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Hybrid power generation for increasing water and energy securities during drought: Exploring local and regional effects in a semi-arid basin

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ABSTRACT

Reservoirs of hydropower plants (HPP) can amend water, energy, and food security in semi-arid regions. However, during severe droughts, the priority of energy demand leads to critical conditions of water availability. To reduce water use for energy, one possible measure is the adoption of solar power, an abundant energy source in semi-arid regions. This study assessed the influence of adding floating photovoltaic power (PV) in the large-scale reservoir of Sobradinho HPP, located in the São Francisco River (SFR), in Brazil, from 2009 to 2018. The simulated scenarios varied the installed PV power capacity from 50 to 1000 MW. For each scenario, water allocation was modified based on the solar-hydro equivalence that restrained the historical outflow of Sobradinho to maintain water in the reservoir. Besides, a diverse operation rule for the reservoirs in cascade of SFR was adopted to avoid ecological impacts of low streamflow. The scenarios were assessed in water security, solar-hydro electricity output, capacity factor of the powerplant, water and energy losses by evaporation and spilled water. Results show that a PV system starting from 250 MW was necessary to improve water security during the severe drought, reserving 0.7–2.3 of the annual water demand. In addition, the capacity factor was optimized from 29% to 34–47%. However, as the HPPs installed at SFR work as one system, the constrain of the river flow reduced the hydroelectricity by 4.4% for 750 MW. We concluded that PV significantly influenced water security and ecological conditions of SFR, with benefits in the range of 250–750 MW. The research provides assessment on substituting hydro for solar power on the operation of reservoirs in cascade and identifies the correlated benefits in social and ecological aspects. This information can support decisions of water and energy supply system operators and public policies focused on integrated resources management in semi-arid regions.

1. Introduction

Reservoirs can provide water security to water-stressed regions (Pereira et al., 2019; Scott et al., 2020). However, for multi-purpose reservoirs, the prioritization for other functions such as hydropower generation may jeopardize water security (Bahri, 2020). Here, the inclusion of a second power source to the existing HPP, turning it into a hybrid powerplant, can help to save water in the reservoirs, making it available for other purposes and providing a solution for developing integrated resources management and rising governance (Hunt et al., 2018; Maués, 2019).

Resource availabilities are driven by environmental characteristics of the site (Link et al., 2016) and the dynamic process of positive and negative feedbacks involving anthropogenic interventions (Van Oel et al., 2014; Van Loon et al., 2016; Garcia et al., 2020) and ecosystem regeneration (Srinivasan et al., 2013). The authors classify natural and anthropogenic factors regarding resource availability, infrastructure, economic dependence, and governance. Biggs et al. (2015) defend security as complementarily driven by: availability of resources in nature, capability to access, dynamics of social power, strength of institutions, and operating governance. Accordingly, the capacity to manage the resources plays an important role to concomitantly protect ecosystems, distribute the resources equitably, and apply them efficiently, making use of advances in research and new technologies.

In semi-arid regions, environmental and anthropogenic factors jointly impose low availability of water resources, vulnerability in the access, and conflicts in the use. In these water-stressed regions where the

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Nomenclature

ANA	National Water Agency
CF	Capacity Factor
FPV	Floating Photovoltaic
HPP	Hydropower Plant
ONS	National Electric System Operator
PAC	Paulo Afonso Complex
PV	Photovoltaic
SFB	São Francisco Basin
SFR	São Francisco River
CBHSF	São Francisco River Basin Committee
SIN	National Interconnected Power System
EV	Effective water storage volume in the reservoir

availability is inherently compromised, the low precipitation and high evaporation rates over periods of severe drought aggravate water scarcity and intensify the competition by its multiple uses (Huang et al., 2019). Here, the population is constantly exposed to vulnerability in human health, economic development, social interactions, and cultural activities. Although reservoirs alleviate the supply condition, the perception of water security may also bring collateral effects due to unawareness on the demand side (Van Oel et al., 2018), leading to a reboot process in supply versus demand. Furthermore, whereas the demand is projected to rise in the next decades (ANA, 2016a), global environmental changes will probably intensify water scarcity in semi-arid areas since drought events are expected to become more frequent and severe (IPCC, 2018), enhancing the drivers of pressure on water cycles, food production, and human settlement (IPCC, 2014). In this context, the appropriate management of the available resources and governance can play an essential role in security of resources use.

In order to address contexts of jeopardized security, vulnerability, and conflicts, Nexus stands as an approach to assess resources availability and their interactions. The concept recognizes water, energy, and food security as intrinsically connected (Hoff, 2011; FAO, 2014) in different spatial and temporal scales (Kurian; Ardakanian, 2013). Studies on Nexus are supposed to capture interrelations, synergies, and trade-offs associated with resources use and their mutual influence (Scott et al., 2015). In resources-competing regions, Nexus can work as an adequate approach in assessing vulnerabilities and ecosystem resilience to address the balance of supply and demand. The analysis of multiple scenarios – for example, in the adoption of technologies, infrastructures, practices, or public policies – enables to estimate the outcomes on resources use and conservation, to qualify the valid solutions, and to identify the adequate conditions to improve security in several scales. Moreover, the Nexus framework proposes the use of a transdisciplinary approach and governance: scientific knowledge and participatory environment in decision making applied to the proposal and implementation of strategic solutions to society and economic sectors (Al-Saidi; Ribbe, 2017; Mannan et al., 2018).

The application of the Nexus concept in semi-arid areas leads to the identification of solar energy as an abundant resource (Solargis, 2020). Actually, large-scale PV plants are preferably installed in arid or semi-arid regions (Crook et al., 2011). Associated to water resource, PV can energetically feed equipment that withdraws, pump or treat water. Properly, PV can replace water to generate electricity. Associated with the existing HPP, PV has the potential to improve the infrastructure or preserve water for the multi-purposes. In the last case, a hybrid solar-hydro powerplant may change the pattern of resources use by reversing the policy of water for energy into energy for water. This allows to meet the demands (water security) and generate renewable electricity to the grid (energy security).

In this study, we analyzed the result of adding floating photovoltaic solar power (FPV) in the Sobradinho HPP, located at the São Francisco River (SFR) in the semi-arid region of Brazil. We selected the years 2009–2018 to evaluate the potential benefits in a critical water shortage period. A range of PV power capacity scenarios was simulated to evaluate the influence on water security and conservancy on local and basin scales, and electricity dispatches to the national electric grid.

Hybrid power plants combining solar and wind sources with hydro present high potential in the Brazilian semi-arid region (Viviescas et al., 2019; Santos et al., 2020). Currently, the potential of solar is highly promising, winning a significant share in auctions for the grid expansion with competitive values (MME, 2018; CCEE, 2020a), and being promoted by CHESF, the Company of hydroelectricity of São Francisco (CHESF, 2020). A floating solar PV system was the technology selected in this study to convert Sobradinho because it responds to relevant issues. Firstly, PV is a renewable source to substitute the use of fossil energy in thermal power plants that feeds the grid during events of water shortages and, consequently, mitigate greenhouse gas emissions. Secondly, the semi-arid portion of the São Francisco basin has high radiation over the entire year, with potential for photovoltaic production higher than 1750 kWh/kWp.year (Pereira et al., 2017). Thirdly, the installation of PV panels in a floating mechanism is a promising solution because the panels can benefit from the cloudiness regime of the lake breeze (Gonçalves et al., 2020), and the cooling effect of water on the local atmosphere and interface with panels (Liu et al., 2017). Alternatively, the complementary optimization of solar-hydro can reduce evaporation from the reservoirs by reserving sufficient water to meet the demand and partially covering the lake, which improves the synergy between the energetic sources.

The novelty of this study stands in providing a sensitivity analysis for a range of PV plants to improve both water and energy securities and discuss the trade-offs on local and regional scales. Previous studies have separately discussed water allocation strategies at São Francisco river (Lima; Abreu, 2016; Brambilla et al., 2017; Basto et al., 2020), the local effects of converting hydro into hybrid power plants (Maués, 2019; Velloso et al., 2019), and the water-energy Nexus for increasing the performance of the Sobradinho HPP (Hunt et al., 2018). Silvério et al. (2018) investigated adding floating PV to the HPPs of SFR focused on the optimized design of the solar plant and the gains for the energy sector in changing water allocation.

This paper is organized as follows: Section 2 shows the description of the methodology and dataset used in the modeling of the reference scenario (RS) and the simulated scenarios (PV), the indicators used to quantify the water and energy outputs to analyze the scenarios. Section 3 provides the results of the proposed indicators. In Section 4, we discussed the results and presented additional analysis regarding the technical solution and the implications in social, environmental, and economical aspects. Section 5 summarizes the main conclusions.

2. Methods

2.1. Assessment framework

The simulation strategy was partially replacing hydro power with solar power to maintain the volume of water stored in the reservoir, the quantity necessary to produce the electricity generated by the PV panels. The floating PV was proposed in a range of 50–1000 MW of installed power. The scenarios were adopted in a wide range to carry out a sensitivity analysis of the proposed solution.

The investigation involved the following steps: 1) to model the study area to reproduce water allocation and power generation of SFR in 1999–2018, designed based on governmental dataset; 2) to quantify the solar-hydro equivalence in power generation for each scenario of installed PV system; 3) to set operative rules for water storage and outflow among the reservoirs; 4) to model the alternative scenarios (based on step 1), modified by the hydro-solar energy equivalence (step 2) and the operative rules (step 3); 5) to quantify the water and energy indicators.

The model was carried out in computer simulations using WEAP software, chosen due to its capacity to quantify the interactions on water allocation and energy generation automatically and compare the results of multiple alternatives derived from a reference scenario, modeled based on the data observed. We validated the model using water and energy outputs for the HPPs, and classified the scenarios using the results for water security, solar-hydro electricity generation, capacity factor of Sobradinho, water and energy losses by evaporation and spilled water.

2.2. Study area

SFB extends for 638,576 km^2 in the Brazilian Northeast (Fig. 1A) (geographical coordinates 7.3°S-20.9°S; 36.3°W-47.6°W), consisting of an appropriate site for solar powerplants (Fig. 1B), with potential for photovoltaic production of >1750 kWh/kWp.year (Pereira et al., 2017).

