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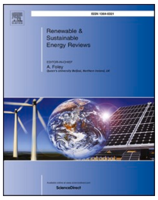

Existing and new arrangements of pumped-hydro storage plants

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ABSTRACT

The energy sector is undergoing substantial transition with the integration of variable renewable energy sources, such as wind and solar energy. These sources come with hourly, daily, seasonal and yearly variations; raising the need for short and long-term energy storage technologies to guarantee the smooth and secure supply of electricity. This paper critically reviews the existing types of pumped-hydro storage plants, highlighting the advantages and disadvantages of each configuration. We propose some innovative arrangements for pumped-hydro storage, which increases the possibility to find suitable locations for building large-scale reservoirs for long-term energy and water storage. Some of the proposed arrangements are compared in a case study for the upper Zambezi water basin, which has considerable water storage limitations due to its flat topography and arid climate. Results demonstrate that the proposed combined short and long-term cycles pumped-storage arrangement could be a viable solution for energy storage and reduce the cost for water storage to near zero.

1. Introduction

The development of a sustainable future requires better management of natural resources. New resource management approaches and the UN's Sustainable Development Goals (SDGs) [1] have been focusing on the need to optimize interactions between water, energy and land, to provide society and the economy with the required resources at an affordable cost, while minimizing the adverse impacts on the environment [2,3].

Water resources are essential for the development of society, industry, irrigation, transportation, recreation and hydropower generation. Water management can be a great challenge in dry regions, where there is a conflict in water demand between different sectors. Storage reservoirs play an important role to manage water resources across a basin and between time periods. However, storage reservoirs require appropriate geological formations that allow the reservoir level to vary significantly for storing a considerable amount of water. In plain regions, storage reservoirs can impose large land requirements, evaporation and capital costs to store small amounts of water and energy.

A reliable balance between energy supply and demand is facing more challenges with the integration of intermittent renewable energy sources such as wind and solar [4]. This has led to a growing demand for flexibility options such as energy storage [5]. These variable energy sources have hourly, daily and seasonal variations, which require back-up and balancing technologies to maintain a secure supply. Currently most pumped-hydro storage (PHS) plants only store energy in daily storage cycles, however, this might not be competitive in the future due to the reduction in battery costs [6]. Other reviews on PHS types can be seen in Ref. [7–9]. An high quality interactive map of the existing, under-construction and planned PHS projects can be seen in Ref. [10], as shown in Fig. 1. This figure shows that China has more than 20 GW of pumped storage plants in construction or planning stage [11].

An approach for optimizing the integration of water, energy and land resources, is the application of PHS for both short and long-term energy and water management. Instead of building storage reservoirs on main rivers, which causes large environmental impact and requires large land areas, a pump-station can store some of the water on the main river to a reservoir parallel to the river, usually in a tributary river [13]. These

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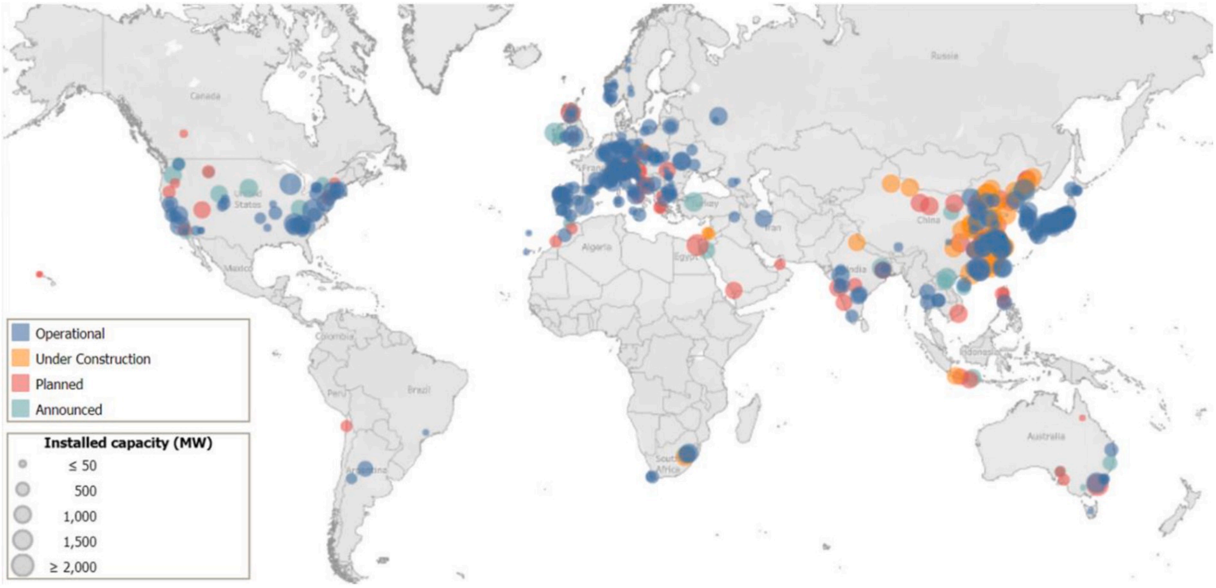


Fig. 1. World map with all operational, under construction, and planned pumped-hydro storage plants [10].

reservoirs would require considerably less land to store the same amount of water and energy because the upper reservoir water level would be able to vary much more than in typical conventional dams [10,13]. This approach for combining energy and water management with PHS plants has been applied in countries such as Austria [14–17], Switzerland [18–21], and Norway [22] for combined energy and water storage. However, there are only a limited number of arrangements that have been designed and built for combined water and energy storage with PHS.

This article presents the most common configurations of PHS and proposes new arrangements of PHS with the intent of increasing the possibilities for building large reservoirs with minimum impacts on society and the environment. The proposed arrangements will optimize hydropower generation in the dams downstream, minimize land requirement for water storage, reduce evaporation, and smoothen energy from intermittent renewable sources, among other applications. The superiority of the proposed pumped-hydro configurations compared to the existing methods will be examined through a case study on the Zambezi Basin. We apply a GIS-based potential assessment method, which is described in detail in Ref. [23], to estimate the reservoir volume storage and the costs of the projects to locate suitable sites for the proposed arrangements. The results of this study will inform energy planners and decision makers with more optimal solutions for land-water-energy management.

This paper is divided into six sections. Section 2 reviews conventional types of PHS plants. Section 3 presents the concepts behind the proposed PHS arrangements in this paper. Section 4 presents the results of this paper, which consists of the proposal of PHS projects in the Zambezi river basin. Section 5 discusses the findings of this paper. Section 6 concludes the paper.

2. Classification of existing pumped-hydro storage plants

PHS plants can be categorized based on different criteria, which will be reviewed in this Section. These were divided into storage size, pump-turbine rotation speed, storage need, and existing PHS arrangements.

2.1. Storage size

PHS plants can be divided according to storage size (see Table 1). The larger the upper reservoir storage size the higher the operational flexibility of the plant. A project with a large reservoir can provide the same services of a small reservoir and more, as explained as follows. Hourly pumped-hydro storage (HPHS) is used mainly to provide ancillary services such as frequency balancing, remove harmonics in the grid, provide backup power in case of disturbances in supply. HPHS can function on short circuit mode and they can make more than 100 reversions per day. An example of such plant is the Kops II in Austria [24,25].

Daily pumped-hydro storage (DPHS) is usually built for day-night energy arbitrage. This storage type is the most frequent PHS application today. The reduction in cost of batteries and the decentralization of power generation will probably reduce the importance of this type of pumped storage plant. An example of DPHS is Goldisthal in Germany [26,27].

Weekly pumped-hydro storage (WPHS) is usually built for storing energy from intermittent sources of energy such as wind and solar. This storage type has received an increased focus in recent years due to the ever-growing share of variable renewable energy. An example of WPHS is La Muela in Spain [28–31].

Seasonal pumped-hydro storage (SPHS) is further explained in this paper. SPHS is not widely employed in current energy systems, leaving this storage type with a large potential for the future. An example of SPHS is Limberg in Austria [17].

Pluri-annual pumped-hydro storage (PAPHS) are rare, built for storing large amounts of energy and water beyond a yearlong horizon. Interest in this PHS type will increase due to energy and water security needs in some countries. An example of this is Saurdal in Norway [18,22].

