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Comparison between seasonal pumped-storage and conventional reservoir dams from the water, energy and land nexus perspective

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ABSTRACT

Renewable sources of energy are providing an increasing share of the electricity generation mix, but their intermittency drives a need for energy storage. At the same time, water resources are increasingly scarce due to changes in demand, such as from population growth, supply side pressures such as climate change and governance challenges relating to poor management. Large storage reservoirs are used for water management and for energy storage. However, some existing and proposed hydropower reservoirs require vast areas of land and have considerable social and environmental impacts. Growing concerns on water and energy storage from a water-energy-land nexus approach motivated this study. Our objective is to compare how energy and water storage services, such as hydropower generation, electricity grid and water management, are provided with Seasonal Pumped-Storage (SPS) and Conventional Reservoir Dams (CRD) plants. Our case study region is Brazil, a country with extensive hydropower capacity and development plans, for which we compare the cost, land requirement and social impacts between CRD and potential SPS plants. Whilst seasonal pumped-storage have higher capital costs than conventional reservoir dams, given the much lower land requirements and evaporative losses, they are a valuable water and energy storage alternative especially in locations with plain topography and high evaporation. Results show that if Sobradinho CRD was built today it would result in a $USD 1.46 billion loss, on the other hand, Muquém SPS plant would result in a $USD 0.67b revenue.

1. Introduction

Reservoir dams are used to store water to reduce river flow seasonality, guarantee the supply of water and optimize hydropower downstream. They are also used for flood control [1], and for the various other water uses: agriculture [2,3], environment [4,5], human consumption, transportation and leisure. A further advantage of storage reservoirs is to reduce the water and energy supply vulnerability of a country [6–9].

Although estimates vary, world-wide hydropower production in 2016 was estimated at 4102 TWh from an installed hydropower capacity of 1096 GW [10]. This installed capacity is growing by an estimated 28 GW per year and it is estimated that the world-wide hydroelectricity energy potential is as much as 52,000 TWh/year [11]. Due to the drive for more sustainable and low-carbon sources of electricity production, the number of hydroelectric dams is expected to surge in the coming decades [12]. Fig. 1 presents the expected increase in hydropower generation until 2050 [13].

Pumped-Storage (PS) plants, a less common form of reservoir dams, are used to store energy and water [14]. When electricity demand is low, normally from midnight to 6 am (when most people are sleeping), excess generation is used to pump water from a lower reservoir to a higher reservoir. When demand increases, during the day or peak hours, the stored water is released to the lower reservoir and transformed into electricity. In other words, pumped-storage plants have been used previously mainly to store inflexible excess thermal generation (coal, nuclear) during the night to generate electricity during peak hours, when it is most valuable. Although efficiency losses in the pumping, storage, and generation processed are in the order of 15–30%, i.e. a PS plant actually uses more electricity than it produces, this is often still an economical way to provide responsive peak generation capacity that is often otherwise provided by expensive gas combustion turbines [14].

The surge in renewable energy generation, particularly intermittent wind and solar power [15–17], is also renewing global interest in pumped-storage plants. These sources of energy are unpredictable and intermittent and benefit greatly with a storage alternative [18]. This has contributed to the increase of pumped-storage development from 95 GW in 2000 to 167 GW in 2016 [19].

Furthermore, it is increasingly difficult to find locations with

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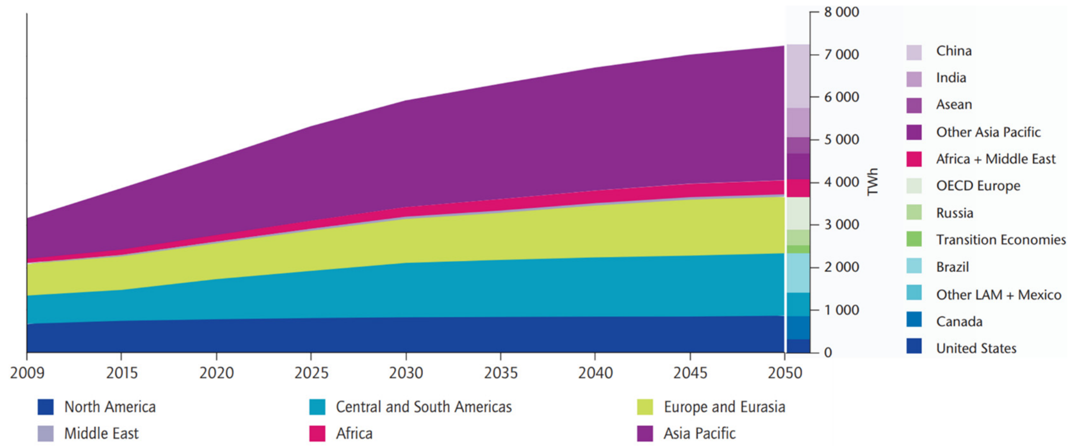

Fig. 1. Comparison of reservoirs with a (a) steep valley, and (b) shallow topography [13].

appropriate water resources and topography where conventional reservoir dams can be built for better water and energy management (see Section 2.1).

An alternative and seldom considered approach to the pumped storage described above is the use of Seasonal Pumped-Storage (SPS) plants [20]. These plants can play a similar role to conventional reservoir dams, storing large amounts of water and energy for long periods [21]. The main difference between these technologies is that in conventional reservoir dams, the water flows naturally into the reservoir and in seasonal pumped-storage reservoirs, water is pumped to the reservoir.

One of the advantages of SPS, is that the upper reservoir can vary considerably in depth, from 60 up to ~150 m. These arrangements became viable with the development of variable speed pump/turbines, as they allow greater variation on the pumping/generation head [22]. Currently, the SPS plant with the highest head variation SPS plant is Limberg II in Austria with 164 m [23]. This considerably reduces the amount of land required to store the same amount of water and energy. However the water inlet flow into the reservoir is limited to the installed pumping capacity, which can result in high installation costs.

This paper presents the main challenges for conventional reservoir dams and compares them with seasonal pumped-storage. First, we introduce the key characteristics of storage reservoirs, reviewing and discussing the storage capacity of PS plants and compare conventional and seasonal pumped storage systems. Then we present a novel assessment of the land requirements compared with the water and energy storage potentials of conventional reservoir dams and SPS plants in Brazil. Electricity generation in Brazil heavily relies on hydropower (providing around 70% of its electricity supply) and suffers from severe energy crises during drought years. SPS was the possibility of increasing the country's energy and water storage capacity, improving energy security of the country and reducing its vulnerability to climate change.

2. Technological review

This section introduces the key characteristics of pumped storage reservoirs, in particular the land requirements, storage capacity of different types of pumped storage, and a detailed look into seasonal pumped storage plants.

2.1. Land requirement in storage reservoirs

Several aspects are considered when designing and building a storage reservoir (Table 1) and often depend greatly on the topography of the reservoir location. There are other aspects, which are also important for storage reservoir planning that are not fully considered in this article. These are basin hydrology [24], droughts [25,26], soil erosion caused by hydropower [24,27,28], fish habitat destruction [29–31], reservoir sedimentation [32–34], CO_2 emissions [35], water quality degradation [36], transportation [37], multiple uses of water [38–40], climate change [41,42], induced earthquakes [43], flood control [1], river temperature [44], river regime related issues [45], vegetation flooding, environmental impacts, [46,47] among others.

Only a few aspects can be controlled when planning a storage reservoir. The main parameters are the location of the dam, dam height and length, and reservoir level variation. The resulting storage volume, land use, flooded area variation, evaporation, will depend on the topography, geology and climate of the location.

Some topographical formations are more appropriate for storage reservoirs than others. For example, steep valley topographies (Fig. 2(a)), allow a large reservoir water level variation (60 + m), resulting in large reservoir volume with low land requirements. Additionally, the flooded area variation and evaporative losses would be low. For example, the cross-section of a reservoir with a full reservoir could reduce from 5 km, when full, to 4 km, when empty.

On the other hand, reservoirs in shallow topographies (Fig. 2(b)) are not appropriate because the water level variation is comparatively small. This results in lower water and energy storage capacities per land use, high flooded area variation and high evaporative losses.

Reservoirs with high flooded area variation have greater impact on their surroundings. Fig. 3 shows two examples of reservoirs when full and when at dead storage, which happens on a seasonal basis (minimum storage for electricity generation) (data used in Fig. 3(a) and (b), were taken from [49,50] respectively). There are places on the Sobradinho and Tucuruí reservoirs in Brazil where the distance from the reservoir surrounding and the reservoir at its minimum level (seasonal variation distance) reaches 15 and 20 km respectively. In these cases, the flooded area variation grows with the distance from the dam. Such reservoirs have a huge impact on the ecosystems because, during the dry season, the fauna and flora that adapted to life close to a river, find themselves at a few kilometres distance from the river, with wasteland in between. For this reason, droughts can be particularly devastating.

Subsequently, these reservoirs use vast amounts of land to store limited amounts of water and energy. If the area were used for other means, such as agriculture, the economic return would be higher than its storage use. For example, comparing with different electricity generation options, if the tidal variation area (gray) of the Sobradinho reservoir (3053 km^2) was used for eucalyptus-based biomass electricity generation, it would consume around 122 m^3/s (1260 mm/y) [51] of water and generate around 9.5 TWh/y[1] [52], considering the reduction

[1] For this approximation it is assumed a eucalyptus dry mass of 25 tonne/ha.y, heat of combustion of 5.4 MWh_t/tonne and an electricity generation efficiency of 30%.

Table 1
Aspects considered when planning a storage reservoir and topographical influence.