Administratively organized in 4 sub-basins (Fig. 1C): Upper (16% of the area), Middle (63%), Lower-Middle (17%), and Lower (4%), more than half of the basin is inserted in a semi-arid area (CBHSF, 2016).

Water scarcity is predominant in the region. The climatology along the basin varied extensively from 1961 to 2018, with accentuated variability in annual precipitation at the sub-basins: 543–2134 mm at Upper sub-basin, 603–1393 mm at Middle, 587–1306 mm at Lower-Middle and 221–1068 mm at Lower sub-basins (FUNCEME. Fundação Cearense de Meteorologia e Recursos Hídricos,). The wet season in SFB is reported from December to April. The evaporation rate in the semi-arid portion is intense: varies between 1000–2000 mm/year (Maneta et al., 2009). The precipitation at Upper and Middle sub-basins charges the surface water of the SF riverbed and the existing reservoirs, which provides water locally and downstream (EMBRAPA).

The population of 14.3 million (2010) lives in 505 municipalities (CBHSF, 2016), distinguished by the dependence on the river (Maneta et al., 2009; CBHSF, 2016). The vulnerability in the water access causes conflicts that have been gradually intensified by the growth in demand (ANA, 2016a), control of the river flow imposed by the HPP operators (ANA, 2018a), and frequent events of drought (Marengo et al., 2017a,b).

Five HPP connected to the national electric grid take advantage of the river's intense streamflow. Three HPP contain large reservoirs (Fig. 1D): Três Marias (storage capacity: 19.5 Gm^3), Sobradinho (34 Gm^3), and Itaparica (10.7 Gm^3), which jointly represent ~15% of the water storage capacity of the national electric grid (ANA, 2017a). The other two HPP – PAC and Xingó – work as run-of-river (ANA, 2020a), being influenced by the operating rules of the reservoir's system. Accordingly, reservoirs were installed to provide two types of benefits on different scales: (1) access to water during dry seasons at local and regional levels and (2) control of electricity production at regional and country levels.

After the installation of the HPP, the streamflow of the São Francisco river started to be intensively controlled by the SIN operators, leading to negative impacts on the natural environment (Correia et al., 2006; Bezerra et al., 2019; Cavalcante et al., 2020). Induced by its water storage capacity, several public irrigation districts were installed nearby and downstream Sobradinho (Codevasf, 2017). Nowadays, Sobradinho supports an important regional economy, including a large-scale fruit culture (Carvalho et al., 2020; CEPEA/ESALQ, 2020) that traded US$ 480 million[1] in 2018 (IBGE, 2019) with national and international markets (MAPA, 2018). The region is classified by the National Water Agency (ANA) as a special area for water resource management due to the intense demand and economic relevance (ANA, 2017b).

In 2010, water demand at SFB accounted for 279 m^3/s, shared by irrigation (77%), human consumption (12%), industry (7%) and animal consumption (4%) (CBHSF, 2016). The irrigation share is higher at the sub-basin under semi-arid conditions: 87% at Middle (90 m^3/s) and 93% at Lower-Middle sub-basins (96 m^3/s) (CBHSF, 2016). To manage the demand, in 2004, the basin committee set 360 m^3/s as the limit for total withdrawal (CBHSF, 2004). However, the demand projections for 2025 are estimated in 246–424 m^3/s at Middle and 100–225 m^3/s at Lower-Middle sub-basins (CBHSF, 2016), which denotes the urgency in managing water resources on both supply and demand side.

2.3. Influence of the severe drought on water and energy resources

In the 2010s, a prolonged and severe drought affected the Brazilian Northeast (Alvalá et al., 2017; Marengo et al., 2017a,b; Marengo; Torres; Alves, 2017). The annual average precipitation of 653 Gm^3 in 1961–2008 was reduced to 575 Gm^3 in 2009–2018, reaching less than 450 Gm^3 in four years (2012, 2014, 2015, and 2017) (FUNCEME. Fundação Cearense de Meteorologia e Recursos Hídricos,), the worst drought in 50 years (SI–F1). Consequently, SF streamflow was intensively reduced. The average inflow at Sobradinho reservoir registered <1100 m^3/s in 2014–2018 (ANA, 2019a), decreasing to 661 m^3/s in 2017. In the dry season of 2017, the inflow varied 306–484 m^3/s (ANA, 2019a), or ~20–30% of the long-term average (ONS, 2019a).

In 2013, the National Water Agency (ANA) created a governance committee composed of regulatory, technical, and environmental bodies to periodically assess the precipitation projections, evaluate the basin conditions and set the minimum outflow of the reservoirs (ANA, 2018b). Before the recent severe drought, the restriction for Sobradinho outflow was 1300 m^3/s, with a minimum intended of 1.100 m^3/s, to be authorized by ANA in critical climate conditions (ONS, 2011). During the drought, the governance committee gradually decreased the minimum operative outflow at Sobradinho and Xingó to 1100 m^3/s in 2013 (ANA, 2013), 900 m^3/s in 2015 (ANA, 2015), 700 m^3/s in 2016 (ANA, 2016b), and 550 m^3/s in 2017 (ANA, 2017c). In December 2017, the committee also interfered in the demand side by prohibiting irrigation and water withdrawal once a week (River Day), except for human and animal consumption (ANA, 2017d).

At this period, water availability, power generation, and fruit production were significantly affected. The lack of rainfall and the late response of decision-makers – confronted by this unprecedented drought – substantially reduced water availability (ONS, 2019a). Every dry season in 2014–2017, the effective storage at Sobradinho declined below 20% of the capacity, reaching less than 2% in December 2015 and November 2017; Três Marias and Itaparica reached less than 6% and 12%, respectively (ONS, 2019a).

On the energy side, hydroelectricity generation was drastically reduced according to the outflow constraint and high withdrawal volume for irrigation. Sobradinho output (SI–F2) declined from 5.11 TWh in 2007 to 1.16 TWh in 2017 (ONS, 2019a), dropping the capacity factor from 0.40 in 1999–2008 to 0.29 in 2009–2018, attaining 0.17 in 2014–2018. This expresses the low utilization of the installed infrastructure. Considering the five HPP of SFR, the generation declined from 56.5 TWh in 2007 to 14.9 TWh in 2017 (ONS, 2019a), reducing the participation to SIN from 11.7 to 2.5% (MME/EPE, 2018). The shortage of electricity from SFR negatively had an impact on the national scale because hydropower attributes a high share in Brazil (74% of public utility power plants in 2018), making SIN susceptible to climate conditions (ONS, 2019b).

Similarly, fruit culture was hindered by the water shortages in reservoirs when irrigation must compensate for the low precipitation. The largest fruit producer, Senador Nilo Coelho irrigation district (DINC), directly withdraws water from the Sobradinho reservoir to irrigate 23,486 ha. DINC demanded 78% more water in 2017 (394 Mm^3) than in 2011 (221 Mm^3), a regular meteorological year (DINC, 2019). At this time, the fruit production at the Petrolina municipality, where DINC is located, increased the production from 0.7 Mt on 2005–2015 average to 1.0 Mt in 2017, and 1.28 Mt in 2018 (IBGE, 2019). In comparison, the Juazeiro municipality, which is contingent on rainfall and water access

[1] 1 US$ = R$ 5.35 (02/02/2021).

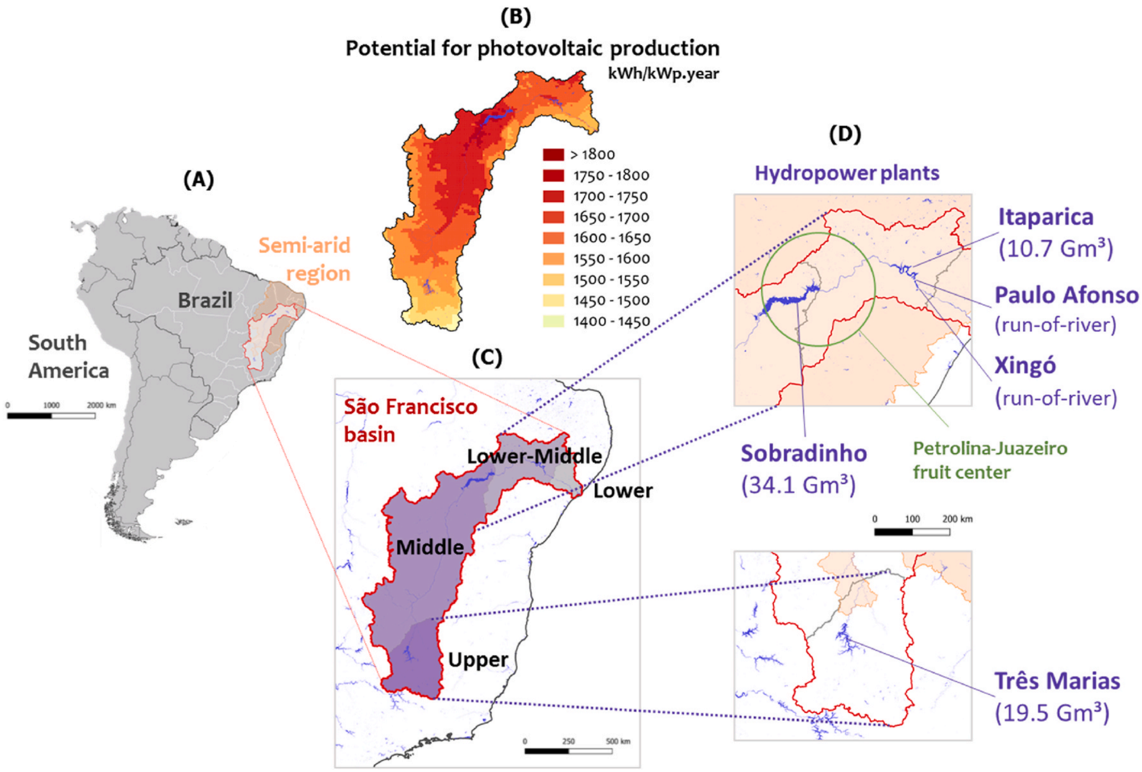

Fig. 1. São Francisco Basin: (A) location; (B) potential for solar photovoltaic production; (C) distribution in four sub-basins; (D) location and volume of the three HPP with reservoir. Source: (CBHSF, 2016; ANA, 2017a; Pereira et al., 2017).

from the SFR (harmed by the river level), increased the production over wet years, reaching 0.79 Mt in 2007, but declining to 0.36 Mt (46%) in 2015 (IBGE, 2019). Indeed, the opposite results for Petrolina and Juazeiro municipalities can be jointly explained by several factors that reflect productivity: size of properties, type of cultures, irrigation method, and technological improvements. However, in this period, such an immediate difference in trends possibly can express the role of the reservoirs (SI–F3). Although the water demand by fruit culture was not significant compared to Sobradinho's capacity, the crops were only dependent on irrigation. This context enhances the role of adopting a Water-Energy-Food Nexus perspective and the necessity of managing water for dependent activities instead of prioritizing its use to generate electricity. In this region, governance revealed determinant to guarantee water access and balance in use by the multi-purposes.

