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3 **Existing and new arrangements of pumped-hydro storage plants**

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5 Julian David Hunt<sup>a\*</sup>, Behnam Zakeri<sup>ab</sup>, Rafael Lopes<sup>c</sup>, Paulo Sérgio Franco Barbosa<sup>c</sup>,  
6 Andreas Nascimento<sup>a</sup>, Nivalde José de Castro<sup>d</sup>, Roberto Brandão<sup>c</sup>, Paulo Schneider<sup>d</sup>,  
7 Yoshihide Wada<sup>a</sup>.

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9 a. International Institute for Applied Systems Analysis, Vienna, Austria.\* hunt@iiasa.ac.at

10 b. Sustainable Energy Planning Research Group, Aalborg University, Copenhagen, Denmark

11 c. State University of Campinas, Campinas, Brazil

12 d. Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

13 e. Federal University of Rio Grande do Sul, Porto Alegre, Brazil

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

26 pumped-storage arrangement could be a viable solution for energy storage and reduce the  
27 cost for water storage to near zero.

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29 Keywords: Electricity storage, Environmental impacts, Hydropower, Pumped-hydro storage,  
30 Sustainable energy, Variable renewable energy, Water management.

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## 32 **1. Introduction**

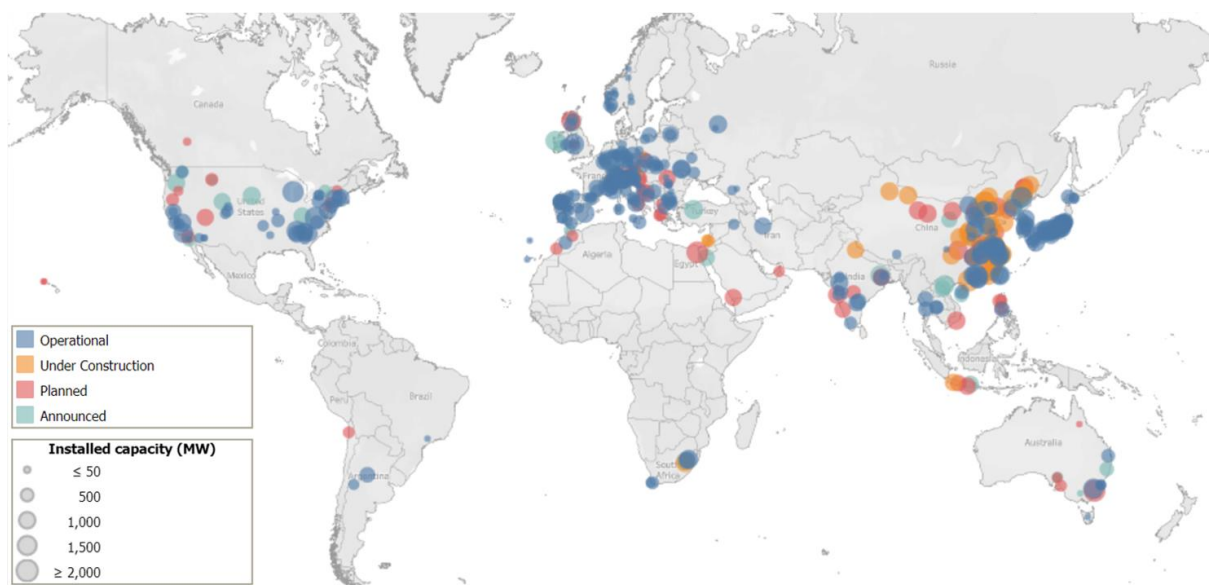
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34 The development of a sustainable future requires better management of natural  
35 resources. New resource management approaches and the UN's Sustainable Development  
36 Goals (SDGs) [1] have been focusing on the need to optimize interactions between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

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

47 A reliable balance between energy supply and demand is facing more challenges with  
48 the integration of intermittent renewable energy sources such as wind and solar [4]. This has  
49 led to a growing demand for flexibility options such as energy storage [5]. These variable  
50 energy sources have hourly, daily and seasonal variations, which require back-up and

51 balancing technologies to maintain a secure supply. Currently most pumped-hydro storage  
52 (PHS) plants only store energy in daily storage cycles, however, this might not be  
53 competitive in the future due to the reduction in battery costs [6]. It should be noted that both  
54 technologies have a negative energy balance (i.e., it consumes more energy that it produces).  
55 Other reviews on PHS types can be seen in [7]. And an high quality interactive map of the  
56 existing, under-construction and planned PHS projects can be seen in [8], as shown in Figure  
57 1.



58  
59 Figure 1: World map with all operational, under construction, and planned pumped-hydro  
60 storage plants [8].

61 An approach for optimizing the integration of water, energy and land resources, is the  
62 application of PHS for both short and long-term energy and water management. Instead of  
63 building storage reservoirs on main rivers, which causes large environmental impact and  
64 requires large land areas, a pump-station can store some of the water on the main river to a  
65 reservoir parallel to the river, usually in a tributary river [9]. These reservoirs would require  
66 considerably less land to store the same amount of water and energy because the upper  
67 reservoir water level would be able to vary much more than in typical conventional dams  
68 [9,10]. This approach for combining energy and water management with PHS plants has been

69 applied in countries such as Austria, Switzerland, and Norway [11–20] for combined energy  
70 and water storage. However, there are only a limited number of arrangements that have been  
71 designed and built for combined water and energy storage with PHS, which are particularly  
72 not appropriate to locations with low topography variations.

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

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

89

## 90 **2. Classification of Existing Pumped-Hydro Storage Plants**

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

94

### 95 **2.1 Storage Size**

96 PHS plants can be divided according to storage size (see Table 1). The larger the  
97 upper reservoir storage size the higher the operational flexibility of the plant. A project with a  
98 large reservoir can provide the same services of a small reservoir and more, as explained as  
99 follows. Hourly pumped-hydro storage (HPS) is used mainly to provide ancillary services  
100 such as frequency balancing, remove harmonics in the grid, provide backup power in case of  
101 disturbances in supply. HPS can function on short circuit mode and they can make more  
102 than 100 reversions per day. An example of such plant is the Kops II in Austria [21,22].

103 Daily pumped-hydro storage (DPHS) is usually built for day-night energy arbitrage.  
104 This storage type is the most frequent PHS application today. The reduction in cost of  
105 batteries and the decentralization of power generation will probably reduce the importance of  
106 this type of pumped storage plant. An example of DPHS is Goldisthal in Germany [23,24].

107 Weekly pumped-hydro storage (WPHS) is usually built for storing energy from  
108 intermittent sources of energy such as wind and solar. This storage type has received an  
109 increased focus in recent years due to the ever-growing share of variable renewable energy.  
110 An example of WPHS is La Muela in Spain [25–28].

111 Seasonal pumped-hydro storage (SPHS) is further explained in this paper. SPHS is  
112 not widely employed in current energy systems, leaving this storage type with a large  
113 potential for the future. An example of SPHS is Limberg in Austria [14].

114 Pluri-annual pumped-hydro storage (PAPHS) are rare, built for storing large amounts  
 115 of energy and water beyond a yearlong horizon. Interest in this PHS type will increase due to  
 116 energy and water security needs in some countries. An example of this is Saurdal in Norway  
 117 [15,16].

