



## Research Papers

## Mapping the potential for pumped storage using existing lower reservoirs



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## ABSTRACT

The increasing utilization of wind and solar power sources to lower CO<sub>2</sub> emissions in the electric sector is causing a growing disparity between electricity supply and demand. Consequently, there is a heightened interest in affordable energy storage solutions to address this issue. Pumped Hydropower Storage (PHS) emerges as a promising option, capable of providing both short and long-term energy storage at a reasonable cost, while also offering the advantage of freshwater storage. To identify potential PHS locations in Brazil existing hydroelectric reservoirs as the lower reservoirs, we employed an innovative methodology that combines (i) plant-siting model that leverages high-resolution topographical and hydrological data to identify the most promising sites for further studies. (ii) An economic methodology was applied to configure PSH projects identified by the plant-siting model in terms of their installed capacity and discharge time, and to select the most attractive projects. (iii) A comprehensive analysis of the socio-environmental impacts of the projects was carried out, which enables the elimination of projects with severe impacts. Results created a ranking of 5600 mutually exclusive projects by net present value (NPV). The highest NPV is 2145 USD which refers to a PHS plant in the Doce Basin and Salto Grande dam as the lower reservoir. The upper reservoir stores 0.36 km<sup>3</sup> of water and a 75 m high dam, the PHS has a 2 km tunnel, a 1 GW power capacity and discharge rate of 220 h. The paper shows a vast potential for weekly, monthly, and seasonal PHS with existing lower reservoirs in Brazil.

## 1. Introduction

The need to reduce CO<sub>2</sub> emissions and alleviate the effects of climate change has led to an increased demand for short and long-term energy storage services. Among the available energy storage technologies for grid management, pumped hydropower storage (PHS) systems stand out as the most mature and extensively employed method for large-scale electricity storage [1–8]. The total installed PHS energy producing capacity is roughly 165 GW, and it accounts for the great bulk of global electricity storage, with 25 GW defined as mixed plants that are also conventional reservoir-based hydropower plants [9]. PHS is sometimes regarded as a technology capable of storing energy for daily or weekly

cycles, as well as up to months [10–15]; nevertheless, the technology can also work over annual and pluri-annual cycles [16,17]. Given the ongoing cost reductions in competing technologies that enable daily energy storage (especially batteries), PHS is expected to gain traction as a seasonal energy and water storage alternative. Other seasonal energy storage alternatives are described in [18–22].

PHS plants in the Europe, Japan and USA have seen an abrupt reduction in construction after the collapse of the Soviet Union in 1991 (Fig. 1). This is because of the cheap availability of natural gas in global markets. PHS then lost its position as the cheapest alternative to supply flexible electricity to natural gas [23]. In the current geopolitical landscape marked by the war in Ukraine, a substantial surge in natural gas

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Fig. 1. Historical PHS installed capacity in the USA, Europe, Japan and China. Adapted from [25,26].

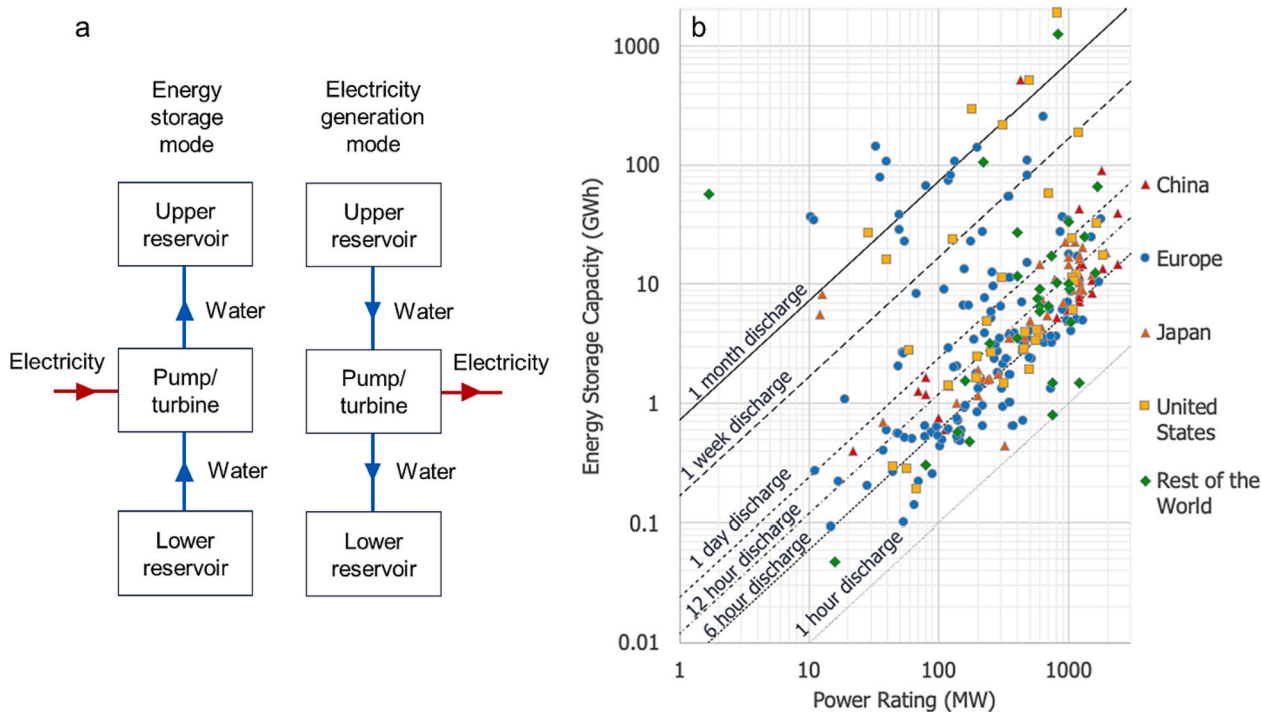


Fig. 2. (a) Block diagram describing the operation of PHS plants, (b) Discharge durations in relation to the installed capacity and energy storage capacity are documented for approximately 250 operational pumped storage stations. [26].

prices, and the resurgence of polarized international relations, pumped hydropower storage (PHS) and other energy storage technologies are poised to reclaim their position as the most cost-effective solution for delivering flexible electricity in certain regions of the world [24].

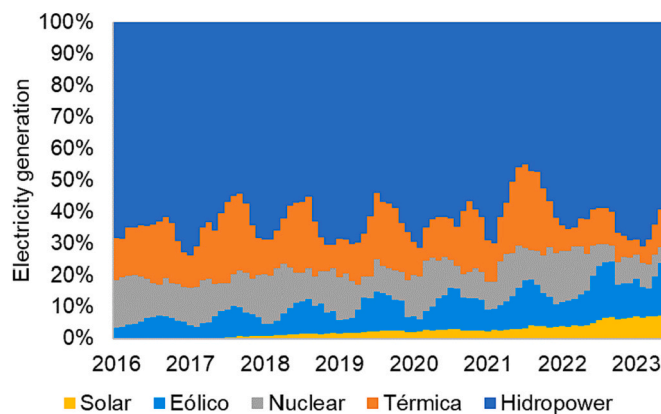
Fig. 2a presents a block diagram of PHS plants, showing that energy is stored by pumping water from a lower reservoir to an upper reservoir and electricity is generated when water passes through the turbine. With the recent competition with other energy storage alternatives, PHS will soon lose its position as the cheapest alternative for an hourly and daily energy storage for batteries [27–30] and possibly other energy storage alternatives. Until the end of the century when the costs of hydrogen (H<sub>2</sub>) and synthetic fuels decrease, pumped hydropower storage (PHS) will continue to serve as the most affordable option for weekly, monthly, seasonal, and pluriannual energy storage [31–33]. Currently, most pumped storage stations have discharge durations between 6 and 24 h (Fig. 2b) [26]. However, in the future, more and more PHS plants might be built to store variable energy at the weekly, monthly, seasonal and

pluri-annual scale. PHS reservoirs can also be used for other storage needs, in particular: i) water for drought alleviation, ii) flood control and iii) energy and water security in a changing climate.

To better estimate the global potential of PHS to meet future energy and water storage needs, several research have been undertaken. In a study conducted in [34], the global potential of pumped hydropower storage (PHS) was assessed by considering the construction of two reservoirs in a closed loop system, primarily targeting daily and weekly operations. The study calculated a worldwide potential of  $23 \times 10^6$  GWh across >600,000 plants. However, the projected sizes of these plants may be deemed unrealistic or unfeasible for applications involving seasonal storage or water availability due to a lack of thorough cost analysis and assessment of water resources [34]. Other research endeavors have explored the feasibility of PHS initiatives in specific regions, such as Europe [35–37] and Iran [38]. Nevertheless, these regional models often overlook cost estimations, failing to provide comprehensive insights into the economic viability of such projects.

**Table 1**  
Pumped hydropower storage mapping efforts in the literature.

Institute	PHS arrangement	Scope	Methodology	Cost	Year	Reference
IIASA	Seasonal PHS, river as lower reservoir	Global	One upper reservoir dam (single, straight dam reservoir)	Yes	2020	[39]
MIT	Integrated Pumped Hydro Reverse Osmosis systems	Global	Altitude and distance comparison	No	2016	[40]
Australian National University	Closed loop PHS, two new reservoirs	Global	Scan flat areas (circular dams)	No	2021	[34,41,42]
University of Stuttgart	Two existing reservoirs, existing lower reservoir, ocean as lower reservoir and river as lower reservoir	Regional: Chile, Bolivia and Peru	Scan flat areas (circular dams)	Yes	2021	[43]
North China Electric Power University	Two existing lakes	Regional: Tibet Plateau	Altitude and distance comparison	No	2023	[44]
University of Chinese Academy of Sciences	Two existing reservoirs, one existing reservoir	Regional: Tibet Plateau	Altitude and distance comparison, One upper reservoir dam	No	2017	[45]
IIASA	Seasonal PHS and hydropower, river as lower reservoir	Regional: Indus Basin	One upper reservoir dam (single, straight dam reservoir)	Yes	2021	[46]
NTNU SINTEF	Two existing lakes	Regional: Norway	Altitude and distance comparison	Yes	2013	[47,48]
Al-Azhar University	Existing lower reservoir and river as lower reservoir	Regional: Egypt	Altitude and distance comparison	No	2021	[49]
PSL Université Paris	Two existing reservoirs, one existing reservoir and one depression, two depressions	Regional: France	Altitude and distance comparison	Yes	2017	[36]
NREL	Closed loop PHS, two new reservoirs	Regional: USA	Scan flat areas (circular dams)	Yes	2022	[50,51]
GESEL	Daily and seasonal PHS, river as lower reservoir	Regional: Brazil	One upper reservoir dam (single, straight dam reservoir)	Yes	2021	[52–54]
European Commission, DG JRC	Two existing reservoirs, one existing reservoir	Regional: Europe	Altitude and distance comparison, Scan flat areas (circular dams)	No	2014	[35,37]
Lappeenranta University of Technology	Two existing artificial reservoirs, one existing reservoir, ocean as lower reservoir	Regional: Iran	Altitude and distance comparison, Scan flat areas (circular dams)	No	2019	[38]
University College Cork	One existing reservoir	Regional: Turkey	Scan flat areas (circular dams)	No	2012	[55]



**Fig. 3.** Monthly percentage electricity generation in Brazil by sources from 2016 to 2023.

Table 1 reviews the existing pumped hydropower storage mapping efforts in the literature.

The limitations of the most applied methodologies are described as follows: (i) scan flat areas, proposes two circular reservoirs in a closed loop plant. This PHS arrangement is limited to daily storage plants because the plants might be far from water sources and the cost of circular dams is prohibitively expensive for more than daily storage plants. These types of plants will soon not compete with batteries. (ii) altitude and distance comparison, gives a good estimate for the plant power costs, however, it does not allow the calculation of energy storage costs for the plant. (iii) single, straight dam reservoir, is the methodology applied in this paper and consists of building a straight dam, connect to a reservoir and flood it. It allows us to build large and cheap upper reservoirs and to estimate its cost. This paper upgrades the existing methodology with higher resolution, applies it for the first time in existing lower reservoirs, instead of rivers, and combines the technical potential with economic and environmental analysis for the Brazilian energy grid and legislation.

Fig. 3 presents the monthly percentage electricity generation of Brazil by source from 2010 to 2020. It shows that solar and wind generation have increased significantly and reached 24 % of total

generation in June 2023, which is a significant share of the power generation in the country [56]. The increase in these variable sources of electricity will also increase the demand firm capacity such as biomass [57] or energy storage solutions in the country in the future. Today the energy storage capacity of the country is practically zero, with no grid scale pumped hydro storage or batteries storage plants. This paper upgrades the global model for seasonal pumped storage [39] and Indus Basin model [46] and applies it to map seasonal, monthly, weekly and daily PHS project with existing lower reservoirs in Brazil. The paper is also the first to describes an economic methodology to rank the proposed PHS projects according to their net present values applied to the Brazilian electricity grid and an environmental methodology to classify projects according to Brazilian legislation. Section 2 describes the methodology of the model, including model upgrades. Section 3 presents the results of the model, which includes an interactive map and the data that is made available for download. Section 4 concludes the paper.