2.4. Proposal of scenarios

2.4.1. Solar power and water-solar equivalence

To assess the solar power's influence on the allocation of water in the São Francisco river over the severe drought period, we investigated scenarios varying the installed PV at 50, 100, 250, 500, 750, and 1000 MW. Instead of developing an engineering solution with one response for the photovoltaic plant, we defined a wide range of solar power scenarios to carry out a sensitivity analysis of the Nexus Water-Energy. The technological solution was the floating PV, although the electricity output was quantified for a ground-mounted system, using characteristics of the polycrystalline silicon cell modules with panel efficiency of 0.2 currently available in the market (NREL). We selected the Sobradinho reservoir to install the PV system considering several factors: the relevance of this reservoir for population and economic activities on local and regional scales; the large area and storage capacity, which enhances the associated benefits of conserving water; the underused connection to the grid (ONS, 2019a); and the existence of a pilot 1 MWp floating PV already operating at Sobradinho (Planalto, 2019a) as part of the Petrolina Solar Energy Reference Center (CHESF, 2018a).

Solar photovoltaic energy is variable, as it depends on the incoming solar radiation at the PV modules, which, in turn, critically depends on the local cloudiness, incidence angle, surface albedo, and operating temperature of the PV modules. The solar electricity output was estimated from the solar irradiation data acquired at the BSRN[2] meteorological station, an observational ground-measured data, operating at the Petrolina municipality (~70 km from Sobradinho), managed by the SONDA project (Pereira et al., 2017; INPE, 2020). The 30-min global horizontal irradiation (GHI) dataset was converted into monthly averages, resulting in 110–216 kWh/m^2 for 2009–2018 (SI–F4). Data gaps were filled by the average of the specific month. To convert the solar irradiation into a potential power generation, we used Equation (1) from Lorenzo (2002) for photovoltaic systems connected to the grid:

$$E_{AC} = P * (G_{daeff}/G) * FS * PR \quad (1)$$

where E_{AC} is the electricity produced by the PV system (kWh/month); P is the nominal power of the PV modules (kWp); G_{daeff} is the global irradiation that reaches the panel surfaces at the latitude tilted angle (kWh/m.[2] month); G is the irradiance that determines the nominal power of the modules under standard test conditions (STC), usually 1 kW/m^2 at 25 °C; FS is the factor of shading losses due to obstacles (0 for permanently in shadow, and 1 for permanently under light); and PR is the performance ratio of the PV system, considering optical, thermal, and electrical losses.

In this study, E_{AC} was quantified in monthly time-step. P assumed the solar power intensity ranging between 50 and 1,000 MW. The monthly average of the solar irradiation observed at the Petrolina station was used for G_{daeff}. For performance ratio (PR), we adopted the 0.8 based on former studies (Lima et al., 2017). We assumed complete unshaded

[2] *World Radiation Monitoring Center (WRMC)/Baseline Surface Radiation Network* (*BSRN* https://bsrn.awi.de).

conditions since the system configuration is for PV panels floating in the reservoir and, therefore, clear of obstacles ($FS = 1$). The potential E_{AC} was estimated in the range 88–173 Wh/Wp.

For hydropower simulation, water allocation varied in correlation with the PV installed power capacity. We associated the hydroelectricity output with the turbinated outflow (ONS, 2019a) to estimate the saved flow by the PV operation. In each PV scenario, the outflow required to generate the same quantity of electricity produced by PV was deducted from the historical dataset of Sobradinho (ONS, 2019a), conserving more water in the reservoir. The Sobradinho HPP produced 0.051–0.074 kWh/m^3 (average: 0.0614 kWh/m^3) in 1999–2018. For the solar-hydro equivalence, we adopted the average value. Table 1 shows for each scenario of PV power capacity the equivalent water volume and saved flow, which varied in 45–904 m^3/s.

2.4.2. Operative rules for the reservoirs

To make the study adherent to the operating rules under drought conditions, we followed the National Water Agency Resolution 2081/2017 (ANA, 2017e). To avoid future events of reservoir depletion, ANA established three operational stages related to the effective storage volume (EV) of Três Marias and Sobradinho, defining minimum operating outflow for Três Marias, Sobradinho, and Xingó (SI-T1). Based on the historical operation and ANA's resolution, we set the following rules:

- Três Marias: minimum outflow 150 m^3/s;
- Sobradinho and Xingó:
  - o Regular stage (EV>60%): historical outflow dataset (ONS, 2019a);
  - o Alert stage (20% < EV<60%) and Restriction stage (EV<20%): historical outflow dataset reduced by the saved outflow; with minimum operating outflow of 800 m^3/s.

An exception to the ANA's resolution refers to the minimum operating outflow of 700 m^3/s for Restriction stage. We adopted the same parameter of the Alert stage since we were trying to avoid low water outflows. The saved water flow rule was not applied to the Regular stage for two reasons: low outflows would not be realistic in high levels of water storage because it creates the risk of flood and waste of potential electricity when high outflows occur after filling the reservoir. At the Alert stage, the outflow equivalent to generating the electricity added by the PV panels was deducted from the historical dataset respecting the limit of 800 m^3/s (SI–F5). It is important to mention that Restriction stage rules were applied in the model as the minimum operating outflow, which means that the simulation assumed higher values when water was available in the system. For Três Marias, we just set the minimum outflow of 150 m^3/s, which enabled the allocation of water under the priorities established for the model.

Table 1
Six scenarios with varying levels of installed power of floating photovoltaic panels, estimates of annual electricity from solar source, and the equivalent volume and outflow of water.

Scenario	PV Installed power MW	Potential annual solar electricity MWh	Equivalence to hydropower[a]	
			Water volume 10^6 m^3	Saved flow (EqOut) m^3/s
PV-50	50	87,600	1426	45
PV-100	100	175,200	2851	90
PV-250	250	438,000	7129	226
PV-500	500	876,000	14,257	452
PV-750	750	1,314,000	21,386	678
PV-1000	1000	1,752,000	28,515	904

[a] Hydropower productivity at Sobradinho = 0.0614 kWh/m^3.

2.5. Assessment of the scenarios

The scenarios were analyzed in three contexts: water security, water conservancy, and electricity generation. Indicators were quantified regarding water (2 indicators), energy (3), water-food (1), and water-energy (3) related to the different components of the SFR system, as described in Table 2. The scenarios were considered valid by avoiding water shortage: meeting the demand, conserving water above the minimum operating volume of the reservoirs, and sustaining the minimum outflow at Sobradinho and Xingó. The food Nexus was embedded in water security and, therefore, mandatory for the scenario validation. After the validation, indicators were quantified and compared to the reference scenario of 2009–2018.

2.6. Water and energy system modeling

The São Francisco basin water system was modeled using the Water Evaluation and Planning (WEAP) software (Sei, 2015). This integrated platform based on semi-distributed hydrological modeling can incorporate interconnected components such as rivers, reservoirs, HPPs, crops, and multiple demands. Model configuration can include rules for water allocation among different uses such as agriculture and hydroelectricity (Yates et al., 2005).

The program provided the download of GIS information on the geographic position, basin limits, and the course of the main rivers (SI–F6). Hereafter, the elements that made up the model were manually inserted: three HPP with reservoir (Três Marias, Sobradinho, and Itaparica); two run-of-river HPP (PAC and Xingó); the water withdrawals (demand) from the river and reservoirs, and the nodes. Nodes are elements offered by WEAP to input water (reaches) and simulate the streamflow (minimum flow requirements). The operation of SFR was designed for the period 1999–2018; and the proposed scenarios were simulated for 2009–2018.

Water allocation and energy generation were designed to reproduce the dataset of the Brazilian governmental agencies ANA and ONS (Brazil's National Grid Operator). We informed data on the physical features of the HPPs and water inputs and outputs from the river and the reservoirs in the study period. The water in the riverbed and the reservoirs fed by the river consists of the available water under management. We did not take into account groundwater because surface water accounts for 90% of the demand (CBHSF, 2016). Fig. 2 illustrates the components of the SFR system and the water flow of inputs and outputs of the water balance with the width of the arrows/flows corresponding to their relative volumes; values in brackets account for the volume in billion cubic meters for the average 2009–2018.

Water was allocated using node components and priority between the model components. Four nodes were created to apply the historical dataset and limit the minimum outflow at Três Marias, Sobradinho, and Xingó, located just downstream the HPPs (ONS, 2019a), and at the river mouth, using the dataset of Traipu gauge (ANA, 2019b). The priority to deliver water followed the sequence: 1) water demand, 2) minimum flow requirement, 3) storage at Três Marias, Sobradinho, and Itaparica reservoir.