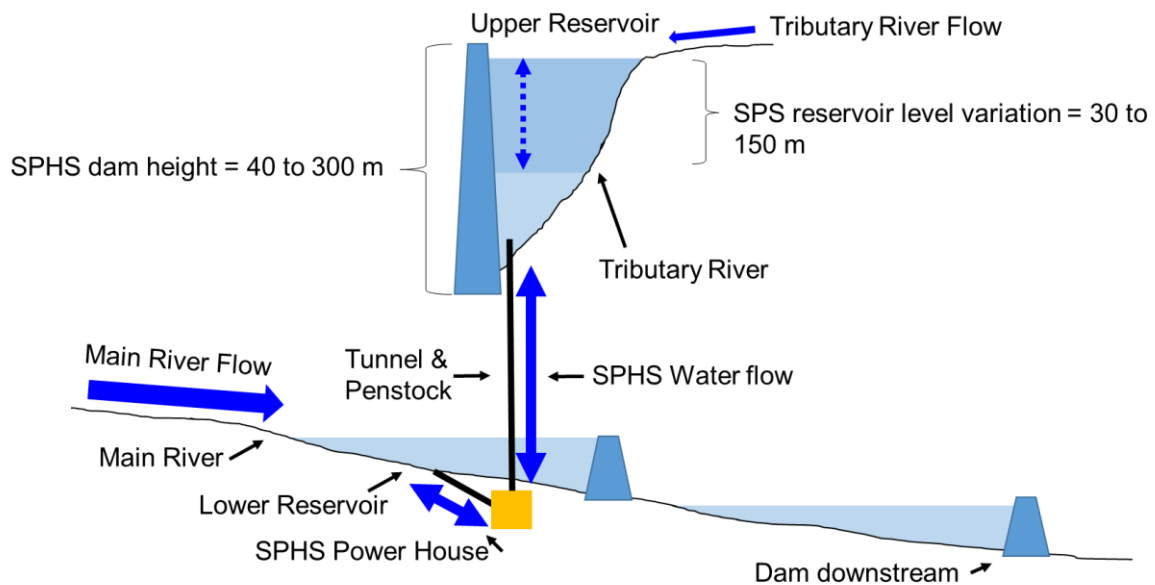
118 Table 1: Different PHS cycles types for meeting energy needs [29].

PHS Type	Operation Mode	Occasions when the PHS type operates
<b>Pluri-annual Pumped-Storage (PAPHS)</b>	Pump	Annual surplus in hydroelectric generation.
		Annual fuel prices cheaper than average.
		Lower than average annual electricity demand.
	Generation	Annual deficit in hydroelectric generation.
		Annual fuel prices more expensive than average.
		Higher than average annual electricity demand.
<b>Seasonal Pumped-Storage (SPHS)</b>	Pump	Rainy seasons or ice melting seasons, with high hydropower generation.
		Summer, with high solar power generation.
		Windy seasons, with high wind power generation.
		Low demand season, when electricity demand reduces.
	Generation	Dry period or freezing winters, with low hydropower generation.
		Winter, with low solar power generation.
		Not windy seasons, with low wind power generation.
		High demand season, when electricity demand increases.
<b>Weekly Pumped-Storage (WPHS)</b>	Pump	During the weekends, when power demand reduces.
		Windy days, with high wind power generation.
		Sunny days, with high solar power generation.
	Generation	During weekdays, when power demand increases.
		Not windy days, with low wind power generation.
		Cloudy days, with low solar power generation.
<b>Daily Pumped-Storage (DPHS)</b>	Pump	Night, when electricity demand reduces.
		Day, when there is solar power generation.
	Generation	Day, when electricity demand increases.
		Night, when there is no solar power generation.
<b>Hourly Pumped-Storage (HPS)</b>	Pump & Generation	Ancillary services: frequency control, remove harmonics in the grid, provide backup power in case of disturbances in supply.

119

120 SPHS consists of two reservoirs, a lower and an upper reservoir connected by a power  
 121 conversion system (pump/turbine) and a tunnel Figure 2. The lower reservoir is meant for

122 storing water and it may or may not have a large storage capacity. Typically, a month-long  
 123 storage capacity in the lower reservoir is enough to store water in days with intense rainfall  
 124 allowing the water in the main river to be pumped to the upper reservoir. The upper reservoir  
 125 should have a large storage capacity to take up a large part of the water from the main river  
 126 during the wet period, and possibly store water for use during droughts. Thus, most of the  
 127 water will be stored in the upper reservoir and the lower reservoir would control flow  
 128 fluctuation in the main river so that water will be available to be pumped to the upper  
 129 reservoir.



130

131 Figure 2: Diagram of a seasonal pumped-hydro storage plant.

132 The upper reservoir of a SPHS plant allows for a large level variation, of up to 250 m,  
 133 reducing the land requirement for water and energy storage. This low-flooded area and high-  
 134 level variation results in a low evaporation per stored water ratio. This makes SPHS suitable  
 135 for regions where evaporation has a large impact on water management. Locations where a  
 136 250 m high conventional dam with 200 m level variation can be constructed are not common  
 137 because the shores of major rivers are typically populated areas, with valuable infrastructure  
 138 and important economic activities. SPHS increases the possibility of building large reservoirs

139 considerably as there are many more potential sites in small tributaries compared to  
140 conventional dams in large rivers.

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

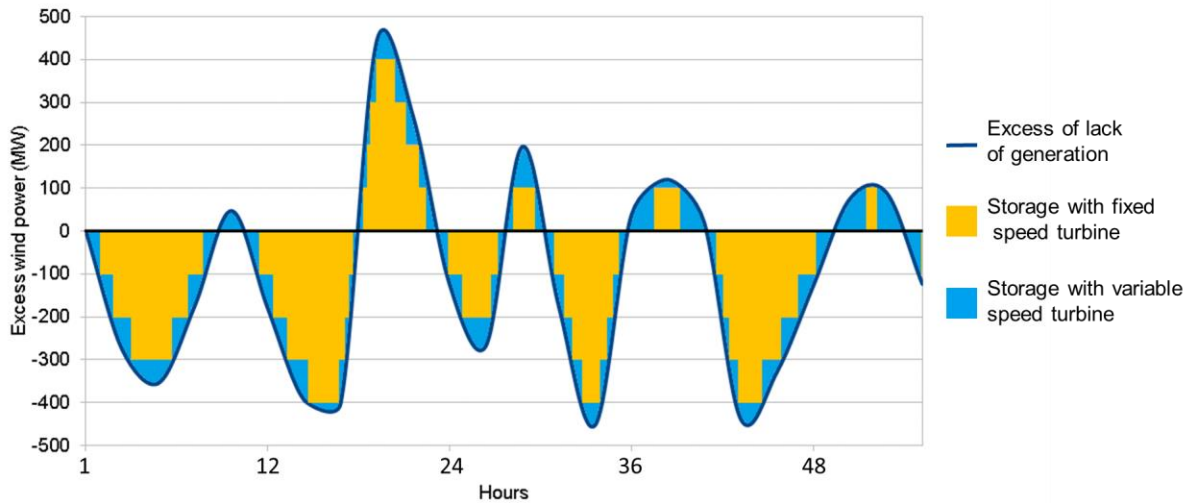
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## 152 **2.2 Pump-Turbine types**

153 PHS plants can have turbines that operate with a fixed rotation speed or variable  
154 speed. Fixed-speed turbines have an invariable generation and pumping capacity. This is not  
155 ideal if the PHS plant is to be used to store and complement the electricity generated from  
156 variable energy sources, given its inflexibility in power output [30]. It allows the final  
157 generation potential to vary, which apart from storing energy from variable energy sources,  
158 has considerable advantages for controlling the frequency of the grid. In other words, a fixed  
159 speed pump-turbine with a nominal 100 MW capacity will only generate or pump 100 MW  
160 of electricity under designed working conditions, while a variable speed pump-turbine will be  
161 able to generate and pump with a capacity varying from around 60 to 100 MW. This allows  
162 the pumped-turbine to store almost all excess wind generation in a system as shown in Figure  
163 3 for a system with five operating units. The fixed-speed turbine would not be able to store or



164 generate electricity in the areas in colored in light blue. Variable speed pump-turbines cost  
 165 approximately 30% more than fixed-speed alternatives and are not commonly used [31]. The  
 166 final choice between fixed and variable speed turbines depends on techno-economic and  
 167 demand aspects [32]. With the increase of intermittent renewables in the grid, variable speed  
 168 turbines might become more common, which would reduce its price.



169

170 Figure 3: Operation of fixed and variable speed turbines.

171 The most relevant application of variable speed pump-turbines in this paper is the  
 172 possibility of benefiting from a greater variation of the pumping/generation head. For  
 173 example, if the maximum pumping head is 500 m, the pump-turbine would operate at the  
 174 maximum power of 100 MW to maintain a reasonably high efficiency. When operating at  
 175 low heads of 250 m, the power of the turbines would have to reduce to, for example 60 MW.  
 176 This would reduce the need for flow variation that passes through the pump-turbine when  
 177 changing the operational head of the plant, maintaining a relatively high efficiency with large  
 178 level variations [33,34]. Another advantage of a variable speed pump-turbine is its ability to  
 179 operate efficiently even with large head variations.