SPHS consists of two reservoirs, a lower and an upper reservoir connected by a power conversion system (pump/turbine) and a tunnel Fig. 2. The lower reservoir is meant for storing water and it may or may not have a large storage capacity. Typically, a month-long storage capacity in the lower reservoir is enough to store water in days with intense rainfall allowing the water in the main river to be pumped to the upper reservoir. The upper reservoir should have a large storage capacity to take up a large part of the water from the main river during the wet period, and possibly store water for use during droughts. Thus, most of the water will be stored in the upper reservoir and the lower reservoir would control flow fluctuation in the main river so that water will be available to be pumped to the upper reservoir.

The upper reservoir of a SPHS plant allows for a large level variation, of up to 250 m, reducing the land requirement for water and energy storage [13]. This low-flooded area and high-level variation results in a low evaporation per stored water ratio. This makes SPHS suitable for

Table 1
Different PHS cycles types for meeting energy needs [13].

PHS Type	Typical reservoir volume size (km^3)	Operation Mode	Occasions when the PHS type operates
Pluri-annual Pumped-Storage (PAPHS)	100–5	Pump	Annual surplus in hydroelectric generation [22]. Annual fuel prices cheaper than average. Lower than average annual electricity demand [32].
		Generation	Annual deficit in hydroelectric generation [22]. Annual fuel prices more expensive than average. Higher than average annual electricity demand [32].
Seasonal Pumped-Storage (SPHS)	30–1	Pump	Rainy seasons or ice melting seasons, with high hydropower generation [33]. Summer, with high solar power generation [23]. Windy seasons, with high wind power generation [34,35]. Low demand season, when electricity demand reduces.
		Generation	Dry period or freezing winters, with low hydropower generation [33]. Winter, with low solar power generation [23]. Not windy seasons, with low wind power generation [34,35]. High demand season, when electricity demand increases.
Weekly Pumped-Storage (WPHS)	5–0.1	Pump	During the weekends, when power demand reduces [36]. Windy days, with high wind power generation [35]. Sunny days, with high solar power generation [4].
		Generation	During weekdays, when power demand increases [36]. Not windy days, with low wind power generation [35]. Cloudy days, with low solar power generation [4].
Daily Pumped-Storage (DPHS)	1–0.001	Pump	Night, when electricity demand reduces [37]. Day, when there is solar power generation [38].
		Generation	Day, when electricity demand increases [37]. Night, when there is no solar power generation [38].
Hourly Pumped-Storage (HPHS)	1–0.001	Pump & Generation	Ancillary services: frequency control, remove harmonics in the grid, provide backup power in case of disturbances in supply.

regions where evaporation has a large impact on water management. Locations where a 250 m high conventional dam with 200 m level variation can be constructed are not common because the shores of major rivers are typically populated areas, with valuable infrastructure and important economic activities. SPHS increases the possibility of building large reservoirs considerably as there are many more potential sites in small tributaries compared to conventional dams in large rivers.

The water intake in a SPHS reservoir has two different origins. Firstly, water flows from the tributary river directly to the SPHS reservoir. This can be due to precipitation and/or ice melting. The other portion of the water in the SPHS reservoir comes from pumping water from the lower reservoir. SPHS can be operated with a combination of daily, weekly and yearly energy storage cycles and it may also be used to store water for water supply purposes. It can be used, for peak generation, ancillary services, storing intermittent wind and solar energy, hydropower optimization and water supply. The SPHS arrangement presented in this section is limited to pumping water from a lower reservoir to an upper reservoir. The following sections will present different arrangements where a single pump-turbine can be applied in a variety of configurations to provide different services.

2.2. *Pump-turbine speed and arrangement types*

PHS plants can have turbines that operate with a fixed rotation speed or variable speed. Fixed-speed turbines have an invariable generation and pumping capacity. This is not ideal if the PHS plant is to be used to store and complement the electricity generated from variable energy sources, given its inflexibility in power output [39]. It allows the final generation potential to vary, which apart from storing energy from variable energy sources, has considerable advantages for controlling the frequency of the grid. In other words, a fixed speed pump-turbine with a nominal 100 MW capacity will only generate or pump 100 MW of electricity under designed working conditions, while a variable speed pump-turbine will be able to generate and pump with a capacity varying from around 60 to 100 MW. This allows the pumped-turbine to store almost all excess wind generation in a system as shown in Fig. 3 for a system with five operating units. The fixed-speed turbine would not be able to store or generate electricity in the areas in colored in light blue. Variable speed pump-turbines cost approximately 30% more than fixed-speed alternatives and are not commonly used [40]. The final choice between fixed and variable speed turbines depends on techno-economic and demand aspects [41]. With the increase of intermittent renewables in the grid, variable speed turbines might become more common, which would reduce its price.

The most relevant application of variable speed pump-turbines in this paper is the possibility of benefiting from a greater variation of the pumping/generation head. For example, if the maximum pumping head is 500 m, the pump-turbine would operate at the maximum power of 100 MW to maintain a reasonably high efficiency. When operating at low heads of 250 m, the power of the turbines would have to reduce to, for example 60 MW. This would reduce the need for flow variation that passes through the pump-turbine when changing the operational head of the plant, maintaining a relatively high efficiency with large level variations [42,43]. Another advantage of a variable speed pump-turbine is its ability to operate efficiently even with large head variations.

Table 2 presents some PHS sites with pumping/generation head variations as high as 42.5%. This paper assumes maximum pumping/generation head variation percentage of 50% for the development of SPHS projects. This is a large value and could be reduced, however a reduction would affect some important design parameters, especially storage capacity and operational flexibility of the proposed SPHS plants.

Another alternative to further increase the head variation of a SPHS plant is to operate two pump-turbines in parallel when the pumping head is small and operate them in series when the pumping head is high [44]. This is not ideal because the plant loses some of its flexibility.

Another type of turbine is named ternary [40,47,49]. This turbine combines a Pelton turbine and a Francis pump. In this setup the power electronics for variable frequency AC excitation system and motor starter are no longer necessary, eliminating additional harmonic voltage or current source in the grid. Coupling to Francis pump can be swiftly engaged and disengaged. This enables shorter transition between power consumption mode and power generation mode, as reversing the turbine rotation is not necessary. This is very suitable to response to fluctuating power supply from wind and solar generation sources.

The quaternary PHS technology is the fastest responding pumped

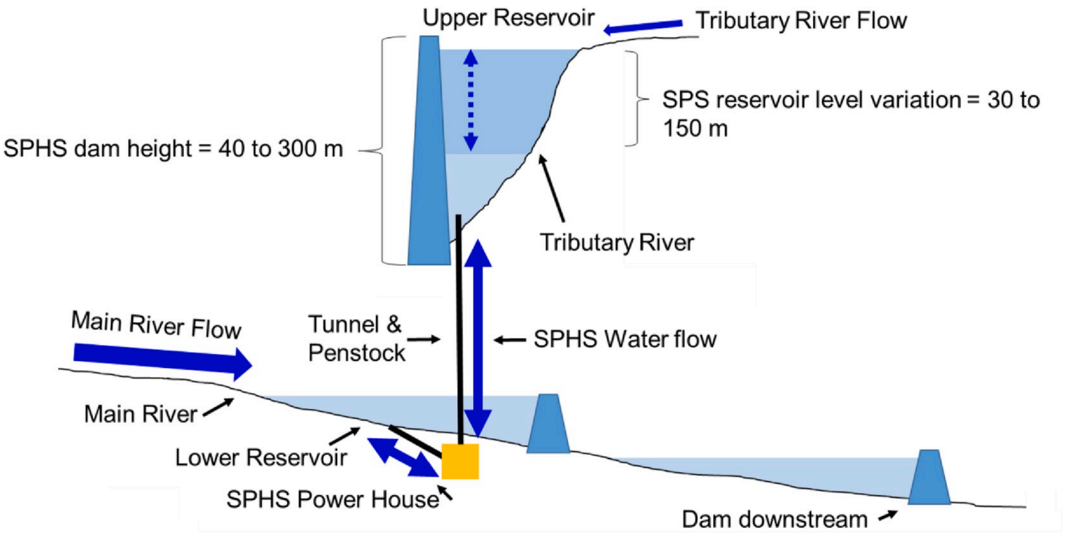


Fig. 2. Diagram of a seasonal pumped-hydro storage plant [13].