## 2. Methodology

The methodology employed in this paper can be divided into three primary components, as illustrated in Fig. 4. The first stage involves mapping the technical potential of pumped hydropower storage (PHS) utilizing the existing lower reservoirs in Brazil. It consists of finding existing reservoirs, creating potential PHS reservoirs, calculating their storage capacities and costs. The second stage involves: i) Configuring each project for its optimal installed capacity. This refers to the capacity that yields the maximum Net Present Value (NPV) for each storage identified in the first stage. This configuration takes into account the installed capacity unit costs estimated in the first stage for each storage and the economic benefits of storage projects to the system based on discharge time. ii) Ranking each project based on its NPV. iii) Selecting the best non-mutually exclusive projects. This means choosing the project with the highest NPV from each group of projects that have overlapping storage. Projects are optimized Net Present Value for each project is calculated using costs estimated in the calcu PHS plants with respect to their net present values, according to the need for power and energy storage capacity in the Brazilian grid. The economic benefits of storage projects were evaluated using a long-term system expansion and dispatch model designed for the Brazilian power system. Simulations were executed using Plexos 8.3, developed by Energy Exemplar. The

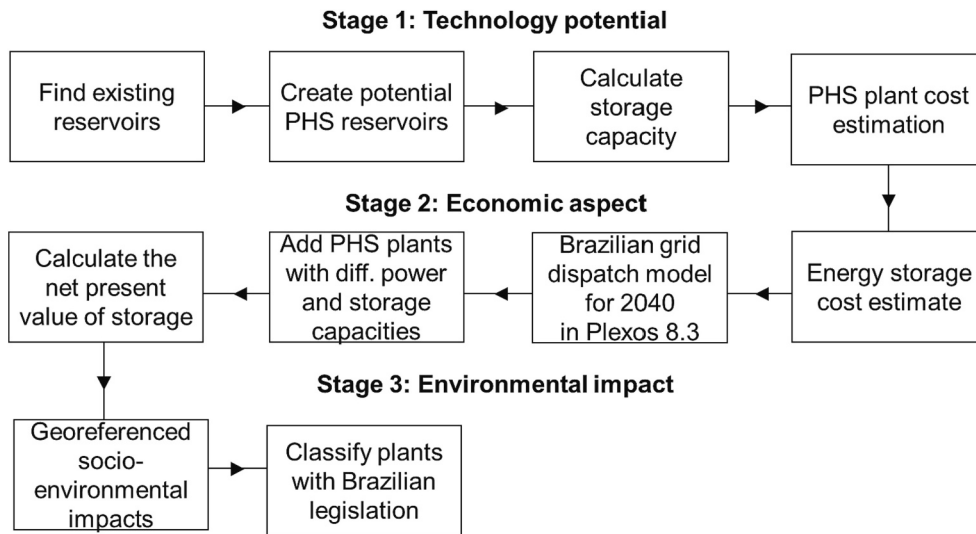


Fig. 4. Workflow of the methodology applied in the paper.

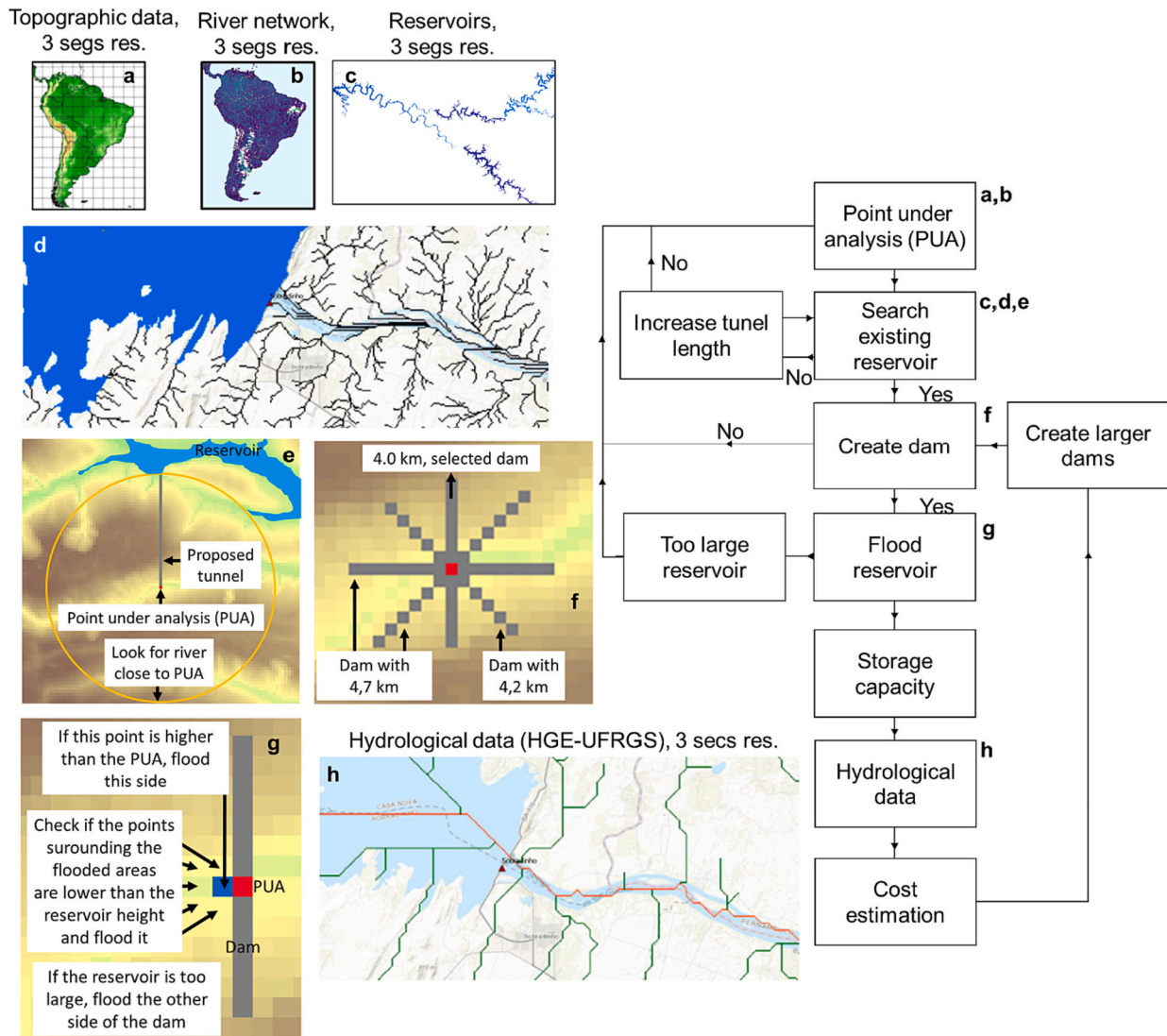


Fig. 5. Model framework for PHS mapping. (a) MERIT topographical data [58], (b), river network derived from ArcGIS, (c), existing hydropower reservoir data [59], (d), integration of the different databases, (e) searching existing reservoirs, (f) investigating potential dams, (g) flooding the reservoir, (h) adding hydrological data.

**Table 2**  
Overview of the data sources and methodologies utilized in the model.

Data and methods description	Comments	Reference
Topographical data (MERIT)	The old model used SRTM (Shuttle Radar Topography Mission), a Digital Terrain Model. The updated model uses MERIT (Multi-Error-Removed Improved-Terrain), a Digital Surface Model (DSM). The DSM excludes trees, buildings and other infrastructure from the topographical representation. The difference between both data is further explained in [64,65]. The old model has a resolution of 450 m* (15 s), which led to imprecise estimations of the length, height, and costs of the upper reservoir dam. This has been significantly improved with the use of 90 m* resolution (3 s). This upgrade is the most significant when compared to the old model.	[58]
River network	The river network data applied in the model was derived from the MERIT data using the ArcGIS software to estimate the catchment area of the river streams. Several steps were required to generate the flux accumulation raster from the elevation model. ArcGIS Pro 2.7 [60] and the Hydrology module (Spatial Analyst) were used to process these steps. The Hydrology module presents a set of tools for the ArcGIS system to support applications in water resources. Thus, the following variables were obtained: altimetry, flow direction, accumulated flow, drainage area. The resulted river network represents well rivers in mountainous regions, but not so well flat regions. This is not a problem for our application, because the lower reservoir is assumed to be an existing reservoir. The river network is used to limit the points under analysis in the model to valley locations, where a single, short, straight dam can form the upper reservoir. This significantly reduces the computational time of the model. For a better understanding of the hydrological network data in the model, the rivers were divided into 12 different levels (Strahler). If the river Strahler is small, the module restricts the flooded area of the reservoir so that the model does not waste too much time trying to fill large reservoirs. The reservoir data is used to locate the lower reservoirs considered in the model. These include large and small hydropower plants. Details such as altitude, river flow, reservoir name, catchment area are linked with each reservoir. Only existing reservoirs are considered as lower reservoir of the proposed PHS plant. The resolution of the data is 3 s. We used hydrology data from the Large-Scale Hydrology model (HGE-UFRGS), with 3 s resolution, annual hydrological data. This database is only for Brazil. The data represent the average flow from 1999 to 2009. As river network data does not match perfectly with hydrology data, a methodology to combine river network data with hydrological data was developed. The river flow of the lower reservoir assumes the highest flow that coincides with the reservoir.	–
Reservoir data (ANEEL)	To regulate the dimensions of storage reservoirs based on water availability, hydrological data was integrated into the model. This approach ensures that an adequate water supply remains accessible for filling the storage reservoir while minimizing any significant impact on river flow. To mitigate the potential impact of the pumped	[59]
Hydrological data (HGE-UFRGS)		[61]

**Table 2 (continued)**

Data and methods description	Comments	Reference
Pumped storage costs	hydropower storage plant on the natural flow of the river, a cautious storage value was adopted. In this work, a maximum volume available for river capture is equivalent to 50 % of the annual flow. Detailed cost data pertaining to pumped-storage facilities, including dam construction, tunnels, excavation, electrical equipment, and turbine costs, are provided in the cited reference [63]. The model primarily relies on the cost estimates proposed by this reference for accuracy. Additionally, the model assumes a singular construction design for each component of the pumped hydropower storage plant. This simplification is necessary since comparing various designs for each component to determine the optimum configuration would introduce significant complexity. Nonetheless, this approach allows for a reliable preliminary cost estimation. Regarding the dam construction, the model assumes an embankment dam design [52]. For tunnel construction, the model considers the drill and blast method, as illustrated in Fig. B.1.4. Penstock costs encompass both the excavation expenses (as shown in Fig. B.9.2) and the costs associated with embedded steel pipes (as depicted in Fig. M.6.C). Excavation costs vary based on the generation head and installed capacity, as indicated in Fig. B.10.1. The model adopts the Francis turbine design (as described in Fig. M.1.B and Fig. M.4.A), and the generator cost is outlined in Fig. E.8.2.A. To optimize the turbine/generator system, the costs associated with different rotation speeds (as depicted in Fig. E.1.1.A and Fig. E.8.1.B) are compared to the average generation head and flow rate under analysis, and the most cost-effective option is selected. It's important to note that the model proposes one turbine/generator system per tunnel. It is assumed a high land cost of 575,000 USD/km <sup>2</sup> to all regions. The optimization methodology employed for tunnel construction draws upon the approach outlined in [62]. This methodology involves a comprehensive comparison of capital costs associated with tunnel construction, including factors such as tunnel diameter and the number of tunnels, along with considerations of operational costs. The efficiency of the plant is significantly influenced by energy losses caused by friction within the tunnels. By increasing the diameter and number of tunnels, the overall efficiency of the plant improves, leading to reduced operational costs.	[52,63]
Tunnelling design		[62]

\* The distance measurement at the equator is adjusted to account for variations in latitude.

baseline scenario is a least-cost system expansion for 2040 without incorporating any prospective PSH plant candidates. Alternatively, several scenarios were analysed, each embedding a single PHS plant within the current system framework (without additional expansion or operational costs) maintaining a uniform power capacity but with differentiated storage capacities. The value of a storage project with a particular discharge duration was calculated by contrasting the total expansion costs (combining both investment and operational expenditures) of the scenario against the baseline scenario's total expansion cost. The third stage is to investigate the impact of these PHS projects in the environment and society. It consists of investigating georeferenced

**Table 3**  
Description of the stages in the PHS potential mapping model.

Model stages	Description
Point under analysis (PUA)	All points in the river network with a catchment area higher than 1 km <sup>2</sup> were analysed to find appropriate locations to site the upper reservoir dam.
Reservoir screening	This stage examines the distance between the Point Under Analysis and an existing lower reservoir. It verifies that the PHS upper reservoir is situated in a parallel river rather than the same river as the lower reservoir. If rivers within 1 to 12 km from the PUA are identified, the model proceeds to the next stage.
Dam screening	In this stage, the model generates four distinct dam orientations: west to east, north to south, northeast to southwest, and northwest to southeast. The height of each dam is adjustable and ranges from 50 to 250 m, with intervals of 25 m.
Reservoir side and flooding	During this stage, the model determines the appropriate side of the dam that should be flooded to create the reservoir. The decision is guided by the increase in catchment area, which helps determine the optimal reservoir side.
Reservoir storage capacity	After the storage reservoir is filled, the water level of the reservoir is adjusted to determine the curves depicting the relationship between the flooded area and the water level, as well as the storage volume and the water level.
Reservoir, hydrology comparison	The analysis includes hydrological considerations to constrain the water and energy storage capacities of PHS projects based on the availability of water in the main river. The maximum water storage capacity is capped at 50 % of the average annual river flow.
Estimate project cost	In this section, the costs of the project are computed, encompassing various components such as the dam, tunnel, powerhouse excavation, pump-turbine, electro-technical equipment, and land expenses.