180 Table 2 presents some PHS sites with pumping/generation head variations as high as  
 181 42.5%. This paper assumes maximum pumping/generation head variation percentage of 50%  
 182 for the development of SPHS projects. This is a large value and could be reduced, however a

183 reduction would affect some important design parameters, especially storage capacity and  
 184 operational flexibility of the proposed SPHS plants.

185 Another alternative to further increase the head variation of a SPHS plant is to operate  
 186 two pump-turbines in parallel when the pumping head is small and operate them in series  
 187 when the pumping head is high [35]. This is not ideal because the plant loses some of its  
 188 flexibility.

189 Table 2: PHS sites with high pumping/generation head variation [36,37].

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

190

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

198

199 **2.3 Uses for PHS**

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

203

Table 3: Possible uses for PHS.

Uses for PHS	Theme	Description
<b>Energy storage</b>	Energy	- Energy storage for peak generation, intermittent renewable energies such as wind and solar, optimize electricity transmission, among others.
<b>Highly seasonal hydropower generation</b>		- 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.
<b>Goal for CO<sub>2</sub> emissions reduction</b>		- 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 <sub>2</sub> . A seasonal storage option should be considered by countries that intends to considerably reduce CO <sub>2</sub> emissions.
<b>Seasonal energy supply and demand variations</b>		- 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.
<b>Energy security</b>		- 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.
<b>Water Storage</b>	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.
<b>High storage reservoir sedimentation</b>		- PHS projects have much smaller sedimentation rates than conventional dams due to the small catchment area.
<b>Better water quality control</b>		- 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.
<b>Flood control</b>		- PHS plants can be used in combination with conventional flood control mechanisms to improve their efficacy.
<b>Transport with waterways</b>		- 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.
<b>Inter-basin Transfer</b>		- 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 [38] and the Grand Coulee dam in the USA [39,40].

<b>Low evaporation</b>		- In some cases, PHS are used for water storage due to the lower evaporation in these plants [41].
<b>Water security</b>		- Increase the water storage capacity in regions where conventional storage reservoirs are not appropriate.
<b>Lower environmental and social impacts</b>	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.

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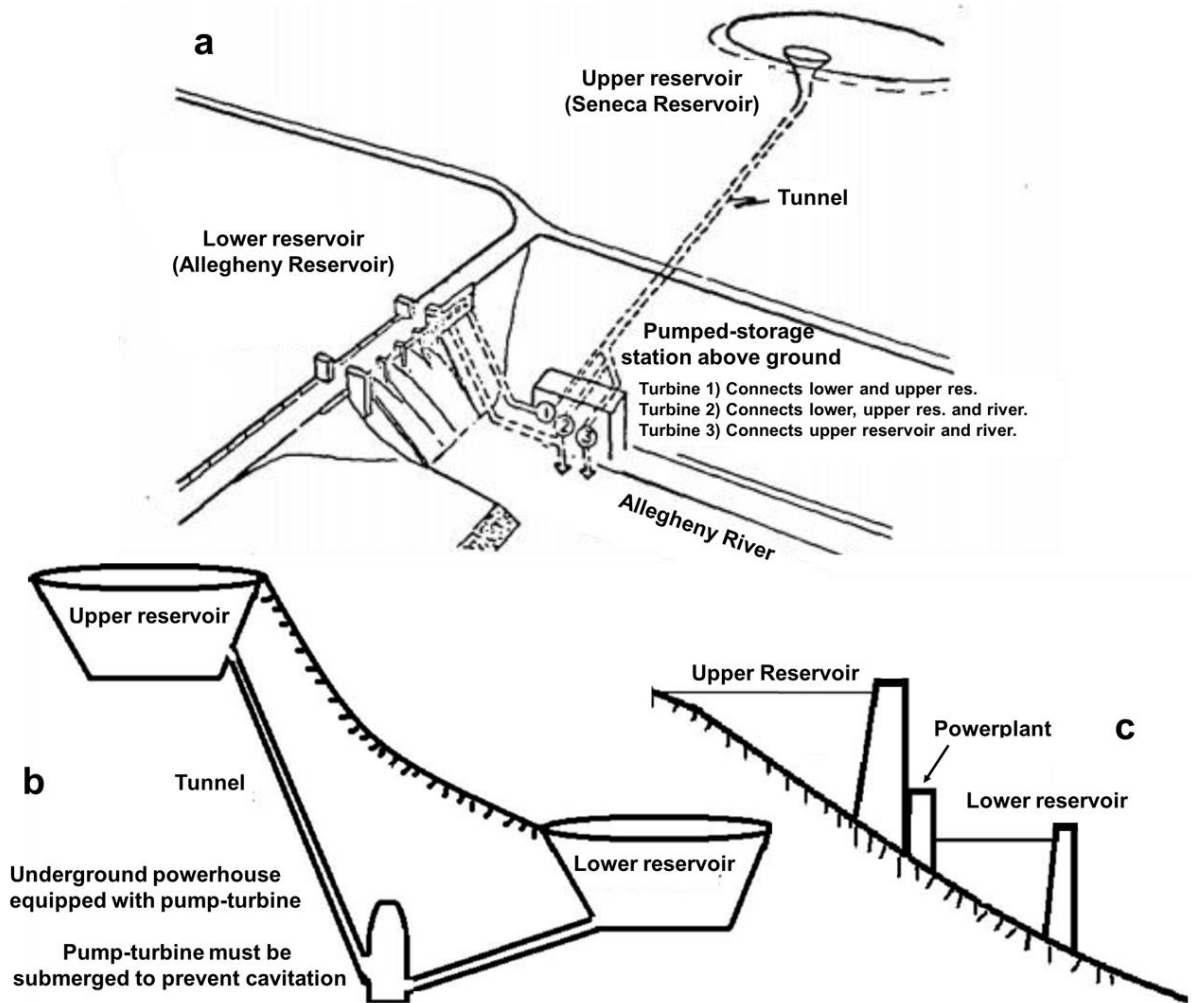
207 **2.4 Existing pumped-hydro storage arrangements.**

208           The most well-known PHS arrangements are open-loop, closed-loop and pump-back  
209 storage. Open-loop consists of a PHS plant where there is a significant stream of water to the  
210 upper or the lower reservoir (Figure 4 (a)). In this setup the operation of the pump-turbine  
211 may interfere with the river flow and this should be carefully cared for. In order to minimize  
212 the impact on the river flow, PHS schemes usually make use of existing hydropower dams as  
213 the lower reservoir. In cases where the lower reservoir is an existing dam, the powerhouse  
214 can be built downstream the dam. This way, the powerhouse will not require to be excavated  
215 as the head of the dam already increases the pressure in the powerhouse, like Seneca PHS in  
216 the USA [42] as shown in Figure 4 (a).

217           Close-loop PHS consists of an upper and lower reservoir far from a large water source  
218 and, thus, with a limited water input into the system (Figure 4 (b)). These systems can be  
219 implemented in small artificial lakes, filled either by the precipitation of its limited catchment  
220 area or on water brought from a different location [43,44]. The environmental impact of  
221 closed loop PHS plants is usually smaller than open-loop plants. however they are usually  
222 limited to daily or weekly storage cycles. An example of a close-loop project is the Marmora  
223 PHS in Canada [45].

224           Pump-back storage consists of installing pump-turbine in hydropower dams wherever  
225 there is another reservoir immediately downstream. This allows the water flow back and

226 forward between the two reservoirs [46] (Figure 4 (c)). This arrangement increases flexibility  
227 and operational range as the pump-turbines can be used for both hydropower conventional  
228 generation and storage. For example, in case of a drought, conventional hydropower  
229 generation will be reduced, but the plant can still be used as pumped storage. The head in  
230 pump-back storage plants is usually low. However, the system is viable as long tunnels are  
231 not required. In Japan, a number of dams were built with reversible turbines [47]. This is due  
232 to the historic dependence of Japan on nuclear energy, an inflexible source of generation,  
233 which creates the need for daily energy storage. The pump-back plants can also be used as  
234 part of a water supply solution. The precipitation downstream Japanese rivers can be pumped  
235 upstream by pump-back storage plants to be stored on the head of the river for later use.  
236 Without a pump-back solution, some of the water would be discharged to the sea. An  
237 example of such scheme is Kannagawa in Japan [48].



