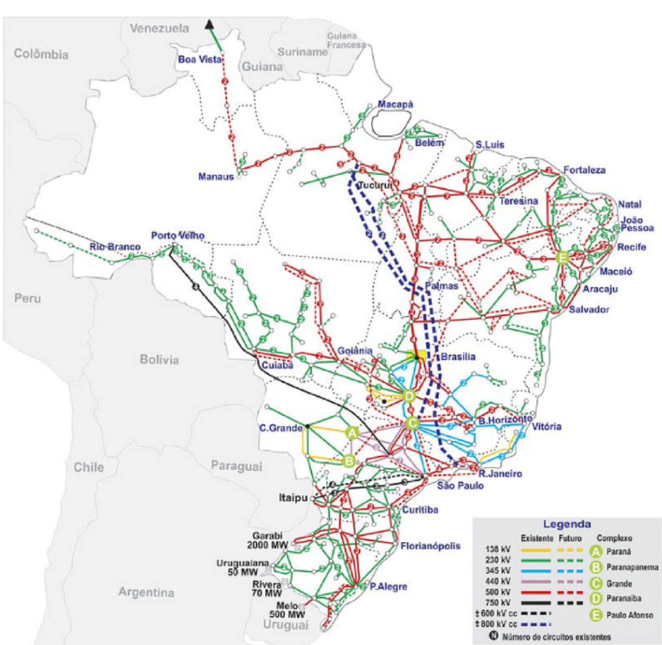

Fig. 1. Brazilian interconnected system [2].

decreasing the water supplies and affecting the reliability of power generation [8,31]. The Jirau dam and Santo Antonio dam on the Madeira River in Brazil, completed in 2013, are estimated to generate only a fraction of the projected power (3 GW each) due to the smaller storage capacity of run-of-the-river reservoirs [8,32]. The Belo Monte dam on the Xingu River, completed in 2016, is also estimated to produce only 4.46 MW of the projected power (11.23 GW) [31–33]. Another factor affecting the power generation is the deforestation in the Amazon River Basin, which has been investigated by Ref. [8]. In the Xingu Basin, the location of the Belo Monte dam, with changes in rainfall, the projections of forest loss could reach 40% by 2050, and could potentially lead to 25% reduction of the current power capacity [8,34]. In Brazil, it can be estimated that there is around 12 GW of underproduction of rated capacity considering operational dams [30]. The nominal capacities of the dams, fiscal power production and underproduction percentage as calculated from the reported values in 2018 b y Ref. [30] are shown in Table 2.

2.2. Wind and PV power in Brazil

In Brazil, the largest state in the Amazon is the state of Amazonas, with a large surface area of 1,559,148 km^2. As shown in Figs. 2–4, the Amazon region has a strong solar irradiation and high potential of PV power output [35]. Despite the seasonal variation and climate characteristics along the Brazilian territory, the total daily average value of solar irradiation as recorded for 16 years (1999–2015) shows that the global irradiation is fairly uniform with average value reaches 46.2 kWh/m^2. Further, the daily average of PV potential power as recorded for the same period of time along the Brazilian territory ranges between 3.8 and 4.8 kWh/kWp, with yearly average ranges between 1387 and 1753 kWh/kWp. The amount of solar radiation and potential of PV along Brazilian territory is considerably high comparing to the majority of the leading countries where more investments towards PV power installation have gained a great momentum [36]. Although Brazil has on average a high PV power potential and Global Horizontal Irradiation (GHI) compared to some leading countries, such as Japan with a GHI of 1022–1607, has a total installed capacity of 56,162 MW, Germany with a GHI of 949–1241 with a total installed capacity of 45,452 MW and France with a GHI of 494–1680 with a total installed capacity of 10, 562 MW as shown in Table 3, Brazil has only accumulated 2296 MW of PV system so far [37]. According to Ref. [2], Brazil is planning to increase the investment towards PV installations to bring the total projected capacity to 4241 MW by the year 2024. However, wind power has received more investments in Brazil along the coastal areas where the potential of wind speed is high as shown in Fig. 5. Noticeably, as mentioned in Section 2, solar power has more potential than wind power especially in the Amazon region largely due to: wind power having less potential power especially in the Amazon region where the tall, dense forests and low-pressure gradients are concentrated, high potential of PV power across the Brazilian territory, and changing policies toward a more balanced generation mix investment [18–20,22]. Therefore, in this work, wind power is not considered as an alternative solution to dam expansion in the Amazon basin. However, the adequacy assessment of the Brazilian power network is conducted for the generation mix including the existing wind farms and PV systems.

3. Environmental and social impact of dams

Contrary to popular belief, the notion of hydraulic dams with reservoirs being completely green is inaccurate. Dams cause environmental and social issues, some of which are: increase greenhouse gas emission [38–43], increase likelihood of toxic methylation [44,45], increase evaporation of river water [42], interruption or complete blockage of water-borne animal migration and natural living patterns, and deforestation and unnatural levels of flooding for the dam reservoir. These

Table 2
Dams underproduction.

Dam Name	Nominal Capacity (MW)	Fiscally Reported Power (MW)	Percent under Rating (%)	Dam Name	Nominal Capacity (MW)	Fiscally Reported Power (MW)	Percent under Rating (%)
Ado Popinhaki	22.6	16.9	25.0	Pedrinho I	16.2	16.0	1.0
Alto Benedito Novo	6.5	2.2	66.3	Pereira Passos	99.9	99.1	0.8
Balbina	250.0	249.7	0.1	Piabanha	20.0	9.0	55.0
Bariri	143.1	136.8	4.4	Porto Colômbia	320.0	319.2	0.3
Belo Monte	11233.1	3938.6	64.9	Primavera	25.7	24.7	3.7
Bugres	24.1	11.1	53.9	Rio Fortuna	7.0	6.9	2.0
Cachoeira do Ronca	0.9	0.3	62.2	Ronuro	1.0	0.9	15.9
Calheiros	19.5	19.0	2.7	Santa Cruz	0.6	0.4	33.8
Canastra	44.8	42.5	5.13	Santa Cruz	1.5	1.4	6.7
Capigui	4.5	3.8	15.8	Santa Luzia Alto	29.3	28.5	2.6
Capivari	18.7	18.1	3.5	Santa Rosa	1.6	1.4	11.4
Cedros	8.4	7.3	13.3	Santana	0.7	0.5	23.1
Celso Ramos	12.8	5.6	56.3	Santo Antonio	3150.4	2286.1	27.4
Chave do Vaz	1.6	0.7	57.5	São Domingos II	24.7	24.3	1.5
Paranoá	30.0	29.7	1.0	São Lourenço	30.0	29.1	3.0
Passo de Ajuricaba	6.2	3.2	48.3	São Manoel	700.0	175.0	75.0
Passo do Inferno	4.9	1.3	10.6	São Pedro	2.2	1.5	30.5
Coaracy Nunes	78.0	77.0	1.3	Tudelândia	2.5	2.4	5.8
Venâncio	3.8	1.6	58.1	Walter Rossi	16.5	15.8	4.4
Congonhal I	1.8	1.6	11.0	Ypê	30.0	27.4	8.7
Cristo Rei	1.8	1.0	46.6	Mello	10.7	9.5	10.7
Ernestina	4.9	4.8	3.2	Nilo Peçanha	380.0	378.4	0.4
Estreito	1050.0	1048.0	0.2	Mascarenhas	198.0	189.0	4.5
F	3.9	3.8	4.5	Marumbi	9.6	4.8	50.0
Ferraria Gomes	252.0	168.0	33.3	Marco Baldo	16.8	16.6	1.2
Fontes Nova	131.9	130.3	1.3	Jirau	3750.0	2100.0	44.0
Forquilha	1.1	1.0	10.5	Itiquira	157.4	156.0	0.9
Glória	13.8	11.4	17.7	Itapebi	462.0	456.0	1.3