**Table 4**  
Socio-environmental diagnosis guidelines in the preliminary studies stage.

	<ul style="list-style-type: none"> <li>- Indigenous lands</li> <li>- Rural and urban clusters</li> <li>- Quilombola remaining communities</li> </ul>
Excluding	<ul style="list-style-type: none"> <li>- Underground natural cavities</li> <li>- Archaeological sites and heritage sites</li> <li>- Environmental conservation areas or priority areas for biodiversity conservation</li> </ul>
High restriction	<ul style="list-style-type: none"> <li>- Suppression of primary vegetation or in the medium and advanced stages of regeneration of the Atlantic Forest biome</li> <li>- Areas with endemic or endangered species</li> <li>- Mining processes in the mining application and concession phase</li> </ul>
Medium restriction	<ul style="list-style-type: none"> <li>- Rural settlements</li> <li>- Conflict area for water use</li> <li>- Fishing activity</li> <li>- Sustainable use conservation unit</li> </ul>
Low restriction	<ul style="list-style-type: none"> <li>- Native vegetation</li> <li>- High susceptibility to erosion</li> <li>- Non-native vegetation</li> <li>- Medium susceptibility to erosion</li> </ul>
Non-restrictive	<ul style="list-style-type: none"> <li>- Low sensitivity areas</li> <li>- Low susceptibility to erosion</li> <li>- Pasture areas</li> </ul>

socio-environmental impacts and classifying PHS projects according with Brazilian legislation.

### 2.1. Technical potential

The technical feasibility of a pumped hydropower storage (PHS) project relies heavily on geographical factors such as the specific terrain, proximity to rivers, and water availability. In contrast, the economic viability of the project is influenced by various contextual considerations, including the distance from energy consumption centers,

**Table 5**  
Reference data for analysis of socio-environmental aspects.

Type	Exclusion zone	Description	References
	Indigenous lands	The indigenous lands (TI) are represented by polygons delimited by FUNAI. A radius of 40 km in the Legal Amazon region and 15 km in other regions, calculated as a buffer around the Indigenous Lands.	[69]
Excludent zone	Quilombola communities	The Quilombola Communities are represented by polygons delimited by the Palmares Foundation.	[70]
	Population density	The population density was taken from MapBiomias, which presents annual maps of land cover and land use in Brazil divided into 37 classes.	[71]
	Full Protection conservation units	The Integral Protection Conservation Units (CU) were elaborated from several available sources.	[72]
	Settlement projects	The Rural Settlement Projects were found on the website of the National Institute of Colonization and Agrarian Reform (INCRA).	[73]
	Sustainable use conservation units	Same source of data used for the subject of Conservation Units of Full Protection (CU) mentioned above.	[73]
Restrictive zone	Forest	The forest fragments were elaborated from two databases, the Brazilian Foundation for Sustainable Development and the MapBiomias Collection 6.0. For each UHR project, the area of interference in a forest fragment was calculated, thus giving an estimate of the vegetation suppression necessary for the implementation of the reservoir.	[71,74]

transmission infrastructure losses, and associated expenses. To comprehensively assess the global potential of PHS, our methodology integrates five essential components: analysis of topography, evaluation of river network characteristics, utilization of reservoir and hydrological data, estimation of infrastructure costs, and optimization of project design. Since the storage capacity and infrastructure costs are strongly influenced by the underlying topography, our model effectively identifies and evaluates the cost aspects of multiple technically feasible candidate sites.

The PHS world potential model framework is described in detail in Fig. 5, Table 2 and Table 3. The topographic data used is MERIT [58] with a resolution of 3 s. The river network data was derived from the MERIT data using ArcGIS [60]. The existing reservoir data was taken from [59]. The integration of topography and river network data is conducted in conjunction with hydrological data sourced from HGE-UFRGS [61]. Our methodology incorporates optimization techniques for determining the optimal number and diameter of tunnels [62], as well as cost-estimation procedures [63]. For further insights, refer to Table 2. The model operates on a grid cell basis with a resolution of 3", enabling a comprehensive evaluation of potential sites that considers both topography and hydrology in the calculation of project-level costs.

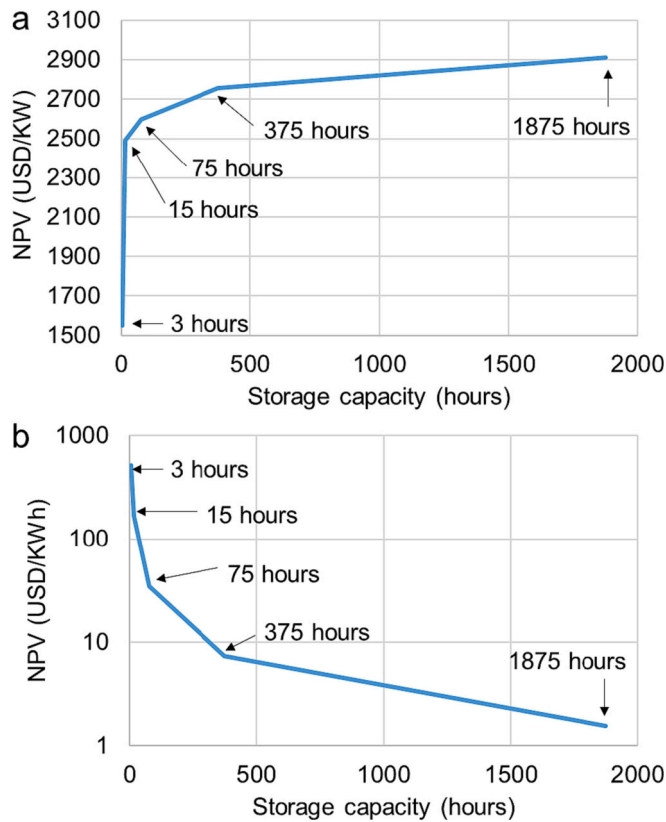


Fig. 6. Relationship between PSH discharge time and (a) the unit net present value of capacity costs (USD/kW) and (b) the unit net present value of storage costs (USD/kWh).

The model follows a sequential process, beginning with the identification of a reservoir within a reasonable flowrate range up to 12 km away from an existing reservoir (Fig. 5 (e)). Next, it assesses the feasibility of constructing a dam with a maximum height of 200 m (Fig. 4 (f)). Subsequently, the model simulates reservoir flooding (Fig. 5 (g)), calculates storage volume, flooded areas, project costs, and other pertinent characteristics.

The site selection model is broken down into eight major steps presented in Table 3. The model connects rivers (upper reservoir) with existing reservoirs (lower reservoir) with a 1 to 12 km tunnel. We limited the length of the tunnel to reduce the computational time of the model, which took more than a month to run. If a reservoir is discovered, the model constructs dams with heights of 50, 75, 100, 125, 150, 175, 200 m, along four axes (W-E, N-S, NE-SW, NW-SE), with a maximum length of 10 km. If the geography permits the construction of such dams, the model selects the side of the dam to flood using the catchment area data and floods the reservoir. The reservoir flooding step takes 80–90 % of the model computational time and consists of checking if the altitude of surrounding pixels is higher or lower than the upper reservoir level.

Subsequently, adjustments are made to the water level of the reservoir to derive the flooded area vs. water level and storage volume vs. water level curves. The estimation of project costs incorporates various factors, such as dam construction, tunnel development, excavation of the powerhouse, pump-turbine installation, electro-technical equipment, and land expenditures, as outlined in the referenced works [52,63]. Detailed assumptions regarding cost estimation can be found in Table 2. The study reveals that the water storage capacity of pumped hydropower storage (PHS) projects is limited by the availability of water in the primary river. To ensure operational feasibility, the maximum storage capacity is capped at 50 % of the annual river flow. If the storage capacity significantly exceeds the available water, the projected cost of storage increases because a portion of the reservoir would remain unfilled.

The main limitations of the computation model are: (i) The model's tunnel design is constrained to linking the river with the center of the dam. While this configuration is typically optimal for tunnel designs, it may not always represent the best tunnel layout. (ii) The pumped hydro storage projects considered in the model are exclusively focused on a single dam, thus excluding other potential arrangements. The main uncertainty of the computation model is the lack of geological information. An appropriate geological formation, without fractures is crucial for the construction of PHS reservoirs. This is because PHS reservoirs suffer from great pressure due to the high column of water. Future work will include geological data to exclude unsuitable PHS projects.

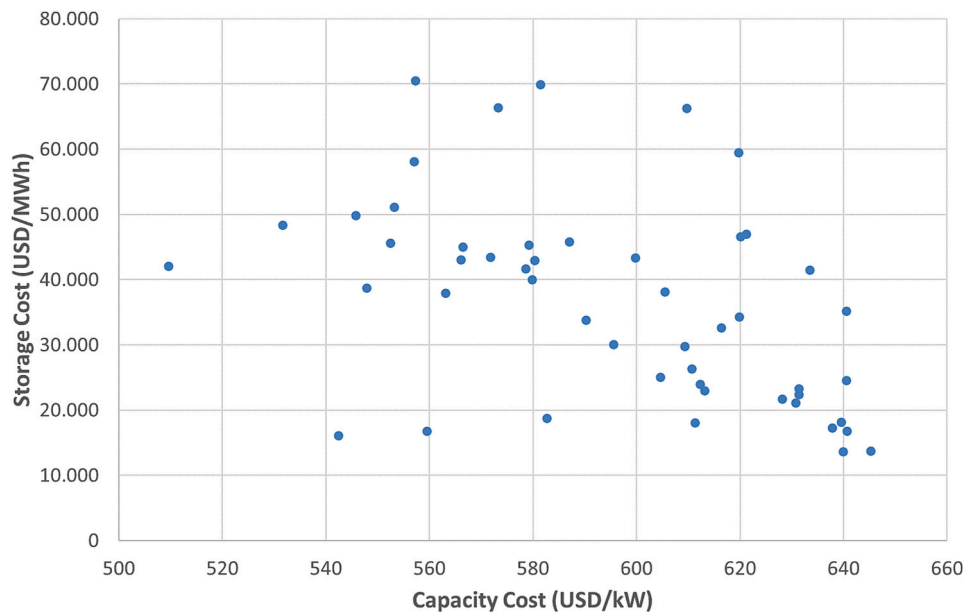


Fig. 7. Pedra storage projects capacity cost (USD/kW) and storage cost (USD/kWh) for the top 50 projects ranked according to capacity cost.