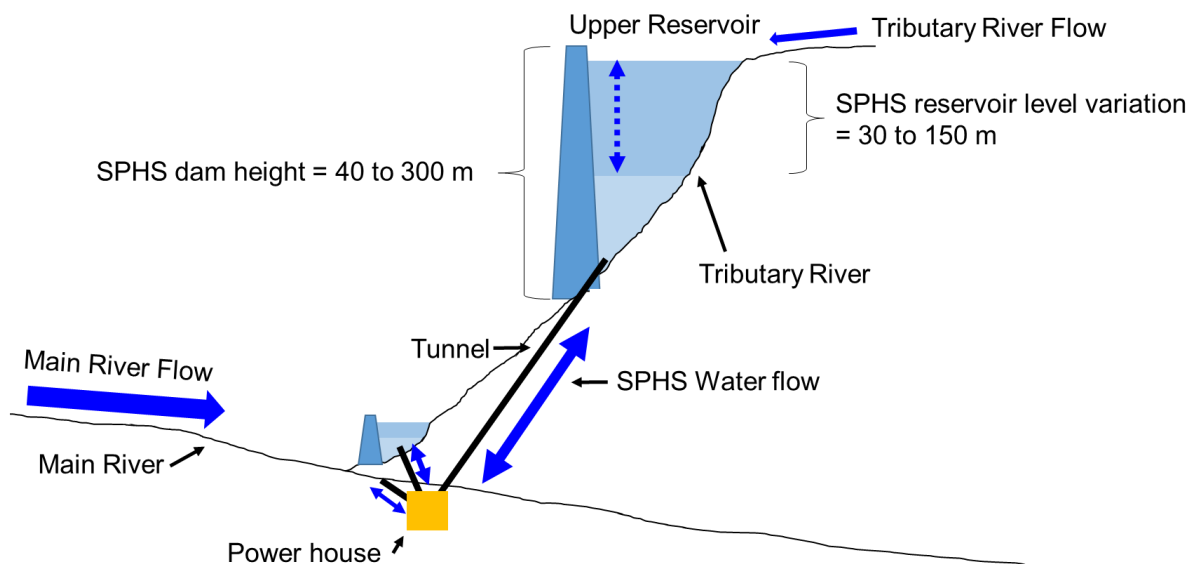
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239 Figure 4: Three types of PHS arrangements. (a) Open-loop PHS plant with no need for  
 240 excavation [29], (b) closed-loop PHS with no considerable inflow in the upper or lower  
 241 reservoir [47], (c) pump-back PHS with no need for excavation [47].

242 PHS can provide energy and water storage combined with desalination and demand  
 243 side management as a very effective way to optimize the energy and water supply in an  
 244 island, especially in the presence of variable energy sources in the system. An example of this  
 245 integration happens in the Soria-Chira plant in the Canary Islands [49,50]. Other less  
 246 common configurations of PHS include underground PHS [51–54], decommissioned open pit  
 247 mines PHS [55,56], seawater PHS [57–59], gravity-based cylindrical systems [60,61],

248 offshore water storage at sea [62], and storage of water and energy inside wind turbine towers  
249 [63].

250 Run-of-the-river SPHS plants can store water from a main river, without the need to  
251 dam the river (Figure 5), thus, reducing social and environmental impacts [37,64]. Run-of-  
252 the-River SPHS are used to extract continuous amounts of water from the river during  
253 periods of high river flowrate and return continuous amounts of water to the river during  
254 periods with low river flowrate. The constant return of water intends to reduce the impact of  
255 river flow variations, which impacts the ecosystem in and around the river. The lower  
256 reservoir, which is not on the main river, is used as a standard PHS lower reservoir. In this  
257 way, the same pump-turbines can be used both to regulate the river and as an energy storage  
258 solution. The high head pump-turbines can only move water from the lower reservoir or from  
259 the river to the upper reservoir and vice-versa. There might also be the need of a low head  
260 pump-turbine to pump water from the river to the lower reservoir, to keep the river flow  
261 constant. An example of run-of-the-river PHS is Malta in Austria [14].



262  
263 Figure 5: Run-of-the-river seasonal pumped-hydro storage with a large upper reservoir and a  
264 small lower reservoir.

265

266 **3. Methodology: Proposed Pumped-Hydro Storage Arrangements**

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

270

271 **3.1 Combined Short and Long-Term Cycle Seasonal Pumped-Hydro Storage**  
272 **(CCSPHS)**

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

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

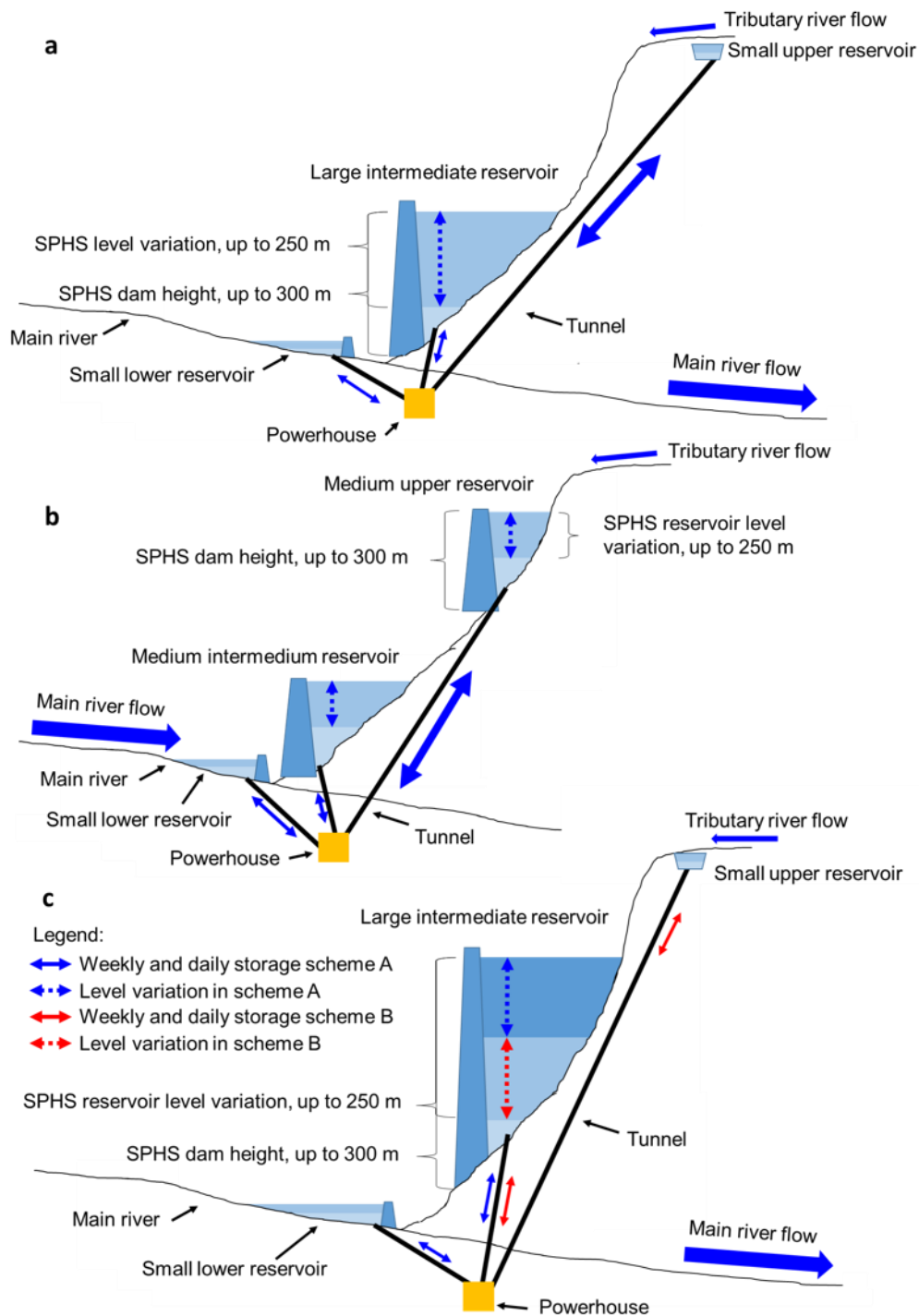
281 In order to solve this head variation limitation and increase the designed reservoir  
282 storage capacity, this paper proposes new SPHS arrangements with three reservoirs. In these  
283 arrangements the water can be shifted around the three reservoirs and fulfil short-term energy  
284 storage needs and long-term energy and water storage needs. These arrangements are further  
285 explained in the paragraphs below.