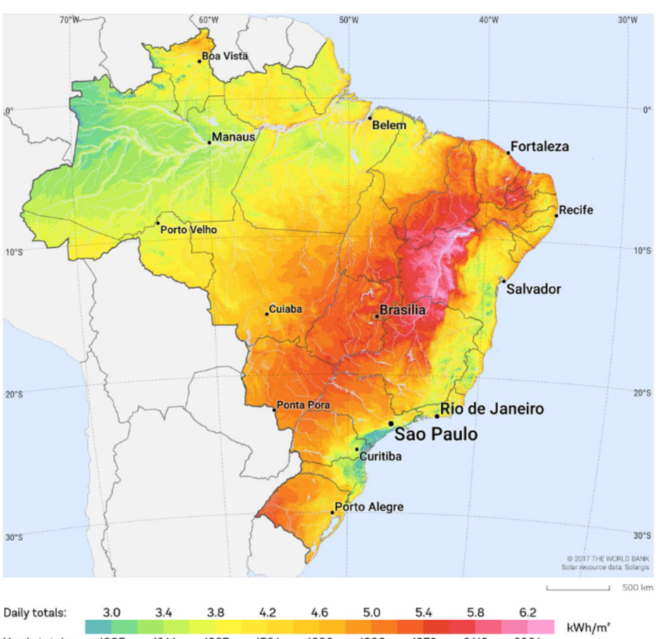

Fig. 2. Direct normal irradiation in Brazil from 1999 to 2015 [35].

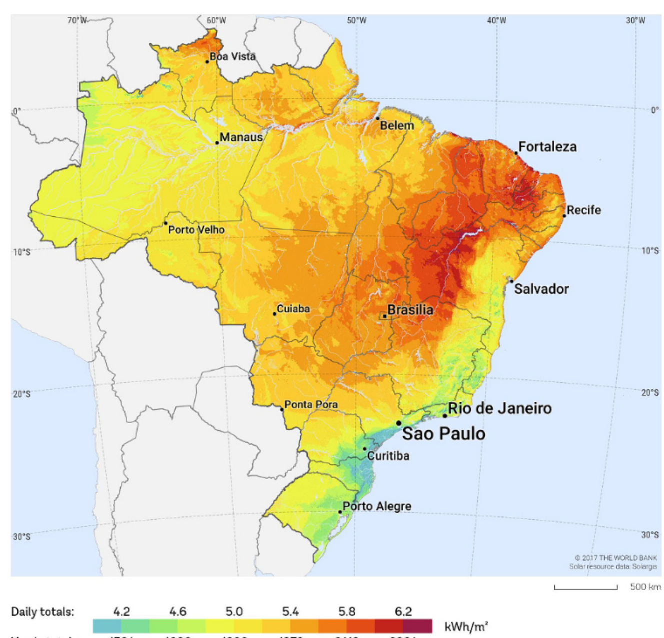

Fig. 3. Global horizontal irradiation in Brazil from 1999 to 2015 [35].

environmental issues are also simultaneously social issues, with the addition of forced relocation of local people for the introduction of the dam and reservoir via the destruction of the local area for the reservoir itself, or from the resulting flooding from filling the reservoir [46].

4. Floating PV systems on hydropower dam reservoirs

The addition of off-grid PV systems and grid-level PV systems floating on the reservoir of dams can help prevent social and environmental issues associated with dams from worsening in the future by offsetting the planned need for power from dams. Integrating grid-level FPV systems to existing dams add more flexibility to the operation of

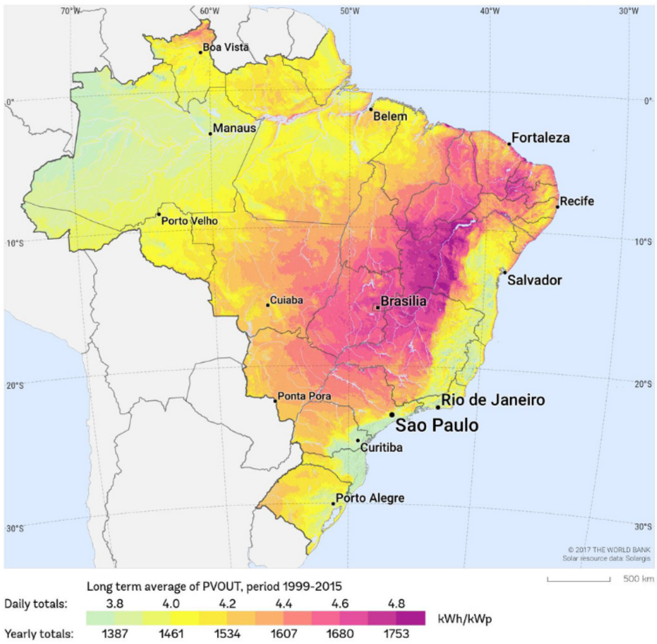

Fig. 4. Potential of average photovoltaic power in Brazil from 1999 to 2015 [35].

Table 3
Installed PV capacity and horizontal solar irradiation for different countries.

Country	Yearly Average GHI (kWh/m^2)	Installed Capacity (MW)	Grid-connected (MW)	Off-grid (MW)
China	949–2118	175,400	175,032	368
Japan	1022–1607	56,162	55,989	173
U.S.A	330–2191	62,498	62,498	n/a
Germany	949–1241	45,452	45,402	50
India	1241–2264	34,831	34,831	n/a
Italy	1022–1899	20,107	20,107	n/a
Australia	1387–2264	10,953	10,669	284
France	494–1680	10,562	10,532	30
South Korea	1241–1461	10,505	10,505	n/a
Spain	1095–1972	5659	5513	146
Brazil	1387–1753	2296	1796	500

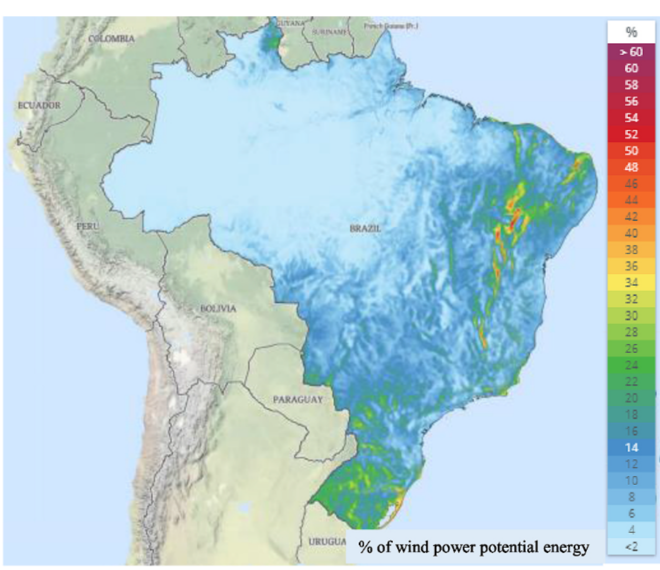

Fig. 5. Percentage of potential wind power in Brazil [35].

large dams by allowing large dams to operate not following base-load but rather adopting an approach of following the load. The investment toward integrating such alternative systems open up more opportunities for deployment of environmentally-friendly and yet efficient power sources that can supply the current and future power needs of the country, both on and off of the grid. Despite the fact that the deployment of large-scale grid-connected FPV systems are still in early stages, the deployment of PV systems alongside existing dams or floating on the reservoirs recently has been gaining more attention. As depicted in Fig. 6, globally, China and Japan are leading on PV systems installation with total capacity of 376 MW and 23 MW, respectively. Other countries such as Canada (0.0005 MW), Singapore (0.005 MW) and India (0.06 MW) contribute a small amount to the worldwide installation of PV systems along side hydropower plants. Meanwhile, also in other countries such as Afghanistan, Azerbaijan, Colombia, Ghana, and the Kyrgyz Republic, development of FPV systems projects are in progress [9,10]. This is largely because of the fact of high potential and efficiency of FPV system installed on the reservoir of dams and the ability to provide a storage system that can be utilized and dispatched to provide a balance to the system operation including the intermittent sources. Furthermore, FPV systems can help reduce environmental issues due to the fact that the FPV systems providing shade that minimize water evaporation, improve water quality and help fish and other water speciesâ€™ population stability but also symbiotically increasing the PV system efficiency by providing a cooling mechanism [47–49].