2.6.1. Hydropower plants and reservoirs

HPPs were modeled using fixed characteristics of the reservoir and operational data (SI-T2): total storage capacity, minimum operational volume (ANA, 2020a), maximum turbinated outflow, powerplant efficiency (CHESF, 2018b), reservoir inflow and outflow (m^3/s), turbinated outflow (m^3/s), effective storage volume (%), water level (m), the water storage on January 01, 1999 (ONS, 2019a), and electricity generated (GWh) (ANA, 2019a; ONS, 2019a). To quantify hydroelectricity, WEAP combines these inputs of water allocation and physical information of the reservoirs. In practice, the number of turbines effectively working are defined by the operators based on the streamflow and the maintenance scheme (ONS, 2019c), whose information was not available.

Table 2
Assessment of the scenarios.

Indicator	Description	Nexus	Influence	Component	Unit
1: Water security	Relation of the minimum water volume to the yearly demand	Water, Water-Food	Water storage	Sobradinho	Ratio of the yearly demand
2: Solar electricity	PV electricity generated	Energy	Solar radiation	Sobradinho	GWh/month
3: Hydro electricity	Hydro electricity generated	Water-Energy	River flow	Sobradinho SFR HPP	GWh/month GWh/year
4: Capacity factor of Sobradinho	Capacity factor of the Sobradinho hybrid power plant	Energy	River flow and PV scale	Sobradinho	%
5: Electricity output	Total electricity generated	Energy	Solar radiation and river flow	Sobradinho SFR HPP	GWh/month GWh/year
6: Water loss by evaporation	Water volume lost by evaporation from the reservoirs	Water	Water storage	Sobradinho Reservoirs	m^3/year
7: Energy loss by evaporation	Hydroelectricity not generated due to water losses by evaporation from the reservoirs	Water-Energy	River flow	Sobradinho SFR HPP	GWh/month
8: Energy loss by spilled water	Energy lost by outflow higher than the maximum turbinated outflow of the HPP	Water-Energy	River flow	Sobradinho and HPP downstream	Total GWh 2009–2018

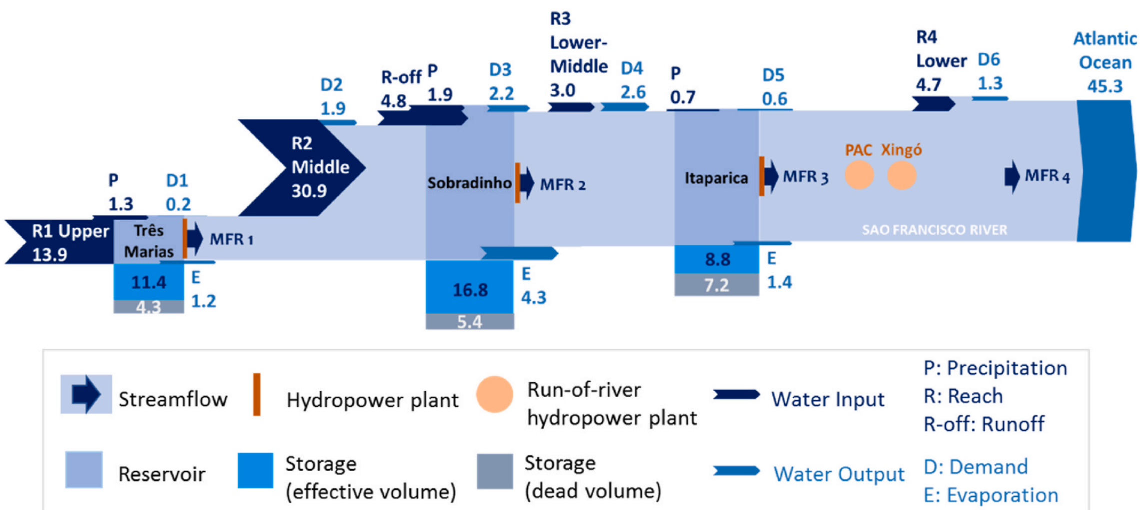

Fig. 2. Water flow in the components of the San Francisco River model [Gm^3 for average 2009–2018].

Therefore, we adjusted the number of turbines in operation and the tailwater elevation using the reference of hydroelectricity output.

Sobradinho has an installed capacity of 1,05 GW (CHESF, 2018b) and results in the maximum potential output of 9200 GWh/year, or 767 GWh/month, on average. The existing transmission line capacity limited the dispatches of solar and hydroelectricity to the SIN.

Although the run-of-river HPPs do not significantly influence the river flow (Silvério et al., 2018), water allocation influences their outcomes. For this reason, the run-of-river HPPs were included to evaluate the overall impact of the scenarios on the total electricity generated from SFR. Input data was maximum turbine flow and energy efficiency, respectively, 2,310 m^3/s and 95% at PAC, and 3,000 m^3/s and 92% at Xingó (CHESF, 2018a,b). Turbines in operation and tailwater elevation were used to adjust the model. Although we recognize that residual storage may occur upstream of the turbines of run-of-river HPP, we could not access information to consider its effect in the model.

2.6.2. *Water input*

2.6.2.1. Incremental streamflow. Incremental streamflow expresses the variation of the streamflow between two locations as a result of water inputs and outputs along the river: direct precipitation, runoff, contributing watercourses, withdrawals, evaporation, and transfers with underground water. For the reaches R1-R4[3] (see Fig. 2), the incremental streamflow was quantified using the inflow and outflow of the three reservoirs (ANA, 2019b; ONS, 2019a) and streamflow of Traipu gauge (ANA, 2019b). Traipu gauge was selected among the gauges located near the river wedge due to its more complete dataset. We assumed for R1, R2, R3, and R4, respectively, the dataset of Três Marias inflow, the variation from Três Marias outflow to Sobradinho inflow, Sobradinho outflow to Itaparica inflow, and Itaparica outflow to Traipu streamflow. Water inputs at R1 and R2 influence more the streamflow than R3 and R4 because the precipitation rate and area are both higher at the sub-basin associated with R1 (Upper) and R2 (Middle). Water inputs were quantified in cubic meters per second (m^3/s) and uploaded in monthly timestep using the “read from file” tool of WEAP.

2.6.2.2. Precipitation in the reservoirs. The precipitation in the reservoirs was quantified by multiplying the monthly precipitation rate of the correspondent sub-basins (FUNCEME. Fundação Cearense de Meteorologia e Recursos Hídricos,) by the lake area (ANA, 2020a). Upper, Middle, and Lower-Middle precipitation rates were adopted for Três Marias, Sobradinho, and Itaparica, respectively. The maximum flooded area was admitted for Três Marias (1040 km^2) and Itaparica (828 km^2). For Sobradinho (SI–F7), we estimated the area from the volume of water in the reservoir using data from (Azevedo et al., 2018).

[3] R1, 2, 3, and 4 stand for regions of SFB, as shown in the schematic of Fig. 2.

2.6.2.3. Runoff at the sobradinho reservoir. We quantified the runoff into Sobradinho from the area between the inflow (Morpará and Boqueirão gauges) and the outflow measurements location (~350 km). We estimated the contributing area of both sides of the SF river (Sigeo, 2018) and multiplied it by the Middle monthly precipitation rate (FUNCEME. Fundação Cearense de Meteorologia e Recursos Hídricos,) and the runoff coefficient of 8% (MMA, 2006).

2.6.3. Water output

2.6.3.1. Demand. The demand included withdrawals from the reservoirs and SFR. We adopted data on ANA's authorizations of water withdrawal from federal watercourses. The authorizations can be interpreted as the government's commitment to deliver a certain volume of water to the users, which can be associated with water security. Database for the water grant is available in GIS format (ANA, 2020b), and includes information on localization, user, volume, data of emission, and validity of the authorization. The dataset was classified by location (latitude and longitude) and the active period, regarding date of emission and validity. We grouped the annual authorized volume for Três Marias (D1 – see Fig. 2), Sobradinho (D3), Itaparica (D5), and the river downstream of each reservoir (D2, D4, D6). Some adjustments were made regarding the first years of the simulation (SI–F8–F9). An additional demand was ascribed: the East Transposition of the SF river to the neighboring basin of the Paraíba do Norte river (ANA, 2020c), which confers to the basin an additional driver for water scarcity. To simulate the seasonality of the demand in dry and wet months (SI–F10), we adopted the monthly estimates provided by CBHSF for each sub-basin (CBHSF, 2016), except for DINC and irrigation from Sobradinho reservoir, for which we applied the variation in monthly withdrawal informed by DINC (2019).

2.6.3.2. Evaporation. WEAP simulates monthly evaporation losses from the reservoirs as a function of the lake area and the evaporation rate (SI–F11). The lake area was quantified by the software using the volume-elevation curve (ONS, 2019a). For the evaporation rate, we adopted the monthly estimation provided by FUNCEME. Fundação Cearense de Meteorologia e Recursos Hídricos, for Três Marias, Sobradinho, and Itaparica, 42, 147, and 41 m^3/s, respectively, on average, for 1999–2018.

2.6.4. Model validation

We used three criteria to verify the correlation of the reference scenario (RS) and the observed data in monthly timestep of 1999–2018: 1) water storage at the three reservoirs, 2) streamflow, 3) electricity generation from the HPPs. The model validation classified the responses as very good, except for storage at Itaparica and outflow of Três Marias, which was considered fair. The hydroelectricity output revealed an adequate level of accuracy, appropriate to simulate the investigating scenarios. More details are provided in the Supplementary Information (SI–F12-14).

3. Results

The simulated scenarios were analyzed in terms of water allocation and energy output under the solar power adding and operative rules set to the reservoirs in cascade. We classified as valid the scenarios that met the water demand, maintained the water storage above the minimum operational level, and sustained the river flow above 800 m^3/s. Next, we quantified indicators of the valid scenarios for local and regional scale: for Sobradinho – water security, electricity generated by solar and hydropower, capacity factor as hybrid powerplant – and for Sobradinho and the SFR system – hydro and total electricity output, water and energy losses.