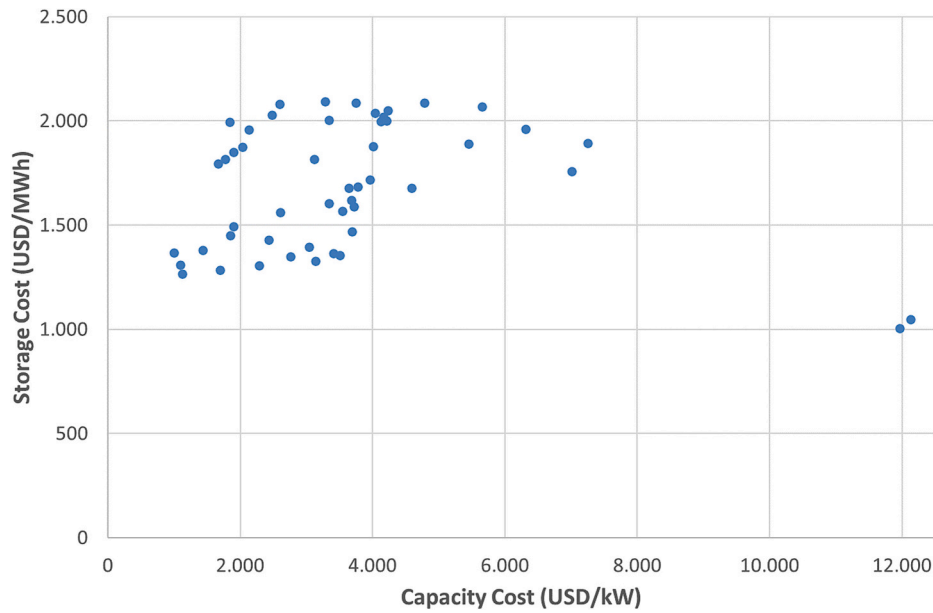


Fig. 8. Pedra storage projects capacity cost (USD/kW) and storage cost (USD/kWh)for the top 50 projects ranked according to storage cost.

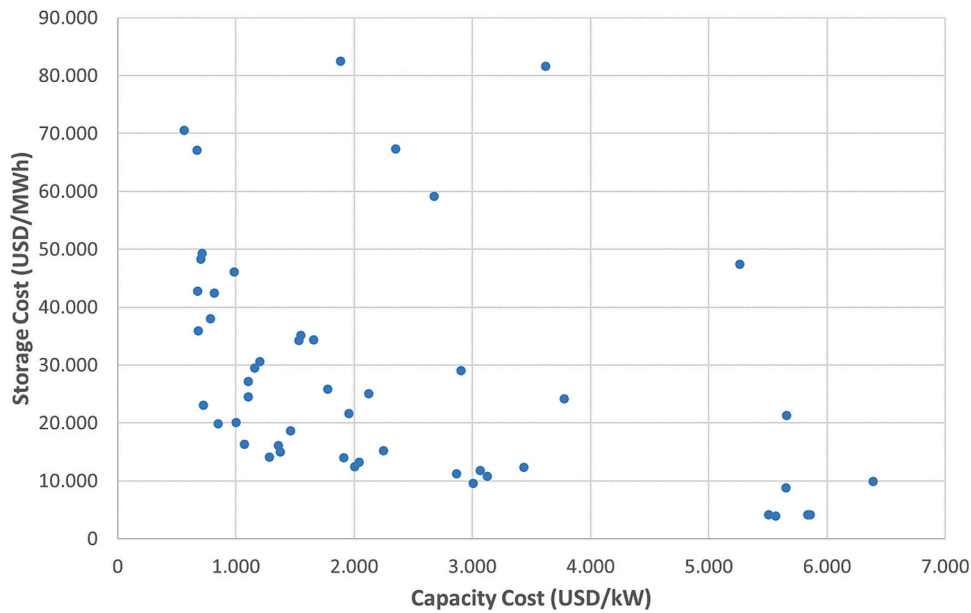


Fig. 9. Pedra storage projects capacity cost (USD/kW) and storage cost (USD/MWh)for the top 50 projects ranked according to length to head ratio.

2.2. Economic aspect

2.2.1. Costs for projects with one tunnel

The Estimate Storage Cost step evaluates the expenses associated with water and energy storage services for projects with an installed capacity corresponding to a single tunnel by considering factors such as the annual river flow, seasonal variations, and inter-annual fluctuation indices. These hydrological parameters fulfil three essential objectives. Firstly, they ensure that an adequate water supply exists in the river to fill the upper reservoir. Secondly, they guarantee that the need for water and energy storage does not adversely impact the natural flow of the river. Lastly, the water storage potential aims to regulate the river's flow and maintain a consistent water supply, mitigating the effects of seasonal and inter-annual fluctuations.

Eq. 1 illustrates the relationship between water availability for storage and the corresponding costs of water and long-term energy

storage [39]. If 50 % of the yearly flow is enough to fill up the reservoir, the reservoir storage capacity can be used every year and, thus, the cost for storage reduces. If it takes more than a year to fill up the reservoir, the reservoir storage capacity will be underutilized and the cost for storage increases. On the other hand, Eq. 2 outlines the costs associated with additional short-term energy storage.

$$C_W = \frac{C_P}{W_S}; C_{Ewc} = \frac{C_P}{E_{Rwc} \frac{W_R}{W_S}}; C_{Ewoc} = \frac{C_P}{E_{Rwc} \frac{W_R}{W_S}} \begin{cases} \text{if } W_R \leq Q_A \rightarrow W_S = W_R \\ \text{if } Q_A < W_R < 2Q_A \rightarrow W_S = Q_A + 0.5W_R \\ \text{if } W_R \geq 2Q_A \rightarrow W_S = 1.5Q_A \end{cases} \quad (1)$$

In Eq. 1,  $C_W$  represents the cost of water storage in USD/km<sup>3</sup>,  $C_P$  denotes the cost of the project, including the dam, tunnel, turbine, electrical equipment, excavation, and land, in USD. These costs are



**Table 6**  
Details of PHS projects.

Details	Minimum	Maximum	Average	Lower 25 % quartile	Median	Upper 75 % quartile
<b>Physical characteristics</b>						
Average generation head (m)	46	1704	203	95	162	274
Tunnel length (km)	1	12	4.3	1	3	7
Tunnel length/average generation head (m/m)	2.6	118.5	23.0	12.7	19.2	29.7
Dam level variation (m)	25.5	157.5	51.4	40	40	60
Dam height (m)	50	200	68.1	50	50	75
Dam length (km)	0.087	9.844	1.350	0.756	1.092	1.653
Base of the dam altitude (m)	49	2128	673	511	687	821
River altitude (m)	39	1082	554	416	578	716
Lower catchment area (km <sup>2</sup> )	32	822,331	35,225	8882	29,046	51,811
Upper catchment area (km <sup>2</sup> )	1	19,151	45	1	2	7
Total projects per mutually exclusive group	1	5681	205	2	8	32
<b>Storage characteristics</b>						
Useful volume (km <sup>3</sup> )	0.001	2.903	0.061	0.011	0.023	0.050
Energy storage without cascade (TWh)	0.0003	0.7985	0.0165	0.0038	0.0112	0.0181
Energy storage with cascade (TWh)*	0.0013	2.9729	0.0682	0.0156	0.0343	0.0642
<b>Environmental impact</b>						
Flooded area (km <sup>2</sup> )	0.04	194.73	3.32	0.45	0.89	2.26
Vegetation suppression (km <sup>2</sup> )	0	39.05	0.73	0.10	0.23	0.53
<b>Cost and benefits with installed capacity with one tunnel (G1)</b>						
Installed capacity (GW)	0.063	1	0.275	0.125	0.2	0.333
Discharge time (hours)	1.47	4406	94.58	18.41	38.04	78.46
Dam cost (million USD)	17.20	1483	227.83	114.04	180.07	289.90
Tunnel cost (million USD)	8.85	187.03	50.75	8.87	28.25	79.71
Excavation cost (million USD)	6.00	65.29	20.09	10.68	16.00	24.66
Turbo/pump cost (million USD)	11.66	89.31	29.26	18.05	24.91	34.77
Other mechanical costs (million USD)	0.84	8.93	2.60	0.98	1.99	3.50
Generator and electric cost (million USD)	16.25	188.28	56.53	29.36	44.31	68.85
Cost of land (millions USD)	0.023	116.84	1.99	0.27	0.54	1.36
Total cost (millions USD)	64.99	1599	389.05	249.01	349.31	484.91
Water storage cost (USD/m <sup>3</sup> )	0.006	31.203	1.662	0.509	1.116	2.036
Energy storage cost without cascade (USD/MWh)	36.55	24,110	4013	1533	2812	5250
Energy storage cost with cascade (USD/MWh)	5.67	10,059	1081	406.75	816.22	1419
Additional cost per GW (million USD/GW)	371.65	1478.72	612.38	515.83	587.00	679.72
CAPEX (USD/kW)	431.90	17,190.72	1977.04	1003.40	1502.84	2409.79
<b>Cost and benefits with optimum installed capacity (G2)</b>						
Installed capacity (GW)	0.107	1	0.942	1	1	1
Discharge time (hours)	3	1438.9	23.3	4.0	12.4	19.8
Tunnel cost (million USD)	6.68	968.15	175.22	78.25	136.23	239.38
Excavation cost (million USD)	10.14	96.66	73.91	69.08	75.56	83.24
Turbo/pump cost (million USD)	18.03	189.41	115.14	90.92	110.46	136.45
Other mechanical costs (million USD)	1.04	14.28	9.15	8.25	9.57	10.38
Generator and electric cost (million USD)	27.52	261.57	205.30	193.93	210.45	229.20
Total cost (millions USD)	88.98	2270.83	808.55	644.88	791.08	955.08
Water storage cost (USD/m <sup>3</sup> )	0.026	29.485	2.903	1.251	2.384	3.840
Energy storage cost without cascade (USD/MWh)	75.23	35,521.92	8190.80	3169.25	5495.79	12,840.61
Energy storage cost with cascade (USD/MWh)	24.19	20,534.12	2049.16	937.19	1676.90	2861.07
CAPEX (USD/kW)	406.04	2270.83	865.43	711.45	834.93	978.61
Net present value (million USD)	52.22	2144.75	1167.35	829.41	1221.06	1579.45

\* Energy storage with cascade consists of the electricity that can be generated with a filled PHS reservoir in the PHS turbine and in the hydropower dams downstream that are impacted by the release of water from the PHS plant.

further described in Table 2, column “Pumped storage costs”.  $W_s$  corresponds to the adjusted water storage capacity based on water availability in km<sup>3</sup>.  $E_{woc}$  represents the cost of long-term energy storage without considering the cascade, in USD/MWh.  $C_{Ewc}$  denotes the cost of long-term energy storage including the cascade, in USD/MWh.  $W_R$  represents the water storage capacity of the reservoir generated by the model in km<sup>3</sup>, while  $C_{Ewc}$  represents the cost of long-term energy storage including the cascade, in USD/MWh.  $E_{Rwc}$  and  $E_{Rwoc}$  are the energy storage capacities, in MWh, of the reservoir produced by the model with and without cascade, respectively,  $Q_A$  is 50 % of the yearly flowrate of the river that passes through the lower reservoir

$$C_{GW} = \frac{C_{PGW}}{G} \tag{2}$$

In Eq. 2,  $C_{GW}$  represents the cost of new generation capacity in USD/kW,  $C_{PGW}$  denotes the cost of additional generation capacity, including the tunnel, turbine, electrical equipment, and excavation, in billions of dollars.  $G$  represents the generating capacity in gigawatts (fixed at 1 GW for all proposed PHS plants).  $C_{GW}$  is used to estimate costs associated

with adding additional capacity any one tunnel project.