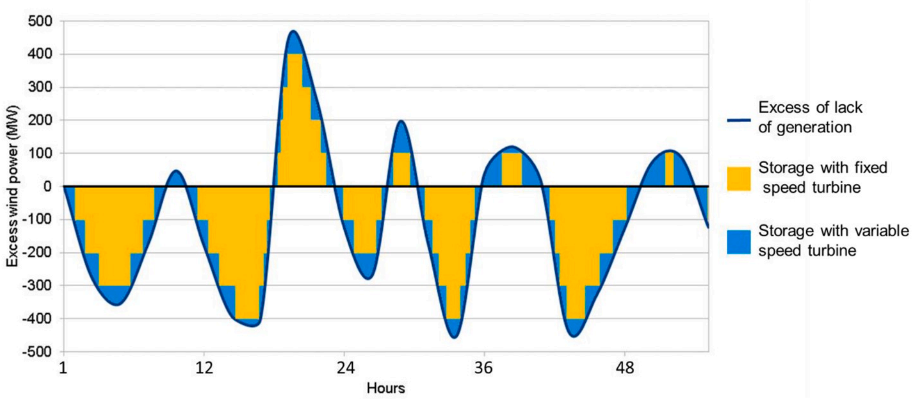


Fig. 3. Operation of fixed and variable speed turbines.

Table 2
PHS sites with high pumping/generation head variation [45,46].

Project Name	Units	Head (m)	Head Variation (m)	Variation Percent (%)	Power (MW)	Speed (rpm)	Rotation Speed	Country
Nant de Drance	6	250–390	140	35.9	157	428.6±7%	Variable	Switzerland
Linthal	4	560–724	164	22.7	250	500±6%	Variable	Switzerland
Tehri	4	127–221	94	42.5	255	230.8±7.5%	Variable	India
Limberg II	2	273–432	159	36.8	240	428.6	Fixed	Austria

hydro technology available for grid services [50]. An example is the Gordon Butte facility. It's configuration consists of separate pumps and turbines, each with a dedicated 134 MW motor and 134 MW generator [51]. The equipment is also connected in a hydraulic short circuit - basically a hydraulic loop connecting the turbine and the pump utilizing the lower reservoir. This configuration allows the facility to both pump and generate at the same time and seamlessly switch from pumping to generating and back again (including cold-start) at an estimated 20+ MW/sec.

2.3. Uses for PHS

Another aspect that great influences PHS types is the requirements. PHS plants could be used in combination with different needs. Some of the possible uses for PHS are explained in Table 3.

2.4. Existing pumped-hydro storage arrangements

The most well-known PHS arrangements are open-loop, closed-loop and pump-back storage. Open-loop consists of a PHS plant where there is a significant stream of water to the upper or the lower reservoir (Fig. 4 (a)). In this setup the operation of the pump-turbine may interfere with the river flow and this should be carefully cared for. In order to minimize the impact on the river flow, open-loop PHS schemes usually make use of existing hydropower dams as the lower reservoir. In cases where the lower reservoir is an existing dam, the powerhouse can be built downstream the dam. This way, the powerhouse will not require to be excavated as the head of the dam already increases the pressure in the powerhouse, like Seneca PHS in the USA [64] as shown in Fig. 4 (a). The difference between the arrangement presented in Fig. 4 (a) and a conventional open-loop PHS plant is that in conventional plants the powerhouse is excavated, and the arrangement in Fig. 4a the

Table 3
Possible uses for PHS.

Uses for PHS	Theme	Description
Energy storage	Energy	- Energy storage for peak generation, intermittent renewable energies such as wind and solar, optimize electricity transmission, among others.
Highly seasonal hydropower generation [32,33,53]		- Increase water and energy storage in water basins to regulate the river flow and increase hydropower generation. - Store excess water during periods of high hydropower generation and reduce spillage.
Goal for CO_2 emissions reduction [54–56]		- Hydropower, solar and wind generation usually do not have the same seasonal generation profile as the demand for electricity. Natural Gas is an option for flexible electricity generation, however, it is a fossil fuel-based source of energy and emits CO_2. A seasonal storage option should be considered by countries that intends to considerably reduce CO_2 emissions.
Seasonal energy supply and demand variations [57]		- Countries in high latitudes have a very seasonal solar power generation profile. Seasonal storage allows using the energy stored in the summer during the winter, when there is lower solar generation. - Countries in mid and high latitudes tend to have a seasonal electricity demand profile, consuming more electricity summer for cooling and during the winter for heating purposes, respectively. Typically, the peak national grid demand can be two to three times as high as the minimum demand. - With the electrification of the heating sector in countries at high latitude, the demand of electricity during the winter will increase even further.
Energy security [58]		- Reduction in fluctuation of electricity prices with fossil fuel prices and supply. - Reduction in fluctuation of electricity prices with renewable energy availability, especially hydropower. - Reduction in fluctuation of electricity prices with the demand for electricity.
Water Storage	Water	- PHS plants can store water on higher ground away from the river, in cases where along the river is infeasible or due to high evaporation rates.
High storage reservoir sedimentation		- PHS projects have much smaller sedimentation rates than conventional dams due to the small catchment area.
Better water quality control		- Storing the water parallel to the river, allows for a better control of the water quality in the reservoir. As it would not be directly affected by the fluctuations in water quality in the main river.
Flood control		- PHS plants can be used in combination with conventional flood control mechanisms to improve their efficacy.
Transport with waterways		- PHS plant channels could be also used for transport in waterways, combining the transport of water and goods. Additionally, the improvement in water management resulted from a SPHS plant would reduce the changes that a waterway runs out of water.
Inter-basin Transfer		- PHS projects can be combined with an inter-basin transfer project to increase the water security of a region or provide balancing between watersheds. PHS plants used for inter-basin transfer usually have longer tunnels or use the upper reservoir as a canal to facilitate water basin transposition, e.g., Snowy Mountain scheme in Australia [59] and the Grand Coulee dam in the USA [60,61].
Low evaporation		- In some cases, PHS are used for water storage due to the lower evaporation in these plants [62].
Water security		- Increase the water storage capacity in regions where conventional storage reservoirs are not appropriate.
Lower environmental and social impacts [63]	Environment	- Damming a major river for storage would affect a higher environmental and social impact than damming a small tributary river. SPHS allows water storage without fragmenting the ecosystem of a main river.

powerhouse does not require to be excavated, as the head of the dam in the river, upstream the powerhouse provides enough head to avoid cavitation.

Close-loop PHS consists of an upper and lower reservoir far from a large water source and, thus, with a limited water input into the system (Fig. 4 (b)). These systems can be implemented in small artificial lakes, filled either by the precipitation of its limited catchment area or on water brought from a different location [37,65]. The environmental impact of closed loop PHS plants is usually smaller than open-loop plants. However, they are usually limited to daily or weekly storage cycles. An example of a close-loop project is the Marmora PHS in Canada [66].

Pump-back storage consists of installing pump-turbine in hydropower dams wherever there is another reservoir immediately downstream. This allows the water flow back and forward between the two reservoirs [67] (Fig. 4 (c)). This arrangement increases flexibility and operational range as the pump-turbines can be used for both hydropower conventional generation and storage. For example, in case of a drought, conventional hydropower generation will be reduced, but the plant can still be used as pumped storage. The head in pump-back storage plants is usually low. However, the system is viable as long tunnels are not required. In Japan, a number of dams were built with reversible turbines [68]. This is due to the historic dependence of Japan on nuclear energy, an inflexible source of generation, which creates the need for daily energy storage. The pump-back plants can also be used as part of a water supply solution. The precipitation downstream Japanese rivers can be pumped upstream by pump-back storage plants to be stored on the head of the river for later use. Without a pump-back solution, some of the water would be discharged to the sea. An example of such scheme is Kannagawa in Japan [69].

PHS can provide energy and water storage combined with desalination and demand side management as a very effective way to optimize the energy and water supply in an island, especially in the presence of variable energy sources in the system. An example of this integration happens in the Soria-Chira plant in the Canary Islands [34,35]. Other less common configurations of PHS include underground PHS [71–74], decommissioned open pit mines PHS [75,76], seawater PHS [77–79], gravity-based cylindrical systems [80,81], offshore water storage at sea [82], and storage of water and energy inside wind turbine towers [83].