286 The SPHS arrangement presented in Figure 6 (a) consists of a small lower reservoir in  
287 the river, a large intermediate reservoir and a small upper reservoir. As in Section 2.3.1, water  
288 flows from the lower and intermediate reservoir to the upper reservoir and vice-versa.  
289 However, it would be difficult and expensive to operate a pumping system from the lower to



290 the intermediate reservoir due to the large head variation, as explained above. Thus, this  
291 arrangement would only work if short and long-energy storage needs are combined. For  
292 example, water pumped from the river to the upper reservoir at night is released during the  
293 day to the intermediate reservoir as part of a daily energy storage cycle. During the day water  
294 from the upper reservoir flows to the intermediate reservoir generating electricity while at the  
295 same time storing water in the seasonal reservoir. The large intermediate reservoir can have a  
296 large head variation given that the water used to fill up this reservoir come from the upper  
297 reservoir. The combination of the two cycles (short and long-term) is important because a  
298 pump-turbine system would not be able to pump water from the lower reservoir to the  
299 intermediate reservoir due to the pump-turbine limitation in head variation. This arrangement  
300 is proposed for a location where the topography does not allow the construction of storage  
301 reservoirs and there is a need for short and long-term energy or water storage, for example, in  
302 the Amazon and upper Zambezi basins.

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



310

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

314 Figure 6 (c) presents the arrangement that allows the highest water level variation in  
 315 flat topography regions, which in turn contributes to a smaller land requirement in relation to

316 water storage capacity. It would also reduce evaporation. In this arrangement, the  
317 intermediate reservoir would be filled up with water from the lower reservoir when the  
318 intermediate reservoir level is high enough, and it would be filled from the upper reservoir,  
319 when the intermediate reservoir level is low. This change in operation from the lower to the  
320 upper reservoir is important because the head of the pump-turbine cannot vary with all the  
321 reservoirs level variation as it is limited to, for example to 50% of the maximum head. The  
322 operation in Figure 6 (c) divides the maximum head variation of the pump-turbine in almost  
323 half. In this arrangement, the minimum designed pumping head capacity is higher than in  
324 Figure 6 (a), which reduces tunnel costs.

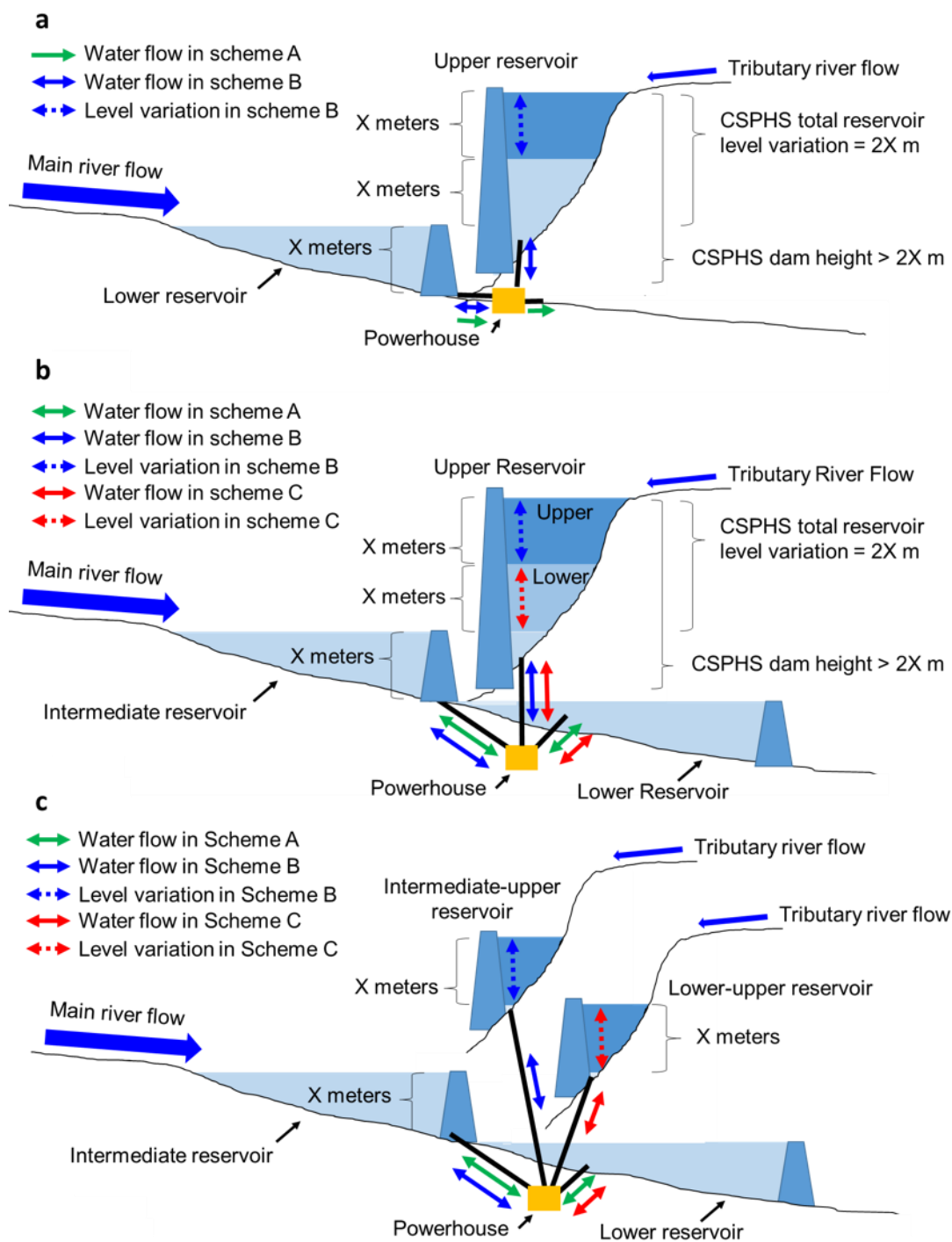
325         The arrangements presented above allow the pumping head and reservoirs to have a  
326 head variation larger than 50%. This is particularly interesting to store large amounts of  
327 energy and water in locations where the topography does not permit the construction of  
328 conventional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

329

### 330 **3.2 Combined Hydropower and Pumped-Hydro Storage (CHPHS)**

331         A CHPHS plant can be used for hydropower generation or for energy storage (Figure  
332 7 (a)). The lower reservoir is built on the main river and the powerhouse is built downstream  
333 of the dam. This arrangement does not require excavation, as the water level in the river dam  
334 already maintains the required pressure on the pump-turbine to prevent cavitation. This  
335 considerably reduces project costs, especially if the plant has a low generating head [65]. This  
336 arrangement is similar to the one in the Seneca PHS [42] (Figure 4 (c)). It offers flexibility  
337 for the operation of the system, making it possible to decide if the dam generates  
338 hydropower, e.g., during periods of large river flow, or if the pumped-hydro storage is to be  
339 used to help manage the grid (energy storage) or to increase river flow during dry periods. In  
340 order for these arrangements to work properly, the height of the reservoirs must match each

341 other as shown in Figure 7, where 'X' represents the height of the reservoir. Table 4 presents  
 342 different pumping/generation head configurations of CHPHS plants.



343  
 344 Figure 7: Combined hydropower and pumped-hydro storage (CHPHS) arrangement. (a)  
 345 Without lower reservoir and without the need for powerhouse excavation. (b) With lower

346 reservoir and upper reservoir divided into two sections. (c) With multiple reservoirs  
 347 connected.

348

349 Table 4: Different configurations for combined hydropower and PHS plants. Possible values  
 350 for 'X' in Figure 7.