3.1. Effect of solar power generation on water conditions

The simulated scenarios of solar power positively impacted the water availability at the Sobradinho HPP during the years of severe drought. The volume of water kept in the reservoir by the constraint to outflow increased water security for Scenarios PV-250, PV-500, PV-750, and PV-1000 (Fig. 3A). For Scenarios PV-50 and PV-100, the reservoir volume dropped to zero and, therefore, these scenarios were classified as invalid. Water storage for the valid scenarios was maintained at EV>20% for the entire period, except for PV-250, which crossed this level for four consecutive months (September–December) during the dry season of 2017. Scenarios PV-750 and PV-1000 presented the same water storage volume after 2014 due to climatic conditions when the lack of precipitation limited the influence of adding solar power. After several years of severe drought, the available water proved to be insufficient to maintain the minimum streamflow of the SFR and conserve high levels of water in the reservoirs. When the lack of precipitation went critical, the stored water was applied to sustain the outflow above 800 m^3/s, reducing the reservoirs' water level. Water storage was not completely recovered after 2014 and fluctuated by 40–70% in 2017–2018.

Although the operating rules were supposed to constraint the outflow depending on the PV installed power, Sobradinho predominantly assumed an outflow close to the minimum, starting in June 2015 for PV-250, November 2013 for PV-500, and March 2013 for PV-750-1000, as shown in Fig. 3B. The wet season of 2009, 2011, and 2012 achieved the maximum water storage requiring the release of the exceeding volume. All scenarios assumed similar outflow from July 2015 until the end of the simulation period, operating close to the minimum, with episodical increases to water allocation events between the reservoirs.

3.2. Water security

Water security was improved for the scenarios PV-250-1000 during the study period. Over the driest season in 2017, the lowest storage volume at Sobradinho corresponded to the annual water demand of the reservoir (D3 – see Fig. 2B) and the river between Sobradinho and Itaparica (D4) by 0.7, 1.7, and 2.3 years, respectively, for PV-250, PV-500, and PV-750-1000 (Fig. 4). Scenario PV-750 presented the best performance concerning water security because the volume of stored water resulted similarly in Scenario PV-1000 due to the lack of water to both maintain the streamflow and reserve more water, as explained in the previous section.

3.3. Solar electricity

If we now turn to solar power generation, for each 250 MW of PV installed at Sobradinho, we estimated the monthly production by 22–43 GWh (average: 34 GWh), with ranges of 384–433 GWh/year. The Scenarios PV-250 to PV-1000 generated annually from 404 to 1615 GWh, on average, as illustrated in Fig. 5. Despite a monthly seasonality, PV annual generation stood constant along the study period. PV powerplant was able to surpass the quantity of electricity provided by Sobradinho HPP during the critical dry months of 2017 in the Scenario PV-500 and from August 2015 to December 2018 in the PV-1000.

3.4. Hydroelectricity

The hydroelectricity in the simulated scenarios ranged between 110 and 503 GWh in PV-250 and 128–665 GWh in the PV-1000, while the historical dataset registered 76–479 GWh/month dispatched to the national grid (ONS, 2019a). The scenarios resulted similarly on the average of 228 GWh/month. Fig. 5 shows the monthly hydroelectricity produced in the Scenarios PV-250 (Fig. 5A), PV-500 (Fig. 5B), PV-750 (Fig. 5C), and PV-1000 (Fig. 5D).

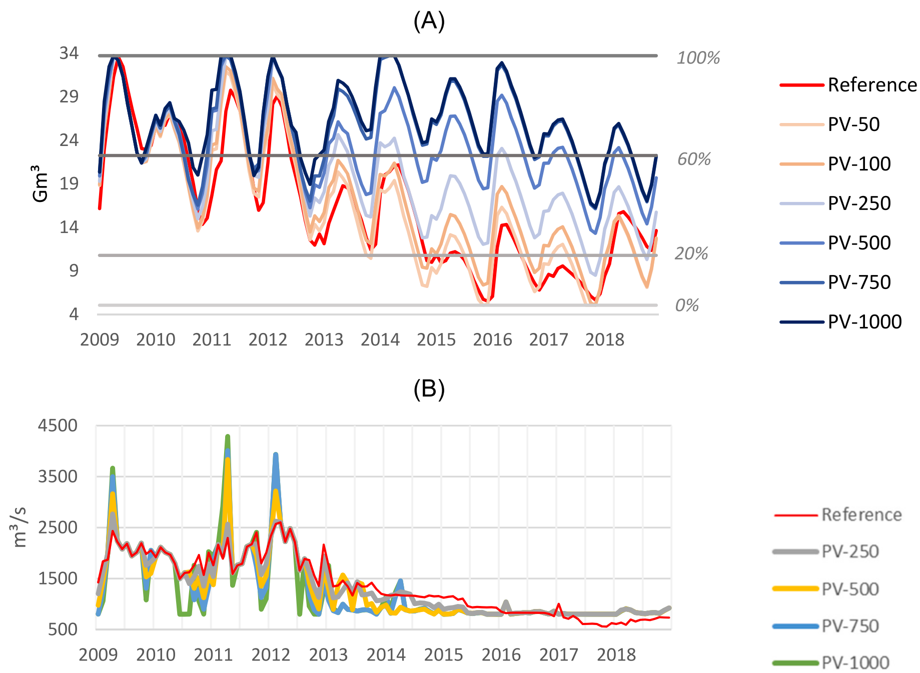

Fig. 3. Sobradinho conditions in simulation: (A) water storage for PV ranging from 50 to 1000 MW. The valid scenarios are shown in blue line, invalid scenarios (discarded) are in orange line, and reference scenario is in red line; (B) outflow for valid scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

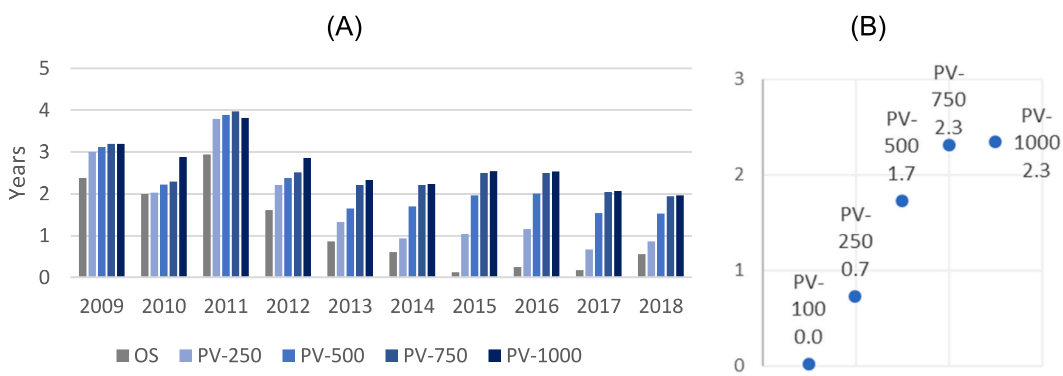

Fig. 4. (A) Time length (in years) of the water storage in Sobradinho to meet the demand of water withdrawal from the reservoir (D3) and between the Sobradinho and Itaparica (D4); (B) results for 2017.

The hydroelectricity output presented trade-offs in the short (seasonal) and long term (interannual). In the Scenario PV-1000, the outflow was lower in most of the months, with hydroelectricity generation peaks in wet months. The total annual generation at the Sobradinho HPP had similar results among the scenarios, around 3.1–4.4 TWh in 2009–2012, and diminished to 1.7–2.4 TWh in 2013–2018 (Fig. 6). Compared to OS, an interannual compensation occurred, as water reserved in the first period was used in the second, increasing the energy dispatch. This trade-off could have meant a significant increment of renewable source share over the critical years of 2015–2018.

3.5. Capacity factor of sobradinho

The capacity factor of Sobradinho increased from 0.29 in the historical time-series 2009–2018 to 0.34 in PV-250, 0.39 in PV-500, 0.43 in PV-750, and 0.47 in PV-1000, optimizing the existing infrastructure to transport electricity to the grid. In either scenario, there is no need for energy curtailment during the period of study.

3.6. Total electricity output from sobradinho and SFR system

Hybrid Sobradinho, which combines solar and hydropower, dispatched more electricity to the SIN in all scenarios compared to the historical time-series, on average: 3.14 (117%), 3.55 (133%), 3.95 (148%), and 4.35 TWh (163%), respectively, for PV-250, PV-500, PV-750, and PV-1000 (Fig. 7A). Analyzing the Sobradinho infrastructure's restrain, the hourly GHI peak was registered at 1124 W/m^2 on February 07, 2011 at 3 p.m. (INPE, 2020). Using Equation (1), solar generation resulted in 225 and 899 MWh for PV-250 and PV-1000 respectively, or the equivalent to 21 and 86% of the Sobradinho total capacity of electricity dispatch. Therefore, the highest hourly PV power generation would not have led to energy losses in the hybrid power plant. The integration of PV and hydropower generation in Sobradinho would dispatch solar power predominantly during the day and the reservoir's outflow during the night. Accordingly, the integrated operation can bring additional gains in renewable energy resource management.