Considering the environmental and social concerns associated with the dam expansion in Brazil as mentioned in Section 3 and herein, the proposed solution aims to minimize such concerns by installing grid level FPV systems *(floating on the reservoir area)* alongside the existing dams. The FPV system design facilitates local fishing activities and the cohabitation of marine life when PV arrays are presented as depicted in Fig. 7.

5. Generation adequacy assessment

In general, generation adequacy assessment is used to evaluate short-term and long-term power generation capacity planning studies. Probabilistic methods are commonly used in power system adequacy studies as they take into account the stochastic nature of system behavior, such as component failures and load-level changes [50–54]. For power system planning projects, probabilistic methods are used to examine the ability and the adequacy of the total generating system to meet the demand [52]. In addition, power system reliability assessment has played a major role in evaluating the contribution of variable energy resources to the adequacy of generation system for both operation and planning process [54]. In this work, an analytical method is used to evaluate system adequacy and calculate reliability indices. Reliability indices such as but not limited to; *loss of load probability (LOLP)*, *Loss of Energy Expectation (LOEE)*, *Expected Demand not Supply (EDNS)* and *Loss*

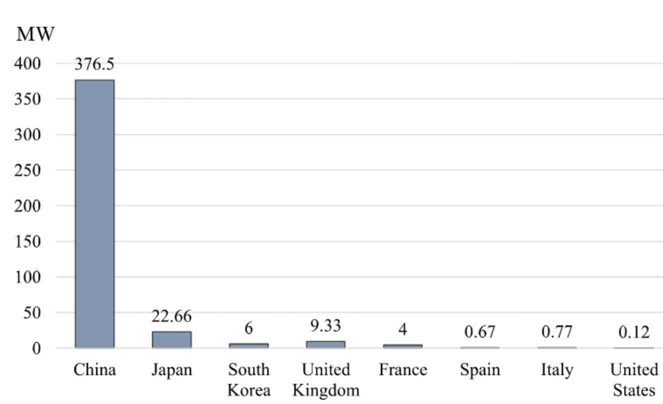

Fig. 6. Integrated PV system with hydropower installed capacity worldwide.

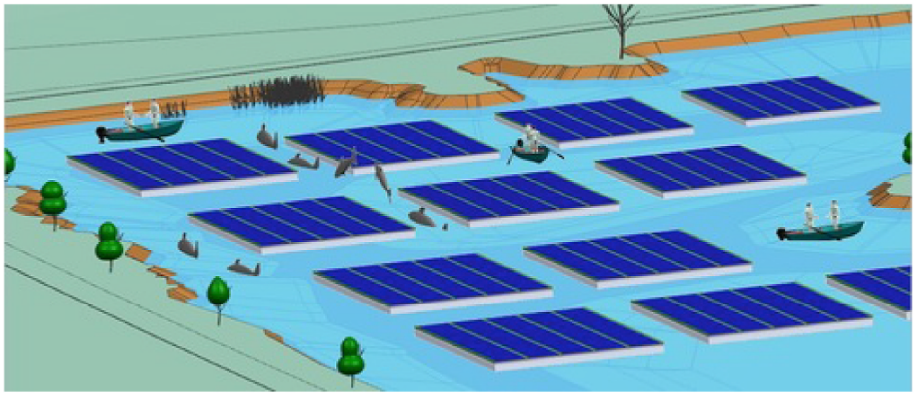

Fig. 7. Floating PV system on reservoir in which marine life and fishing activity are not disrupted by placing PV systems on the reservoir.

of Load Frequency (LOLF) are among the most commonly used indices as a metric to measure the contribution of additional generation resources to adequacy of the system [55,56]. These indices are briefly defined as follows [57]:

- A Loss of Load (LOL) event is one in which a system is unable to meet its total demand.
- Loss of Load Probability (LOLP) is the probability of encountering one or more LOL events during a given time period.
- The EDNS index is the sum of the products of probabilities of failure states and the corresponding load curtailments. It is expressed in MW/year or GW/year.
- Loss of Load Expectation (LOLE) is the expected number of LOL hours during a given time period. It is expressed in hr/year.
- Loss of Energy Expectation (LOEE) is the expected energy that the system is unable to serve as a result of LOL events during a given period. It is calculated as the weighted sum of the energies curtailed during the LOL events, the weights being the probabilities of the corresponding LOL events. It is expressed in MWh/year or GWh/year.
- Loss of Load Frequency (LOLF) is the expected frequency of encountering one or more LOL events during a given time period.
- Loss of Load Duration (LOLD) is the expected duration of LOL events occurring during a given time period.

6. System modeling

Due to the complexity of the power system, the reliability assessment of the bulk power system has mainly been applied in three different hierarchical levels [52]. The assessment of generation adequacy, known as hierarchical level-I (HL-I). At HL-I studies, the transmission lines are considered highly reliability able to transfer the generated power to all load points. Whereas, when both generation units and transmission systems are considered in the reliability evaluation, its known as the reliability of composite system or Hierarchical level-II (HL–II) studies. Further, the reliability evaluation at Hierarchical level-III (HL–III) considers the entire system. However, due to the complexity of power system and high computation time, reliability evaluation at the HL–III level is rarely attempted. Instead, power system reliability is evaluated at three different levels separately: generation system level (HL–1), composite power system level (HL–2), and distribution level [52,58]. In this work, reliability evaluation at HL–I is considered. In this process, the failures of generating units are considered to be independent events, so that the probability of failure of a generation unit can be modeled as Markovian components with two states, *up* and *down* states with known failure and repair rates, λ and μ respectively (λ is the failure transition rate from an up state to a down state, and μ is the repair transition rate from a down state to an up state).

6.1. Wind turbine output power

The wind turbine power curve provides a quantitative relationship between wind speed and the output power. It describes the operational characteristics of a wind turbine generator (WTG).

The output power that can be extracted from WTGs can be calculated as follows [59].

$$P=\frac{1}{2}C_p\rho A v^3 \tag{1}$$

where P is the output power (Watts), ρ is the air density (kg/m^3), v is the wind speed (m/sec), A is the swept area of the turbine (m^2), and C_p is the power coefficient.

The output power curve combines (1) with the physical constraints in the system. The output power curve including the physical constraints can be expressed as follows.

$$P=\begin{cases} 0 & \text{if } v < v_{cut-in} \\ \frac{1}{2}\rho A C_p v^3 & \text{if } v_{cut-in} \le v < v_r \\ P_r & \text{if } v_r \le v < v_{cut-out} \\ 0 & \text{if } v_{cut-out} \le v \end{cases} \tag{2}$$

where v_{cut-in} is the designed cut-in speed, $v_{cut-out}$ is the designed cut-out speed, v_r is the rated speed and P_r is the rated power of the wind turbine.

6.2. Output power of PV systems

The maximum output power ratings of PV-systems are provided by the manufactures and usually are expressed in peak–watt (W_P). The current–voltage characteristics ($I-V$ characteristics) under the standard test conditions (the radiation level of 1kW/m^2 is given for temperature of 25°C) can be calculated using the following relationship [60]:

$$I=S[I_{sc}+K_I(T_c-25)], \tag{3}$$

$$V=V_{oc}-K_V T_c, \tag{4}$$

where S is the radiation level, I_{sc} is the short circuit current, K_I is the short circuit current temperature coefficient in A/C^o, V_{oc} is the open circuit voltage, K_V is the open circuit voltage temperature coefficient in V/C^o and T_c is the cell temperature in C^o which can be expressed as follows [60].

$$T_c=T_a+S\left(\frac{T_{no}-20}{0.8}\right), \tag{5}$$

where T_a is the ambient temperature and (T_{no}) is the nominal operating temperature of the cell (C^o).