Dam aspects	Aspect description	Reservoir planning influence	Topography	
			Steep valley	Shallow
Storage volume	The main objective of a storage reservoir is to store water and energy.	The higher the usable storage volume the better.	Set Value	Set Value
Land requirement	The area occupied by the reservoir.	One of the main causes of environmental, social and economic impact of reservoir dams. Should be minimized as much as possible.	Small	Large
Flooded area variation	The amount of reservoir area which changes with the tidal variation as the reservoir is utilized.	Flooded area variation has social, environmental and economic impacts and should be reduced as much as possible.	Small	Large
Level variation	The total variation of the reservoir level from full to empty.	The higher the level variation, the higher the storage volume/ land use ratio.	Large	Small
Evaporation	Evaporative losses that scale with the flooded area and reduce the overall stored volume [48].	A storage reservoir should have a high storage volume/ flooded area ratio to reduce evaporation.	Small	Large

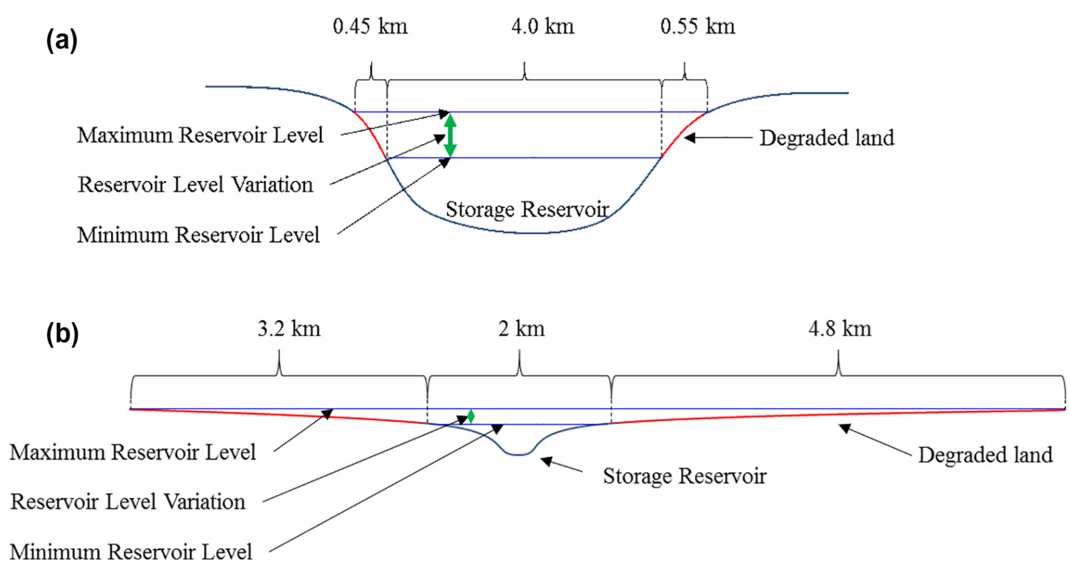

Fig. 2. Comparison of reservoirs with a (a) steep valley, and (b) shallow topography.

in hydropower generation of 2.9 TWh/y[2] due to the water withdrawals for irrigation (i.e. a 2 GW_e plant with 70% capacity factor). Additionally, not using the Sobradinho reservoir storage capacity, would reduce the evaporation in the reservoir by around 95.7 m^3/s, which corresponds to 2.3 TWh/y (see Footnote 2) lost hydropower generation [53]. Thus, there will be a net gain of 8.9 TWh/y with the eucalyptus alternative.

Due to hydro capacity downstream of Sobradinho, in years with high river flows the Sobradinho reservoir can increase hydropower generation up to 21.7 TWh/y (energy storage capacity of Sobradinho reservoir). However, this amount of storage might not be required anymore as the average river flow has reduced from 2.000 m^3/s to 800–600 m^3/s in the past 5 years due to irrigation demands and climate change [53]. A comparison analysis between the Sobradinho reservoir (Fig. 3(a)) and the proposed Muquém SPS reservoir (Fig. 9) is presented in the water-energy-land analysis section. We show how the São Francisco river flow can be regulated with the proposed Muquém SPS reservoir and use orders of magnitude less land and evaporate orders of magnitude less water.

In conclusion, if a watershed has available water resources, and at the same time it does not have an appropriate location to build conventional reservoir dams, seasonal pumped-storage plants should be considered. Due to the high land requirement and evaporation, we concluded in Section 3.1 that Sobradinho CRD should stop operation and Muquém SPS with multiple storage cycles should be built.

2.2. Pumped-storage plants and storage capacity

In recent decades pumped-storage plants have been used in countries with inflexible thermal-based electricity generation systems, such as the USA, Japan, and Germany to store energy during the night when the demand for electricity is reduced and generate electricity during peak hours [14]. In countries with a hydrothermal electricity generation system, such as Austria, Switzerland, Norway, pumped-storage has operated in a seasonal cycle, storing water and energy during the summer and generating electricity during the winter [54].

Pumped-storage plants are used for storing energy during periods of low energy demand and generating electricity during periods of high energy demand. They are usually known to have short storage cycles of days or weeks, however, they can also be used to store large amounts of water, as well as energy. During the 1970s and 1980s, there was a boom in pump-storage plants, which reached around 75 GW in 1990 [55]. Details on most energy storage projects in the world can be found in [19,56].

Currently the world's electricity generation sector is going through a paradigm shift with the addition of renewable sources of energy to the grid. Some of these sources generate intermittent and variable amounts of energy, such as solar, wind [57,58], ocean and run-of-the-river hydropower, which is increasing need for storing energy. The cheapest

[2] This assumes a cascade generation head of 306 m [69] and 90% hydroelectric generation efficiency.

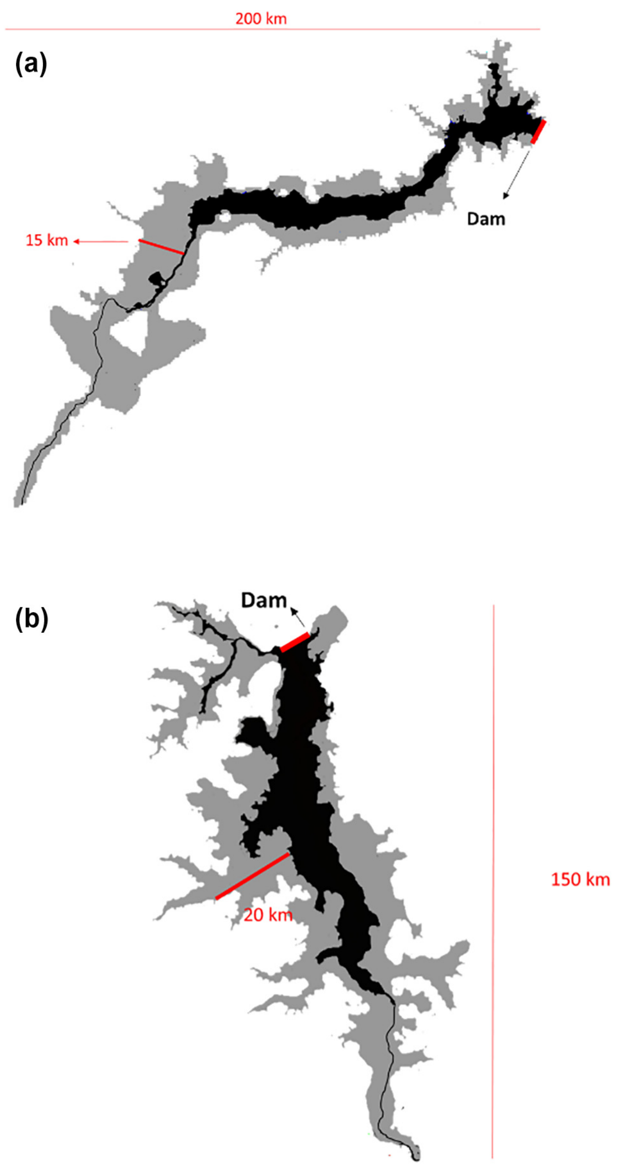

Fig. 3. Flooded area variation of (a) Sobradinho and (b) Tucuruí reservoirs in Brazil (see Fig. 11) when full (gray) and when reaches dead storage (black) [49,50].

approach for storing energy on a nationwide scale is by storing water [55]. Norway is looking at building new pumped-storage plants for smoothing wind power variation from other European countries [59] and so become the "battery" from renewable sources of energy in Europe [60]. This energy storage need could be combined with the need for storing water in different countries. This would bring the combined benefits of both water and energy services to a country or region.

Table 2 presents the different pumped-storage cycles available and the occasion when each pumped-storage cycle type is used [61,62]. The flexibility of a pumped storage plant depends largely on the size of the upper storage reservoir. The larger the storage, the more flexibly the plant can operate either over seasons or on a daily/weekly cycle. Pluri-Annual Pumped-Storage (PAPS) plant have the largest upper reservoirs, and can thus perform the tasks of Seasonal Pumped-Storage (SPS), Weekly Pumped-Storage (WPS), Daily Pumped-Storage (DPS) plants. However, DPS plants cannot perform the tasks of WPS, SPS and PAPS plants because their water storage capacity is limited to one day's storage.

The growth in solar power generation is changing the way in which daily pumped-storage sites operate. As solar power only generates electricity during the day, the increase in solar power can complement the increase in electricity demand during the day. Thus, pumped-storage would not be required to store energy at night and generate during the day. This pattern is happening in Germany, which has considerably increased its solar power generation. On some days in Germany, the daily pumped-storage plants, that were built with the intention of storing energy from inflexible thermoelectricity sources at night, such as coal and nuclear, are now storing solar energy during the day and generating energy at night [64,65].