Although electricity output increased at Sobradinho, PV was insufficient to compensate for the reduction of total power generation when

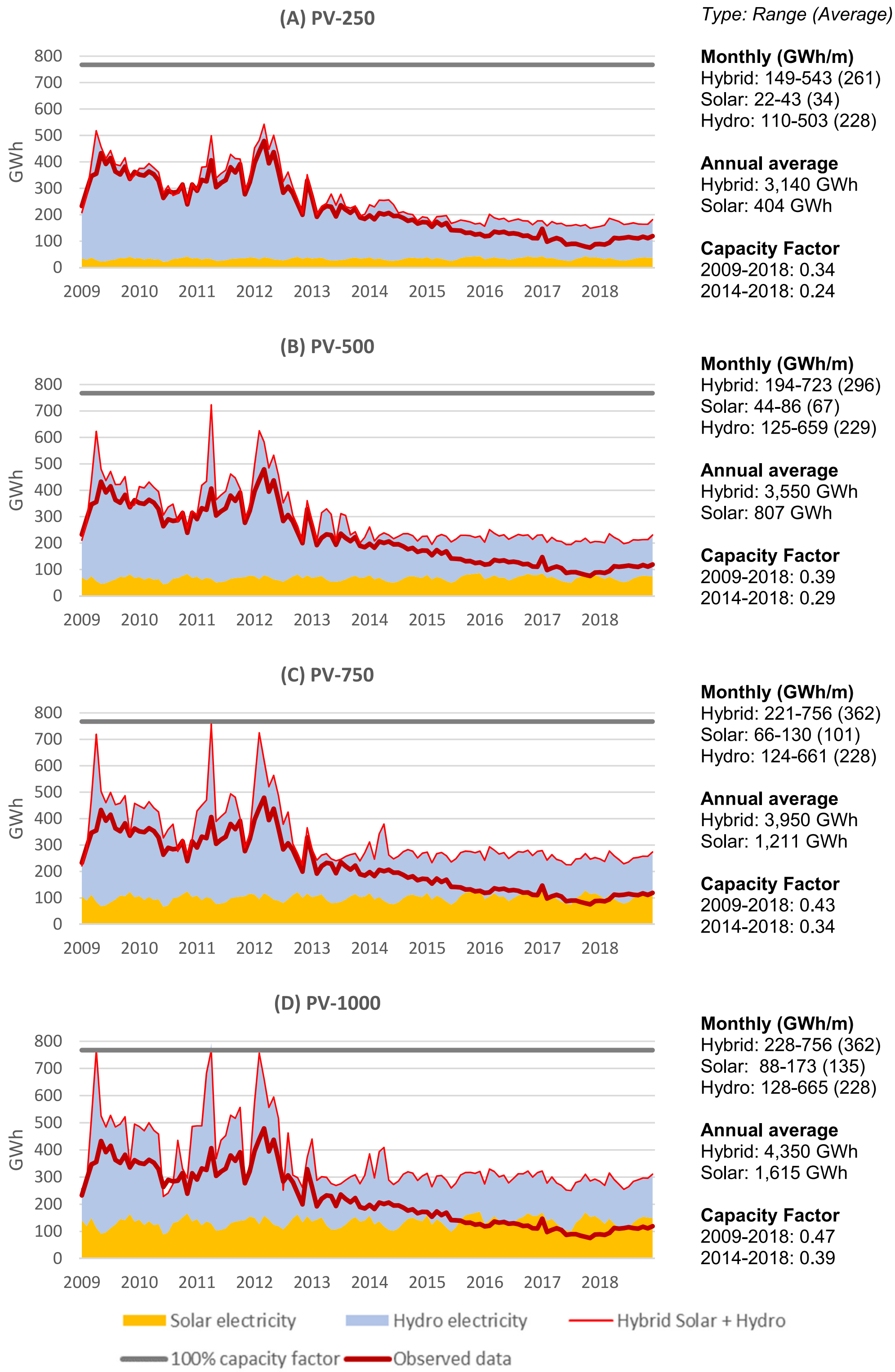

Fig. 5. Scenarios of monthly electricity generation from the Sobradinho hybrid power plant from 2009 to 2018 compared to the historical time-series (red bold line): (A) PV-250, (B) PV-500, (C) PV-750, and (D) PV-1000. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

considering all HPPs in cascade at SFR. Scenario PV-250 would maintain the total electricity outputs, but Scenario PV-750 would diminish it to 95.6%, as illustrated in Fig. 7B. In effect, the results showed that the hydroelectricity output is inversely proportional to the PV addition: the hydropower generation was reduced from 33.0 TWh in the historical dataset to 32.6 in PV-250 (99%), 31.2 in PV-500 (95%), 30.4 in PV-750 (92%), and 30.1 TWh in PV-1000 (91%). Two factors contribute to that: first, more water losses by evaporation occur as more water is stored in reservoirs; second, larger river flows can induce water release without generating hydroelectricity (spilled water).

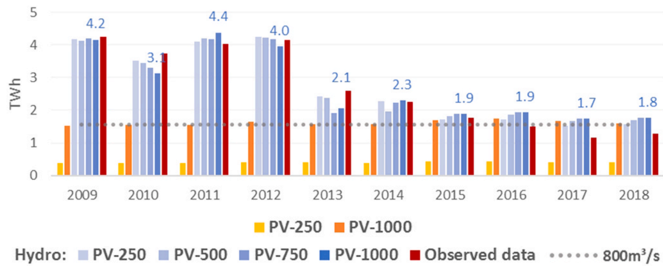

Fig. 6. Annual electricity generation for PV scenarios in Sobradinho: PV-250 (yellow), PV-1000 (orange), hydroelectricity outputs of the simulated scenarios (blue), the observed data from ONS (red), and the equivalent generation for HPP outflow of 800 m^3/s. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.7. Water loss by evaporation from the reservoirs

Evaporation is a collateral effect of reserving water, especially in areas with high rates of water deficit. Compared to the reference scenario, all PV scenarios retained additional water in the reservoirs, expanding the lake's surface area and, consequently, increasing water losses by evaporation. As we considered PV-250 the minimum scenario that provides water security, incremental evaporation was quantified comparing the results relative to PV-250 instead of the reference scenario. Considering the evaporation from Três Marias, Sobradinho, and Itaparica, on average, 7.6 Gm^3/year evaporated in PV-250. Scenarios PV-500, PV-750, and PV-1000, respectively, resulted in the total evaporation of 8.3, 8.8, and 8.9 Gm^3/y, resulting in incremental evaporation relative to PV-250 by 0.7, 1.2, and 1.3 Gm^3. Around 80% of the water losses by evaporation occurred for Sobradinho reservoir, 0.59–1.09 Gm^3/y, due to the lake's geometry and the largest increase in water storage compared to the other reservoirs.

3.8. Energy loss by evaporation from the reservoirs

We assumed the incremental evaporation as a loss of potential hydroelectricity. From that perspective, as more solar was added, the increase in water storage resulted in more evaporation. At Sobradinho, with HPP productivity of 0.062 kWh/m^3, the evaporated water could generate the equivalent of 37–68 GWh/year. Considering the HPP in cascade, for each cubic meter released from Sobradinho, this HPP and the ones downstream produce, on average, 0.73 kWh/m^3. Hence, the water lost by incremental evaporation at Sobradinho could generate the equivalent of 430–800 GWh/year, respectively, for PV-500-1000. This estimative offset 50–60% of the PV output of the scenarios.

3.9. Energy loss by spilled water

Spilled water occurs once the outflow is higher than the maximum turbinating outflow of the HPP. In this condition, water is released into the river without generating electricity. This loss of potential energy is enhanced by the HPPs downstream from Sobradinho because they present lower turbinated outflow and higher productivity. Sobradinho turbinates 4,260 m^3/s and produces 61 Wh/m^3. The HPPs downstream have maximum turbinated flow and production factor, respectively, 2,745 m^3/s and 126 Wh/m^3 at Itaparica; 2,310 m^3/s and 319 Wh/m^3 at PAC; 3,000 m^3/s and 305 Wh/m^3 at Xingó.

Overall, spilled water occurred in 2009, 2011, and 2012, summing the hydroelectricity loss at 1.0, 4.3, 6.8, and 13.0 TWh for Scenarios PV-250, PV-500, PV-750, and PV-1000, respectively (SI–F15). Sobradinho only registered spilled water in Scenario PV-1000 in April 2011. The ratio of electricity loss per PV power installed due to spilled water was estimated at 3.9 GWh/MW for PV-250; 8.7 GWh/MW for PV-500; 9.1 GWh/MW for PV-750; and 13.0 GWh/MW for PV-1000.

4. Discussion

In this case study, we have simulated the use of solar power in the range of 50–1000 MW to partially replace the hydropower generation and manage the water allocation among three large-scale reservoirs in cascade aiming to reduce water shortage over a severe drought in the semi-arid region of Brazil. The simulations revealed the influence of PV systems on water and energy resources at Sobradinho and São Francisco River in 2009–2018. The research framework was defined in the severe drought to provide information for stakeholders to better prepare for future climate conditions at semi-arid areas since climate projections point to an intensification of dry periods (IPCC, 2018).

The PV-50 and PV-100 scenarios could not improve water security and were disregarded. The results of the valid simulated scenarios embodied positive and negative outputs and their interpretation expressed the trade-offs in spatial and temporal scales. In the overall analysis, the gains in water security were concomitant to losses in power generation. The opportunities and limitations for each scenario are presented in Table 3.

Water security was improved by adding PV but limited by the volume of water in the system. The lack of precipitation in the study timeframe was intense and the reservoirs got depleted in the simulations at Sobradinho by applying a constant outflow higher than 1000 m^3/s (SI–F16). This value is equivalent to about half the historical average outflow (ONS, 2019a). Consequently, we adopted the minimum outflow of 800 m^3/s to consider this water limitation, to mitigate the ecological negative impacts, and to be adherent to the current management rules established by the National Water Agency (ANA, 2017e). Comparing the PV scenarios, water availability was only improved by adopting

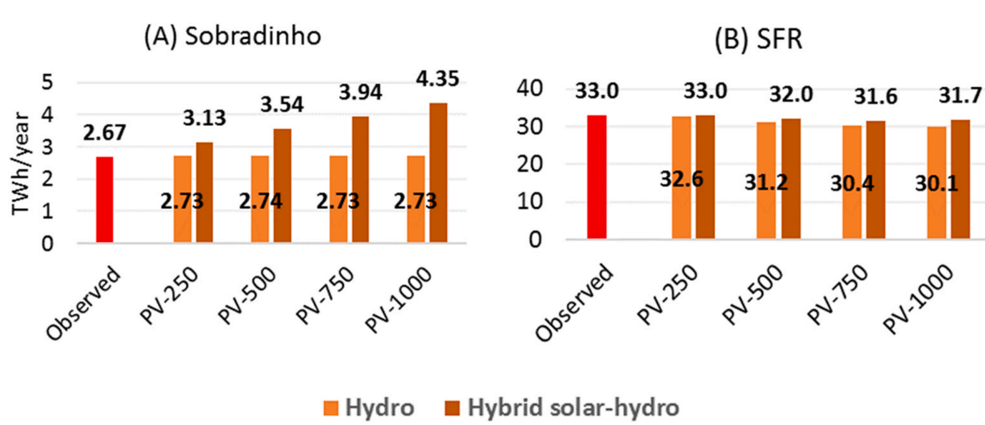

Fig. 7. Average electricity generation (GWh/year) in historical dataset 2009–2018 and simulated PV scenarios at (A) Sobradinho and (B) five SFR HPPs.