Run-of-the-river SPHS plants can store water from a main river,

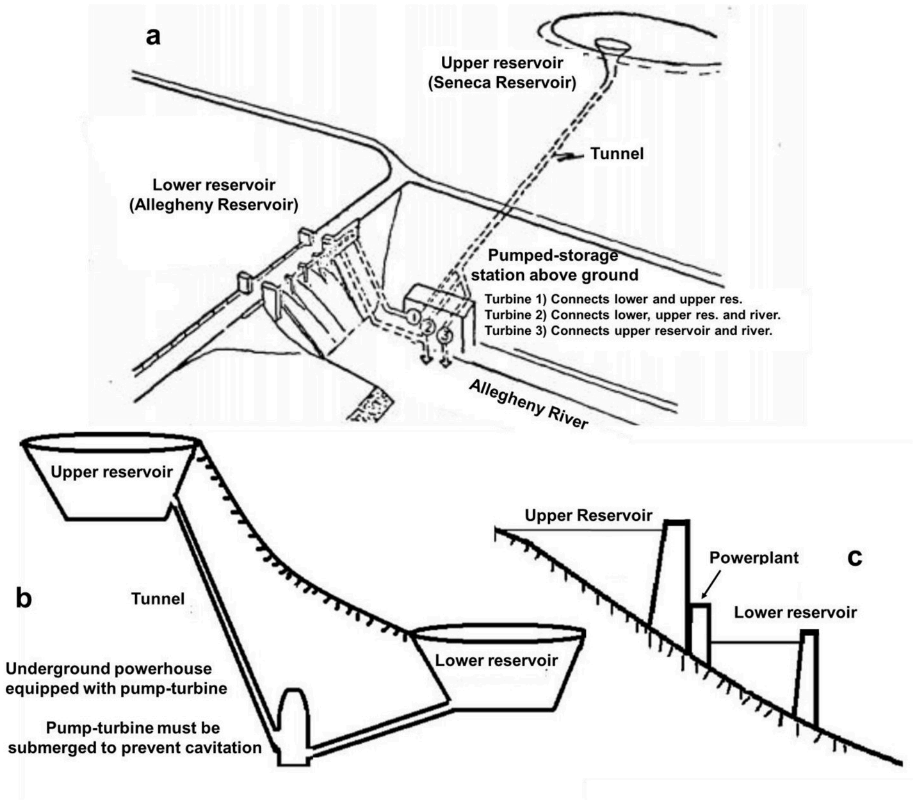


Fig. 4. Three types of PHS arrangements. (a) Open-loop PHS plant with no need for excavation [70], (b) closed-loop PHS with no considerable inflow in the upper or lower reservoir [68], (c) pump-back PHS with no need for excavation [68].

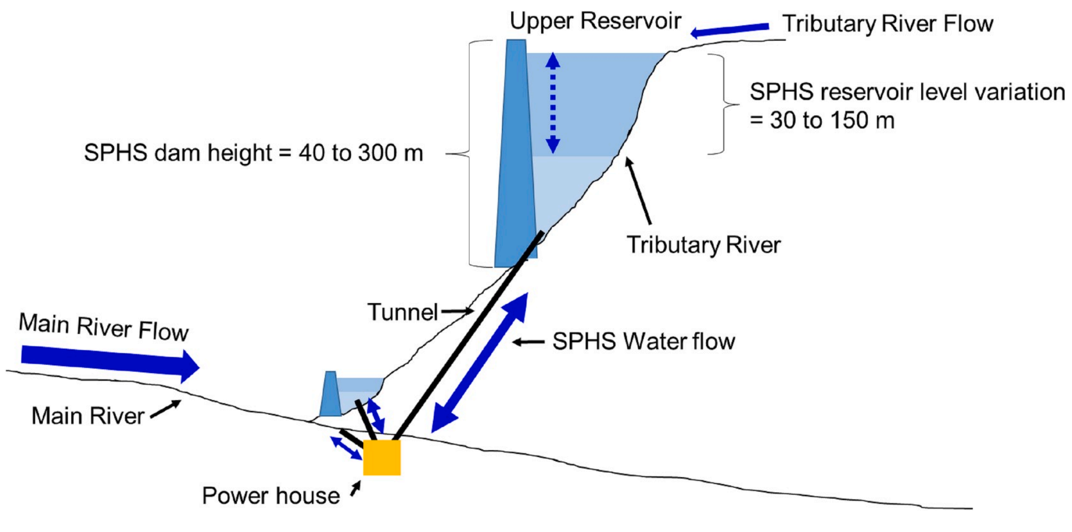


Fig. 5. Run-of-the-river seasonal pumped-hydro storage with a large upper reservoir and a small lower reservoir [13].

without the need to dam the river (Fig. 5), thus, reducing social and environmental impacts [46,84]. Run-of-the-River SPHS are used to extract continuous amounts of water from the river during periods of high river flowrate and return continuous amounts of water to the river during periods with low river flowrate. The constant return of water intends to reduce the impact of river flow variations, which impacts the ecosystem in and around the river. The lower reservoir, which is not on the main river, is used as a standard PHS lower reservoir. In this way, the same pump-turbines can be used both to regulate the river and as an energy storage solution. The high-head pump-turbines can only move water from the lower reservoir or from the river to the upper reservoir and vice-versa. There might also be the need of a low-head pump-turbine to pump water from the river to the lower reservoir, to keep the river flow constant. An example of run-of-the-river PHS is Malta in Austria [17].

3. Methodology: proposed pumped-hydro storage arrangements

This section presents some PHS arrangements that have not yet been implemented. They could be considered for specific water and energy storage services on locations with low topographical variations and low water availability.