Fig. 4 shows the comparison between pumped-storage installed capacity sorted by different storage capacities in Germany, Austria and Switzerland [66]. Germany has mainly daily pumped-storage plants, while Switzerland and Austria have mostly monthly and seasonal pumped-storage plants. This is because Germany had an inflexible thermal electricity generation based on coal and Switzerland and Austria have a hydrothermal electricity grid, with greater needs for seasonal storage. Weekly PS capacity in Austria and Switzerland are expected to increase due to the growing needs to store wind energy from European countries.

Table 3 compares the different pumped-storage cycles from a water perspective. The reservoir size for water storage purposes varies considerably with the storage requirements. For example, reservoirs can be planned to store water to regulate the flow of a main large river, or it can be built to supply water for a city or for industrial processes.

The interesting aspect of pluri-annual and seasonal pumped-storage projects is that they can provide both energy and water storage services in a single project, as show in Tables 2 and 3. Given its low land requirements, SPS is an important alternative for balancing the water-energy-land nexus and should be given more focus.

2.3. Comparing conventional and seasonal pumped-storage reservoirs

Some river basins have good water resources, but lack appropriate topography, or have other issues that impede the construction of effective storage reservoirs. In this case, an alternative to storing water and energy in the watershed is the creation of seasonal pumped-storage reservoirs. Fig. 5 presents examples describing the comparison between the operation of conventional reservoir dams and seasonal pumped-storage plants. In conventional reservoir dams, all river flow is stored in the reservoir, if there is enough storage capacity. With SPS, on the other hand, the storage reservoir is parallel to the river basin and the inlet flow is limited to the SPS pumping capacity.

The water inflow in SPS reservoirs has two different sources. Either the water comes from the tributary river, due to precipitation and/or ice melting, as presented in Fig. 6, or it can come from pumping water from the lower reservoir. The water inflow sources to the existing SPS projects cited in this paper varies a considerably. In Austria, Switzerland, Norway and Sweden, around 50% of the water is pumped and the other 50% of the water comes from natural flow [65]. At the SPS projects in the USA, Australia and Canary Island, most of the water that enters the seasonal pumped-storage reservoir is pumped.

An interesting approach for building storage reservoirs with minimum impact on the main river is proposed in Fig. 7. This approach, named Run-of-the-River Seasonal Pumped-Storage, has the main intentions of avoiding ecosystem fragmentation of the main river (damming the main river) reducing the possibility of the river to become an Intermittent River and Ephemeral Stream (IRES) [67], and reducing the required flooded area of the lower reservoir, subsequently reducing evaporation. Ecosystem fragmentation impacts the river's fauna and flora biodiversity and river's nutrients concentration [68].

Run-of-the-River Seasonal Pumped-Storage is used to extract continuous amounts of water from the river during periods of high river flow and return flexible amounts of water to the river during periods with lower flows. This seasonal flexibility enables operation, that is, contribute to environmental flow requirements when needed. The lower reservoir, which is not on the main river, is used as a standard

Table 2
Different pumped-storage cycles types for meeting energy needs [63].

Pumped-storage type	Reservoir volume size (km^3)	Operation mode	Occasions when the pumped-storage type operates
Pluri-annual pumped-storage (PAPS)	100–5	Pump	Annual surplus in hydroelectric generation. Annual fuel prices cheaper than average. Lower than average annual electricity demand.
		Generation	Annual deficit in hydroelectric generation. Annual fuel prices more expensive than average. Higher than average annual electricity demand.
Seasonal pumped-storage (SPS)	30–1	Pump	Rainy seasons or ice melting seasons, with high hydropower generation. Summer, with high solar power generation. Windy seasons, with high wind power generation. Low demand season, when electricity demand reduces.
		Generation	Dry period or freezing winters, with low hydropower generation. Winter, with low solar power generation. Not windy seasons, with low wind power generation. High demand season, when electricity demand increases.
Weekly pumped-storage (WPS)	1–0.1	Pump	During the weekends, when power demand reduces. Windy days, with high wind power generation. Sunny days, with high solar power generation.
		Generation	During weekdays, when power demand increases. Not windy days, with low wind power generation. Cloudy days, with low solar power generation.
Daily pumped-storage (DPS)	0.1–0.001	Pump	Night, when electricity demand reduces. Day, when there is solar power generation.
		Generation	Day, when electricity demand increases. Night, when there is no solar power generation.

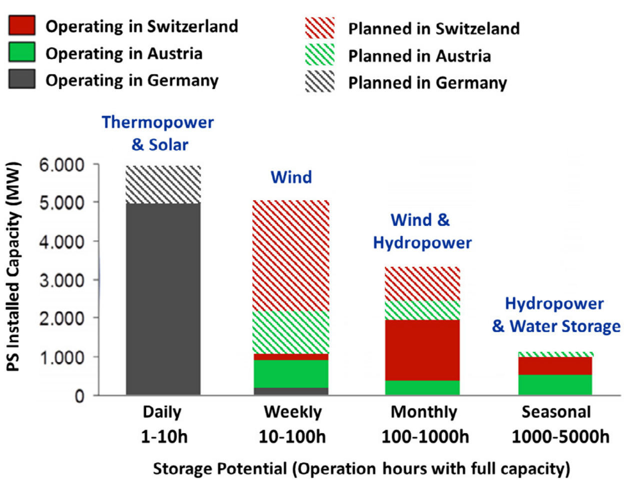

Fig. 4. Operating and planned pumped-storage potential in Germany, Austria and Switzerland, including the main purposes of the storage cycles ().
adapted from [66]

pumped-storage plant lower reservoir. In this way, the same pump-turbines can be used both as seasonal river regulation and as a daily and weekly energy storage solution. If the SPS would be used only for seasonal storage, there would be no need to build the lower reservoir and the buffer power house. The buffer power house is required to regulate the main river flow by exchanging water from the lower reservoir and the main river, especially when the SPS power house is generating electricity during the wet period, as water from the main river should be stored, and when the SPS power house is pumping during the dry period, as water should be released to the main river. Ultimately, Run-of-the-River Seasonal Pumped-Storage is a good alternative to store water and energy, and to regulate the flow of the main river without the need of damming the main river.

Several advantages and disadvantages between conventional reservoir dams and seasonal pumped-storage plants are presented in Table 4.

Fig. 8 presents a comparison of the water, energy and land nexus between CRD and SPS. Assuming the same water availability in the river, SPS would require less land to store the same amount of water. In addition, the energy storage potential of the water would increase with SPS as the water has to the pumped up during the storage process, further increasing the potential energy of the water.

The design and implementation of SPS can vary according to the requirements for water and energy storage, depending on the available topography. SPS projects with high-energy storage requirements and low water storage requirements should be implemented with high pumping/generation heads to maximize electricity storage. Projects with low energy storage requirements and high water storage requirements should be implemented with low pumping/generation heads.

Table 5 presents examples of the water flows which demands 100 MW pumping capacity with different pumping/generation heads, assuming a 90% generation efficiency. This water flow could be stored in a reservoir or transposed to another river. Eq. (1) presents the relation between the energy required for pumping and the water flow into

Table 3
Different pumped-storage cycles types for meeting water needs.

Pumped-storage type	Operation mode	Occasions when the pumped-storage type operates
Pluri-annual pumped-storage (PAPS)	Pump	Annual surplus in water availability. Lower than average annual water demand.
	Generation	Annual deficit in water availability. Higher than average annual water demand.
Seasonal pumped-storage (SPS)	Pump	Rainy seasons or ice melting seasons, with high water availability.
	Generation	Dry period or freezing winters, with low water availability.

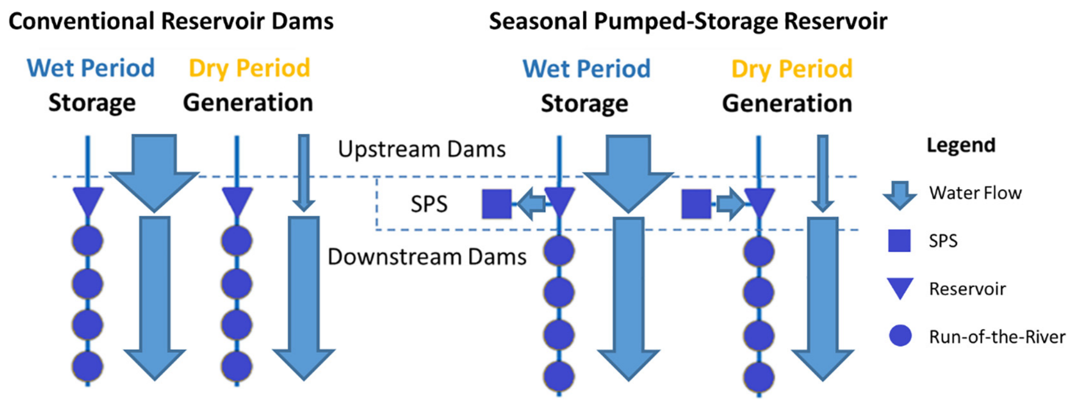

Fig. 5. Diagrams presenting (a) reservoir hydropower dams and (b) seasonal pumped-storage.