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

351

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

361 The arrangements in Figure 7 (b) and (c) can operate in three different ways detailed  
 362 in Table 5. In the Scheme A, the pump-turbine operates close to the lowest generation head  
 363 similarly to a pump-back power plant allowing water to flow from the intermediate reservoir  
 364 into the lower reservoir and vice-versa. The Scheme B is similar to a SPHS plant. Water is  
 365 pumped from the intermittent reservoir into the upper section of the upper reservoir for  
 366 storage and vice-versa. It should be noted that generation and pumping cannot happen

367 between the upper section of the upper reservoir and the intermediate reservoir, as the head  
 368 variation would be too low. The Scheme C also operates similarly to a SPHS plant; however,  
 369 the water flows from the lower reservoir into the lower section of the upper reservoir. Note  
 370 that this scheme can only operate if the upper reservoir is in the lower section. Similarly,  
 371 Scheme B can only operate if the upper reservoir is in the upper section, as the pumping head  
 372 would be too small for an efficient operation.

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

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

375

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

385 operate at the same time as Scheme B so that the lower section of the upper reservoir can fill  
386 up.

387 To analyze the proposed configurations, a pumped-storage GIS siting module have  
388 been developed by the authors in Python to find PHS project locations. The Shuttle Radar  
389 Topography Mission (SRTM) 90m Digital Elevation data is used in the module [66]. The  
390 reservoir locations and size have been identified with the objective of storing around 50% of  
391 the total hydrological available flow. The methodology applied to compare the three different  
392 SPHS approaches is based on the hydrological flow obtained from [67], the design of the  
393 PHS components taken from [68] and the cost estimations from [65]. More details on the  
394 methodology applied in this module can be found in [69].

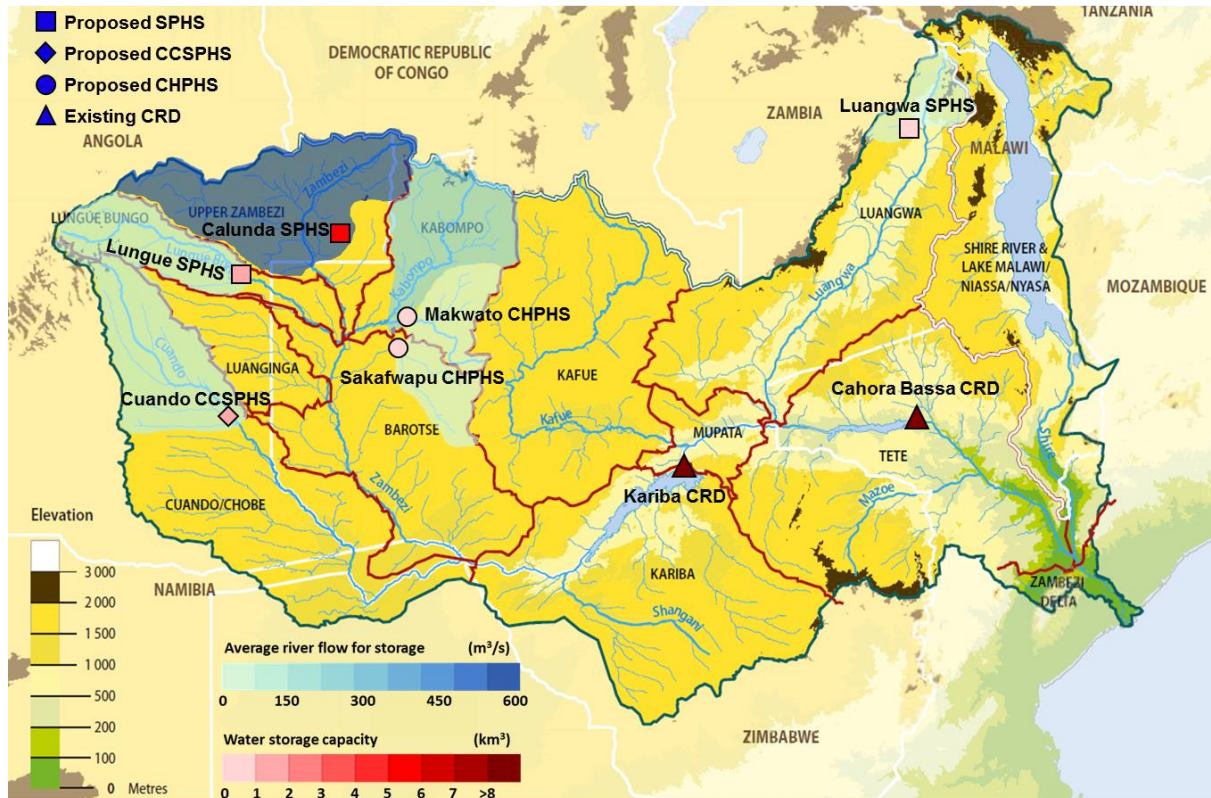
395

#### 396 **4. Zambezi Basin Case-Study: Comparing Proposed Pumped-Hydro**

##### 397 **Storage Arrangements**

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

404 Table 6.



405

406 Figure 8: Different arrangements of PHS plants proposed for the Zambezi river basin, with

407

average river flow and water storage capacity.

408

409

Table 6: Description of proposed PHS plants.

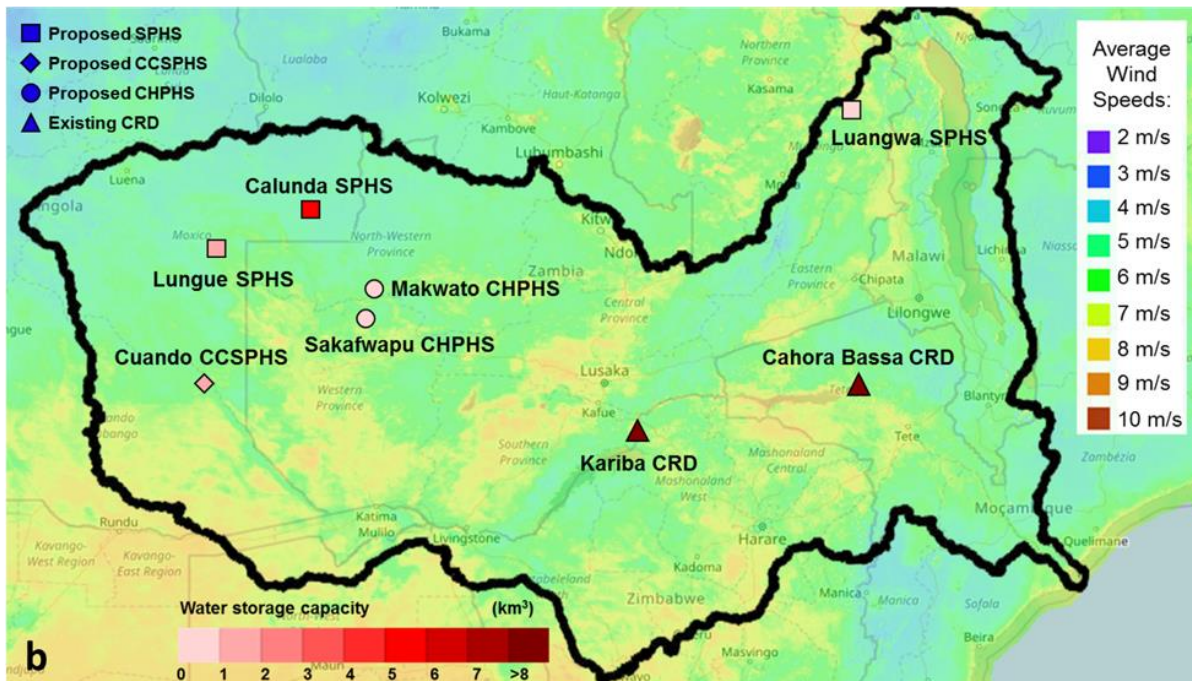
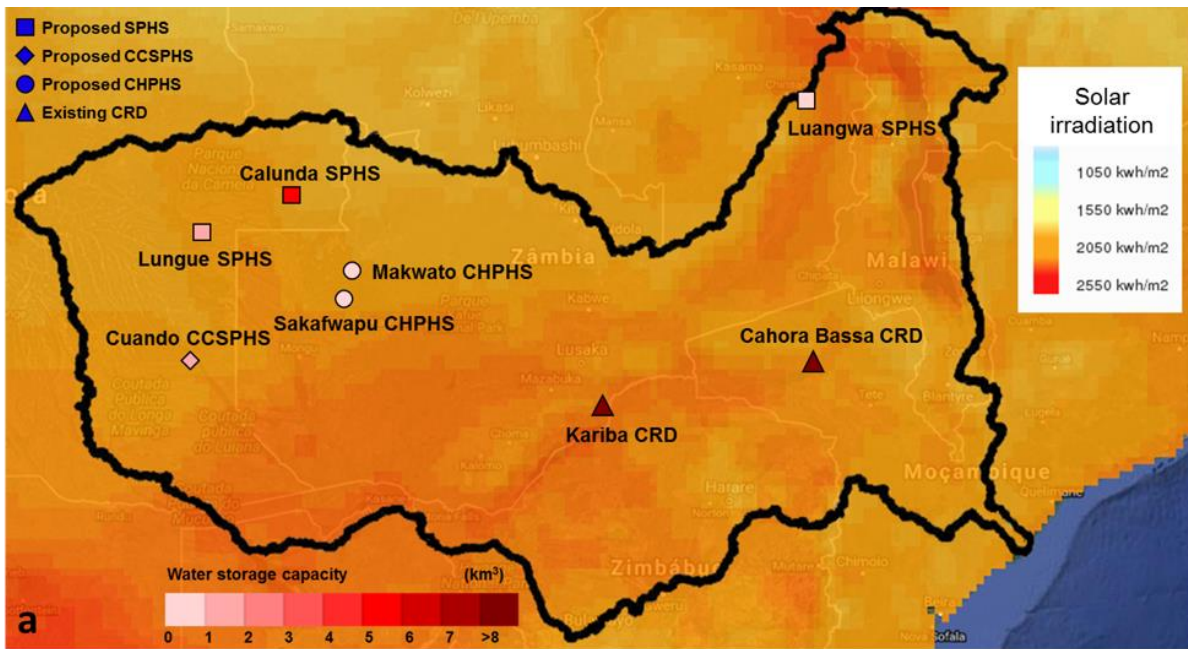
Details	Lungue	Quando	Calunda	Sakafwapu	Mukwato	Luangwa
<b>Storage Type</b>	SPHS	CCSPHS	SPHS	CHPHS	CHPHS	SPHS
<b>Maximum level (m)</b>	1180	1135	1200	1140	1145	955
<b>Minimum level (m)</b>	1150	1100	1160	1100	1100	905
<b>Level variation (m)</b>	30	35	40	40	45	50
<b>Downstream level (m)</b>	1120	1060	1055	1085	1085	680
<b>Dam height (m)</b>	40	55	70	60	60	70
<b>Dam length (km)</b>	4	2	4	2	4	1
<b>Tube (km)</b>	10	6	23	8	9	12
<b>Maximum Flooded area (km<sup>2</sup>)</b>	120	57.5	314.5	39	92	44.6
<b>Minimum Flooded area (km<sup>2</sup>)</b>	40	32	75	30	21	7
<b>Flooded area variation ratio</b>	3	1.8	4.2	1.3	4.35	6.4
<b>Total flooded area (km<sup>2</sup>)</b>	130	67	345	69	160	54