The output power (P_{pv}) for a given radiation level, ambient temperature and the current-voltage characteristics can be calculated using the following relationships [60]:

$$P_{pv} = N \times FF \times I \times V, \tag{6}$$

where N is the number of panels and FF is the fill factor, which depends on the module characteristics, and can be expressed as follows [60].

$$FF = \frac{V_{mpp} I_{mpp}}{V_{oc} I_{sc}}, \tag{7}$$

where V_{mpp} and I_{mpp} are the current and voltage at the maximum power point.

6.3. Generation model

Based on the FOR *(forced outage rate is the failure probability)* of generation units, the COPAFT *(Capacity outage probability and frequency table)* can be built using the unit addition algorithm. This is a recursive algorithm that starts with the distribution of one unit and successively convolves with it the distributions of the remaining units, one unit at a time. The FOR is defined as follows [50].

$$FOR = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \tag{8}$$

where m is the mean time to failure ($MTTF$): $MTTF = \frac{1}{\lambda}$, r is the mean time to repair($MTTR$): $MTTR = \frac{1}{\mu}$.

In general, when adding a new unit of capacity C, the cumulative probability and frequency of an outage of X MW can be determined by the following expression: [50].

$$P(X) = \overline{P}(X)(1 - q) + \overline{P}(X - C)q, \tag{9}$$

where $P(X)$ and $\overline{P}(X)$ denote the cumulative probabilities of the capacity outage state before and after the units are added respectively. Equation (9) is initialized as follows.

$$P(X) = \begin{cases} 1, & \text{if } X \leq 0 \\ 0, & \text{otherwise,} \end{cases}$$

The cumulative probability $P(X)$ for a forced outage of X MW or greater can be in general calculated using (10).

$$P(X) = \sum_i P(X_i), \quad \forall\, X_i \leq X, \tag{10}$$

where

$$\overline{P}(X) = 1, \quad \forall\, X \leq C,$$

In the case of multi-state generating units, (9) can be modified as follows.

$$P(X) = \sum_i^n P(i) \times \overline{P}(X - C_i). \tag{11}$$

The cumulative frequency of capacity outage of X MW can also be calculated using the same approach using (12).

$$F(X) = F_i(1 - q) + F_j q + (P_j - P_i) q\mu, \tag{12}$$

where q and μ are respectively the probability of failure and repair rate of the new added unit; P_i, P_j, F_i, and F_j are determined from the old COPAFT (prior to adding the new unit); i is the index of the existing capacity outage state, $C_i = X$, and j is the index of existing capacity outage state, C_j, such that $C_j = X - C$. F_i and F_j are cumulative frequencies of states i and j respectively.

6.4. Load model

The load model is usually expressed in the form of probability and frequency distribution of the random variable that represents system load [50,61]. The load model can be constructed by scanning the hourly load data of the system over the time period of study, usually one year. In general, the load model can be built in terms of load level L_i with its commutative probability and frequency as follows [50,61].

$$P_L(L \geq L_i) = \frac{H(L \geq L_i)}{T}, \tag{13}$$

$$F_L(L \geq L_i) = \frac{\Gamma(L < L_i \rightarrow L \geq L_i)}{T}, \tag{14}$$

where $H(L \geq L_i)$ is the number of hours that the hourly load is greater than or equal to the load level L_i, T is the number of hours in the interval, $P_L(L \geq L_i)$ is the commutative probability of the load level L_i, $\Gamma(L < L_i \rightarrow L \geq L_i)$ is the number of transitions from $(L < L_i)$ to $(L \geq L_i)$, and $F_L(L \geq L_i)$ is the commutative frequency of L_i.

6.5. Generation reserve model

The generation reserve margin has been used to estimate the reliability indices. The generation reserve margin model consists of the probability and frequency of a random variable M, which represents the difference between the available generation and load [50,61]. Though the rigorous derivation of the generation reserve margin model will not be reproduced here, some expressions will be presented and briefly explained. The reserve margin model can be expressed in terms of generation and load model as follows [50,61].

$$M = C_C - C_O - L, \tag{15}$$

where C_O is the capacity outage, L is the system load, and C_C is the net available generation capacity for commitment which can be expressed as follows.

$$C_C = C_i - C_{OP}, \tag{16}$$

where C_i is the installed capacity, C_{OP} is the capacity on planned outage.

For each generation reserve margin level, M_i, the cumulative probability and cumulative frequency can be calculated using (17) and (18) respectively.

$$P(M \leq M_i) = \sum_{j=1}^{n_G} \left[P_G(C_j) - P_G(C_j + 1)\right] \times P_L(C_C - C_j - M_i), \tag{17}$$

$$F(M \leq M_i) = \sum_{j=1}^{n_G} \left[F_G(C_j) - F_G(C_j + 1)\right] P_L(m_{ij}) + \left[P_G(C_j) - P_G(C_j + 1)\right] F_L(m_{ij}). \tag{18}$$

where n_G is the number of states in the generation model (COPAFT), C_j is the capacity outage level, $m_{ij} = C_C - C_j - M_i$, and $P_G(\cdot)$ and $F_G(\cdot)$ are the cumulative probability and frequency of generation reserve model respectively.

7. Case studies

The Brazilian power system is a large power network that has a total of 4587 generating units with an installed capacity around 161 GW, and the total peak demand exceeding 85 GW as reported in 2018 [30]. In this work, the system adequacy is evaluated with and without FPV system. These case studies are detailed more in the following sections.

7.1. Capacity factor of PV system at the proposed locations

In general, the capacity factor of a power plant is used to measure actual power generated comparing to its rated output during a specific period of time. For PV systems, the capacity factor measures total amount of energy the PV system produced during a period of time to the total amount of energy that the PV system would have produced at full capacity. In general it can be calculated using (19).

$$C.F = \frac{\sum_{n=1}^{T} PV_{power}}{T \times NC} \tag{19}$$

where C.F. is the capacity factor of the PV system, T is the length of the time period where the actual output is recorded, PV_{power} is the actual output of the PV system produced over that period of time and NC is the nameplate capacity of the PV system installed.

The capacity factor of the PV system at different dam locations where the underproduction is reported is calculated using (19) and shown in Figs. 8–11. It can be seen that the capacity factors of the PV systems have values that range from 0.38 to 0.48 with a 0.42 overall average capacity factor for all locations, based on daytime hours. This indicates a high potential for PV systems in the Amazon region as shown in Figs. 3 and 4 and discussed in Section 6.2.

7.2. Attributes of PV power to the peak load shaving

In Brazil, the majority of power comes mainly from large hydropower dams, and the contribution of solar power to the total power capacity is currently less than 2.0%. Until recently, most of the photovoltaic applications are limited to a small-scale deployment. However, the potential of solar power in Brazil has been investigated by several authors [20–22,62], in which investigations reveal that solar power has a high power potential and is economically viable. In this work, the correlation between the system load and PV output is evaluated. As shown in Fig. 12, the correlation between the system load and PV output is significantly high especially during peak hours. As shown in Fig. 13, grid-connected PV systems not only assist in peak load reduction especially during peak hours but also indicate that the grid-level FPV systems could potentially add more flexibility to the operator to dispatch power generated by hydropower plants during off-peak hours. Installing FPV systems alongside the existing dams not only offsets the current underproduction capacities but also takes advantages of the fact that the existing dams offer large capacities that can be used as energy storage that can be dispatched to compensate for the uncertainty and fluctuations associated with variable energy sources such as PV power. Additionally, the examined FPV systems are installed on existing dam reservoirs for all locations with rated capacity equal to the reported

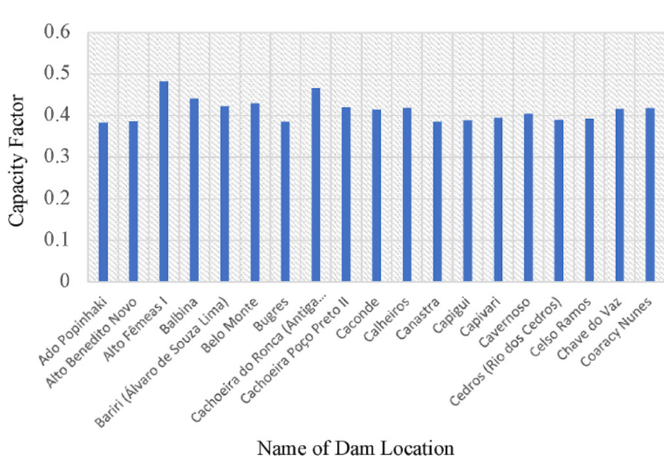

Fig. 8. Capacity factor of PV system at several dam locations—A.