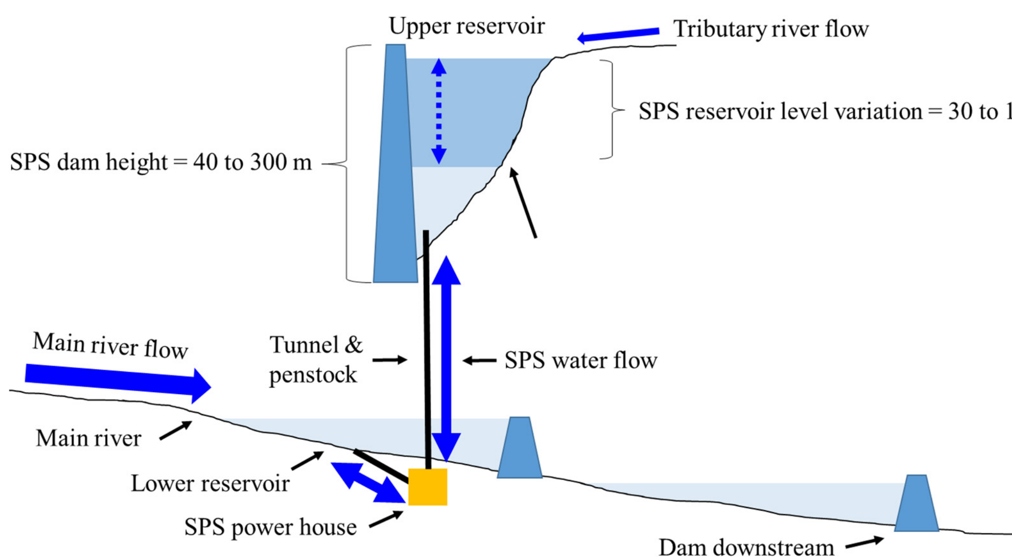

Fig. 6. Schematic presentation of Seasonal Pumped-Storage.

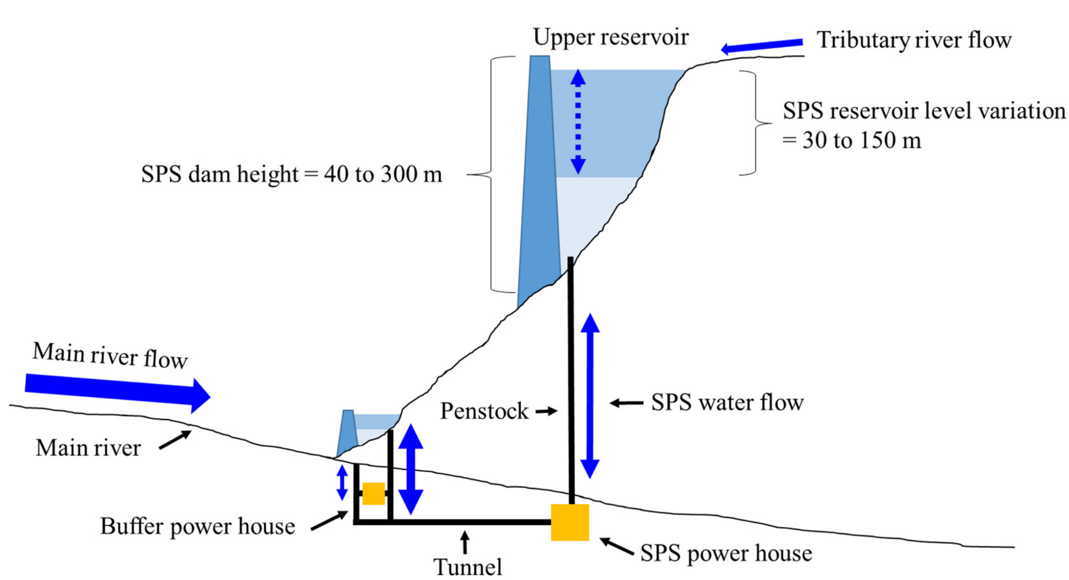

Fig. 7. Schematic presentation of the Run-of-the-River Seasonal Pumped-Storage.

Table 4
Comparison between conventional reservoir dams and seasonal pumped-storage plants.

Technology	Benefits of all technologies	Challenges from all technologies	Benefits from the technology	Challenges from the technology
Conventional Reservoir Dams (CRD)	Regulates the river flow [69]. Reduces spillage in dams downstream [70]. Optimizes hydropower generation [69]. Stores energy and water. Flood control [1]. Multi-purpose of water use: agriculture, environment, human consumption, transportation, etc. [39].	Floods new areas. Impacts on local fauna and flora. Soil erosion caused by hydropower [28]. Environmental pollution. Land appropriation. Flow diversion. People resettlement. Vegetation flooding. Water quality degradation. Induced earthquakes [71]. River temperature change [44]. Environmental impacts [47].	Generates and stores energy. Stores all river flow, if reservoir not full. Cheaper than SPS, if not considering land and evaporation costs.	Most construction sites already developed or considered. Floods large areas. Leaves large desert areas when empty. High environmental impact. Floods main rivers, which are usually more importance for social and environmental aspects then tributary rivers. More sedimentation, as the reservoir is located in the main river. Fish habitat destruction [29]. Reservoir sedimentation [32]. River regime related issues [45].
Seasonal Pumped-Storage (SPS)			Many locations to build reservoirs. Floods small areas. Stores excess generation and intermittent, unpredictable and inflexible energy sources. Smaller evaporation due to higher volume/area ratio. Inter-basin transfer. Lower levels of sediment trapping, as the reservoir is not located in the main river. Floods tributary rivers, which are usually less importance for social and environmental aspects than main rivers. Stores more energy than CRD. Less sedimentation as the reservoir is located in a tributary rivers.	It might not increase hydropower generation and could consume more energy than it generates. Storage flow limited to pumping capacity. More expensive than CRD, if not considering land and evaporation costs. Fish habitat destruction [29]. River regime related issues [45].
Run-of-the-River Seasonal Pumped-Storage (RRSPS)			Same benefits as SPS, plus the benefits below: Do not require a lower reservoir on the main river. Do not need to diverge the course of the main river during the construction of the lower reservoir dam. No ecosystem fragmentation impacts [68].	It might not increase hydropower generation and could consume more energy than it generates. Storage flow limited to pumping capacity. More expensive than CRD, if not considering land and evaporation costs.

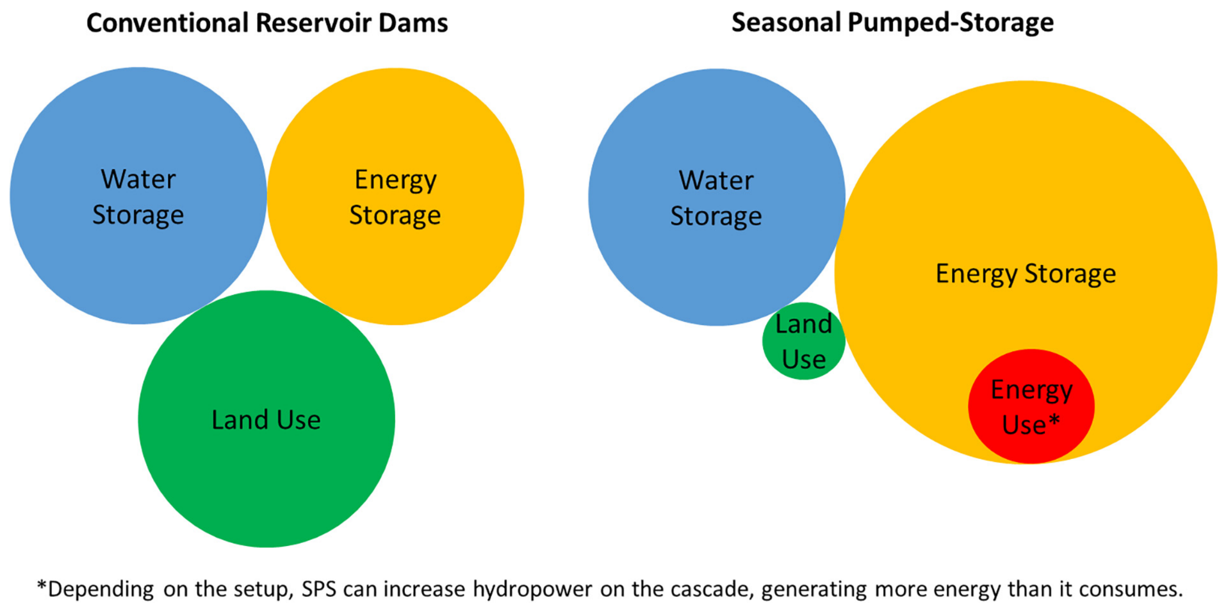

Fig. 8. Water, energy, land nexus comparison between CRD and SPS.

Table 5
Comparison between water flow and pumping capacity in SPS plants.

	Pumping/Generation head				
	50 m	100 m	200 m	500 m	800 m
Pumping capacity (MW)	100	100	100	100	100
Water storage flow (m^3/s)	226	113	56.6	22.7	14.2

the storage reservoir.

$$Pumping\ Capacity\ (\mathrm{WM}) = Water\ Storage\ Flow\left(\frac{\mathrm{kg}}{\mathrm{s}}\right) \times Head\ (\mathrm{m}) \times g\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right) \times e\ (\%) \times 10^6 \tag{1}$$

where g is the acceleration of gravity (9.81 m/s^2) and e is the pumping efficiency, which is assumed to be 90% [72].

A SPS plant built mainly for water management services, such as, flood control, water supply, waterway transport, inter-basin transfer, and hydropower optimization should have a low pumping/generation head so that it can pump large amounts of water with little energy. A SPS plant built mainly for peak hour generation, renewable energy intermittency storage, transmission optimization, energy supply security and hydropower generation should have a high pumping/generation head so that it can store large amounts of energy with little water, land and lower costs. Note that for hydropower optimization the pumping/generation head should be small because pumping losses should be minimized and most of the hydroelectric gain should happen in the dams in cascade downstream of the SPS plant. Evaporation reduction requires a high reservoir level variation with the intent of reducing the evaporation area/water stored ratio. This analysis is described in Table 6.