<b>Useful stored volume (km<sup>3</sup>)</b>	1.80	1.21	5.03	0.94	2.07	0.89
<b>Catchment Area (km<sup>2</sup>)</b>	21536	30509	73054	19023	19741	16152
<b>Average flow (m<sup>3</sup>/s)</b>	0.9	1.27	9.59	0.59	0.82	0.84
<b>Storage / 50% annual flow ratio</b>	92	79	597	37	246	52
<b>Sub-basin drought water availability (m<sup>3</sup>/s) [70]</b>	15	12	40	200	65	0
<b>Wind speed (m/s) [23]</b>	5.7	7,0	5.5	6.9	6.7	7.8
<b>Solar Irradiation (kWh/m<sup>2</sup>) [24]</b>	2050	2100	2050	2050	2100	2300

410

411 Even though water storage with low evaporation is the main objective of the proposed  
412 plants, to make the construction of the plant economically feasible and socially acceptable,  
413 energy storage services are also taken into account for grid management. Given the need of  
414 energy to store water with pumped-hydro storage, it is important to analyze the existing  
415 renewable energy potential of the region. The average wind speed across the river basin is  
416 small. There are only a few locations with average wind speeds higher than 7 m/s (Figure 9  
417 (a)). However, the region has solar power potential reaching a yearly average of 2300  
418 kWh/m<sup>2</sup> (Figure 9 (b)). Solar power could be used to pump the water in PHS plants and PHS  
419 could reduce the intermittence of solar power generation.



420

421 Figure 9: Zambezi basin (a) solar generation potential [71], (b) and wind generation potential

422

[72].

423

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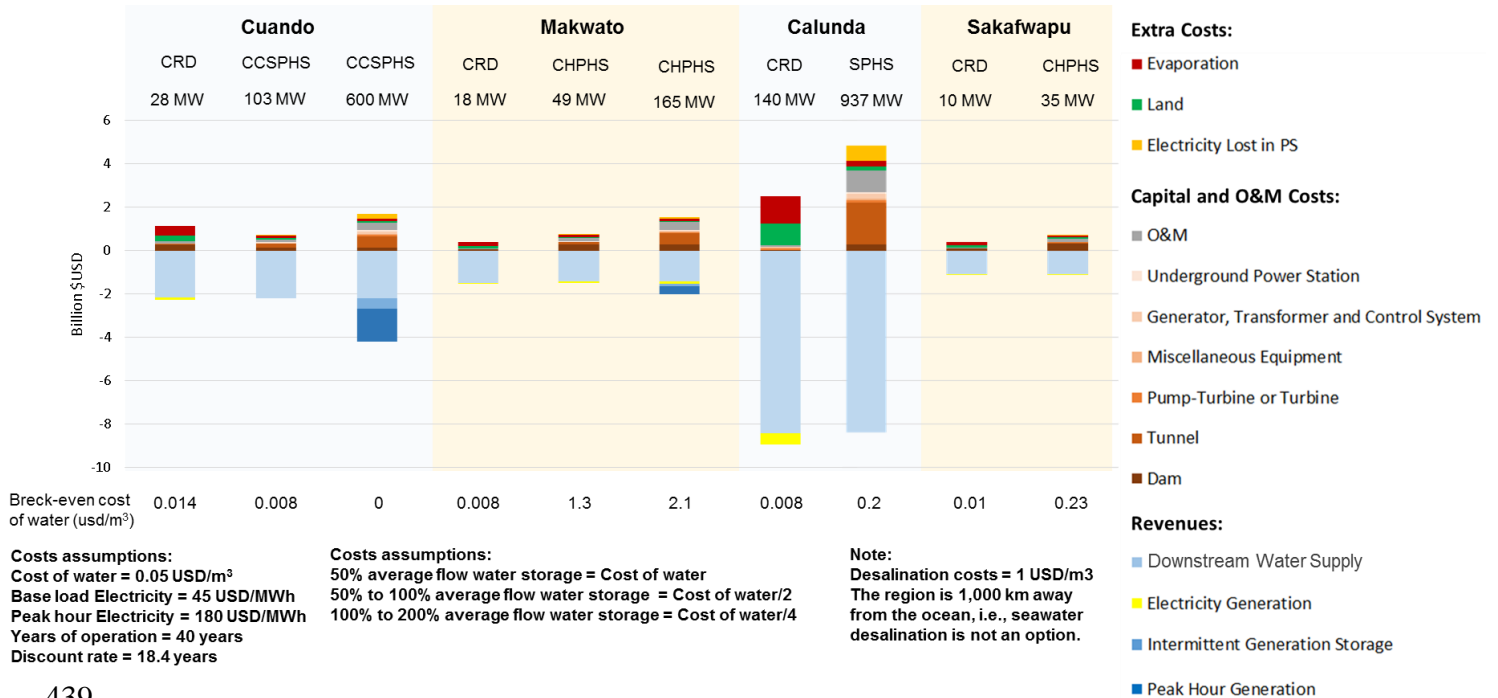
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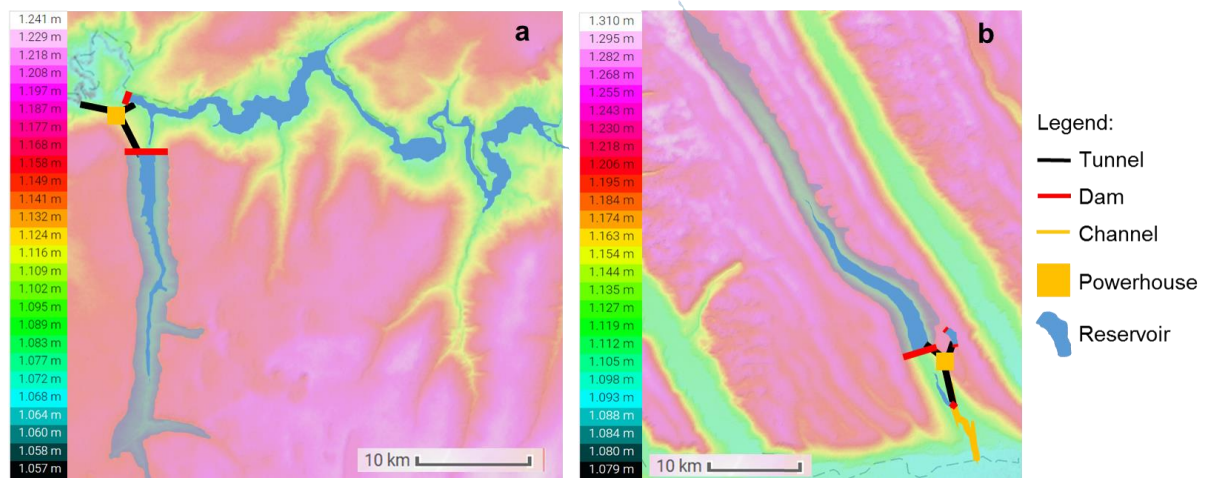
A cost comparison between some of the proposed PHS projects and the compatible conventional reservoir dam for water storage is presented in Figure 10. According to the results, the water storage costs for the Cuando CRD reservoir is more expensive than the Cuando CCSPHS plant with 103 MW and 600 MW. This is mainly because, the Cuando