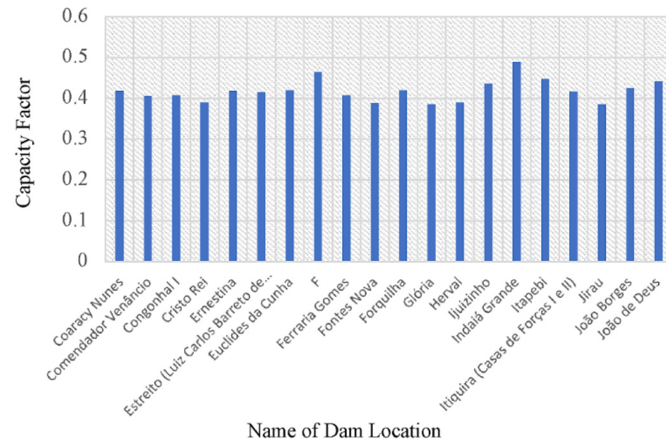

Fig. 9. Capacity factor of PV system at several dam locations—B.

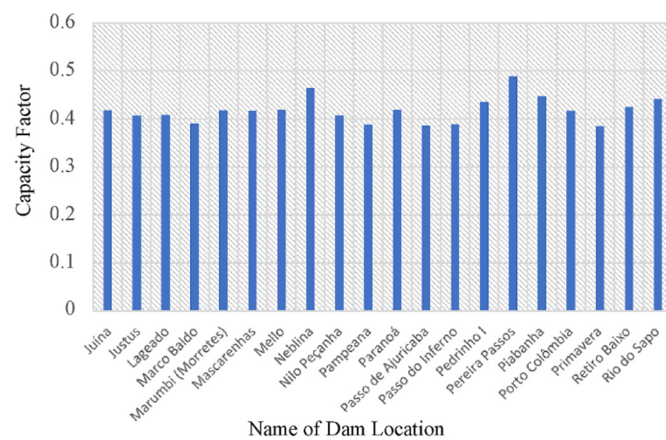

Fig. 10. Capacity factor of PV system at several dam locations—C.

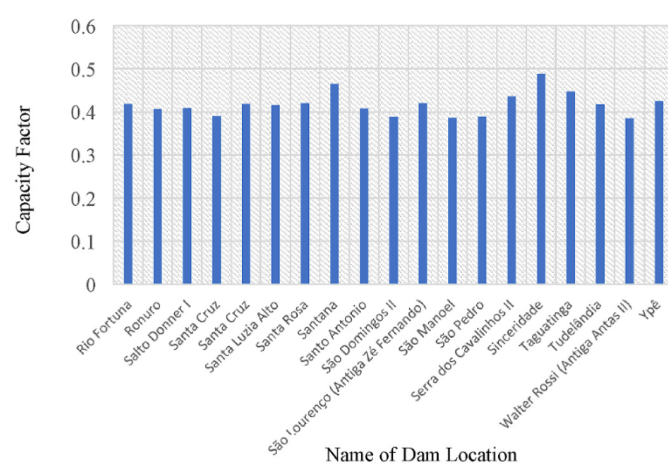

Fig. 11. Capacity factor of PV system at several dam locations—D.

underproduction capacities, thus requiring no additional substations or transmission lines, due to the infrastructure already being rated for the dam capacity.

7.3. System adequacy

The objective of this case study is to evaluate the contribution of large-scale deployment of FPV systems to the system adequacy. To perform such analysis, mean time to failure (MTTF) and mean time to

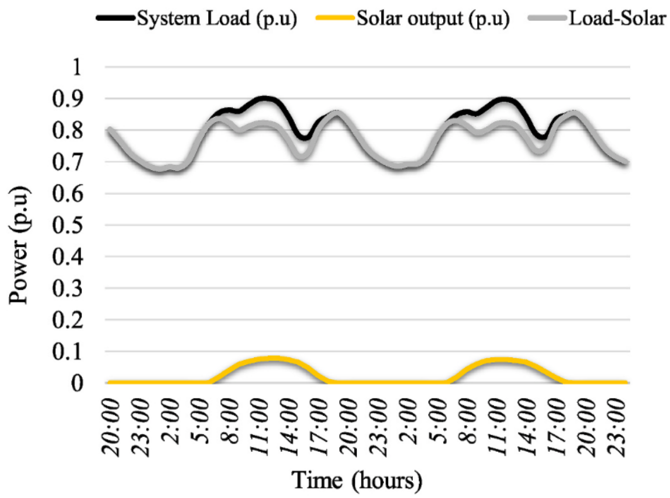

Fig. 12. Contribution of grid-connected PV system to daily peak shaving.

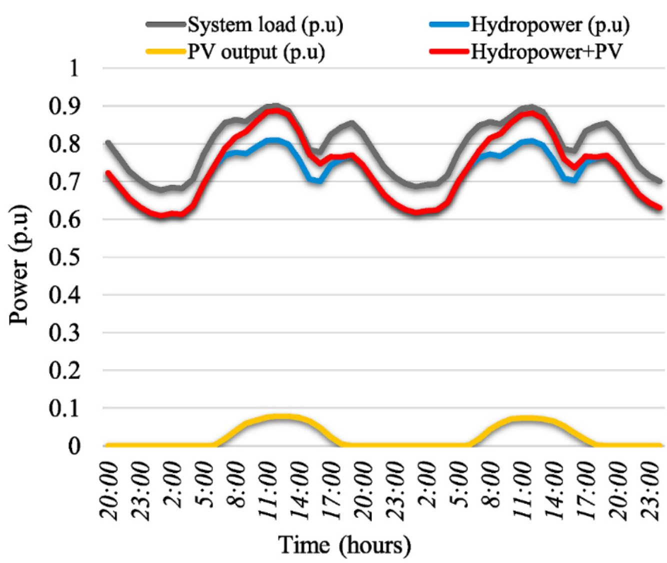

Fig. 13. Attribution of grid-connected PV system to assist Hydropower peak load shifting.

repair (MTTR) for different types of generating units are needed. Since the Brazilian system is quite large and consist of hundreds of different generating units, such data are not fully available to the public. Therefore, system data shown in Table 4, and MTTF and MTTR for different generating units obtained from Ref. [63–65] are used in this work. Due to the complexity of the Brazilian power network, several authors have discussed the protocols and procedures regarding establishing a reliability benchmark for the Brazilian power system [66–69]. The authors used IEEE-RTS test system *(IEEE-RTS has 32 generating units, with a total installed capacity of* 3045 MW *and a peak load of* 2850 MW*)* to compare and discuss the protocols, the conversion criteria, and the computation time to evaluate the reliability indices of the entire Brazilian power grid. Therefore, with the lack of a reliability benchmark for the Brazilian system and to first validate and ensure the accuracy of the mathematical model presented in this work that is scripted using the MATLAB environment, results are obtained and compared to those reported for IEEE-RTS as shown in Table 5. Then Brazilian generation and load system data are incorporated in the script and used to calculate reliability indices. The focus of this work is to evaluate the potential benefits of adding FPV systems to the Brazilian power grid, and not an attempt to establish a benchmark for system adequacy.