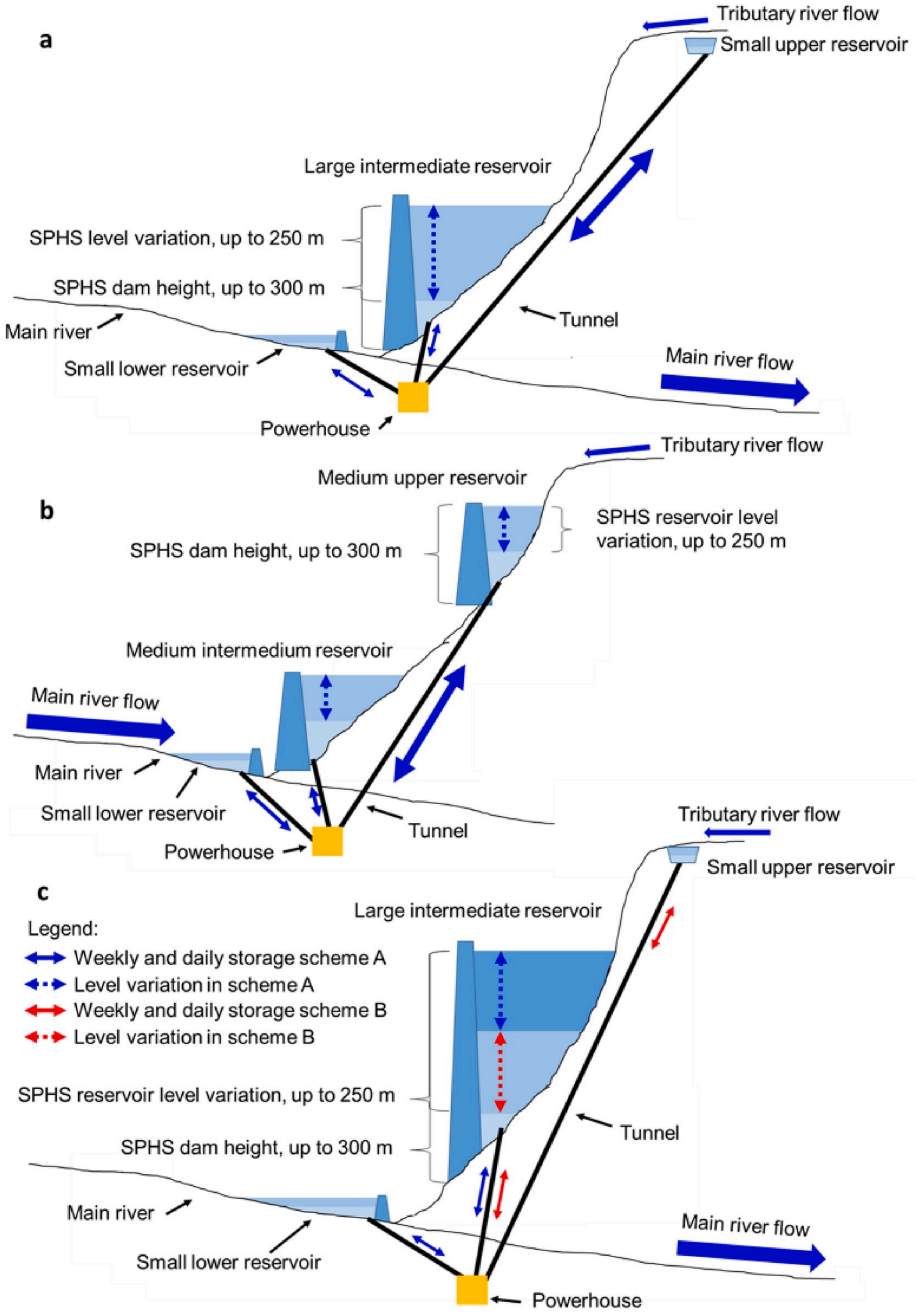


Fig. 6. SPHS arrangements for combined short and long-term storage with (a) small upper reservoir and a large intermediate reservoir, (b) medium upper reservoir and medium intermediate reservoir, (c) intermediate reservoir divided in two sections.

3.1. Combined short and long-term cycle seasonal pumped-hydro storage (CCSPHS)

This arrangement has the main objective to allow for head variation greater than 50% in order to increase water and energy storage capacity in the main reservoir in locations where topography does not allow a more conventional setup.

As shown in Table 2, head variation in conventional PHS setups can be designed to vary up to 50%. If the level variation of an individual turbine is higher than 50%, the efficiency will be considerably affected. It would be possible to build two sets of turbines with different designs to allow a head variations greater than 50%. However, this would considerably impact the feasibility of the project.

In order to solve this head variation limitation and increase the

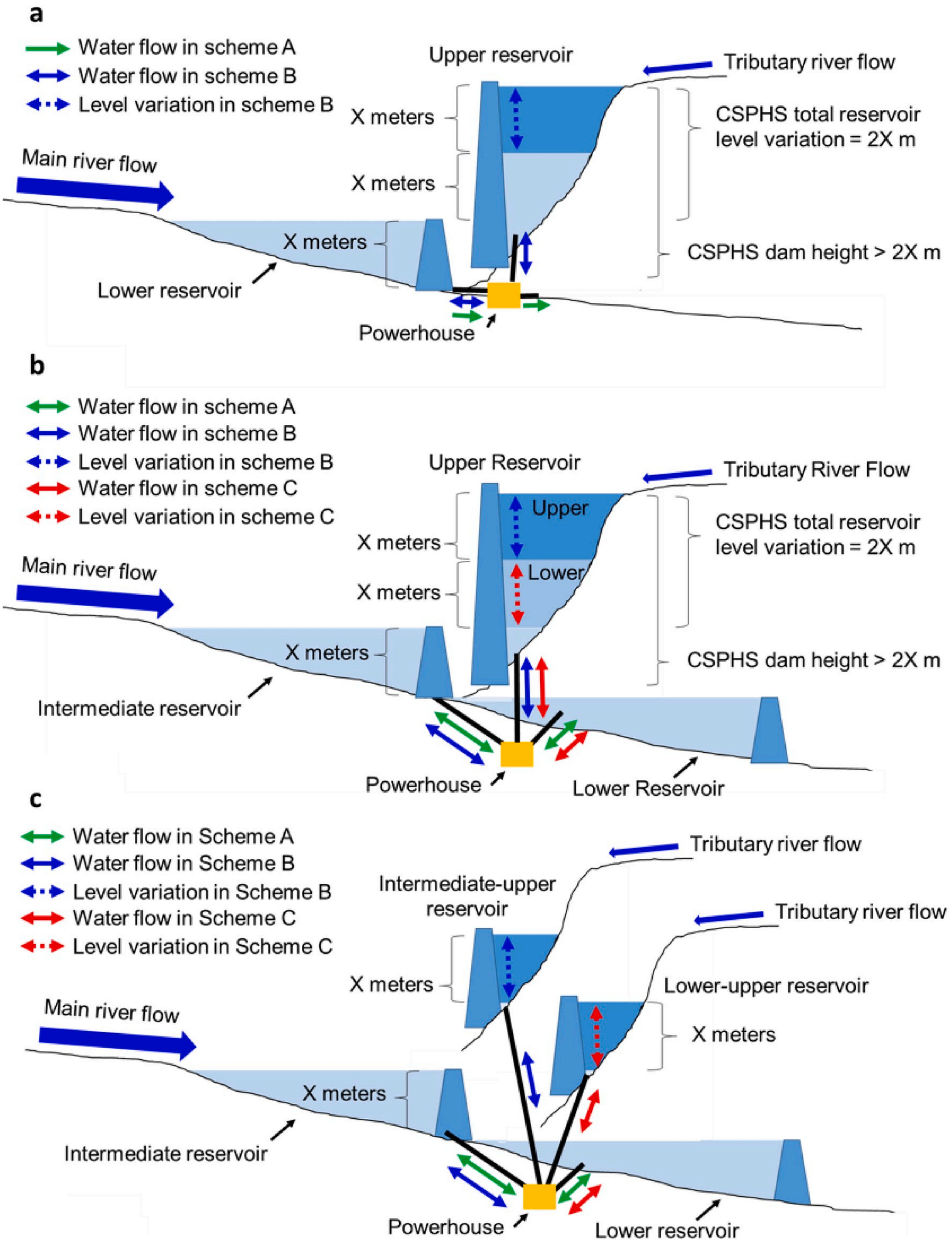


Fig. 7. Combined hydropower and pumped-hydro storage (CHPHS) arrangement. (a) Without lower reservoir and without the need for powerhouse excavation. (b) With lower reservoir and upper reservoir divided into two sections. (c) With multiple reservoirs connected.

designed reservoir storage capacity, this paper proposes new SPHS arrangements with three reservoirs. In these arrangements the water can be shifted around the three reservoirs and fulfil short-term energy storage needs and long-term energy and water storage needs. These arrangements are further explained in the paragraphs below.

The SPHS arrangement presented in Fig. 6 (a) consists of a small lower reservoir in the river, a large intermediate reservoir and a small upper reservoir. As in Fig. 5, water flows from the lower and intermediate reservoir to the upper reservoir and vice-versa. However, it would be difficult and expensive to operate a pumping system from the lower to the intermediate reservoir due to the large head variation, as explained above. Thus, this arrangement would only work if short and long-energy storage needs are combined. For example, water pumped from the river to the upper reservoir at night is released during the day to the intermediate reservoir as part of a daily energy storage cycle. During the day water from the upper reservoir flows to the intermediate

Table 4
Different configurations for combined hydropower and PHS plants. Possible values for 'X' in Fig. 7.

Intermediate Reservoir Generation Head (m)	Turbine pumping/ generation head variation (m)	Upper Reservoir maximum level variation (m)	CHPHS dam height (m)
30	30–60	60	70–90
50	50–100	100	110–150
70	70–140	140	150–210
100	100–200	200	210–300

Table 5
Different operational approaches for multi reservoirs combined hydropower and pumped-hydro storage plant.

Operational Scheme	Main Purpose	Operation Mode	Water from	Water to
A	Pump Back Storage	Generation	Intermediate Reservoir	Lower Reservoir
		Pump	Lower Reservoir	Intermediate Reservoir
B	Water and Energy Storage	Generation	Upper Reservoir, Upper Section	Intermediate Reservoir
		Pump	Intermediate Reservoir	Upper Reservoir, Upper Section
C	Water and Energy Storage	Generation	Upper Reservoir, Lower Section	Lower Reservoir
		Pump	Lower Reservoir	Upper Reservoir, Lower Section

reservoir generating electricity while at the same time storing water in the seasonal reservoir. The large intermediate reservoir can have a large head variation given that the water used to fill up this reservoir come from the upper reservoir. The combination of the two cycles (short and long-term) is important because a pump-turbine system would not the able to pump water from the lower reservoir to the intermediate reservoir due to the pump-turbine limitation in head variation. This arrangement is proposed for a location where the topography does not allow the construction of storage reservoirs and there is a need for short and long-term energy or water storage, for example, in the Amazon and upper Zambezi basins.