Eq. 3 presents the Net Present Value equation applied in the paper. Where,  $R_t$  is the net cash inflow-outflows in USD per year,  $n$  span the entire operational lifespan of the plant in years,  $i$  is the interest rate,  $t$  is the number of years. Eq. 4 presents the Levelized Cost of Storage (LCOS) [66]. Where,  $CAPEX$  encompasses capital expenditure in USD,  $OPEX_t$  operational and maintenance expenses in USD per year, as well as  $C_t$  electricity costs in USD per year, assumed to be zero for better comprehension of results,  $E_{out}$  represent the total electricity generation by the storage system in MWh over its operational lifetime.

$$NPV = \sum_{t=1}^n \frac{R_t}{(1+i)^t} \tag{3}$$

$$LCOS = \frac{CAPEX + \sum_{t=1}^n \frac{OPEX_t + C_t}{(1+i)^t}}{\sum_{t=1}^n \frac{E_{out}}{(1+i)^t}} \tag{4}$$

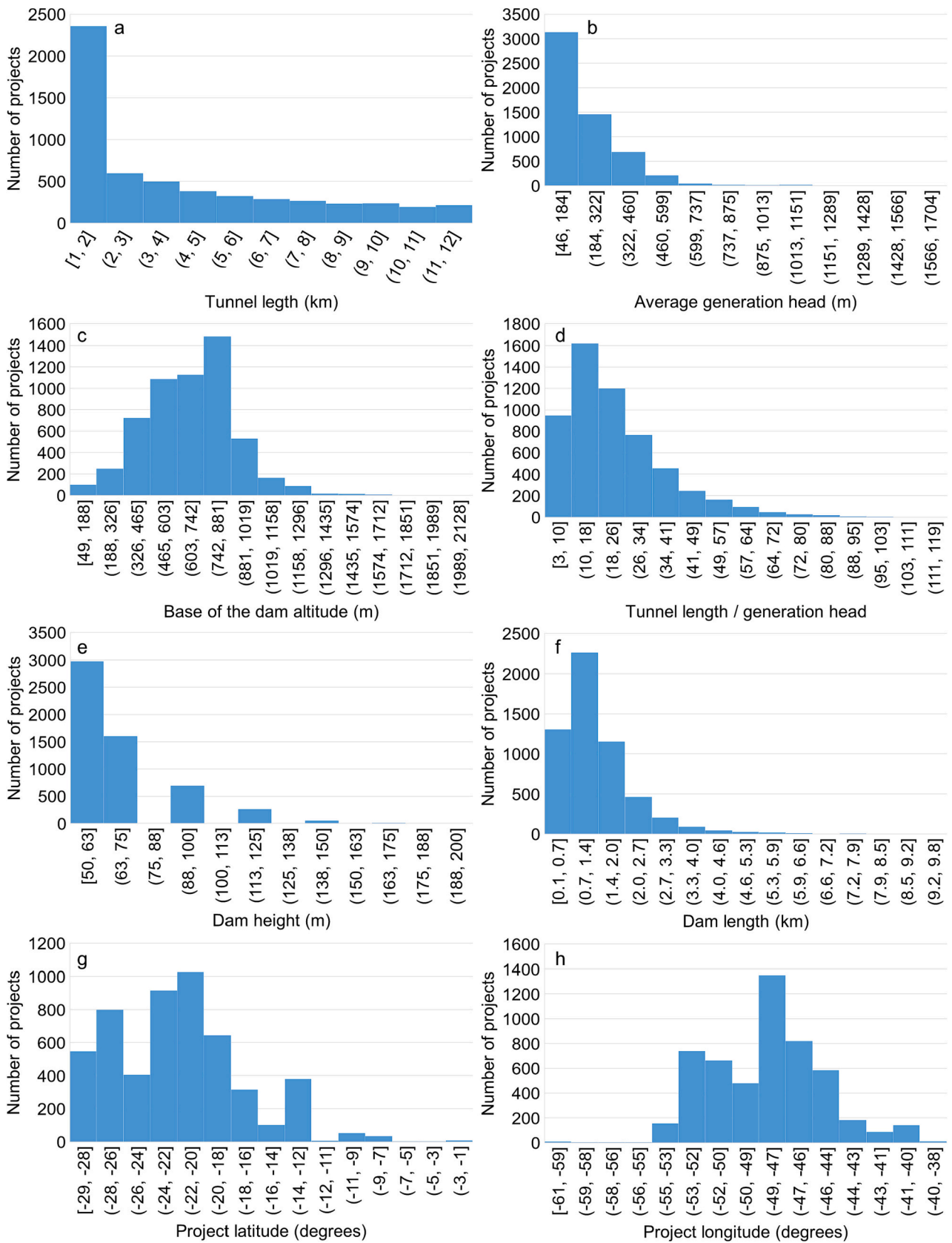
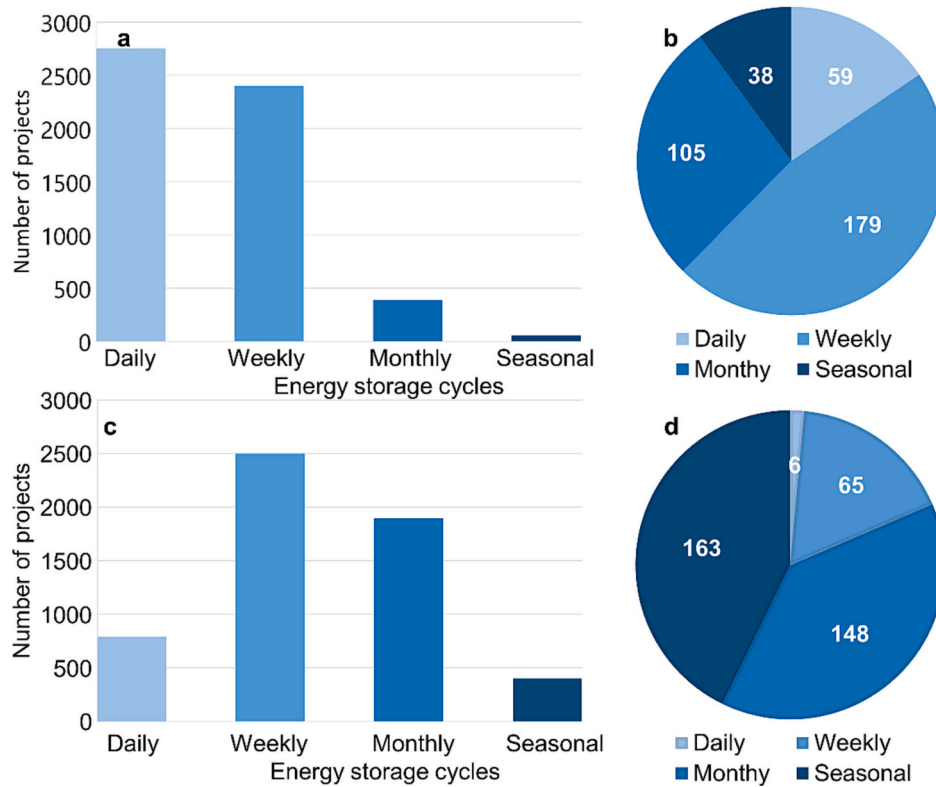


Fig. 10. PHS projects histograms describing (a) tunnel length, (b) average generation head, (c) base of the dam altitude, (d) tunnel length/generation head, (e) dam height, (f) dam length, (g) project latitude, (h) project longitude.



**Fig. 11.** (a) Energy storage cycles histogram, assuming optimal installed capacity (G2), (c) and installed capacity with one tunnel (G1), (b) total energy storage potential with cascade (TWh), assuming optimal installed capacity (G2), (d) and installed capacity with one tunnel (G1).

**Table 7**  
Assumed energy storage cycle duration in hours.

Energy Storage cycles	Hours
Daily	≤12
Weekly	>12 & ≤48
Monthly	>48 & ≤240
Seasonal	>240

2.2.2. PSH configuration and selection criteria

The PHS mapping model (Section 2.1) located and calculated costs and technical characteristics of >145,000 PHS projects using existing hydroelectric lakes as a lower reservoir with one tunnel and the corresponding installed capacity. The research team developed a PSH project selection and configuration methodology that allows for a proper comparison and selection of projects with different characteristics. In a nutshell site selection and project configuration cannot be based on physical ratios or on cost ratios alone but should consider both the project's costs and the project discharge time. Examples of the use of some usual selection ration can be found on Section 3.

The PHH project selection and configuration methodology is presented in detail in [67]. The basis of this methodology is the comparison of costs and benefits of a PSH project. The costs are estimated based on the outputs computational model described in Section 2.2.1, while the benefits are the system expansion cost savings associated with the introduction of a PSH project of a given discharge time. The discharge time is the amount of time that the PHS plant can generate assuming a full upper reservoir, 100 % capacity factor, and no additional inflow or evaporation in the upper reservoir.

The benefit of a project with a given discharge time is obtained by the difference between the total system expansion cost (investment costs plus operation costs) of the Brazilian national grid with one additional PHS plant as part of the existing system and the total system expansion

cost of the system without this PHS plant. The optimal expansion of the Brazilian national grid was modeled with the software Plexos 8.3, replicating the official 2030 Brazilian National Grid Plan [57] as a starting point and using candidates for expansion and their respective costs. In the present study, six simulations of the Brazilian national grid expansion plan were run for the horizon of 2040. For the base case, there is no PHS in the existing system. In the other simulations, the existing system includes a PHS with an installed capacity of 1 GW and discharge time between 3 and 1875 h. The benefit of each PHS configuration is defined as the difference between the system's total cost for each simulation and the system's total cost for the base case. The total cost is the annualized construction cost of all investment projects in generation, transmission, and storage included in the expansion plan, added to annual O&M costs and charges for new projects and to variable costs of all thermal plants. The computed benefit of projects with different discharge times allowed the construction of two curves (Fig. 5). The first curve (a) shows the relationship between the discharge time of a PHS project and the unit present value of capacity costs without considering OPEX and interest during construction. The second curve (b) shows the relationship between the discharge time of a PHS project and the unit present value of storage costs, also without considering OPEX and interest during construction.

The PHS Configuration Methodology [67] was utilized to determine the optimal installed capacity for each project developed by the mapping model in Section 2.1. This methodology finds the best combination of capacity and discharge time for each project. The original projects have the installed capacity corresponding to one standard tunnel. However, the model output data allows us to estimate the cost of a project with the same dam but with a different installed capacity and, therefore, a different discharge time. For instance, suppose the standard project with a tunnel has an installed capacity of 500 MW, a total cost of 1 billion USD, and a cost per additional GW of installed capacity of 1 billion USD. In that case, the total cost of a project with 1.5 GW of

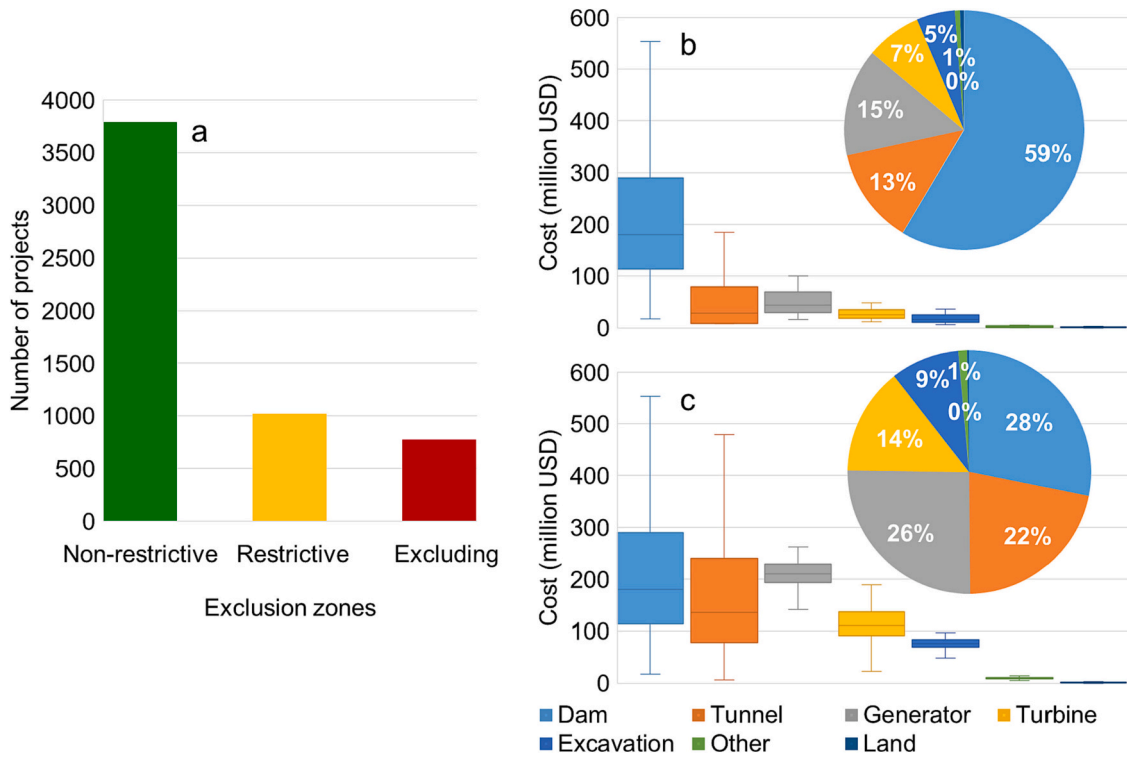


Fig. 12. (a) Environmental restrictions and (b) PHS costs with one tunnel per project (G1) (the circle presents the average costs) (c) PHS costs with optimum installed capacity (G2).