Table 4
Brazilian system data.

Type of Energy Source	Num. of Operational Units/Farms	Power Capacity (MW)
Nuclear	2.0	19,900
Thermal + others	2545	35622.1
wind	502	12296.4
solar	252	1302.6
hydro	1286	107537.0
Total	4587	158748.1

In this work, the random behavior of generation units is represented by two-state Markovian models [70,71]. The hourly wind power and PV power for the existing wind farms and PV systems are calculated based on the installed capacities for each location (i.e., 252 location for PV systems, and 502 wind farms). Using the historical data obtained from Ref. [72] for each wind farm and PV system location, the output power is calculated as described in Section 5. In addition, for the locations where the underproduction of dams is reported as shown in Table 2, a total of 12 GW of FPV power is added to the simulated system. The FPV systems are installed on existing dam reservoirs for all locations with rated capacity equal to the reported underproduction capacities. Due to the complexity of the system in terms of large number of generators, the following are assumed:

1 Given the nominal capacities of existing dams, the existing transmission lines are capable of transmitting the maximum power generated by power sources.
2 Regardless of the point of insertion, the power produced by variable energy resources (*i.e, Wind farms and PV systems*) will be accepted by the network.
3 For a large system such as Brazilian network with very low penetration of wind power, the contribution of wind turbine failure to the system adequacy is insignificant, especially when the observed wind speed tends to have low profile [73].

In this work, the following case studies are considered:

1 System reliability indices are evaluated with and without adding FPV system (*for the current system—2018*).
2 System reliability indices are evaluated with adding FPV to the system and peak load is increased.
3 System reliability indices are evaluated with and without adding FPV system (*projection of generation capacity increase—2023*).

7.3.1. System reliability indices—current system—2018

The generation adequacy of the Brazilian system is evaluated by calculating the reliability indices of the system before and after adding FPV to the system. The annual reliability indices of the system before and after adding FPV systems are shown in Table 6. It can be seen from the obtained results that the system reliability indices have improved significantly. The improvement of system reliability indices after adding FPV power can be attributed to a high capacity factor of the FPV power, correlation with load and high potential output during the high demand times.

To evaluate the effect of peak load increase on the reliability of the system, the system peak load is increased by 4% annually. The annual reliability indices in the case of peak load increase with FPV added to the system are shown in Table 7 *(biannually)*. As expected, the system reliability indices deteriorated when the system load increased. This indicates that after five years of load increase, additional power sources may be needed to meet the increasing demand.

Table 5
Annual reliability indices of IEEE–RTS.

Case	LOLP	EDNS	LOLD	LOLF	LOEE	LOLE
		MW/yr	Hr	occ./yr	MWhr/yr	hr/yr
Reported [63]	0.001069	0.1348396	4.64723	2.01600	1181.1950	9.36
Obtained	0.001069	0.1348396	4.64722	2.01600	1181.1949	9.36

Table 6
Annual reliability indices of the system before and after adding FPV system.

LOLP	EDNS	LOLD	LOLF	LOEE	LOLE
	MW/yr	hr	occ./yr	MWhr/yr	hr/yr
Base case—2018					
0.004177	20.5699	4.35	8.397	179698.7	36.496
Base case after adding FPV system—2018					
0.001859	7.67593	3.69	4.402	67056.9	16.243

Table 7
Annual reliability indices of the system with load increase.

Load	LOLP	EDNS	LOLD	LOLF	LOEE	LOLE
Increase		MW/yr	hr	occ./yr	MWhr/yr	hr/yr
8.0%	0.003671	17.937	3.96	8.08	156669.9	32.06
16%	0.006396	36.293	4.23	13.20	317058.6	58.76
24%	0.010129	65.779	4.51	19.63	574636.5	65.78

7.3.2. System reliability indices—2023 projection

In this case study, the projection of power demand and the power capacity increase shown in Section 2, Table 1 are evaluated in two cases;

- Annual reliability indices without adding FPV system (*Base case—2023 projection*).
- Annual reliability indices after adding FPV to the system (*Base case with FPV—2023 projection*).

For the two case studies, the power demand is assumed to increase by 4% annually. The annual reliability indices for the system before and after adding FPV system are shown in Table 8.

The results shown in Table 8 indicate that adding FPV to the system improves overall system reliability. Additionally, to better assess the contribution of FPV systems to generation adequacy, system reliability improvement factor (SRIF) is introduced. SRIF can be calculated as follows:

$$\mathrm{SRIF} = \frac{ARI_B - ARI_A}{ARI_B} \tag{20}$$

where ARI_B is the annual reliability index without FPV systems added, and ARI_A is the annual reliability index with added FPV systems.

Table 9 shows the SRIF of the system for different reliability indices for two scenarios; I) the SRIF is calculated for the current system after adding FPV system (Scenario—I—2018), and II) the SRIF is calculated for the system with FPV in 2023 (Scenario—II—2023), showing that also after three years load increase all indices for the system with FPV are still better than for the base case without FPV and before load increase.

Table 8
Annual reliability indices of the system with load increase *2023–projection*.

LOLP	EDNS	LOLD	LOLF	LOEE	LOLE
	MW/yr	hr	occ./yr	MWhr/yr	hr/yr
Base case—2023 projection					
0.015121	107.71	5.000	26.435	941009.45	132.09
Base case with FPV—2023 projection					
0.008133	49.454	4.369	16.262	432034.52	71.056

Table 9
SRIF considering different reliability indices.

SRIF	SRIF	SRIF	SRIF	SRIF
(LOLP)	(EDNS)	(LOLF)	(LOEE)	(LOLE)
Scenario—I—2018				
0.5550	0.6270	0.4760	0.6270	0.5550
Scenario—II—2023				
0.4620	0.1279	0.3848	0.1281	0.4620

7.4. Results and discussion

The results obtained in this work show that Brazil has high solar radiation and high potential of PV power output within the Amazon region. As shown in Figs. 12 and 13, large scale deployment of PV system contributes significantly to daily peak load shaving and adds more flexibility to hydropower plant operation. Mainly because of the high correlation between the PV system and system load, especially during peak times. The results also show that the capacity factor of PV systems is significant, with an overall average capacity factor of 42%. The generation adequacy of the Brazilian system is evaluated by calculating reliability indices before and after adding floating PV to the system. The annual reliability indices of the system before and after adding FPV systems are shown in Table 6. It can be seen from the obtained results that the system reliability indices have improved significantly. The improvement of system reliability indices after adding PV power can be attributed to the high capacity factor of PV power, correlation with load, and high potential output during the high demand times. Further, the effect of the peak load increase on the reliability of the system in the presence of the FPV system is also evaluated. As shown in Tables 6 and 7, the system reliability indices are improved in both the 2018 scenario and the 2023 projection scenario. As shown in Table 9, in both situations, SRIF indicates a significant improvement in system reliability when the FPV system is introduced. It can be seen, for instance, the SRIF based on LOLP and LOLE indices indicates a 55.5% improvement of system reliability after adding FPV systems, while the system reliability improves by 62.7% when EDNS and LOEE indices are used as a criterion. When the LOLF index is used as a criterion, the reliability of the system is improved by 47.6%. The results also show that installing FPV systems on the reservoirs of existing dams enhances system reliability. e.g., the LOLP index increases by 55.5% for the current system and by 46.2% for the 2023 projection case when FPV systems are introduced. However, it is up to the planner to decide a proper index; for instance, if the priority is to minimize power interruption, the LOLF index can be used. On the other hand, if expected load curtailment is given importance in the planning process, the LOLE index can be used instead. The results indicate that the utilization of large-scale floating PV systems alongside the existing hydropower plants provides an efficient power source to meet the increasing demand and a pathway to minimize the environmental and social impact of dam expansion in Brazil while meeting the increased power demand.