In order to design multi-purpose optimal SPS projects, all these services should be included into the SPS design in order to find the appropriate pumping/generation head: Water Supply (WS); Flood Control (FC); Transport with Waterways (TW); Evaporation Reduction (ER); Hydropower (HP); Downstream Hydropower Optimization (HO); Peak Generation (PG); Intermittent Electricity Generation Storage (IS); Transmission Optimization (TO); Inter-Basin Transfer (BT); Energy Security (ES). Alternatively, two or more smaller SPS plants could be built, some with high pumping/generation head and others with low pumping/generation head for a better combination of these services.

Table 6 presents examples of multi-purpose SPS applications and how well they work with different pumping/generation heads, qualitatively assessed with the available literature. Some of these applications need not involve a strictly seasonal operation, i.e. filling up in six months and emptying in the other six months. It also considers applications in which the upper reservoir stores larges amount of water for several years, in case of a drought, and other applications. Note that medium and low pumping/ generation heads can also be used for intermittent renewable generation storage or peak generation, however with a small and medium contribution, respectively.

3. Water-energy-land analysis

For our water-energy-land analysis, this section compares existing conventional hydropower plants and proposed SPS plants in Brazil. Brazil is one of the world's largest hydropower producers (installed capacity of 98 GW [94]) with substantial potential for expansion (260 GW [95]), yet many developments have received substantial (and often justified) criticism for negative environmental and social impacts. Additionally, recent SPS assessments for Brazil have been conducted [69], facilitating their comparison. In Section 3.1 we compare the existing Sobradinho reservoir (Fig. 3(a)) and the proposed Muquém SPS reservoir (Fig. 9). Then we make a systematic assessment of 61 existing and planned CRD and 13 proposed SPS plants (Section 3.2).

3.1. Comparison of Sobradinho CRD and Muquém SPS

The proposed Muquém SPS plant consists of a 15 km tunnel that takes the water from the São Francisco River, at an altitude of 410 m, and stores it in the Muquém SPS reservoir. The reservoir consists of a dam 2.7 km long and 230 m high with a water level variation of 150 m (700–550 m above sea level).

The minimum required pumping/generation capacity, operating at full capacity, to fill the Muquém SPS reservoir in 6 months is 1.3 GW. This would allow the reservoir to fill up during the wet period and empty during the dry period. If the Muquém SPS plant were also designed to store energy from intermittent renewable energy sources, the capacity of the plant would have to increase to, for example, 2.1 GW in order to give it more operational flexibility. The pump-turbines will then be used for seasonal, weekly and daily storage cycles according to

Table 6
Qualitative assessment of the main characteristics of multi-purpose SPS applications and their respective pumping/generation heads.

Pumping/Generation head & storage years	Description**	Multi-purpose SPS applications*												Country/(Number of existing SPS projects)/[References]
		Energy						Water					LR	
		PG	IS	TO	HP	ES	HO	WS	ER	TW	BT	FC	LR	
High (500–800 m) multiple years storage	Store water at a reservoir close to full with a high level variation (100–150 m) to reduce flooded area and evaporation, use the water in case of a drought or an energy crisis and use the turbines for energy storage. The upper reservoir has multiple years of storage capacity.	•••	•••	•••	•••	•••	•	•	•••	•	•	•	•	Norway (3) [73,74], Sweden (1) [75].
High (500–800 m) one year storage	Store large quantities of excess energy from intermittent sources of energy; peak hour generation; hydropower generation. The upper reservoir fills up and empties in a yearly cycle.	•••	•••	•••	•••	•••	•	•	•••	•	•	•	•	Austria (6) [66,76–78] Switzerland (7) [79–82].
Medium (100–500 m) multiple years storage	Store energy from intermittent renewable generation and for peak generation in a large upper reservoir close to full, and release the water in case of a drought or in case of an energy crisis. The upper reservoir has a three years or more storage capacity.	••	••	••	••	•••	••	•••	••	•••	•••	••	••	New Zealand (0) [83], Iceland (0) [84], Canada (0) [85,86] and Brazil (0) [69,87,88], Australia (0) [89], USA (1) [90,91].
Medium (100–500 m) one year storage	Provides similar services as CRD, where there is no appropriate location to build CRD. I.e., optimize hydropower generation, water supply. The upper reservoir fills up and empties in a yearly cycle.	••	••	••	••	••	••	••	••	••	••	••	••	Canary Islands (1) [18,92].
Low (50–100) multiple years storage	Store large amounts of water for flood control and use the stored water for hydropower optimization and water supply. In this case, the SPS would operate similarly to a CRD with pump back storage.	•	•	•	•	•	•••	•••	•	•••	•••	•••	•••	USA (1) [93].

* The number of "•" represents the importance of the aspect in the SPS project. Where, "•" represents a small contribution, "••" represents a medium contribution, "•••" represents a high contribution. The abbreviation are: Peak Hour Generation (PG), Intermittent Generation Storage (IS), Transmission Optimization (TO), Hydropower (HP), Energy Security (ES), Cascade Hydropower Optimization (HO), Water Supply (WS), Evaporation Reduction (ER), Transport with Waterways (TW), Inter-Basin Transfer (BT), Flood Control (FC), Land Requirement (LR).

** This analysis assumes SPS projects with tunnels 5 km or longer and does not include pump-back storage projects. The comparison of different heads assumes that the projects have the same water storage volume. The change between one year storage and multiple years storage, is an increase in water storage volume.

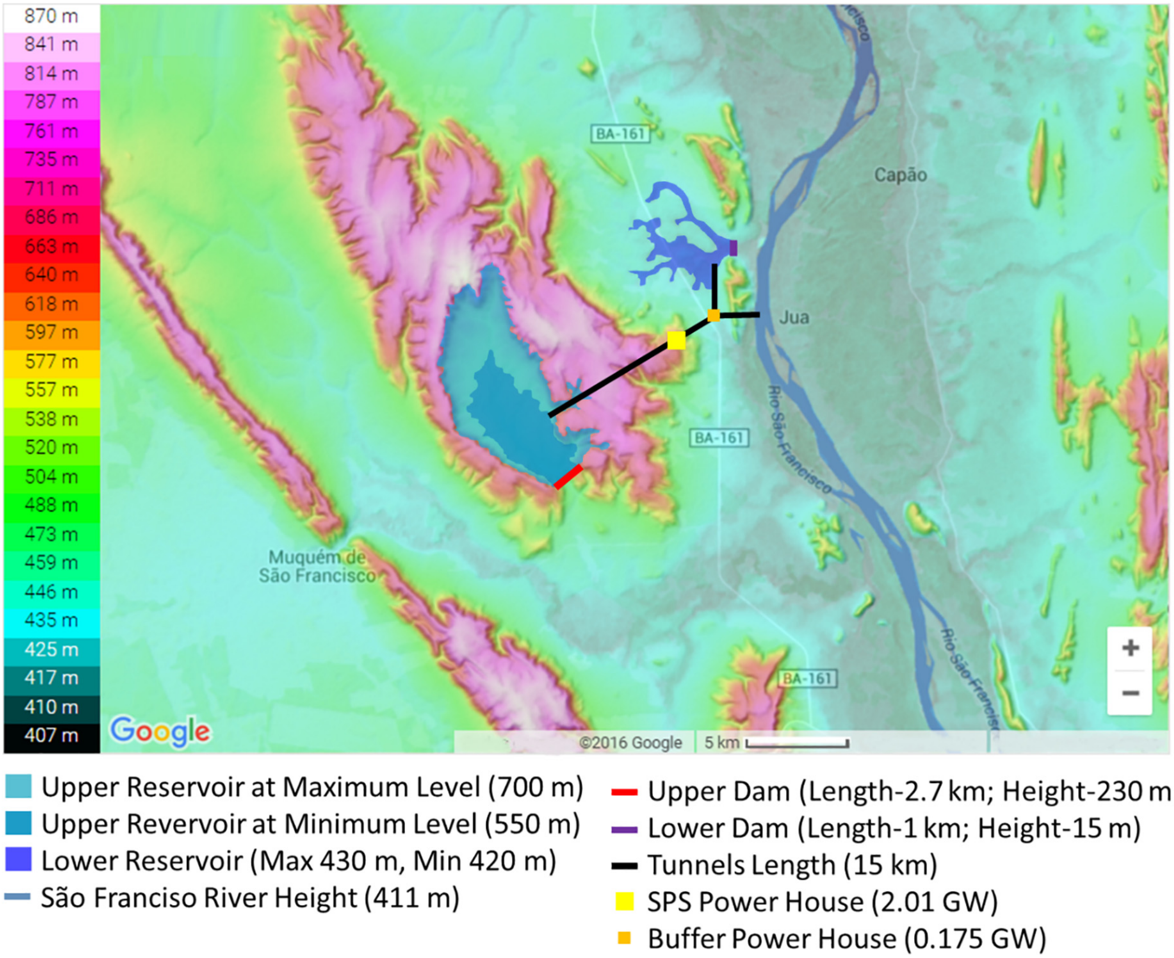

Fig. 9. Proposed Muquém SPS in the São Francisco River operating with seasonal, weekly and daily cycles [53] (map).
adapted from [96]

the energy and water needs.

As the Muquém SPS does not have a reservoir dam in the main river and the plant would also be used to store intermittent renewable sources, a lower regulating reservoir, with a small water storage volume, is required for daily and weekly storage cycles. This reduces the impact of the SPS operation on the São Francisco river flow, as presented in Fig. 7, i.e., the seasonal storage cycle between the upper reservoir and the river will not be affected by the daily and weekly cycles between the upper and lower reservoirs of the SPS plant. In this way, Muquém SPS would actually be a Run-of-the-River SPS plant (RRSPS), but it is called SPS to generalize the comparison.