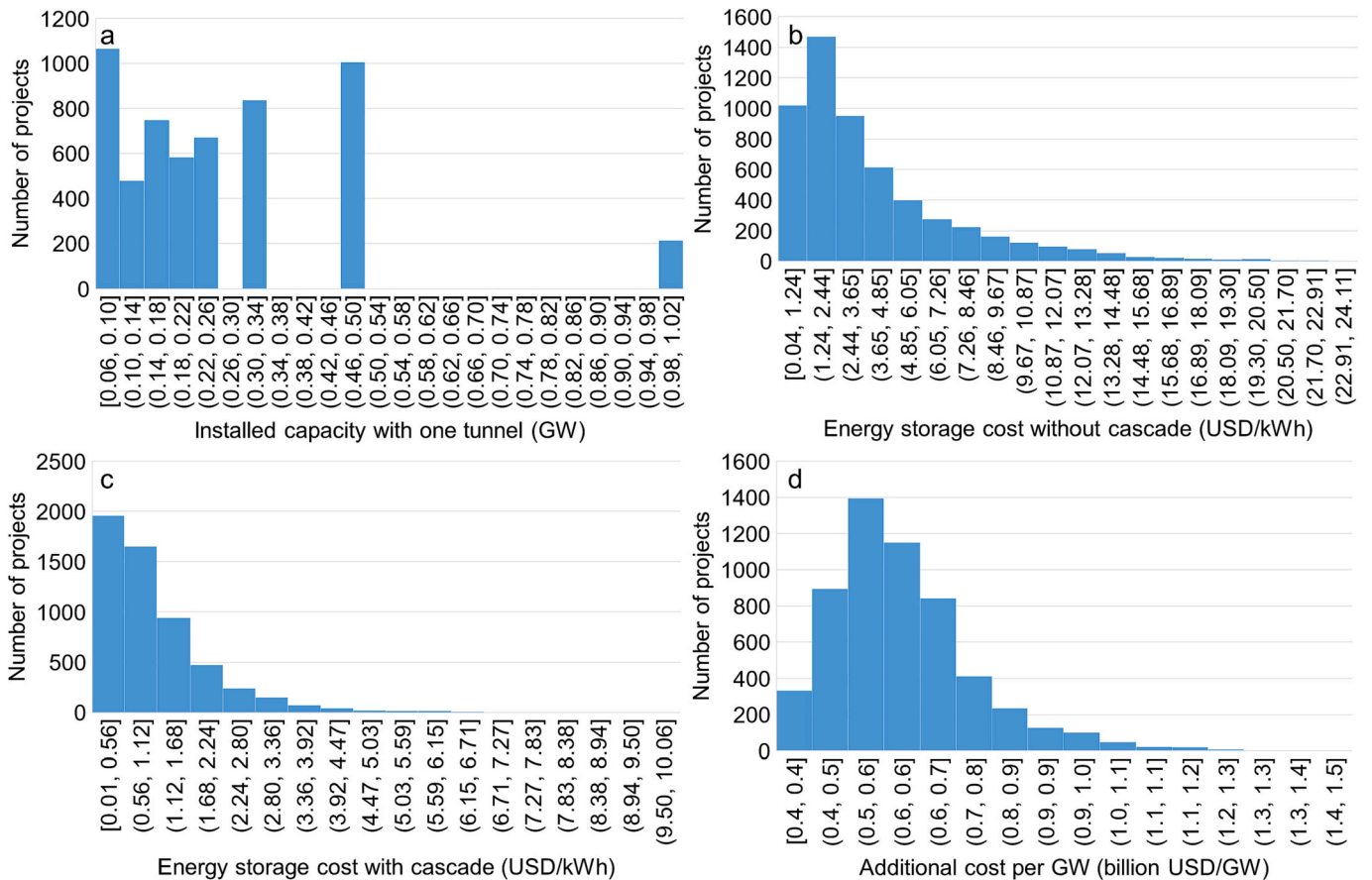


Fig. 13. (a) Installed capacity with one tunnel (G1), (b) leveled cost of storage without cascade, (c) leveled cost of storage with cascade with one tunnel, and (d) additional cost per GW.

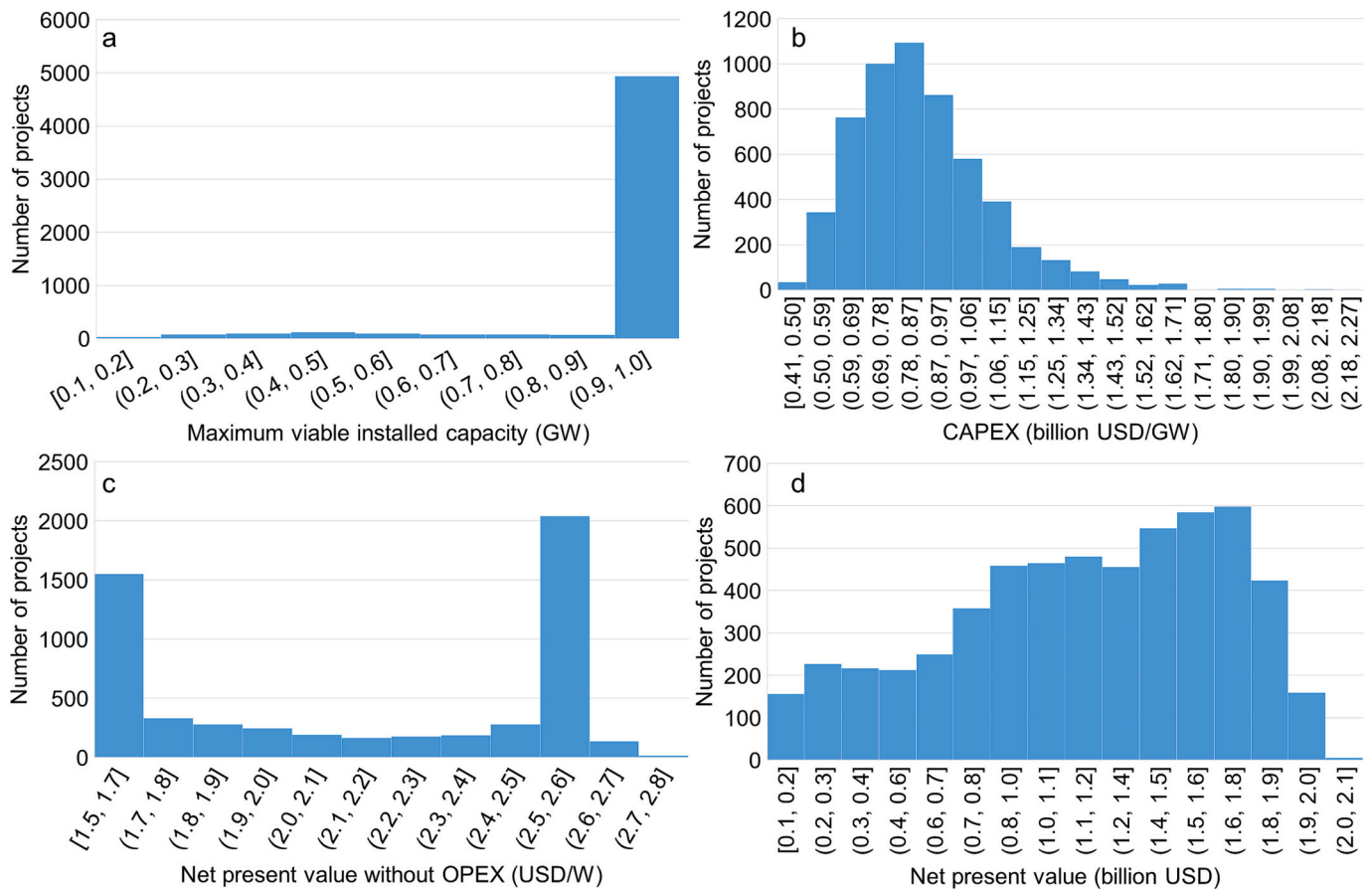


Fig. 14. (a) Optimum installed capacity (G2), (b) CAPEX, (c) net present value without OPEX, (d) net present value with optimum installed capacity.

installed capacity would be 2 billion USD. It is important to note that there are some limitations to this method. For example, the optimal installed capacity may not be an integer multiple of the standard tunnel, and the calculation assumes that the additional cost per GW can be linearly extrapolated.

In order to determine the optimal installed capacity for a project, it is necessary to maximize the Net Present Value (NPV). This is achieved by calculating the present value of benefits (Fig. 5a) and subtracting the present value of costs, taking into account the discharge time for every possible installed capacity and corresponding project costs. As the installed capacity increases, so do the costs, while the discharge time decreases, resulting in a lower benefit per kW. A solver is utilized to calculate the optimal capacity, discharge time, present value of costs, present value of benefits, and NVP for the optimized project. The next step in project selection is to group mutually exclusive projects together to retain only the best ones. This helps reduce the number of projects and select the best option from a group of projects at the same site or in close proximity. For example, several projects at the same location but with different dam heights or overlapping reservoirs. A mutually exclusive project group brings together projects whose reservoirs share at least one pixel with another project in the group. The projects are ranked based on their NPV in the optimal capacity configuration. The final step in project selection is to elaborate a list of projects, including only the best mutually exclusive projects.

### 2.3. Environmental impact

Most countries environmental impact assessment allows for a comprehensive economic accountability of the negative and positive impacts of the project [68]. However, the analysis of the socio-environmental aspects of the PHS projects has the objective to allow

the environmental licensing of the plant according to Brazilian regulations. This was handled using QGIS and ArcGIS geoprocessing software (Model Builder, Spatial Analyst extensions). Layers of georeferenced information of the main environmental interferences were generated and classified according to the environmental impact. Areas of indigenous lands, Quilombola communities, full protection conservation units, urban and rural areas, are qualified as excluding factors as legislation does not allow large infrastructure projects in these areas. Quilombolas are an Afro-Brazilian communities founded by runaway slaves in Brazil. Rural settlements, sustainable use conservation units are considered as restrictive factors, as shown in Table 4. Projects with restrictive factor may obtain a socio-environmental license but at a large compensation cost.. In this phase, environmentally and socially unfeasible PHS projects are eliminated based on georeferenced data from various sources. These are presented in Table 5.

### 3. Results

The computational model, has developed 145,000 viable PHS projects surrounding existing hydropower dams with one tunnel and the corresponding power capacity. The five reservoirs with the highest number of technically viable projects are Segredo and Foz do Areia in the Iguaçú River, Foz do Chapecó and Itá in the Uruguai river and Furnas in the Grande river. Out of these 43 % are in the South region, 46 % in the Southeast/Center-West region, and 11 % in the North and Northeast regions.

The large number of projects poses a selection problem. Due to the vast number of alternatives, it is necessary to have a rule in place to select those that deserve further study. Criteria commonly cited in the literature for comparing pumped storage projects prove challenging when these projects have varying characteristics. To illustrate, data from

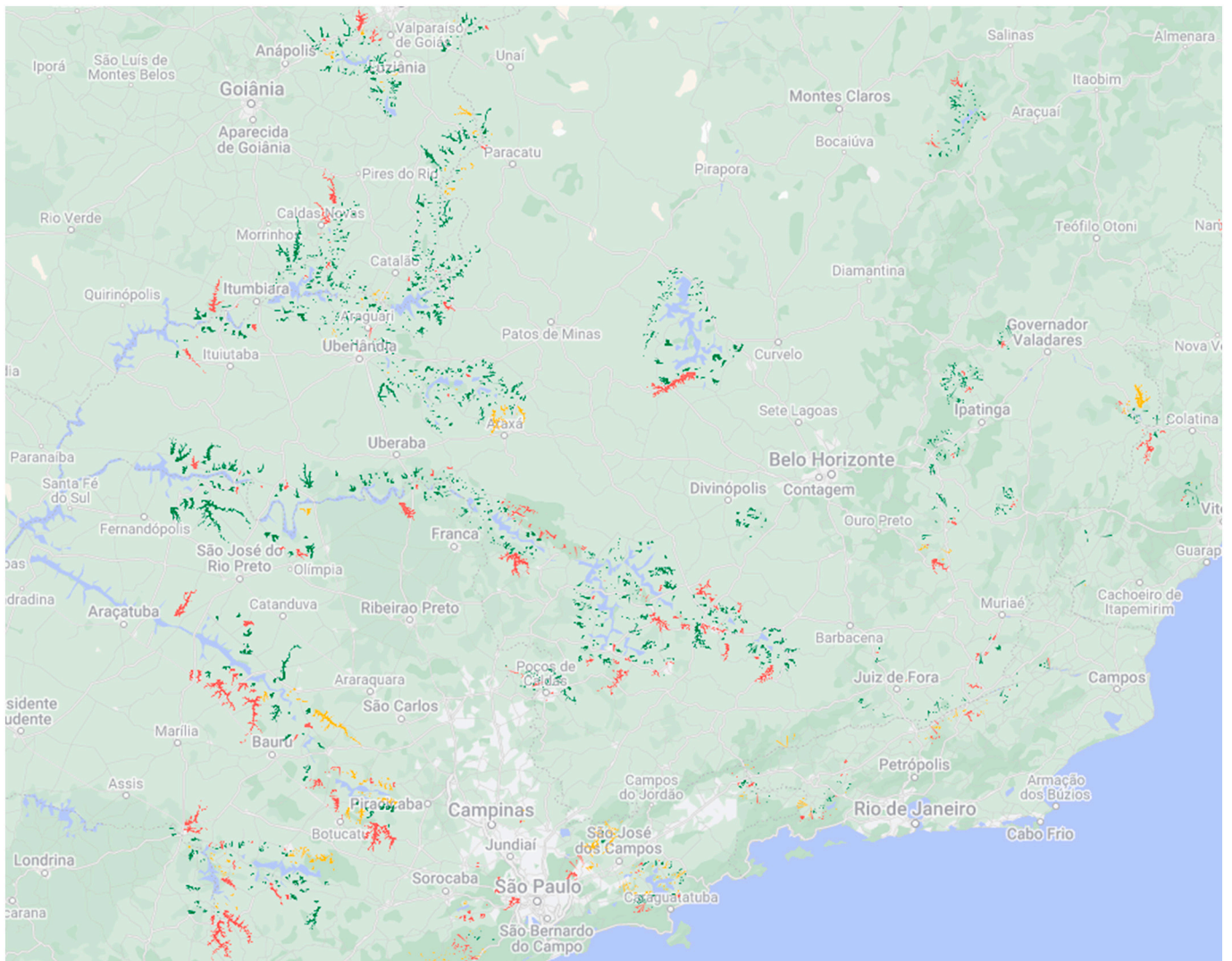


Fig. 15. Interactive map showing proposed PHS plants using existing lower reservoirs in Southeast Brazil [76].