Another possibility is to build two medium-sized reservoirs, as shown in Fig. 6 (b). The operation would be similar to the presented in Fig. 6 (a). Given that the storage is split in two medium-sized reservoirs, the overall water storage would be smaller and the social and environmental impacts may be larger. However, this arrangement can be the most cost-effective option for a specific case, depending on the topography. It also has a greater operation flexibility, as the two reservoirs will have enough water for long-term storage cycles regardless of the river flow.

Fig. 6 (c) presents the arrangement that allows the highest water level variation in flat topography regions, which in turn contributes to a smaller land requirement in relation to water storage capacity. It would also reduce evaporation. In this arrangement, the intermediate reservoir would be filled up with water from the lower reservoir when the intermediate reservoir level is high enough, and it would be filled from the upper reservoir, when the intermediate reservoir level is low. This change in operation from the lower to the upper reservoir is important because the head of the pump-turbine cannot vary with all the reservoirs level variation as it is limited to, for example to 50% of the maximum head. The operation in Fig. 6 (c) divides the maximum head variation of the pump-turbine in almost half. In this arrangement, the minimum designed pumping head capacity is higher than in Fig. 6 (a), which reduces tunnel costs.

The arrangements presented above allow the pumping head and reservoirs to have a head variation larger than 50%. This is particularly interesting to store large amounts of energy and water in locations where the topography does not permit the construction of conventional SPHS plants.

3.2. Combined hydropower and pumped-hydro storage (CHPHS)

A CHPHS plant can be used for hydropower generation or for energy

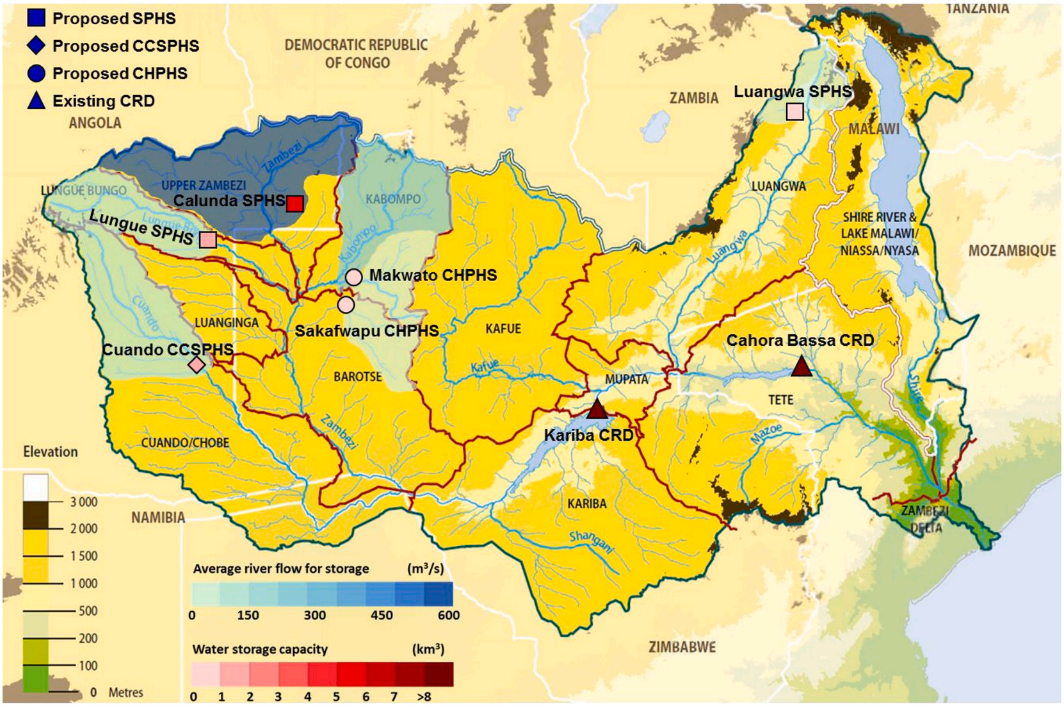


Fig. 8. Different arrangements of PHS plants proposed for the Zambezi river basin, with average river flow and water storage capacity.

Table 6
Description of proposed PHS plants.

Details	Lungue	Cuando	Calunda	Sakafwapu	Mukwato	Luangwa
Storage Type	SPHS	CCSPHS	SPHS	CHPHS	CHPHS	SPHS
Maximum level (m)	1180	1135	1200	1140	1145	955
Minimum level (m)	1150	1100	1160	1100	1100	905
Level variation (m)	30	35	40	40	45	50
Downstream level (m)	1120	1060	1055	1085	1085	680
Dam height (m)	40	55	70	60	60	70
Dam length (km)	4	2	4	2	4	1
Tube (km)	10	6	23	8	9	12
Maximum Flooded area (km^2)	120	57.5	314.5	39	92	44.6
Minimum Flooded area (km^2)	40	32	75	30	21	7
Flooded area variation ratio	3	1.8	4.2	1.3	4.35	6.4
Total flooded area (km^2)	130	67	345	69	160	54
Useful stored volume (km^3)	1.80	1.21	5.03	0.94	2.07	0.89
Catchment Area (km^2)	21536	30509	73054	19023	19741	16152
Average flow (m^3/s)	0.9	1.27	9.59	0.59	0.82	0.84
Storage/50% annual flow ratio	92	79	597	37	246	52
Sub-basin drought water availability (m^3/s) [89]	15	12	40	200	65	0
Wind speed (m/s) [23]	5.7	7,0	5.5	6.9	6.7	7.8
Solar Irradiation (kWh/m^2) [24]	2050	2100	2050	2050	2100	2300

storage (Fig. 7 (a)). The lower reservoir is built on the main river and the powerhouse is built downstream of the dam. This arrangement does not require excavation, as the water level in the river dam already maintains the required pressure on the pump-turbine to prevent cavitation. This considerably reduces project costs, especially if the plant has a low generating head [85]. This arrangement is similar to the one in the Seneca PHS [64] (Fig. 4 (c)). It offers flexibility for the operation of the system, making it possible to decide if the dam generates hydropower, e.g., during periods of large river flow, or if the pumped-hydro storage is to be used to help manage the grid (energy storage) or to increase river flow during dry periods. In order for these arrangements to work properly, the height of the reservoirs must match each other as shown in Fig. 7, where 'X' represents the height of the reservoir. Table 4 presents different pumping/generation head configurations of CHPHS plants.

Another alternative for CHPHS plant is to excavate the powerhouse and integrate a lower reservoir to the system. This would result in three or more reservoirs instead of two. These can be the upper, intermediate and lower reservoirs, as shown in Fig. 7 (b) for a three-reservoir case. This arrangement consists of two dams built in the main river and a larger reservoir dam on a tributary river. These reservoirs are connected via tunnels to the same pump/turbines, providing flexibility to operate at a variety of different modes. The upper reservoir should store large amount of water and energy, similar to SPHS plants. If there is only need to store short-term energy, a pump-back solution would be much more practical and cheaper.

The arrangements in Fig. 7 (b) and (c) can operate in three different ways detailed in Table 5. In Scheme A, the pump-turbine operates close to the lowest generation head similarly to a pump-back power plant allowing water to flow from the intermediate reservoir into the lower reservoir and vice-versa. Scheme B is similar to a SPHS plant. Water is pumped from the intermittent reservoir into the upper section of the upper reservoir for storage and vice-versa. It should be noted that generation and pumping cannot happen between the upper section of the upper reservoir and the intermediate reservoir, as the head variation would be too low. Scheme C also operates similarly to a SPHS plant; however, the water flows from the lower reservoir into the lower section of the upper reservoir. Note that this scheme can only operate if the upper reservoir is in the lower section. Similarly, Scheme B can only operate if the upper reservoir is in the upper section, as the pumping head would be too small for an efficient operation.