8. Conclusion

Considering the environmental and social concerns associated with hydropower plant expansion in the Amazon region, an alternative solution to meet power needs and the corresponding underproduction of hydropower dams is proposed and evaluated. The utilization of mixed generation resources may potentially provide an alternative approach that can be implemented to minimize the environmental and social impact of dam expansion in Brazil while also meeting the increased power demand. The work presented here has focused on assessing the contribution of FPV to the adequacy of generating capacity of the Brazilian electric system, with the capabilities of the FPV systems designed to offset the hydropower dam underproduction. Several cases were considered to evaluate system adequacy by calculating reliability indices before and after adding FPV systems. The results show that installing FPV systems on the reservoirs of existing dams improves system reliability. e.g., the LOLP index improves by 55.5% for the current system and by 46.2% for the 2023 projection case. In addition to the positive outcome for mitigating environmental concerns, a large scale FPV system could add more flexibility to the power system operator in terms of dispatchability and minimize load curtailment during high demand times. PV systems can also be installed locally on the roofs of family homes or on common-use buildings for a community in place of the current diesel generators, which can provide power for local communities or individual families. A PV system is a more environmentally friendly option than the current diesel generator systems due to the absence of greenhouse gas emissions from burning fuel, and less risk of spilled fuel at site and while transporting to the various locations.

Credit author statement

Samer Sulaeman: Conceptualization, Methodology, Writing - original draft, Formal analysis, Erik Brown: Data acquisition, editing, proofreading, Formal analysis, Raul. Quispe-Abad: Visualization, Investigation, Resources, Norbert Müller: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] W. Vision, A new era for wind power in the United States, US Department of Energy .
[2] Operator of the national electricity system, operator of the national electricity system. URL, http://www.ons.org.br; 2018.
[3] Garcia LC, Ribeiro DB, Oliveira Roque F, Ochoa-Quintero JM, Laurance WF. Brazil's worst mining disaster: corporations must be compelled to pay the actual environmental costs. Ecol Appl 2017;27(1):5–9.
[4] Laurance WF, Peletier-Jellema A, Geenen B, Koster H, Verweij P, Van Dijck P, Lovejoy TE, Schleicher J, Van Kuijk M. Reducing the global environmental impacts of rapid infrastructure expansion. Curr Biol 2015;25(7):R259–62.
[5] da Silva Soito JL, Freitas MAV. Amazon and the expansion of hydropower in Brazil: vulnerability, impacts and possibilities for adaptation to global climate change. Renew Sustain Energy Rev 2011;15(6):3165–77.
[6] Sternberg R. Hydropower: dimensions of social and environmental coexistence. Renew Sustain Energy Rev 2008;12(6):1588–621.
[7] Benchimol M, Peres CA. Widespread forest vertebrate extinctions induced by a mega hydroelectric dam in lowland Amazonia. PloS One 2015;10(7):e0129818.
[8] Stickler CM, Coe MT, Costa MH, Nepstad DC, McGrath DG, Dias LC, Rodrigues HO, Soares-Filho BS. Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales. Proc Natl Acad Sci Unit States Am 2013; 110(23):9601–6.
[9] Sahu A, Yadav N, Sudhakar K. Floating photovoltaic power plant: a review. Renew Sustain Energy Rev 2016;66:815–24.
[10] World Bank Group, ESMAP and SERIS. Where sun meets water: floating solar market report–executive summary. 2018.
[11] R. S. Spencer, J. Macknick, A. Aznar, A. Warren, M. O. Reese, Floating PV: Assessing the technical potential of photovoltaic systems on man-made water bodies in the continental US, Environmental science & technology .
[12] Galdino MAE, de Almeida Olivieri MM. Some remarks about the deployment of floating PV systems in Brazil. J Electr Eng 2017;1:10–9.
[13] Armaroli N, Balzani V. The future of energy supply: challenges and opportunities. Angew Chem Int Ed 2007;46(1–2):52–66.
[14] Barroso LA, Bressane JM, Thomé LM, Junqueira M, Camargo I, Oliveira G, Binato S, Pereira MV. Transmission structure in Brazil: organization, evaluation and trends. In: Power engineering society general meeting. IEEE, IEEE; 2004. p. 1301–6. 2004.
[15] Barroso LA, Rosenblatt J, Guimarães A, Bezerra B, Pereira MV. Auctions of contracts and energy call options to ensure supply adequacy in the second stage of the Brazilian power sector reform. Power engineering society general meeting. IEEE; 2006. IEEE, 8–pp, 2006.
[16] Barroso L, Porrua F, Pereira M, Bezerra B. Solving the major challenges in transmission asset investment in the competitive environment: the Brazilian case. In: Power & energy society general meeting. PES'09. IEEE, IEEE; 2009. p. 1–8. 2009.
[17] Silva SB, De Oliveira MA, Severino MM. Economic evaluation and optimization of a photovoltaic–fuel cell–batteries hybrid system for use in the Brazilian Amazon. Energy Pol 2010;38(11):6713–23.
[18] Chaurey A, Kandpal TC. Assessment and evaluation of PV based decentralized rural electrification: an overview. Renew Sustain Energy Rev 2010;14(8):2266–78.
[19] Neto MB, Carvalho P, Carioca J, Canafístula F. Biogas/photovoltaic hybrid power system for decentralized energy supply of rural areas. Energy Pol 2010;38(8): 4497–506.
[20] Martins FR, Rüther R, Pereira EB, Abreu S. Solar energy scenarios in Brazil. Part two: photovoltaics applications. Energy Pol 2008;36(8):2865–77.
[21] Rüther R, Dacoregio M. Performance assessment of a 2 kWp grid-connected, building-integrated, amorphous silicon photovoltaic installation in Brazil. Prog Photovoltaics Res Appl 2000;8(2):257–66.
[22] Antoniolli AF, Nobre AM, Reindl T, Ruther R. A review on grid-connected PV systems in Brazil including system performance. In: European photovoltaic solar energy conference. EU PVSEC; 2014. p. 2747–52.
[23] Ranjbaran P, Yousefi H, Gharehpetian G, Astaraei FR. A review on floating photovoltaic (FPV) power generation units. Renew Sustain Energy Rev 2019;110: 332–47.
[24] U. Stiubiener, T. C. da Silva, F. B. M. Trigoso, R. da Silva Benedito, J. C. Teixeira, PV power generation on hydro dam's reservoirs in Brazil: a way to improve operational flexibility, Renew Energy .
[25] Oliveira-Pinto S, Stokkermans J. Assessment of the potential of different floating solar technologies–Overview and analysis of different case studies. Energy Convers Manag 2020;211:112–747.
[26] Zhou Y, Chang F-J, Chang L-C, Lee W-D, Huang A, Xu C-Y, Guo S. An advanced complementary scheme of floating photovoltaic and hydropower generation flourishing water-food-energy nexus synergies. Appl Energy 2020;275:115389.
[27] Rodrigues IS, Ramalho GLB, Medeiros PHA. Potential of floating photovoltaic plant in a tropical reservoir in Brazil. J Environ Plann Manag 2020:1–24.
[28] Pimentel Da Silva GD, Magrini A, Branco DAC. A multicriteria proposal for large-scale solar photovoltaic impact assessment. Impact Assess Proj Apprais 2020;38(1): 3–15.
[29] Silvério NM, Barros RM, Tiago Filho GL, Redón-Santafé M, dos Santos IFS, de Mello Valério VE. Use of floating PV plants for coordinated operation with hydropower plants: case study of the hydroelectric plants of the São Francisco River basin. Energy Convers Manag 2018;171:339–49.
[30] Brazilian Electricity Regulatory Agency. AgÃªncia nacional de Energia elétrica–ANEEL. URL, http://www.aneel.gov.br/; 2018.
[31] Moran EF, Lopez MC, Moore N, Müller N, Hyndman DW. Sustainable hydropower in the 21st century. Proc Natl Acad Sci Unit States Am 2018;115(47):11891–8.
[32] da Silva RC, de Marchi Neto I, Seifert SS. Electricity supply security and the future role of renewable energy sources in Brazil. Renew Sustain Energy Rev 2016;59: 328–41.
[33] Magrin G, Marengo J, Boulanger J, Buckeridge M, Castellanos E, Poveda G, et al. Central and south America in climate change 2014: impacts, adaptation, and vulnerability, Part B: regional aspects. In: Barros VR, et al., editors. Contribution of working group II to the fifth assessment report of the intergovernmental panel of climate change; 2014. p. 1499–566.
[34] Nobre CA, Sampaio G, Borma LS, Castilla-Rubio JC, Silva JS, Cardoso M. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proc Natl Acad Sci Unit States Am 2016;113(39): 10759–68.
[35] World Bank Group. Solar and wind resource maps and data. URL, http://solargis.com/maps-and-gis-data/download/brazil/; 2018.
[36] Bilgili OASB, Kahraman MA. An overview of renewable electric power capacity and progress in new technologies in the world. Renew Sustain Energy Rev 2015;49(7): 323–34.
[37] Masson G, Kaizuka I. The international energy agency (IEA). 2019.
[38] Louis V L St, Kelly CA, Duchemin É, Rudd JW, Rosenberg DM. Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: a Global Estimate: reservoirs are sources of greenhouse gases to the atmosphere, and their surface areas have increased to the point where they should be included in global inventories of anthropogenic emissions of greenhouse gases. AIBS (Am Inst Biol Sci) Bull 2000;50 (9):766–75.
[39] Fearnside PM. Tropical hydropower in the clean development mechanism: Brazil's Santo Antônio Dam as an example of the need for change. Climatic Change 2015; 131(4):575–89.