PSP projects using the Pedra Hydro Power Plant Lake as a lower reservoir can be taken as examples. The model identified 1863 projects around Pedra Storage. Fig. 7 displays both the capacity cost (USD/kW) and storage cost (USD/MWh) for the top 50 projects, ranked based on capacity cost alone. Notably, while capacity costs are as low as USD 509/kW, storage costs begin at a strikingly high USD 13,645/MWh, with two projects exceeding USD 80,000/MWh.

Fig. 8 depicts the top 50 projects when ranked by storage cost alone. In this scenario, projects exhibit much lower storage costs, down to USD 1006/MWh (less than one tenth of the cheapest project in MWh on Fig. 6). However, capacity costs surge, with the most affordable project priced at USD 995/kW and one project reaching over USD 12,000/kW. Fig. 9 represents the top 50 projects sorted by the Length to Head Ratio. The data dispersion here is broad, with capacity costs varying between USD 557 and USD 6387/kW and storage costs ranging from USD 5560 to USD 82,611/MWh.

The project configuration used the methodology presented in Section 2.2.2. The original one tunnel projects were configured with the optimal capacity (limited to 1GW), that is, with the capacity that maximizes NPV. They were then organized in mutually excluding projects groups (projects with overlapping storages) and only the one with the highest NPV was selected and the other mutually excluding projects were discarded. Finally the selected projects were sorted according according NPV. This reduced the number of projects from 145,000 to 5600. Table 6

presents details on PHS projects, divided in physical, storage, environmental and cost characteristics. These results have been validated with other papers from the literature [39,75].

The results are divided into two groups of the same 5600 PHS projects but with different installed capacities. On the first group (G1) the projects have an installed capacity corresponding to one tunnel with an 11-m diameter and an installed capacity ranging from 63 MW to 1000 MW. On the second group (G2), projects are configured for the optimum installed capacity, limited to 1 GW. For most projects the optimal installed capacity is 1GW as there are strong economies of scale for increasing the installed capacity of the plant. The projects with optimum installed capacity include a detailed net present value analysis and are presented in an interactive map in [76] and in the link below:

[https://www.google.com/maps/d/edit?mid=1XM10\\_TIBBGmbobkCZrmVbwWtaaHKp10&usp=sharing](https://www.google.com/maps/d/edit?mid=1XM10_TIBBGmbobkCZrmVbwWtaaHKp10&usp=sharing)

Fig. 10 (a) presents a histogram of the tunnel length of the 5600 PHS projects. It shows that most of the developed projects have tunnel lengths between 1 and 2 km. This is because, with short tunnels and high heads, the cost for power reduces. This is particularly interesting for projects with daily and weekly energy storage cycles. Fig. 10 (b) presents the average or representative generation head, assuming that all useful volume of the upper reservoir is utilized and that the head of the lower reservoir is maintained at 65 % of its useful volume.

Most of the projects have heads lower than 600 m. Projects with

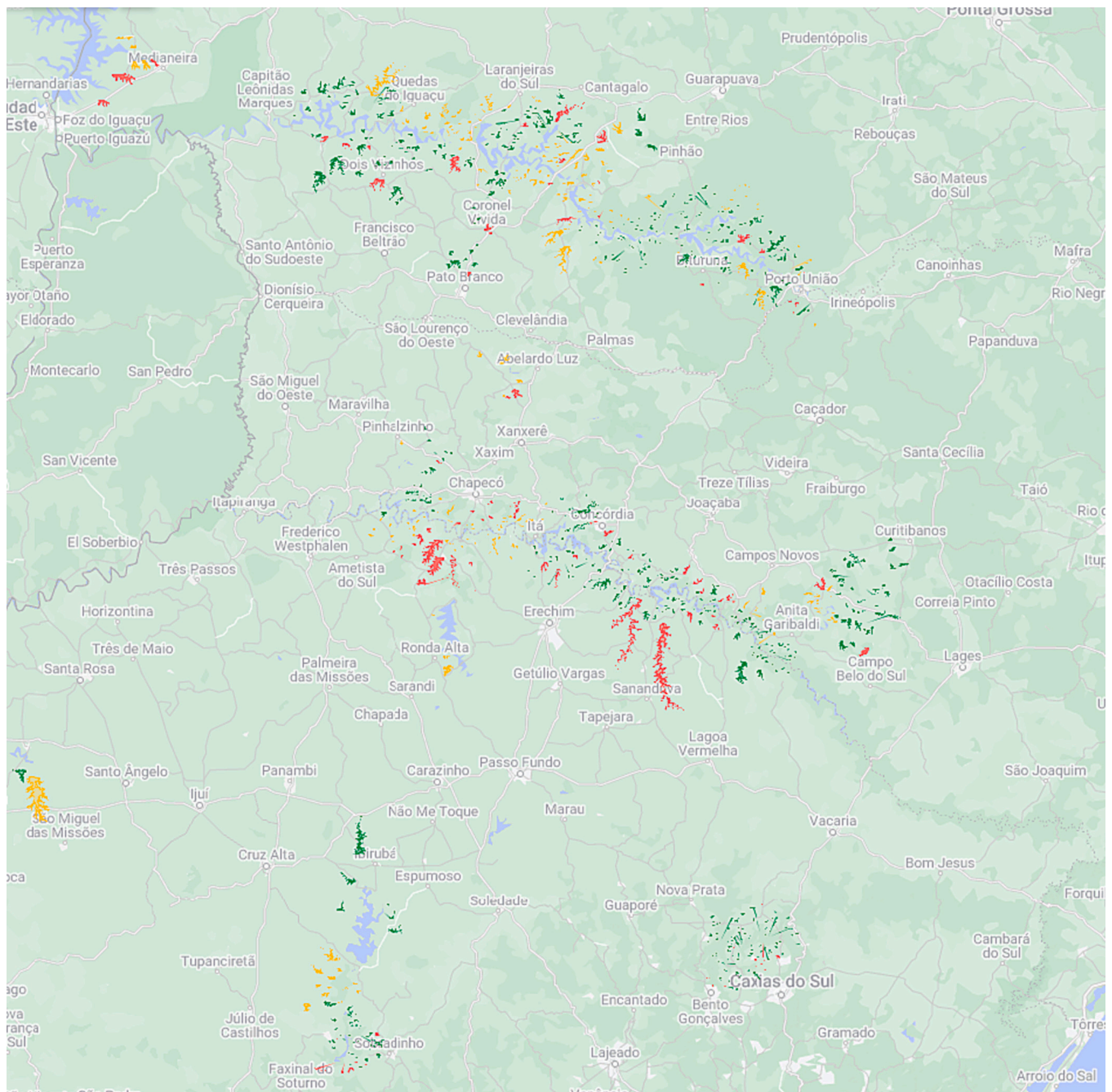


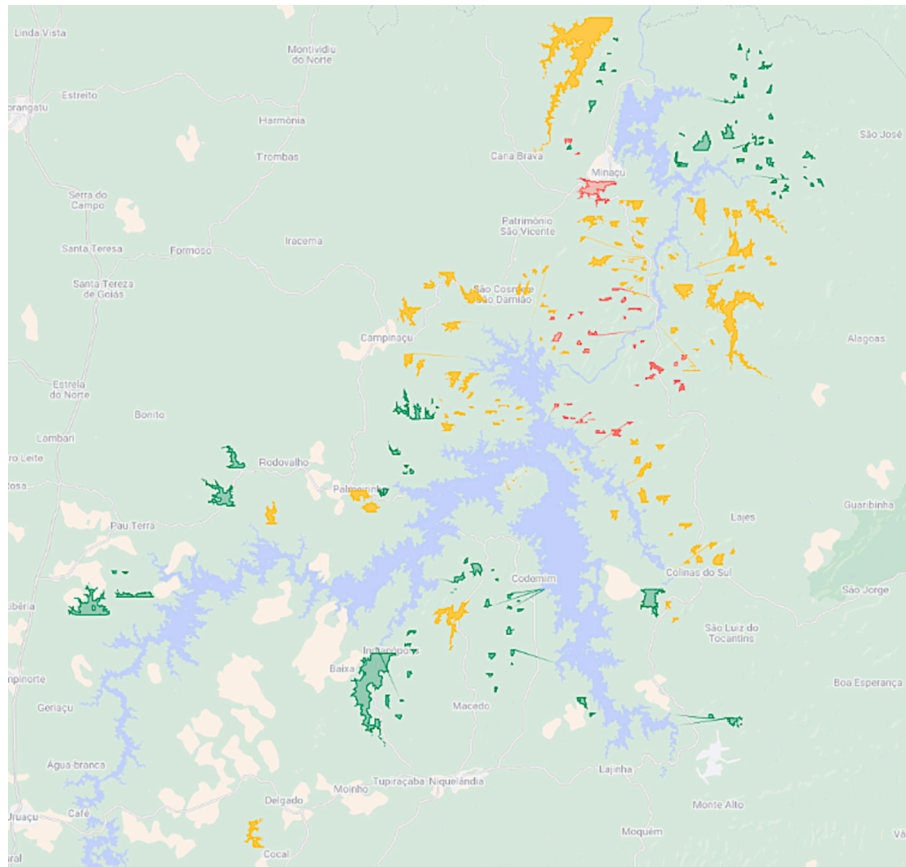
Fig. 16. Interactive map showing proposed PHS plants using existing lower reservoirs in South Brazil [76].

heads lower than 100 m are usually monthly and seasonal PHS plants. Fig. 10 (c) presents the base of the dam altitude. Most of the projects are located at 777–881 m altitude. Fig. 10 (d) presents the tunnel length/generation head. The smaller it is, the lower the cost of installed capacity. The most frequent length/generation head value is between 14 and 20. Projects with length/generation head value larger than 40 are usually for seasonal energy storage projects.

Fig. 10 (e) presents the dam height of the PHS projects proposed in this research. Projects with 50 m dams are usually for daily or weekly storage. Larger dams are usually for longer storage cycles. Fig. 10 (f) presents the dam length. The main dam length is 0.6–1.1 m. The longest dam has 9.844 km. Fig. 10 (g) presents the project latitude and shows that the regions with the most projects are in the Southeast and South regions of Brazil. Fig. 10 (h) presents the project longitude and shows that there are no proposed projects in the Amazon region.

Fig. 11 (a) presents the number of projects per energy storage cycles, assuming the optimum installed capacity (G2). It shows that, with a high installed/power capacity, most plants have either daily or weekly storage capacities. Fig. 11 (c) presents the number of projects per energy storage cycles, assuming the installed capacity with one tunnel (G1). In this case, the most frequent projects have weekly, monthly, daily and seasonal energy storage capacities. This is because, with a smaller power capacity it takes longer to discharge the stored energy. The assumed energy storage cycle durations are described in Table 7. This shows that the same dam can result in a daily or seasonal PHS project just by varying the power capacity.

Table 7 presents the assumed energy storage cycle duration in hours for daily, weekly, monthly, and seasonal storage. It assumes daily storage is smaller than 12 h storage because half of the time it would be storing energy and the other half it would be generating electricity.



**Fig. 17.** Interactive map showing proposed PHS plants using Serra da Mesa and Cana Brava lower reservoirs [76].

Weekly storage larger than 12 and smaller than 48 h because energy could be stored during weekend hours and used during weekdays. Monthly storage larger than 48 and smaller than 240 h because a month usually have 20 working days and electricity would usually be generated during 10 days in monthly storage cycles. Seasonal storage is assumed to have >240 h generation because a seasonal PHS will usually also operate in daily, weekly, and monthly cycles. Thus, to completely fill up the reservoir will take longer than 240 h.