The main function of the lower reservoir is to increase the catchment area of the system, as such, increasing the amount of available water to be stored in the upper reservoir. The lower the dam is in a river basin the bigger its catchment area and, usually, the higher its flow rate. Thus, a lower reservoir would increase the availability of water for storage. However, this arrangement could be built without a lower reservoir. The lower reservoir might not be required, if it would not considerably increase the catchment area of the plant, or if the flow at the intermediate reservoir is large enough, or if it is not viable due to economic, social or environmental reasons. In this case, Scheme C can still be operational the dam downstream outlet can be designed to work as a small lower reservoir and Scheme A can operate at the same time as Scheme B so that the lower section of the upper reservoir can fill up.

To analyze the proposed configurations, a pumped-storage GIS siting module have been developed by the authors in Python to find PHS project locations. The Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation data is used in the module [86]. The reservoir locations and size have been identified with the objective of storing around 50% of the total hydrological available flow. The methodology applied to compare the three different SPHS approaches is based on the hydrological flow obtained from Ref. [87], the design of the PHS components taken from [88] and the cost estimations from [85]. Mode details on the methodology applied in this module can be found in Ref. [23].

4. Zambezi Basin case-study: comparing proposed pumped-hydro storage arrangements

This section examines different arrangements proposed for PHS on the Zambezi basin. The best examples for SPHS, CCSPHS and CHPHS identified in the Zambezi upper basin are shown in Fig. 8. Most projects are proposed in the upper Zambezi basin, upstream the Victorian Falls, which have practically no storage reservoirs due to its low topography and high evaporation rates. The existing Kariba and Cahora Bassa conventional reservoir dams (CRD) are also included in the figure. The details of each project are shown in Table 6.

Even though water storage with low evaporation is the main objective of the proposed plants, to make the construction of the plant economically feasible and socially acceptable, energy storage services are also considered for grid management. Given the need of energy to store water with pumped-hydro storage, it is important to analyze the existing renewable energy potential of the region. The average wind speed across the river basin is small. There are only a few locations with average wind speeds higher than 7 m/s (Fig. 9 (a)). However, the region has solar power potential reaching a yearly average of 2300 kWh/m^2

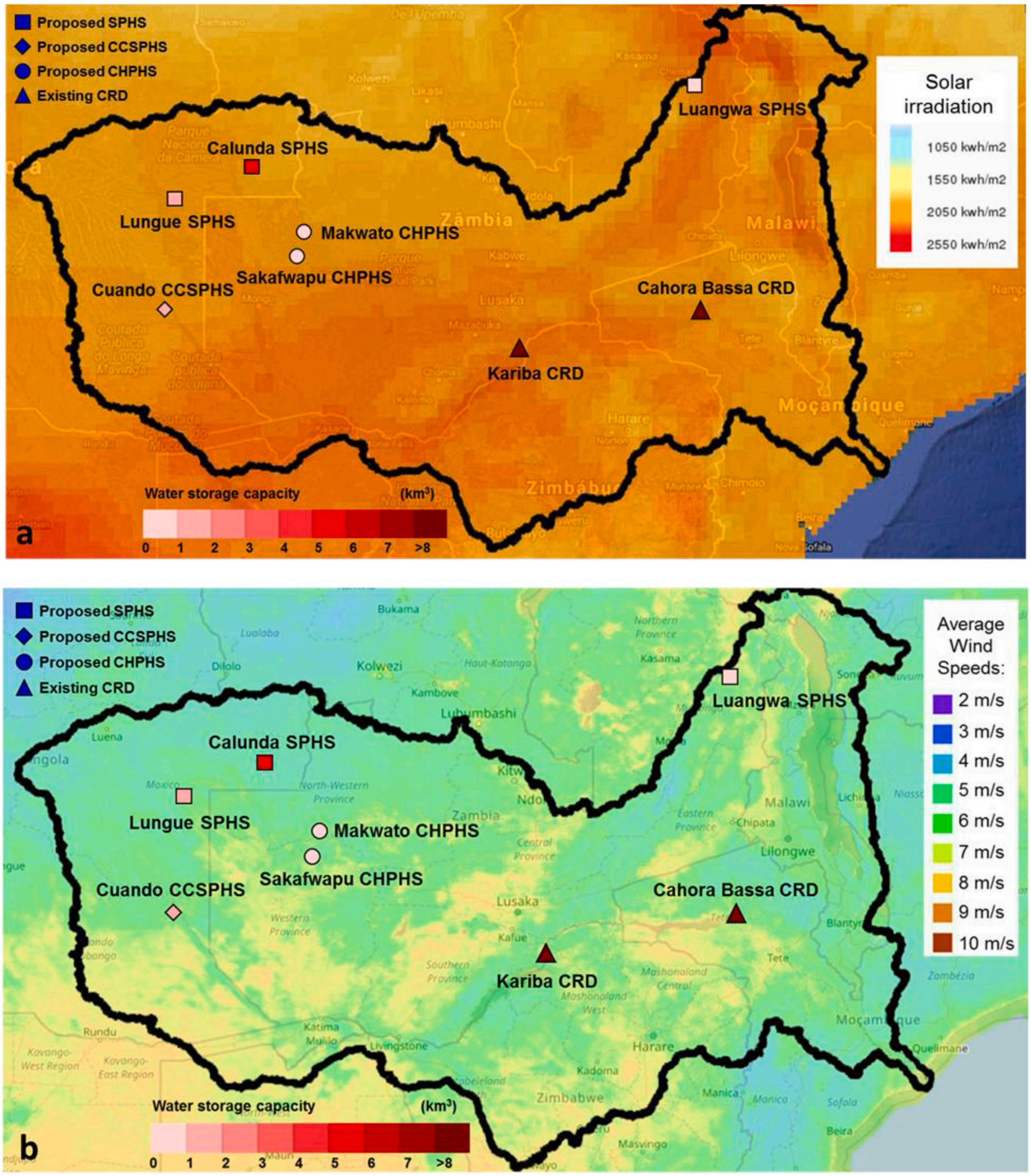
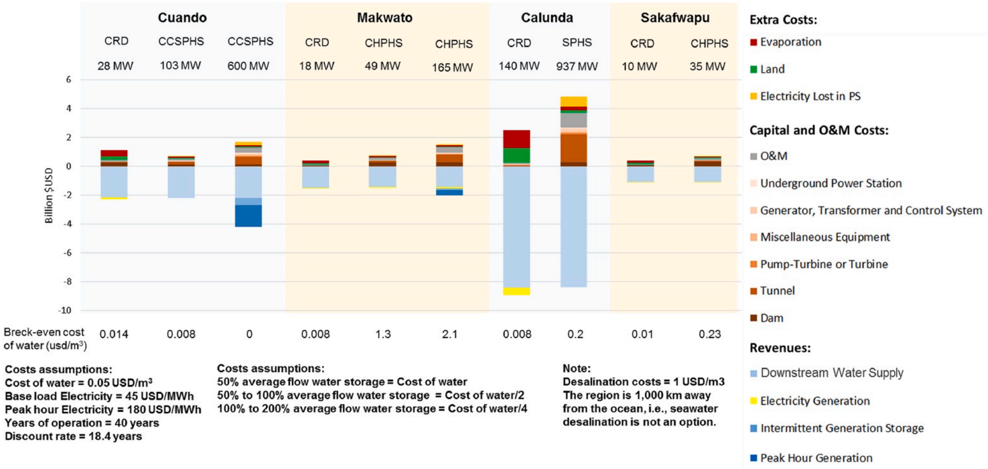


Fig. 9. Zambezi basin (a) solar generation potential [90], (b) and wind generation potential [91].



Costs assumptions:
Cost of water = 0.05 USD/m³
Base load Electricity = 45 USD/MWh
Peak hour Electricity = 180 USD/MWh
Years of operation = 40 years
Discount rate = 18.4 years

Costs assumptions:
50% average flow water storage = Cost of water
50% to 100% average flow water storage = Cost of water/2
100% to 200% average flow water storage = Cost of water/4

Note:
Desalination costs = 1 USD/m3
The region is 1,000 km away from the ocean, i.e., seawater desalination is not an option.

Fig. 10. Cost comparison of different PHS arrangement in the Zambezi basin.