Table 3
Qualitative summary of indicator for the simulated PV scenarios. The colors express improvement (blue) or loss (red) compared to the observed scenario. The gradient expresses the intensity of the change.

		PV			
Item	Indicator	250	500	750	1000
1	Water security	+	++	+++	+++
2	Solar electricity	+	++	+++	++++
3	Hydroelectricity Sobradinho	o	o	o	o
	Hydroelectricity SFR	-	--	---	----
4	Sobradinho capacity factor	+	++	+++	++++
5	Total electricity Sobradinho	+	++	+++	++++
	Total electricity SFR	o	-	--	--
6	Water loss by evaporation	-	--	---	----
7	Energy loss by evaporation	-	--	---	----
8	Energy loss by spilled water	-	--	---	----

less critical *more critical*
Improvement
Loss
Neutral

large-scale photovoltaic power plants in the range 250–1000 MW, in which the water levels at Sobradinho were maintained at EV>40% during the driest years. The water storage increased from 0.1 years of the demand in the historical dataset to 0.7–2.3 years in the 2017 dry season, increasing the water security. The current operation makes decisions based on the projections of the water level for the end of both dry and wet season, embracing a one-year time-span (ONS, 2019b). Assuming the same criteria to classify the water security, PV-500 to PV-1000 provided favorable responses. The conservation of a certain volume of water, equivalent to more than one-year demand, is relevant to water security because projections are not absolute in assuring the climate conditions of the following year. Moreover, after a severe meteorological drought, downstream areas face persisting hydrologic drought conditions that take some years to recover (Van Oel et al., 2018). It is important to notice that the perception of water security during a drought period can also bring collateral effects from unawareness on the demand side (Van Oel et al., 2018), an effect that needs to be jointly addressed by those responsible for water governance.

If we analyze HPPs operation, the higher the water level, the higher the frequency of months with operation under the Regular stage set by ANA regulatory agency, which was more frequently achieved by PV-750-1000. However, water allocation did not respond linearly, and these scenarios presented a predominance of low outflows, but high flow rates in wet seasons. In fact, scenarios of higher PV installed power led to a wider range in the pattern of outflow and dispatches, which makes the grid operation more complex and, consequently, affects the electric system's security.

Another effect is that the increase of water storage led to incremental evaporation, which reduced the benefits of adding solar PV generation. For comparison, incremental evaporation was equivalent to 0.2–0.4 years of the withdrawal authorization conceded over the Sobradinho reservoir. Regarding the power generation, solar power output was counterbalanced by 50–60%, considering the lost water would be turbinated at Sobradinho and downstream HPPs. However, as the proposed measure for this study is attached to water storage improvements, it can be assumed as an intrinsic collateral effect. Although the modules figure as a technical option to cover the water surface and reduce evaporation, it stands unfeasible for Sobradinho's dimensions. Alternatively, PV panels located in other positions in the reservoir cascade system or a diverse composition of HPPs would result differently. The lake geometry, the characteristics inherent to the semi-arid, and the current engineering technology lead to an outcome complicated to avoid in the short term.

Besides the quantified outcomes, the shifts in water resource conditions could be associated with social, environmental, and economic aspects. The lowest outflow of the historical dataset (550 m^3/s) was replaced by a minimum of 800 m^3/s, which would have allowed to 1) maintain the access of water downstream Sobradinho, since the infrastructure for withdrawals became inoperative when the riverbed reached low levels and 2) minimize the most harmful impacts in water quality and ecosystem conservancy (ANA, 2018b). First, the expending of the public sector on construction to provide water access reached ~ US$ 5.6 million in 2017, mainly for the reparation of riverbed and reallocation of withdrawal equipment (CBHSF, 2020). Second, the negative impacts on the ecosystem involved higher salinity concentration, especially at the river mouth. Fonseca et al. (2020) and Cavalcante et al. (2020) analyzed the saline wedge at SFR, concluding that the salt concentration presented less amplitude over the tides and reached more than 10 km beyond the mouth of the river. The authors characterized the river flow pattern as unable to either avoid the estuarine plume or carry sediments from runoff and upstream. The negative impacts are probably long-lasting and cumulative, affecting water quality and human health, causing disturbances in irrigated agriculture and pasture, and promoting substitution of aquatic communities and loss of species (Vasco et al., 2019).

If we now turn to power generation, the PV influence depended on the scale and component under analysis. At Sobradinho, the scenarios increased the dispatches by 17–63%, which would be completely incorporated into the grid using the HPP installed capacity, except in April 2011 for scenario PV-1000. However, analyzing the SFR system, we identified up to 4.4% less hydroelectricity from the five HPPs. The losses ranged from 1.0 to 1.3 TWh/year, from incremental evaporation and spilled water – in equal participation, on average 2009–2018 (Fig. 7). Adding PV to Três Marias or Itaparica, or in ground-mounted PV are alternatives to compensate for the energy loss, which were not explored in this study.

Although the simulations resulted in small energy losses on the average output for the entire SFR hydroelectric system compared to the reference scenario, it is possible to identify more electricity produced in severe drought years. For those years, the improvement in power generation would have led to gains in energy security of the national grid and have maintained the renewable share prevalence. Thermal power generation was inserted into the grid to compensate for hydropower shortages, reaching 24.3% in 2014 (MME, 2019). The dependence on thermal energy implied two additional outcomes: socioeconomic implication, since incremental costs were transferred to the consumers (ANEEL, 2013), and environmental implication, as greenhouse gases (GHG) emissions of the Brazilian electricity reached 0.135 tCO_2/MWh (71.0 $MtCO_2$) in 2014 (MCTI, 2020). Before, the GHG factor was registered by 0.025 tCO_2/MWh in 2009 (MCTI, 2020). Adopting renewable energy and reducing GHG emissions play a role in the international context as both collaborate on the Sustainable Development Goals (ONU, 2015) and Paris Agreement (MMA, 2017). Regarding the last one, the Brazilian Nationally Determined Contribution (NDC) committed to reducing emissions by 37% until 2025 and by 43% until 2030 based on the 2015 level (FED. REP. BRASIL, 2016). Adding solar power to HPP can contribute to this goal while releasing water to be allocated under equalized rules between the multi-purposes.

4.1. Opportunities and limitations in typical and wet years

As the study was carried out in water scarcity, we simulated the adoption of PV in the modeling dataset of 1999–2008 to quantify the benefits and identify the occurrence of energy losses by spilled water in typical and wet hydrologic conditions (SI–F17). Solar and hydropower were completely harnessed, except in April 2007, when spilled water was registered. The CF was improved from 0.40 in historical time-series to 0.44 and 0.57, respectively for PV-250 and PV-1000.

As HPPs are designed based on potential conditions of the river flow, the hydrological seasonality creates an opportunity for complementary systems. Turning Sobradinho into a hybrid powerplant creates a synergic contribution that is enhanced by high irradiation in months of low nebulosity and, therefore, low precipitation. Besides the recent drop in precipitation at SFB (FUNCEME, 2020), probably due to land-use change and other anthropic disturbances (Correia et al., 2006), projections of global climate change show a negative effect on the energy sector (Schaeffer et al., 2012). In this context, optimizing the infrastructure to better manage the available resources becomes desirable.

4.2. Opportunities and limitations for small-scale PV

Although PV power plants with installed capacity lower than 100 MW were insufficient to promote water security in the study period, it represents an opportunity to improve Water-Energy Nexus in less intense dry seasons. We analyzed PV-50 and PV-100 in 1999–2008 (SI–F18), which resulted in gains of 2.3% for each PV-50, or an additional 80 GWh/year, on average, being dispatched. Spilled water was not registered, and PV addition increased CF to 0.41 (PV-50) and 0.42 (PV-100). Therefore, adding any amount of solar power made it possible to obtain incremental electricity, optimize the HPP, and increase water allocation control.

4.3. Opportunities and limitations for large-scale PV

Renewable energies are increasing in share in different transition pathways (Mahlooji et al., 2020). Several aspects contribute to sorting the energy power, e.g. availability of the energy source, availability of the technology, affordability, local climate pattern, efficiency, or jobs creation (IRENA, 2015; MME, 2018). PV is growing fast worldwide due to policy support, technological evolvement, and reduction of installation costs (IEA, 2020). In Brazil, the largest PV plant in operation is Pirapora Solar Complex, a 399 MW ground-mounted plant located at one side of SFR, 150 km downstream Três Marias (IRENA, 2019). SF basin represents an appropriate candidate for solar power due to the abundant solar irradiation of more than 1750 kWh/kWp.year (Pereira et al., 2017).

Increasing in scale since 2007, FPV figures as an emerging technology. Studies qualitatively accessed its advantages and disadvantages (SI-T3) but the mutual influence on reservoirs still needs to be measured for different climate conditions, equipment characteristics, and lake scale. We selected FPV because it potentially responds to relevant issues of the region. Firstly, it is a promising solution for warm weather because the panels might benefit from the water-cooling effect (Liu et al., 2017) or reduced cloudiness over the lake (Gonçalves et al., 2020). These influence factors need to be evaluated and properly quantified. Secondly, the PV panels can reduce water evaporation in the occupied area (Gonzalez Sanchez et al., 2021). However, our preliminary analysis showed a negligible influence due to the small area occupied by the PV modules and floating systems compared to the Sobradinho lake surface. The precise area of a PV system depends on an engineering project that specifies panels, their distribution, floating components, and materials; angle and position over the lake; presence of solar tracking or water veil-cooling, among other technical characteristics. A rough estimate indicates that PV-250 would occupy ~3 km^2, considering panel potential of 325Wp, panel area of 2 m^2, and space between panels of 2 m^2. Sobradinho extends for 4214 km^2, with a minimum area of 1250 km^2 when the effective storage is dried out. Therefore, PV-250 would occupy 0.25% of the minimum area. For the proposed FPV scenarios, Sobradinho's area was not considered a limiting aspect, although we acknowledge the necessity to assess the ecological impacts of panels, floats, and electrical cables for the water quality, aquatic life, and ecosystem.