Fig. 12 (a) presents the number of projects per environmental restrictions. 3795 project have no restrictive exclusion zones, 1025 projects have restrictive exclusion zones and 780 projects have excluding exclusion zones. Fig. 12 (b) presents the project cost with one tunnel (G1) including dam, tunnel, generator, turbine, excavation, land and other cost. Given that the installed capacity of the plants is relatively small (Fig. 13 (a)), the cost of the dam ends up being the highest cost of the projects on average. However, in G2, with a higher power capacity (for example 1 GW), the tunnels, generator, turbine and excavation costs are be significantly larger Fig. 12 (c).

Fig. 13 (a) presents the installed capacity with one tunnel (G1). Projects with smaller power capacity have usually monthly and seasonal storage capacities. Fig. 13 (b) presents the levelized cost of storage without cascade. Projects with high energy storage costs have daily or weekly energy storage cycles. Fig. 13 (c) presents the levelized cost of storage with cascade. Considering the cascade in the energy storage costs is particularly for weekly, monthly and seasonal storage plants, as the operation of these PHS plants can reduce the water spilled in dams downstream and the generation in the PHS plant would also increase the generation in the dams downstream [77]. Fig. 13 (d) presents the additional cost per GW. The average cost per GW is 0.5–0.6 billion USD/GW. Note that this curve is similar to the tunnel length/generation head curve in Fig. 10 (c). The levelized cost of storage and the additional cost per GW is equivalent to the costs presented in [39]. Where the levelized

cost of storage for South America varies from 0.01 to 0.05 USD/kWh and the additional cost per GW varies from 0.38 to 0.6 billion USD/GW.

Fig. 14 (a) presents the optimum installed capacity (G2). Fig. 14 (b) presents the plant's CAPEX, assuming the optimum installed capacity. Fig. 14 (c) presents the net present value without OPEX, assuming the optimum installed capacity. Fig. 14 (d) presents the net present value, assuming the optimum installed capacity.

The main results of this paper are the 5600 PHS proposed projects with optimum installed capacity (G2) in Brazil ranked by NPV and presented in the interactive map in [76]. Fig. 15 presents the interactive map showing proposed PHS plants using existing lower reservoirs in Southeast Brazil. Fig. 16 presents the interactive map showing proposed PHS plants using existing lower reservoirs in South Brazil. Fig. 17 interactive map showing proposed PHS plants using Serra da Mesa and Cana Brava lower reservoirs. Fig. 18 presents the PHS plant with the highest NPV out of the ranking of 5600 mutually exclusive projects. Fig. 19 presents maps with the energy storage cost without and with cascade, and the additional capacity cost.

Comparing the costs for PHS plants with other energy storage alternatives, the energy storage investment cost for PHS, batteries and hydrogen (salt caverns) are 2 to 50 USD/kWh, 125 USD/kWh and 0.2 to 10 USD/kWh, while power costs are 400–1000 USD/kW, 250 USD/kW, 500–700 USD/kW, respectively [79–84]. This shows that in the near future hourly and daily storage will be provided by batteries close to variable energy sources or close to the demand. PHS will be considered to provide a combination of daily, weekly, monthly, and seasonal energy storage, and for water storage, drought alleviation and flood control. PHS will also compete with hydrogen as a long-term energy storage alternative. A significant challenge for the construction of PHS plants is the acquisition of environmental license, which has been difficult to acquire due to lobby from oil and gas industry in national environmental agencies. Another challenge is to estimate the viability for PHS projects



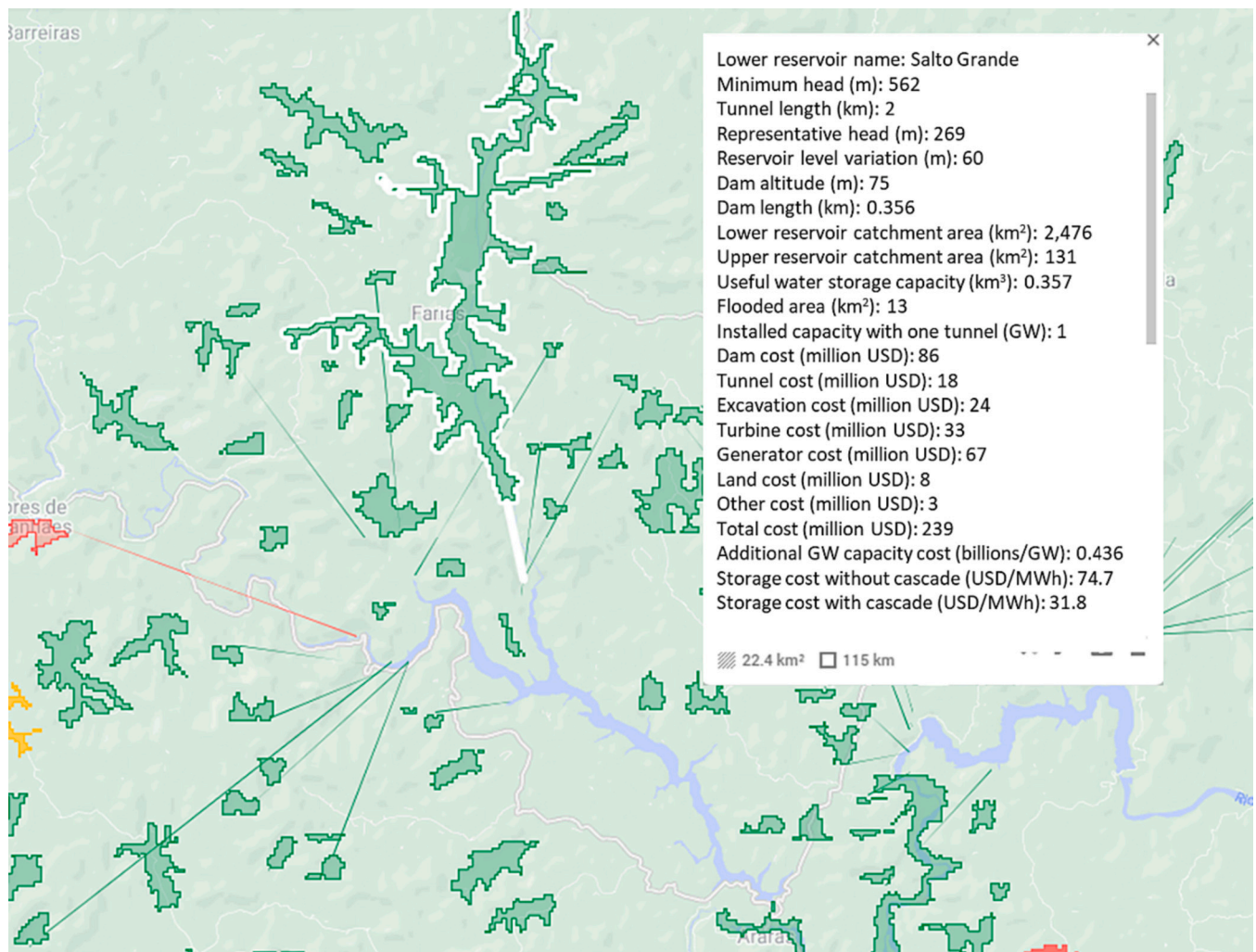


Fig. 18. PHS plant with the highest NPV out of the ranking of 5600 mutually exclusive projects. [76].

due to its high investment costs and long project lifetime. Future work will compare in detail the economic methodology presented in this paper with other work in the literature.

#### 4. Conclusion

PHS not only enables the development of 100 % renewable energy networks but also improves water security in areas with unfavourable terrain for traditional dams, high evaporation rates, and sedimentation. In addition to this, PHS plants built alongside existing reservoirs offer water management and energy storage services without the large land footprint associated with conventional hydropower dams. This makes it a critical global option for sustainable development both for mitigating and adapting to climate change. The article describes a methodology for identifying the technical potential for PHS plants in Brazil, using existing hydropower reservoirs as lower reservoirs. The PSH-siting software identified 145,000 projects in Brazil, which were then reduced to 5600 optimized projects. The described economic methodology analysed PHS project energy and power costs, and discharge time, and ranked the 5600 projects in order of highest net present values. This rank is presented in the interactive map in the link [76]. Results created a ranking of 5600 mutually exclusive projects by net present value (NPV) [76]. The highest NPV is 2145 USD which refers to a PHS plant in the Doce Basin and Salto Grande dam as the lower reservoir. The upper reservoir stores 0.36 km<sup>3</sup> of water and a 75 m high dam, the PHS has a 2 km tunnel, a 1 GW power capacity and discharge rate of 220 h. The selected

projects were ranked based on their economic viability and socio-environmental impact, resulting in a list of PHS sites that can be explored economically and are worth further studies.

#### CRedit authorship contribution statement

Conceptualization, J.H.; Methodology, R.B.; Software, F.D.; Validation, E.Q.; Formal analysis, B.Z.; Investigation, M.M.; Resources, M.F.; Data Curation, B.L.; Writing - Original Draft, J.H.; Writing - Review & Editing; Visualization, B.L.; Supervision, Y.W.; Project administration, A.L.; Funding acquisition, N.C., P.B. All authors have read and agreed to the published version of the manuscript.

#### Declaration of competing interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the

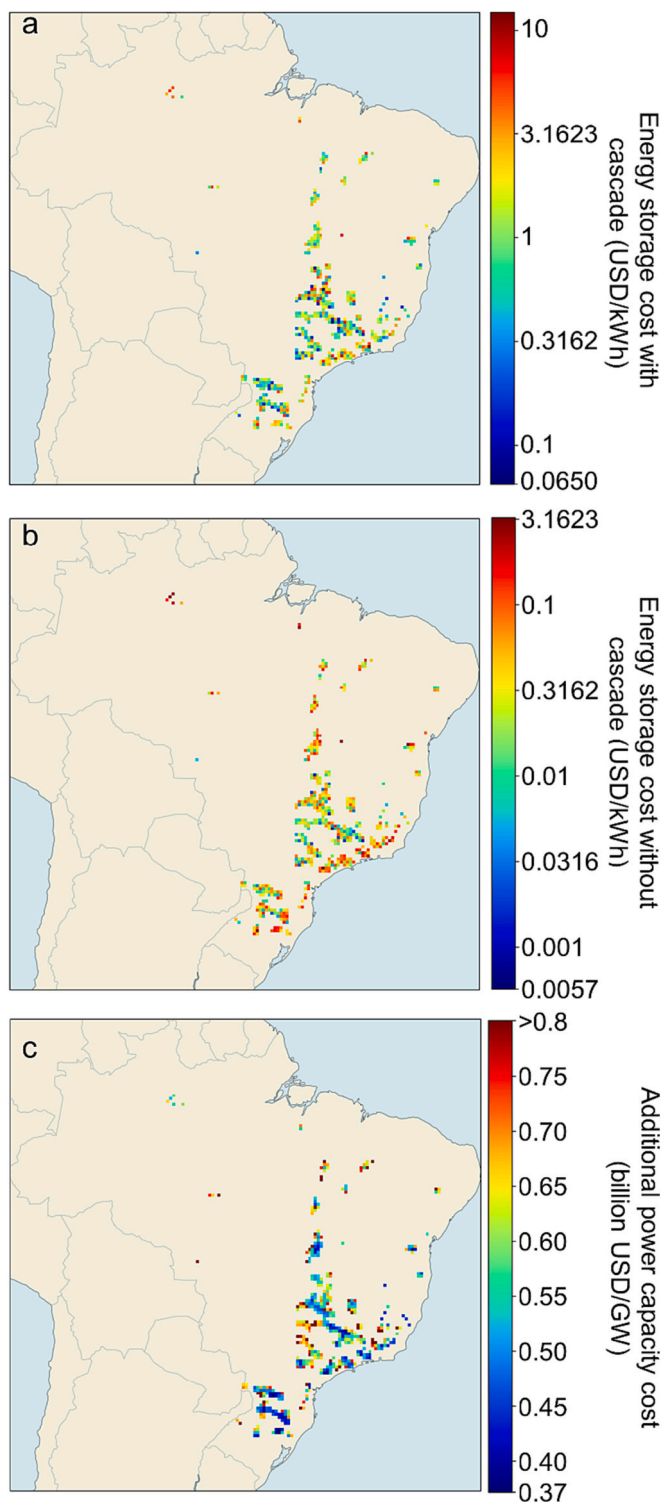


Fig. 19. Energy storage cost (a) without and (b) with cascade, (c) additional power capacity cost [76].

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In other words, there is no conflict of interest involved in this publication.

#### Data availability

The data is provided in a link to an interactive map in the article.

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