427 CRD would require a large area to store water, which would result in large land costs and  
 428 losses due to evaporation. Water storage costs are used for the comparison because the  
 429 electricity generated by the Cuando CRD plant is considerably small and water is a major  
 430 issue in the region. The Cuando CCSPHS project with 600 MW would be more beneficial  
 431 than the Cuando CCSPHS with 103 MW because the turbine would be used both to store  
 432 energy and water, benefiting from both revenues.

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



439  
 440 Figure 10: Cost comparison of different PHS arrangement in the Zambezi basin.



441

442 Figure 11: Representation of proposed (a) Makwato CHPHS and (b) Cuando CCSPHS.

443

444 This case study intends to support the sustainable development of the region and  
 445 increase electricity generation, aiming for 100% wind, hydro and solar generation [73]. It also  
 446 intended to regulate the river flow at their sub-basin level, reduce water storage evaporation,  
 447 reduce the intensity of floods, store water in case of droughts and store electricity from  
 448 intermittent generation sources.

449

## 450 5. Discussion

451 There is a variety of alternatives to implement PHS arrangements for short and long-  
 452 term energy and water storage. Comparing the proposed PHS arrangements in this paper  
 453 demonstrates the benefits and drawbacks of each approach. It is important to examine  
 454 different possibilities of building SPHS by a quantitative method, such as the one proposed in  
 455 this paper, to identify the most feasible and useful projects to be developed in any given  
 456 topography and hydrology, and for meeting the needs for energy and water storage. Table 7  
 457 summarizes the benefits and drawbacks of the main arrangements discussed in this paper.

458

Table 7: Comparison between different PHS arrangements.

Technology	Benefits	Drawbacks
<b>Pump-Back Storage (PBHS)</b>	<ul style="list-style-type: none"> <li>- Good alternative for building dams in cascade, combining hydropower generation, short and long-term storage.</li> <li>- More operation flexibility.</li> <li>- Cheap alternative, if the dams are already planned to be built.</li> </ul>	<ul style="list-style-type: none"> <li>- Need for damming the main river.</li> <li>- Storing water in a main river causes large socio-environmental and economic impacts.</li> <li>- Difficulties in retrofitting existing dams to PHS due to the need for large tunnels with low head.</li> </ul>
<b>Seasonal Pumped-Storage (SPHS)</b>	<ul style="list-style-type: none"> <li>- Large flexibility for the operation of the SPHS plant, including seasonal, weekly and daily cycles.</li> <li>- 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 have higher population concentration and higher importance to the environment.</li> </ul>	<ul style="list-style-type: none"> <li>- Need for damming the main river. However, existing dams may be used as a lower reservoir</li> </ul>
<b>Run-of-the-River Pumped-Storage (RRPHS)</b>	<ul style="list-style-type: none"> <li>- No need to dam the main river.</li> </ul>	<ul style="list-style-type: none"> <li>- Due to the direct influence of the SPHS operation in the main river flow, the operation is limited to seasonal cycles. Daily storage cycles would have a great impact on the main river flow, which is not advisable. This could be resolved by building another pump-turbine circuit between the river and a lower reservoir off the main river.</li> </ul>
<b>Combined Cycles Seasonal Pumped-Storage (CCSPHS)</b>	<ul style="list-style-type: none"> <li>- Increases the possibility of building large reservoirs for energy and water storage. Particularly in regions with low topography.</li> <li>- The high water level variation in the reservoirs is appropriate to reduce evaporation in arid regions.</li> </ul>	<ul style="list-style-type: none"> <li>- 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 be able to fill up the reservoir for long-term storage.</li> </ul>
<b>Combined Hydropower and Pumped-Storage (CHPHS)</b>	<ul style="list-style-type: none"> <li>- Combine hydropower and pumped-storage with the same pump/turbine.</li> <li>- The proposal with two reservoirs does not require excavation of the powerhouse.</li> <li>- More reservoirs could be included to increase the catchment area for hydropower.</li> <li>- It is possible to store large amounts of water and energy.</li> <li>- Increase the operational flexibility of the pump-turbines, generating or storing energy, which increases the capacity factor of the reversible pump-turbines, substations, transmission lines, among others.</li> </ul>	<ul style="list-style-type: none"> <li>- There is a need for damming the main river.</li> <li>- Given to the need to combine hydropower and storage, there are less locations where this would be possible to build.</li> <li>- Low head projects are only feasible with very short tunnel lengths.</li> </ul>

## 460 **6. Conclusions**

461  
462 This paper presented and exemplified different types of PHS plants, focusing on  
463 plants with large reservoirs for water and energy storage, the so called, seasonal pumped-  
464 hydro storage. The cost reduction of battery energy storage technologies will challenge the  
465 feasibility and competitiveness of short-term storage PHS plants. Hence, this paper suggests  
466 that future PHS projects should serve both short and long-term energy storage needs, and  
467 water storage.

468 The proposed PHS methods and configurations in this article have the main objective  
469 to increase the possibilities of building large reservoirs in parallel to a main river while  
470 reducing the socio-economic and environmental impacts of conventional reservoir dams. The  
471 CCSPHS arrangement proved to be particularly feasible for locations with low topography  
472 and limited sites for large storage reservoirs. The CHPHS plant increases the operational  
473 flexibility of the plant generating electricity when the flow of the river is high and stores  
474 energy when the river flow is low, increasing the viability of the plant.

475 Comparing the costs of water storage with Cuando CRD for 0.014  $\$/\text{m}^3$  and with  
476 Cuando CCSPHS for 0.008  $\$/\text{m}^3$ , the case study in the Zambezi region shows that the only  
477 arrangement that was proven competitive to conventional reservoir dams is the CCSPHS  
478 plant. Adding the need for short-term energy storage, the costs of water storage reduces to 0  
479  $\$/\text{m}^3$ , as the energy storage need would cover the total costs of the project. CCSPHS is a  
480 configuration designed for storing large amount of energy and water in regions with low  
481 topography where considerable evaporation losses could occur in conventional reservoir  
482 dams. Even though the new proposed arrangements in this paper increases the viability of  
483 some PHS projects, the topography will remain the main decision driver for future PHS  
484 projects.

485           The growth of variable renewable energy in the future will require the use of short  
486 and long-term storage. PHS will become even more important as it can improve resource  
487 management and security of supply in the energy and water sectors. Thus, the identification  
488 of new arrangements for PHS might enhance the socio, economic and ecological viability of  
489 this technology, hence, contributing to the development of a sustainable future.

490

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492

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495

## 496 **8. References**

497

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