[40] Fearnside PM. Carbon credit for hydroelectric dams as a source of greenhouse-gas emissions: the example of Brazil's Teles Pires Dam. Mitig Adapt Strategies Glob Change 2013;18(5):691–9.
[41] Fearnside PM. Greenhouse gases from deforestation in Brazilian Amazonia: net committed emissions. Climatic Change 1997;35(3):321–60.
[42] Fearnside PM. Greenhouse-gas emissions from Amazonian hydroelectric reservoirs: the example of Brazil's Tucuruí Dam as compared to fossil fuel alternatives. Environ Conserv 1997;24(1):64–75.
[43] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319(5867):1235–8.
[44] Stokes P, Wren CD. Bioaccumulation of mercury by aquatic biota in hydroelectric reservoirs: a review and consideration of mechanisms, Lead, mercury, cadmium and arsenic in the environment. 1987. p. 255–7.
[45] Fearnside PM. Brazil's Samuel Dam: lessons for hydroelectric development policy and the environment in Amazonia. Environ Manag 2005;35(1):1–19.
[46] Fearnside PM. Social impacts of Brazil's Tucuruí dam. Environ Manag 1999;24(4): 483–95.
[47] Yadav N, Gupta M, Sudhakar K. Energy assessment of floating photovoltaic system. In: Electrical power and energy systems (ICEPES), international conference on. IEEE; 2016. p. 264–9.
[48] Cazzaniga R, Cicu M, Rosa-Clot M, Rosa-Clot P, Tina G, Ventura C. Floating photovoltaic plants: performance analysis and design solutions. Renew Sustain Energy Rev 2018;81:1730–41.
[49] Rosa-Clot M, Tina GM, Nizetic S. Floating photovoltaic plants and wastewater basins: an Australian project. Energy Procedia 2017;134:664–74.
[50] Billinton R, Wee CL, Hamoud G. Digital computer algorithms for the calculation of cenerating capacity reliability indices. IEEE Power Eng. Rev. PAS– 1982;101(1): 34–5.
[51] Schilling MT, Da Silva AL, Billinton R, El-Kady M. Bibliography on power system probabilistic analysis (1962-88). IEEE Trans Power Syst 1990;5(1):1–11.
[52] Allan RN, et al. Reliability evaluation of power systems. Springer Science & Business Media; 2013.
[53] Billinton R, Li W. Basic concepts of power system reliability evaluation. In: Reliability assessment of electric power systems using Monte Carlo methods. Springer; 1994. p. 9–31.
[54] Sulaeman S, Benidris M, Mitra J, Singh C. A wind farm reliability model considering both wind variability and turbine forced outages. IEEE Transactions on Sustainable Energy 2017;8(2):629–37.
[55] Billinton R, Chen H, Ghajar R. A sequential simulation technique for adequacy evaluation of generating systems including wind energy. IEEE Trans Energy Convers 1996;11(4):728–34.
[56] Billinton R, Bai G. Generating capacity adequacy associated with wind energy. IEEE Trans Energy Convers 2004;19(3):641–6.
[57] Mitra J, Singh C. Pruning and simulation for determination of frequency and duration indices of composite power systems, Power Systems. IEEE Transactions on 1999;14(3):899–905.
[58] Endrenyi J. Reliability modeling in electric power systems. New York: Wiley; 1978.
[59] Manwell JF, McGowan JG, Rogers AL. Wind energy explained: theory, design and application. John Wiley & Sons; 2010.
[60] Khatod DK, Pant V, Sharma J. Analytical approach for well-being assessment of small autonomous power systems with solar and wind energy sources, Energy Conversion. IEEE Transactions on 2010;25(2):535–45.
[61] Billinton R, Singh C. Generating capacity reliability evaluation in interconnected systems using a frequency and duration approach part I. mathematical analysis. IEEE Trans. Power App. Syst. PAS- 1971;90(4):1646–54.
[62] Holdermann C, Kissel J, Beigel J. Distributed photovoltaic generation in Brazil: an economic viability analysis of small-scale photovoltaic systems in the residential and commercial sectors. Energy Pol 2014;67:612–7.
[63] IEEE Task Force. IEEE reliability test system. IEEE Trans. Power App. Syst PAS-1979;98(6):2047–54.
[64] Schilling MT, de Souza JCS, Do Coutto Filho MB. Power system probabilistic reliability assessment: current procedures in Brazil. IEEE Trans Power Syst 2008;23 (3):868–76.
[65] Schilling MT, Praca J, De Queiroz J, Singh C, Ascher H. Detection of ageing in the reliability analysis of thermal generators. IEEE Trans Power Syst 1988;3(2):490–9.
[66] da Silva AML, Freire MR, Assis FA, Manso LA. Transmission expansion planning based on relaxed N-1 criteria and reliability indices. In: 2016 international conference on probabilistic methods applied to power systems (PMAPS). IEEE; 2016. p. 1–6.
[67] Rei AM, Schilling MT. Reliability assessment of the Brazilian power system using enumeration and Monte Carlo. IEEE Trans Power Syst 2008;23(3):1480–7.
[68] da Silva AML, Fernández RA, Singh C. Generating capacity reliability evaluation based on Monte Carlo simulation and cross-entropy methods. IEEE Trans Power Syst 2010;25(1):129–37.
[69] Schneider A, Raksany J, Gunderson R, Fong C, Billington R, O'Neill P, Silverstein B. Bulk system reliability-measurement and indices. IEEE Trans Power Syst 1989;4 (3):829–35.
[70] Billinton R, Karki R. Application of Monte Carlo simulation to generating system well-being analysis. IEEE Trans Power Syst 1999;14(3):1172–7.
[71] Singh C, Lago-Gonzalez A. Reliability modeling of generation systems including unconventional energy sources. IEEE Trans Power Apparatus Syst 1985;(5): 1049–56.
[72] renewables ninja. Global solar and wind energy estimator. URL, https://www.renewables.ninja/; 2018.
[73] Billinton R, Gao Y. Multistate wind energy conversion system models for adequacy assessment of generating systems incorporating wind energy. IEEE Trans Energy Convers 2008;23(1):163–70.