Table 7 presents a comparison between the existing Sobradinho CRD with the designed average São Francisco river flow of 2.000 m^3/s, a proposed Sobradinho CRD to operate with a river flow of 600 m^3/s, a proposed Muquém SPS operating only with a seasonal cycle and another operation with seasonal, weekly and daily cycles. It should be noted that the seasonal Muquém SPS, does not include the lower reservoir. This is because there are no weekly and daily storage cycles. Table 7 shows that the Muquém reservoir stores around 22 times more water and 37 times more energy per land use than the existing Sobradinho reservoir. Water and energy losses due to evaporation are, respectively, 22 and 21 times smaller in the Muquém than in the Sobradinho reservoir. The Sobradinho and Muquém reservoirs locations are shown in Fig. 11.

Fig. 10 presents an extended comparison of the costs and gains from the Sobradinho CRD and Múquem SPS plants. This analysis compares costs in both storage alternatives if they were built from scratch, i.e., as if the current Sobradinho dam did not exist. It should be noted that other gains such as transmission optimization, water supply, electricity grid ancillary services (frequency adjustment [98,99], harmonics reduction) was not included in the analysis and would additionally contribute to the viability of the projects. Furthermore, environmental and social impacts were not comprehensively included in the analysis. These impacts would considerably favor Muquém SPS, especially due to the smaller land requirement and for avoiding damming of the São Francisco River. The assumptions applied in Fig. 10 are detailed in Appendix A.

As the evaporation and land costs ($USD 2.10[3] and 1.90 billion, respectively) of Sobradinho CRD operating with today's flow (600 m^3/s) adds up to $USD 4.0 billion and the revenues to $USD2.54b, the overall costs of operation Sobradinho CRD are higher than its revenues by $USD 1.46b. As it is important to regulate the flow of the São Francisco River, a profitable and sustainable solution would be to stop operations at Sobradinho CRD and construct Muquém SPS operating with seasonal, weekly and daily cycles. This would optimize hydropower generation downstream, store energy from intermittent source and for peak generation and greatly reduce surrounding environmental impacts.

Comparing the costs ($USD 7.28b) and revenues ($USD 7.96b) of the Muquém SPS project with multiple cycles, it was found an overall profit of $USD 0.67b. This shows that SPS is a better alternative than CRD to regulate the lower section of the São Francisco River.

[3] The costs and revenues assume values from 2017.

Table 7
Comparison between Sobradinho and Muquém reservoirs [53].

Characteristics	Sobradinho designed*	Sobradinho proposed	Muquém seasonal	Muquém S, W, D
Status	Existing CRD and designed operation	Proposed CDR for actual operation	Proposed SPS	Proposed SPS
Storage operation	Seasonally	Seasonally	Seasonally	Seasonally, Weekly and Daily
Generation/pumping capacity (MW)	1050/–	250/–	1050/945	2100/1890
Mean annual river flow (m^3/s)	2000	600	600	600
Reservoir maximum level (m)	392.5	385.7	700	700
Reservoir minimum level (m)	380.5	380.5	550	550
Downstream level (m)	365	365	411	430 & 411
Level variation (m)	12	5.2	150	150
Dams height (m)	32	25.2	230	230 & 30
Dams length (km)	5.5	5.0	2.7	2.7 & 0.7
Tunnels length (km)	–	–	12	15
Generation/pumping flow (m^3/s)	4278	1245	958/862	1916/1724
Buffer generation/pumping capacity (GW)	–	–	–	0.175/0.158
Buffer generation/pumping flow (m^3/s)	–	–	–	958/862
Capacity factor (%)	50	50	70**	64**
Flooded area (km^2)	4214	2085	52	52 & 17
Useful stored volume (km^3)	28.7	7.8	7.8	8.1
Energy storage (TWh)	21.7	5.9	10.0	10.1
Brazilian energy storage share (%)	10.7	2.9	4.8	4.8
Water loss due to evaporation (m^3/s)	168***	105.7	1.2****	1.6****
Energy loss with evaporation (TWh/y)	4.04	2.54	0.05	0.07
Land per energy storage (km^2/TWh)	194	353	5.2	6.8
Land per water storage (km^2/ km^3)	147	267	6.7	6.8
Energy and water storage ratio (TWh/km^3)	0.76	0.75	1.28	1.25

* The designed flow of the São Francisco River for Sobradinho dam is 2.000 m^3/s. The current river flow is 600 m^3/s, due to the prolonged drought since 2012.

** The capacity factor of pumped-storage varies considerably with the needs for storage. For a seasonal storage cycle the capacity factor is around 70–50%, for intermittent energy storage is 60–30% and for a daily cycle is 40–20%. Assuming that the Muquém SPS plant operates with a combination of seasonal, weekly and daily storage, it is assumed a 64% capacity factor. Notice that with 40% capacity factor, the SPS will be operation at approximately 20% of its capacity in pumping mode and 20% in generation mode. The capacity factor of the SPS is particularly important to estimate the tunnels investment. The higher the capacity factor, the more the plant will be used, and the thicker the tunnels should be to reduce losses due to friction.

*** The yearly historical average evaporation in the Sobradinho reservoir is 168 m^3/s. The yearly average evaporation of the Sobradinho reservoir assuming it operates at its lowest head is 72.3 m^3/s. The estimated evaporation from the reservoir with maximum flooded area of 2085 is 105.7 m^3/s [53].

**** The evaporation at Muquém Reservoir per area was assumed to be the same as the one in the Sobradinho reservoir per area. However, with a lower atmospheric pressure and lower temperatures (due to higher altitude) and similar radiation, it is expected that the Muquém Reservoir has a lower evaporation rate per area than the Sobradinho reservoir [97].

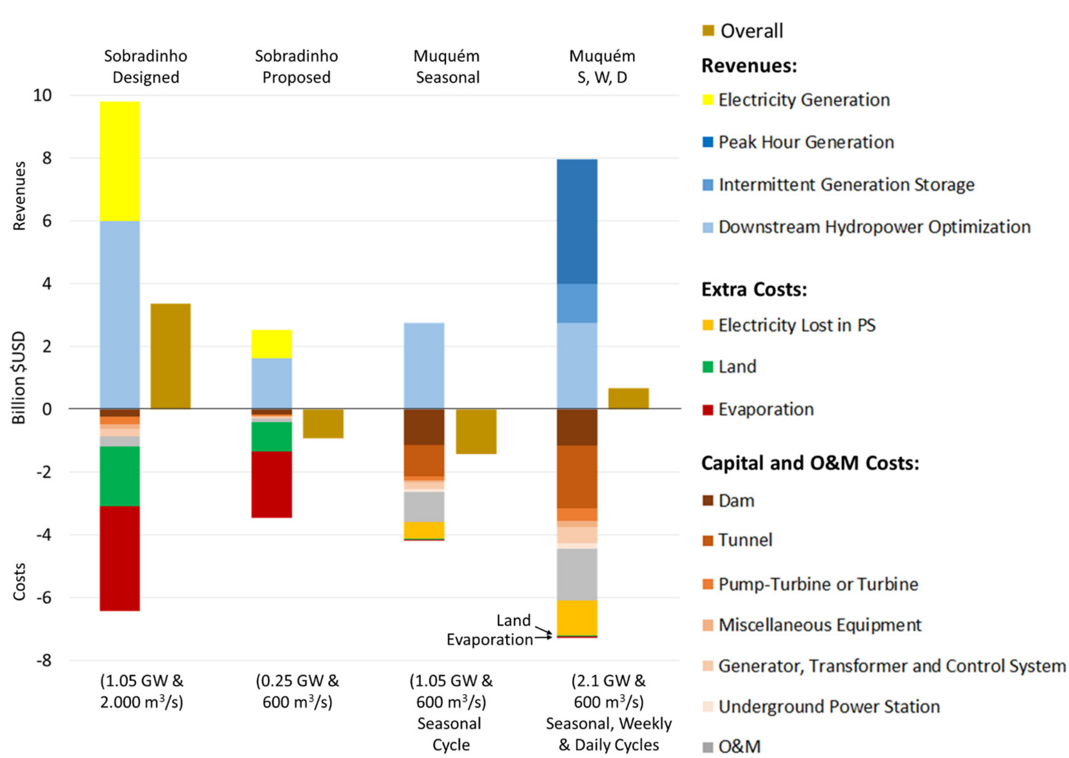

Fig. 10. Overall cost estimates for Sobradinho CRD with 2000 m^3/s (1.05 GW) and 600 m^3/s (0.25 GW) and Muquém SPS plant with 1.05 GW and 2.10 GW generation capacities over 40 years.