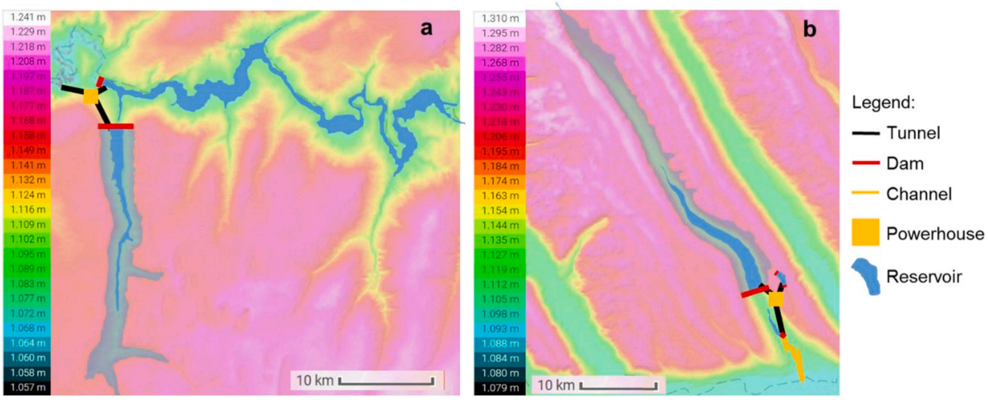


Fig. 11. Representation of proposed (a) Makwato CHPHS and (b) Cuando CCSPHS.

(Fig. 9 (b)). Solar power could be used to pump the water in PHS plants and PHS could reduce the intermittence of solar power generation.

A cost comparison between some of the proposed PHS projects and the compatible conventional reservoir dam for water storage is presented in Fig. 10. The investment, operational and other costs are assigned a positive value, and the revenues are assigned a negative value. According to the results, the water storage costs for the Cuando CRD reservoir is more expensive than the Cuando CCSPHS plant with 103 MW and 600 MW. This is mainly because, the Cuando CRD would require a large area to store water, which would result in large land costs and losses due to evaporation. Water storage costs are used for the comparison because the electricity generated by the Cuando CRD plant is considerably small and water is a major issue in the region. The Cuando CCSPHS project with 600 MW would be more beneficial than the Cuando CCSPHS with 103 MW because the turbine would be used both to store energy and water, benefiting from both revenues.

However, for the other proposed plants (Makwato, Calunda and Sakafwapu), the CRD alternative is cheaper than the PHS alternatives. This is mainly because, hydropower in the Upper Zambezi region has low viability to justify a CHPHS project due to the low head, and furthermore, the Calunda SPHS plant requires a 23 km tunnel, which considerably increases the costs of the project. Fig. 11 presents a representation of the Cuando CCSPHS and Makwato CHPHS projects.

This case study intends to support the sustainable development of the region and increase electricity generation, aiming for 100% wind, hydro and solar generation [92]. It also intended to regulate the river flow at their sub-basin level, reduce water storage evaporation, reduce the intensity of floods, store water in case of droughts and store electricity from intermittent generation sources.

5. Discussion

There is a variety of alternatives to implement PHS arrangements for short and long-term energy and water storage. Comparing the proposed PHS arrangements in this paper demonstrates the benefits and drawbacks of each approach. Table 7 summarizes the benefits and drawbacks of the main arrangements discussed in this paper.

The case study looked at the possibility of using PHS to provide water and energy storage to allow the development of the upper Zambezi basin. Given that hydropower and wind power have small potential in the region, solar power is the best alternative to provide electricity for pumping and storing water in the basin. The PHS projects, would also increase the viability of solar plants, by providing short and long-term storage to guarantee a constant supply of electricity.6.

6. Conclusions

This paper presented and exemplified different types of pumped hydropower storage (PHS) plants, focusing on plants with large reservoirs for water and energy storage, the so called, seasonal pumped-hydro storage. The cost reduction of battery energy storage technologies will challenge the feasibility and competitiveness of short-term storage PHS plants. Hence, this paper suggests that future PHS projects should serve both short and long-term energy storage needs, and water storage.

The proposed PHS methods and configurations in this article have the main objective to increase the possibilities of building large reservoirs in parallel to a main river while reducing the socio-economic and environmental impacts of conventional reservoir dams. The combined short and long-term cycle seasonal pumped-hydro storage (CCSPHS) arrangement proved to be particularly feasible for locations with low topography and limited sites for large storage reservoirs. The combined hydropower and pumped-hydro storage (CHPHS) plant increases the operational flexibility of the plant generating electricity when the flow of the river is high and stores energy when the river flow is low, increasing the viability of the plant.

Comparing the costs of water storage with Cuando conventional reservoir dam (CRD) for 0.014 $\$/m^3$ and with Cuando CCSPHS for 0.008 $\$/m^3$, the case study in the Zambezi region shows that the only arrangement that was proven competitive to conventional reservoir dams is the CCSPHS plant. Adding the need for short-term energy storage, water storage becomes an added benefit, as the energy storage need would cover the total costs of the project. CCSPHS is a configuration designed for storing large amount of energy and water in regions with low topography where considerable evaporation losses could occur in conventional reservoir dams. Even though the new proposed arrangements in this paper increases the viability of some PHS projects, the topography will remain the main decision driver for future PHS projects.

The growth of variable renewable energy in the future will require the use of short and long-term storage alternatives. PHS will become even more important as it can improve resource management and reliability of supply in both energy and water sectors.

Credit author statement

Julian David Hunt: Conceptualization, Methodology, Writing - original draft. **Behnam Zakeri:** Writing - review & editing, Data curation. **Rafael Lopes:** Investigation, Formal analysis, Validation. **Paulo Sérgio Franco Barbosa:** Resources. **Andreas Nascimento:** Visualization. **Nivalde José de Castro:** Supervision. **Roberto Brandão:** Funding acquisition. **Paulo Schneider:** Supervision. **Yoshihide Wada:** Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial

Table 7
Comparison between different PHS arrangements.

Technology	Benefits	Drawbacks
Pump-Back Storage (PBHS)	- Good alternative for building dams in cascade, combining hydropower generation, short and long-term storage. - More operation flexibility. - Cheap alternative, if the dams are already planned to be built.	- Need for damming the main river. - Storing water in a main river causes large socio-environmental and economic impacts. - Difficulties in retrofitting existing dams to PHS due to the need for large tunnels with low head.
Seasonal Pumped-Storage (SPHS)	- Large flexibility for the operation of the SPHS plant, including seasonal, weekly and daily cycles. - A storage reservoir built on a tributary river has lower environmental and social impacts, than one built on the main river. This is because the surrounding of main rivers usually has higher population concentration and higher importance to the environment.	- Need for damming the main river. However, existing dams may be used as a lower reservoir
Run-of-the-River Pumped-Storage (RRPHS)	- No need to dam the main river.	- As RRPHS does not have a lower reservoir, daily storage cycles would have a great impact on the main river flow, which is not advisable. This could be resolved by building a second low-head pump-turbine circuit between the river and a lower reservoir off the main river. This arrangement is presented in Fig. 9 in Ref. [13].
Combined Cycles Seasonal Pumped-Storage (CCSPHS)	- Increases the possibility of building large reservoirs for energy and water storage. Particularly in regions with low topography. - The high water level variation in the reservoirs is appropriate to reduce evaporation in arid regions.	- In order to make this arrangement work, there is the necessity of both short and long-term energy storage needs. This reduces the flexibility of the plant. For example, if there is no need for short-term storage, the plant won't the able to fill up the reservoir for long-term storage.
Combined Hydropower and Pumped-Storage (CHPHS)	- Combine hydropower and pumped-storage with the same pump/turbine. - The proposal with two reservoirs does not require excavation of the powerhouse. - More reservoirs could be included to increase the catchment area for hydropower. - It is possible to store large amounts of water and energy. - Increase the operational flexibility of the pump-turbines, generating or storing energy, which increases the capacity factor of the reversible pump-turbines, sub-stations, transmission lines, among others.	- There is a need for damming the main river. - Given to the need to combine hydropower and storage, there are less locations where this would be possible to build. - Low head projects are only feasible with very short tunnel lengths.

interests or personal relationships that could have appeared to influence the work reported in this paper.

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