Another aspect is the required investment. Assuming PV-250 as the minimum necessary to avoid water shortages in 2017, the investment would start at US$ 0.43 billion. Brazilian studies for energy expansion projected centralized PV increasing by 1000 MW/year in 2019–2029, investing US$ 3.7–5.0 billion only at the Brazilian Northeastern region (MME/EPE, 2020). Just for comparison, Hydropower Belo Monte, concluded in 2019, cost around US$ 8 billion for the installed capacity of 8788 MW (0.9 US$/Wp), but with assured energy of 4500 MW (1.8 US $/Wp) (Planalto, 2019b). Belo Monte is composed of a 500 km^2 reservoir located inside the Amazon rainforest, at the Xingu river (Altamira city). Thus, in addition to the financial comparison, the electric expansion built on large-scale reservoirs brings a wide diversity of social and ecological consequences that must be embraced (Prado et al., 2016). Besides, PV systems bring a social-driver potential to create local jobs involved in the assembling of the panels, construction, installation, and maintenance of the PV systems (IRENA, 2019; ABSOLAR, 2020).

If we now consider this investment is dedicated to water demand control (for example, efficiency, water treatment and reuse technologies, equipment to access groundwater), it would probably benefit the served population. However, the existing infrastructure (for instance, DINC canals comprise ~900 km and 39 pumping stations) is currently necessary to provide broad access to water, and it will take time to be replaced. Towards the shift to a sustainable pathway, there is a need to optimize the existing services of water and energy supply. If the investment is only dedicated to water management, the energy security would not be jointly improved, which is critically necessary as electric demand is estimated to increase by 3.8%/year for 2020–2029 (MME/EPE, 2020), and hydropower is not warranted in the future (De Jong et al., 2018).

The cost of electricity is also an economic perspective that justifies the spending on solar power. However, they were not approached in this study because the regulations on selling prices of electricity from hybrid systems are currently evolving in Brazil (ANEEL, 2020). Instead, we identified the existence of incremental costs to the supply sector over the severe drought. In 2013–2019, thermal energy is estimated to have cost US$ 2.7 billion (Godinho; Lima, 2020). Besides, in 2009–2018, the commercial value of electricity in the Northeastern sub-system resulted in 40 US$/MW, on average, though it reached ~100 US$/MW in 69 weeks, attaining the maximum value of ~150 US$/MW in 19 weeks (CCEE, 2020b).

Accordingly, the technical and economic potential of the proposed solution is demonstrated by several aspects: the FPVs currently in operation, the 1 MW FPV in test at Sobradinho, the Brazilian projections to invest in the electric grid, and the incremental costs of a severe drought.

4.4. Opportunities and limitations for hybrid solar-hydro powerplants

Hybrid power plants combining solar and hydro resources are expected to bring benefits in three aspects: synergy in electricity generation, security for power intermittence, and optimization of existing infrastructure. In the first aspect, solar and hydro are complementary in hourly and seasonal management (Beluco et al., 2012; Kougias et al., 2016). While PV provides electricity during the day, the outflow can be restricted in this period, saving water to be harnessed during the night. This trade-off is relevant in Brazil because, since 2016, the peak-hour in electric consumption has been registered at 3 p.m., when the incoming solar irradiance is the highest (Pereira et al., 2017). The trade-off is also found in seasonal variation, as irradiation presents a slight increase at the end of the dry season (Pereira et al., 2017), while the water storage in reservoirs is declining (ANA, 2019a). Furthermore, the role of solar power might be enhanced by climate change conditions. In the Brazilian Northeastern region, the precipitation rate is associated with more uncertainty than irradiance under the climate projection, in which consecutive dry days are expected to become more frequent (Marengo; Bernasconi, 2014; Alves et al., 2020).

The second aspect is the resource intermittence, which remains an obstacle to the extensive adding of solar, wind, and even run-of-river

HPPs into the electric systems. The low predictability of these energy resources increases the complexity of operating the grid (ONS, 2019b). Simultaneously, HPPs with reservoirs provide operation control by the characteristics of safe and rapid response (MME, 2018). Thus, maintaining appropriate water levels in the reservoirs turns the HPPs into natural batteries to overcome the instant lack of generation from the solar source. The potential energy of HPPs creates the conditions to optimize the electric supply system, improve energy security, and reduce operational costs (David; Moromisato, 2012). Therefore, under the uncertainties of climate change and the growing share of renewable, the management of the existing reservoirs becomes critical.

The optimized use of the existing infrastructure is vastly relevant because the construction of novel HPP with large-scale reservoirs implies negative socio-environmental impacts, as areas of interest in Brazil are environmentally protected or indigenous lands (MME, 2018). The recent expansion implemented run-of-river HPP, whose electricity similarly needs to be immediately dispatched. The incremental impacts of land-use change for wide flooding areas and the collateral effects of constructing reservoirs for energy production enhance the relevance of carefully managing the existing ones (Prado et al., 2016). In addition, the comparison of sources to create novel power plants also brings economic and legal benefits for solar power: additional costs regarding land property, legal processes, infrastructure reallocation, and mitigation of socioenvironmental impacts imply 4–15% for conventional HPP while 0.4–1.9% for PV plants (MME, 2018).

The third aspect is related to optimizing the existing infrastructure and avoiding socio-environmental impacts. HPPs intrinsically create an opportunity to share transmission lines due to their seasonal generation. In the reference scenario, Sobradinho's CF was, on average, 0.55 in 2007 (ONS, 2019a), reaching 0.74 and 0.86, respectively in February and March (ONS, 2019a), which denotes that the existing transmission lines were not a limitation. PV improved CF by ~0.04 for every 250 MW. Instead, the solar electricity allowed to occupy this underused infrastructure and to increment the regional power supply, consequently, avoiding additional losses for electricity transportation (MME, 2019).

The origin and destiny of electricity dispatches in Brazil are variable and prioritize the powerplants based on the cost of production (Godinho; Lima, 2020). Hence, the electricity generated in one region can be transmitted to another depending on the consumption intensity and the capacity of the regional power plants to provide electricity, taking advantage of a unique feature of the country to have an integrated distribution system covering practically the entire national territory. In the annual balance of 2011–2016, the production was inferior to the consumption at the Northeast of Brazil, and the region prevailed receiving electricity from North and Southeast. In 2013, for instance, the dispatches to the Northeastern region reached 28.7 GW (MME, 2019). Energy losses associated with long-distance transportation (~20%) contribute to harm energy security (MME, 2020). Therefore, although the country's electric grid provides national integration to operate the supply, the predominance of regional production conducts energy use to a more sustainable pathway.

Supported by the Nexus capability to provide information for policymakers, the scientific community, and the diversity of actors involved in the decision making, the choice by the appropriate scenarios is contingent upon the basin current condition and the expected goals. The simulated scenarios implied positive and negative impacts on water and energy, with secondary effects on social, environmental, and economic aspects. Thus, to support decisions, the results of the present study need to be confronted with a broad series of additional information: trends in population, economic activities, and climatology; international commitments of sustainable development; governance structure; active policies that interfere in the use of resources; local, regional and national existing programs for water and energy supply, and current measures to control water and energy demand. The pursues of the sector's mutualism in the use of resources depend on the constant monitoring and evaluation – in multiple scales – of the conditions, actions, responses, and rebound effects.

5. Conclusions

In semi-arid regions, the water security of the population and the economic activities are dependent on reservoirs. However, multipurpose reservoirs can reach water shortages when one of the water use options is prioritized. Solar power generation can be an alternative to saving water in the reservoirs and reducing water use to produce energy. Our results show that solar photovoltaic added to a hydropower plant can preserve water and energy security during drought events. In Brazil, the São Francisco river provides water for human activities at the semi-arid part of the basin, while the reservoirs that the river feeds represent ~15% of the water storage capacity of the national electric grid. To meet the demand for water and energy supply, the operation was conducted regardless of ecological aspects. The study demonstrated that a large-scale PV could play a significant role in high-dependent water demand areas such as the Brazilian Northeastern region during severe drought events. Water security was improved at the 34 billion cubic meter reservoir of Sobradinho by adopting floating PV power plants in the range of 250 to 1000 MW. The water reserve achieved 0.7–2.3 years of the water demand in the most critical year while electricity dispatches increased by 17–63%, on average. Besides the local security in water and energy, the measure could produce collateral improvements in social, environmental, and economic aspects such as in river water quality, ecological conservation, jobs and income creation, and the optimization of the existing infrastructure of water and energy supply. However, on a regional scale, as Sobradinho is part of a five-hydropower plant system in cascade, the total electricity output was reduced by 4.4%. Such energy loss counterbalanced the solar power output by 50–60%. Despite this overall loss, a power generation increment was quantified in the critical years of the prolonged drought, which would have contributed to the renewable share of the grid. In fact, scenarios of PV > 500 MW surpassed the hydroelectricity provided by Sobradinho in the critical dry months. As the potential of solar and hydropower complementarity is expected to be enhanced under future climatic conditions, the research provides information to actors responsible for the water and energy supply systems to comprehend the interlinkages across sectors. The results subsidize the actors towards the joint operation and the proposal of appropriate public policies.

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Credit author statement

Érica Campos: Conceptualization, Methodology, Investigation, Data curation, Software, Visualization, Writing - Original Draft; **Enio Pereira**: Conceptualization, Methodology, Validation, Writing - Review & Editing; **Pieter van Oel**: Methodology, Validation, Writing - Review & Editing; **Fernando Martins**: Data curation, Methodology, Validation, Writing - Review & Editing; **André Gonçalves**: Data curation, Formal

analysis, Writing - Review & Editing; **Rodrigo Costa**: Methodology, Writing - Review & Editing.

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.

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Appendix A. Supplementary data

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