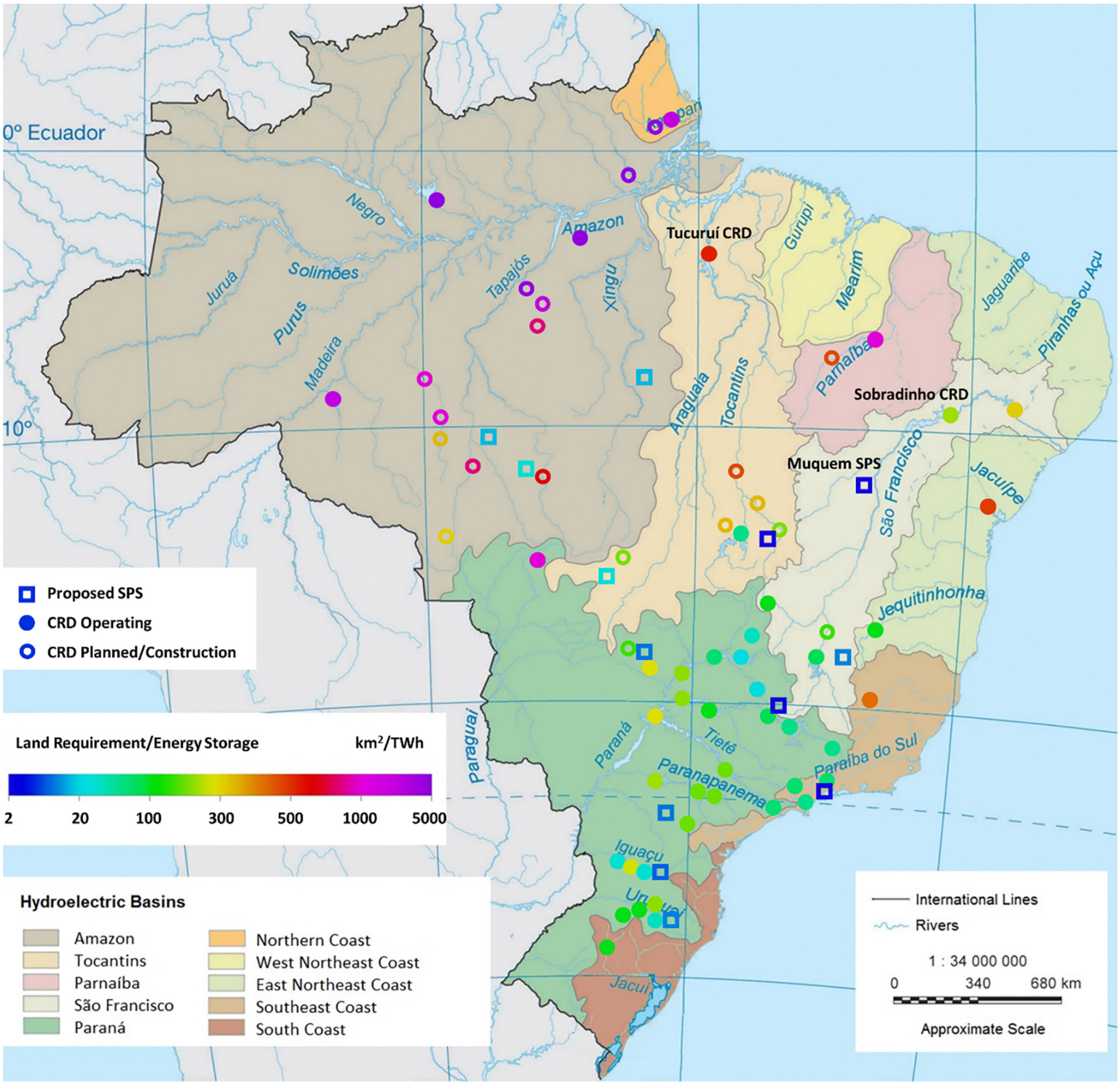

Fig. 11. CRD and SPS reservoir land requirement for energy storage.

3.2. Systematic assessment of Brazilian CRD and SPS plants

For our systematic assessment of Brazil we compare the most important conventional reservoir dams with proposed seasonal pumped-storage plants from a land, water storage and energy storage perspectives. The assessment combines data from two key sources: the Brazilian National Grid Operator (ONS) [100] for the conventional reservoir dams under operation, in construction and being planned; and, a recently published assessment of SPS potential sites in Brazil [69].

The comparison reveals large differences in the amount of land required to store a given amount of energy from both SPS and CRD technologies (Fig. 11). The land requirements of conventional reservoir dams are orders of magnitude higher than SPS plants to store the same amount of energy.

Whilst this is generally true across the country, regional comparison reveals stronger trends. Comparing conventional reservoir dams in the Southeast region in Brazil with dams in the Amazon region, dams in the Amazon require very large areas to store small amounts of energy [101]. Despite the high water availability, the topography of the Amazon basin is flat and not appropriate for the construction of conventional reservoir dams. However, there are locations on the mountains surrounding the rivers in the Amazon basin where SPS plants can be built with low land requirements to store large amounts of energy and water.

Overall, the land use in SPS reservoirs for energy and water storage is in general 1–2 orders of magnitude smaller than in conventional reservoirs (Fig. 12). Thus, the environmental and social impacts, and evaporation of SPS reservoirs are also 1–2 orders of magnitude smaller than in CRD. Additionally, SPS reservoirs are not located on the main rivers, but in fact built on tributary rivers, thus usually resulting in smaller impacts. Fig. 12 is divided in the South & Southeast (Green), and Amazon and Northeast (Red) regions of Brazil. This is because the South and Southeast regions have more appropriate topography to build CRD. On the other hand, the Amazon and Northeast region do not have appropriate topography.

The impact of land requirements can vary according to the uses of the land, one key indicator being the population density impacted at the reservoir location. Using the 2010 gridded population density estimates from Jones and O'Neil (2016) at 0.125° spatial resolution [102] (approximately 12 km at the equator), we compared the impacted population density with the energy storage from three groups of storage reservoirs from Brazil (Fig. 13). The two groups of conventional

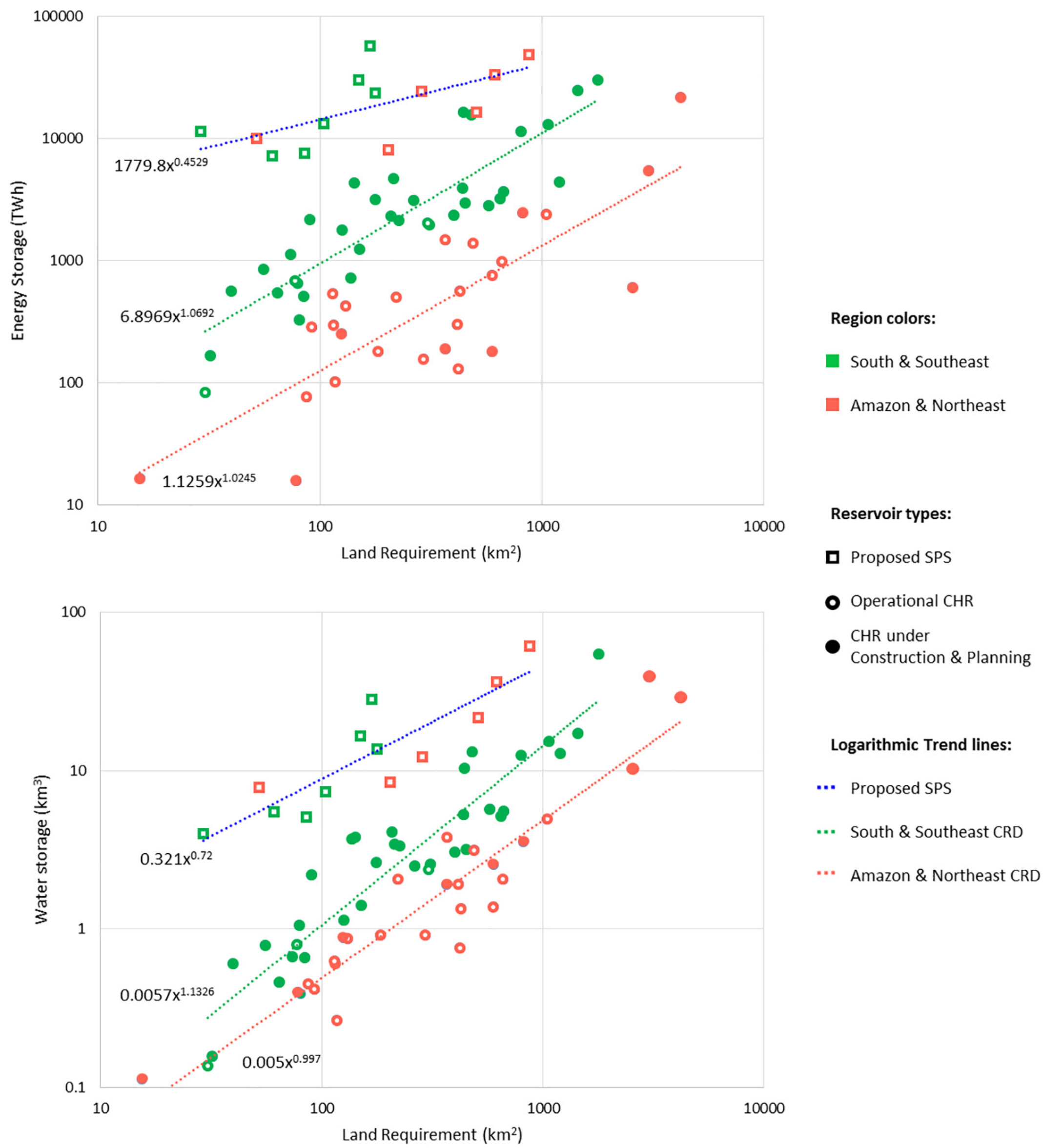

Fig. 12. Comparison between energy storage (upper graph) and water storage (lower graph) and land requirement in CRD and SPS in Brazil.

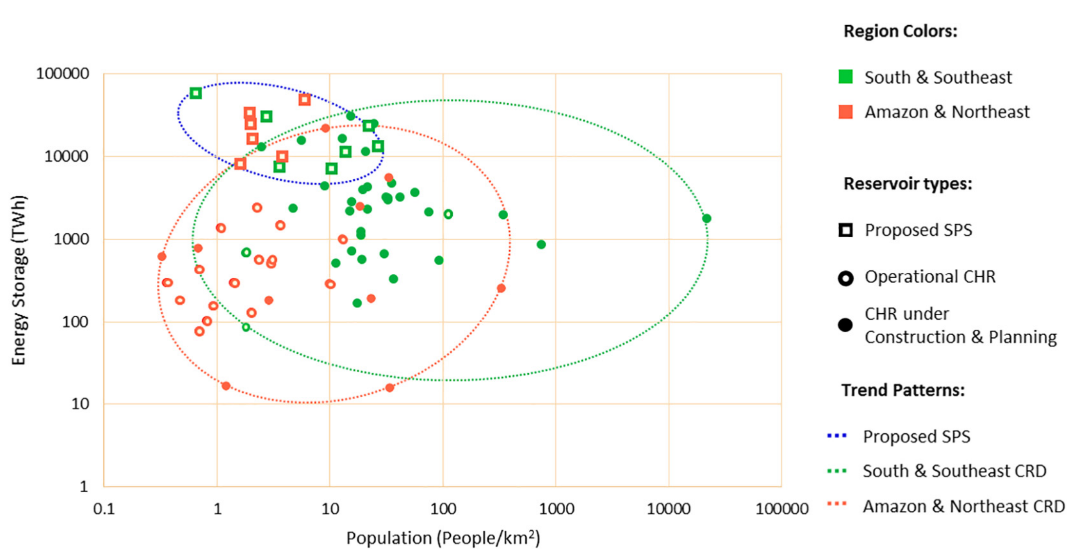

Fig. 13. Comparison between energy storage and population density in CRD and SPS in Brazil.

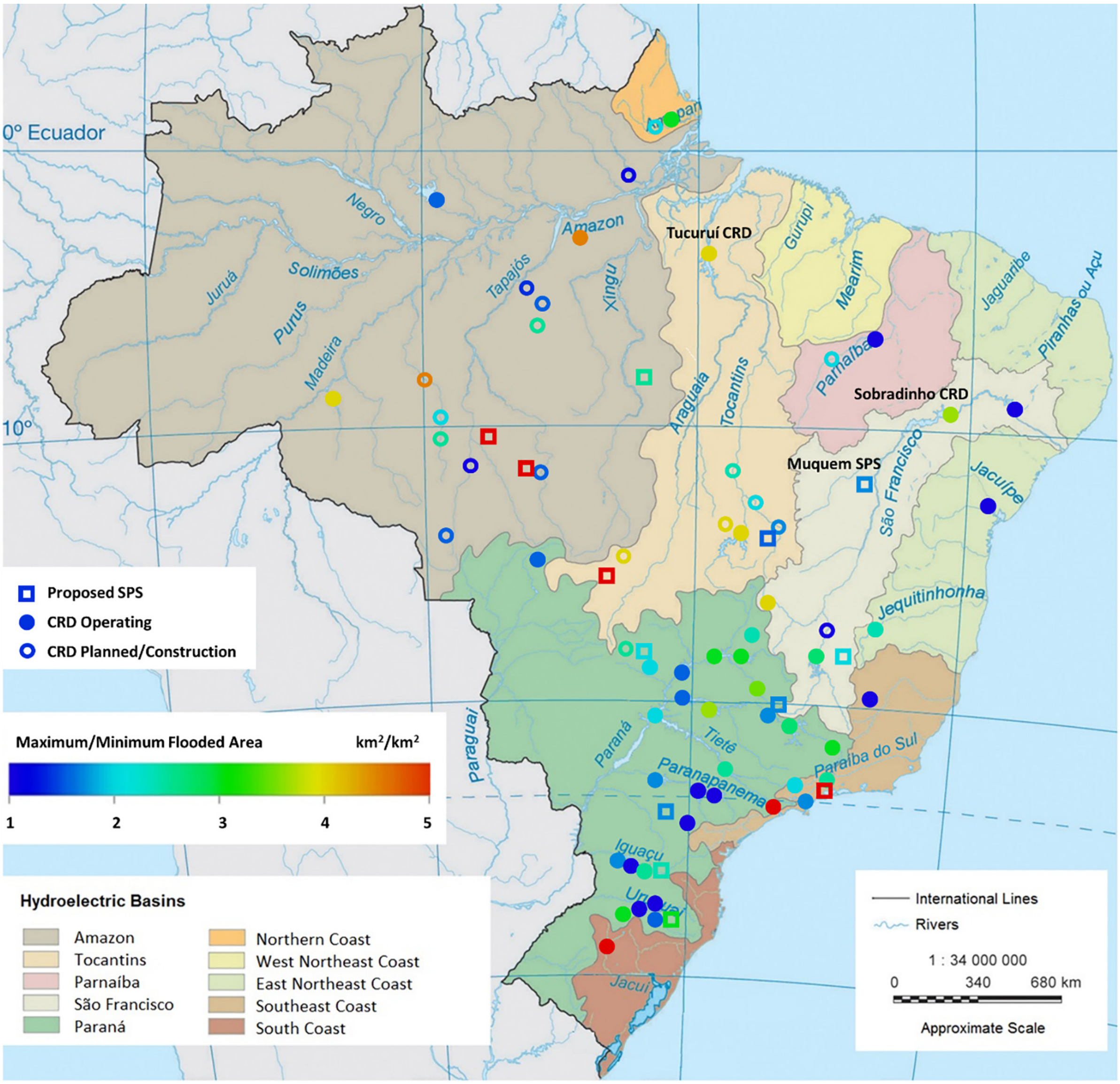

Fig. 14. Ratio between reservoir maximum and minimum flooded area ratio for CRD dams and SPS, representing the difference between the full and seasonal minimum capacity.

reservoir dams (with traditionally large flooded areas) span a wide range of population density for similar energy storage capability, whilst the SPS projects present the potential for an order of magnitude greater energy storage.

Comparing SPS with CRD in the Amazon, Tocantins and Northeast regions, for similarly low population densities (median 3.6 and 2.3 people/km^2 respectively), SPS delivers 2–3 orders of magnitude more energy storage. Whilst when SPS is compared with the CRD in the South and Southeast, SPS delivers an order of magnitude more energy storage in locations where population density impacted is an order of magnitude lower, with a median of 20.6 people/km^2. This lower social impact of SPS is mainly due to the fact that they are built in tributary rivers, where population density tends to be smaller than in main rivers.

Fig. 14 presents the comparison between the maximum and minimum flooded area in storage reservoirs. It should be noted that the reservoir dams at the head of the river are designed mostly as storage reservoirs. These reservoirs usually have large flooded area variations. The dams that are located in the middle of the river, are designed to have both a high generation head and some storage capacity. Thus, the flooded area/energy storage ratio is high (bad), but the maximum and minimum flooded area ratio is low (good). It should be noted that some of the SPS reservoirs taken from [69] have large flooded area variations. This is not convenient as emptying the reservoir would greatly impact the fauna, flora and communities surrounding the reservoir. The proposed SPS projects should take into account maximum and minimum flooded area ratio and reduce it as much as possible, leaving a considerable amount of water in the reservoir to lower their impacts.

4. Conclusions

This article compares the usage of CRD and SPS reservoirs in Brazil looking at the water-energy-land nexus. Whilst the main benefit of conventional reservoir dams is the possibility of storing all the water flowing within the river, there are limited locations with appropriate topography and low socioeconomic and environmental impacts. The main benefits of seasonal pumped-storage reservoirs are small flooded areas and evaporative losses, whilst providing water and energy storage in locations where conventional reservoir dams are not viable. The main challenge for SPS plants is the inlet flow limitation of the SPS pumping capacity, the tunneling for pipelines, and the larger dam required, resulting in higher costs than CRD.

This study found that SPS results in reduced evaporative losses, and can be used for water management, flood control, waterways transport, hydropower generation optimization, peak hour electricity generation, storage of intermittent renewable generation, electricity transmission optimization, inter-basin transfer and to increase energy security. SPS should be designed as a multi-purpose plants to deliver these services.

This paper concludes that SPS in general requires 1–2 orders of magnitude less land than CRD to store similar volumes of water and energy. In our analysis, we concluded that if Sobradinho CRD was constructed today, it would contribute to an overall economic loss of $USD 1.46 billion. A possible solution would be to stop operation at Sobradinho CRD and construct Muquém SPS with multiple storage cycles, which results in economic gains of $USD 0.67 billion. Future work will look at the world potential for SPS considering world topographical and hydrological data.

Acknowledgements

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Appendix A. Cost estimation

The assumptions applied in Fig. 10 are detailed below:

- Capital costs estimates, such as dam, tunnel, pump-turbines, generator, transformer, control systems, miscellaneous equipment, underground power station, were calculated using [103].
- O&M costs were assumed to be 2% of the investment costs per year of operation, not including land costs [104].
- It is assumed a 40 years plant operation, 4.5% interest rate, which accounts to a discount factor of 18.4 years. The discount factor is applied to “Electricity Generation”, “Peak Hour Generation”, “Intermittent Generation Storage”, “Downstream Hydropower Optimization”, “Electricity Lost in PS”, “Evaporation” and “O&M” costs.
- Land cost is estimated to be 4100 $USD/ha, which also includes reservoir preparation [105].
- Electricity cost outside peak hours is estimated to be $USD 40/MWh.
- Electricity cost during peak hours is estimated to be $USD 200/MWh.
- Efficiency of the pumped storage process is 80%.
- The Muquém SPS with 2.1 GW operation integrates several applications. The capacity factor is divided in: 0.35 for seasonal storage, 0.163 for intermittent renewables storage and 0.13 for peak hour generation, which results in a 0.64 final capacity factor.
- Given that water costs are very small at the São Francisco basin (0.01 $USD/m^3) [106], evaporation costs are estimated to be the loss of electricity generation in the dams in cascade due to evaporation. The generation head of the dams in cascade is 280 m, not including the Sobradinho dam (27 m generation head) [100].

Given that Brazil does not establish a price on energy storage and the estimation of a price would involve complicated modelling of the Brazilian electricity sector, it was assumed that energy storage costs a third of electricity costs. Apart from contributing to downstream hydropower optimization, energy storage contributes to the energy security of the system.

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