Seasonal Pumped-Storage Plants: An Integrated Approach for Hydropower, Water Management and Energy Storage

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ABSTRACT

With the current increase in electricity generation from renewable energy sources, pumped-storage plants have been used for energy storage purposes, to guarantee the supply of electricity and reduce the impact of intermittent sources in the grid. In addition, there is an increased demand for water management solutions due to changes in climate and population increase.

Seasonal pumped-storage comes as an alternative to store both energy and water with the intention to optimize hydropower generation, increase energy and water supply security, support the introduction of intermittent renewable energy sources to the grid, enable the construction of new hydroelectric dams in cascade, reduce the dependence on thermal generation, lower transmission costs, control floods and mitigate conflicts over the multiple uses of water.

A case study in the Zambezi River Basin compares a conventional reservoir dam with a seasonal pumped storage plant, with the same storage volume. This comparison shows that seasonal pumped-storage has higher construction costs than conventional reservoir dams, however, as seasonal pumped-storage has much lower land requirements and evaporation losses, it becomes more attractive to conventional reservoir dams in locations with plain topography and where water is scarce.

KEYWORDS

Pumped-storage, energy storage, water storage, hydropower, energy security.

1. INTRODUCTION

The development of a sustainable future brings the need for better management of natural resources. New resources management approaches have been focusing on the need to optimize interactions between water, energy and land to supply society and the economy with the required natural resources, such as water, minerals and food, and also preserve the environment.

Water resources are essential for the development of society, industry, irrigation, transportation, recreation and for hydropower generation. The management of water can be a great challenge in dry regions. Storage reservoirs play an important role to manage water resources, however, they require appropriate geological formations that allow the reservoir level to vary a considerable amount. In plain regions, storage reservoirs can have large land requirements to store small amounts of water. In these cases, evaporation might have a considerable impact on the overall river flow. Energy

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supply and management are also becoming more challenging with the introduction of intermittent renewable sources of energy such and wind and solar, thus there is a growing need for energy storage.

An interesting approach for optimizing the integration of water, energy and land resources is the usage of seasonal pumped-storage. Instead of building storage reservoirs on the main river, which causes more environmental impact and requires more land, a pump-station can store water from the main river in a reservoir parallel to the river. These reservoirs would require considerably less land to store the same amount of water and energy because the upper reservoir would vary 40 to 150 meters. SPS has been widely applied for combined energy and water storage in countries such as Austria [1]–[4] Switzerland [5]–[8]. Norway [9], [10], Sweden [11], [12] Canary Island [13], [14], Australia [15] and USA [12], [16].

2. PUMPED-STORAGE CYCLE TYPES

In recent decades pumped-storage plants have been used in countries with inflexible thermal-based electricity generation systems, such as the USA, Japan, and Germany to store energy during the night when the demand for electricity is reduced and generate electricity during peak hours [17]. In countries with a hydrothermal electricity generation system, such as Austria, Switzerland, Norway, pumped-storage has operated in a seasonal cycle, storing water and energy during the summer and generating electricity during the winter [18].

Currently the world's electricity generation sector is going through a paradigm shift with the addition of renewable sources of energy to the grid. Some of these sources generate intermittent and variable amounts of energy, such as solar, wind [79], [80], ocean and run-of-the-river hydropower, which is increasing need for storing energy [21]. The cheapest approach for storing energy on a nationwide scale is by storing water [22].

storage.

Table 1 presents the different pumped-storage cycles available and the occasion when each pumped-storage cycle type is used [23], [24]. The flexibility of a pumped storage plant depends largely on the size of the upper storage reservoir. The larger the storage, the more flexibly the plant can operate either over seasons or on a daily/weekly cycle. Pluri-annual pumped-storage (PAPS) plant have the largest upper reservoirs, and can thus perform the tasks of seasonal pumped-storage (SPS), weekly pumped-storage (WPS), daily pumped-storage (DPS) plants. However, DPS plants cannot perform the tasks of WPS, SPS and PAPS plants because their water storage capacity is limited to one day's storage.

Table 1: Different pumped-storage cycles types for meeting energy needs [25].

Pumped-Storage Type	**Reservoir Volume Size (km^3)**	**Operation Mode**	**Occasions when the pumped-storage type operates**
Pluri-annual Pumped-Storage (PAPS)	100 – 5	Pump	Annual surplus in hydroelectric generation.
			Annual fuel prices cheaper than average.
			Lower than average annual electricity demand.
		Generation	Annual deficit in hydroelectric generation.
			Annual fuel prices more expensive than average.
			Higher than average annual electricity demand.
Seasonal Pumped-Storage (SPS)	30 – 1	Pump	Rainy seasons or ice melting seasons, with high hydropower generation.
			Summer, with high solar power generation.
			Windy seasons, with high wind power generation.
			Low demand season, when electricity demand reduces.
		Generation	Dry period or freezing winters, with low hydropower generation.
			Winter, with low solar power generation.
			Not windy seasons, with low wind power generation.

			High demand season, when electricity demand increases.
Weekly Pumped-Storage (WPS)	1 – 0.1	Pump	During the weekends, when power demand reduces.
			Windy days, with high wind power generation.
			Sunny days, with high solar power generation.
		Generation	During weekdays, when power demand increases.
			Not windy days, with low wind power generation.
			Cloudy days, with low solar power generation.
Daily Pumped-Storage (DPS)	0.1 – 0.001	Pump	Night, when electricity demand reduces.
			Day, when there is solar power generation.
		Generation	Day, when electricity demand increases.
			Night, when there is no solar power generation.

Figure 1 shows the comparison between pumped-storage installed capacity sorted by different storage capacities in Germany, Austria and Switzerland [2]. Germany has mainly daily pumped-storage plants, while Switzerland and Austria have mostly monthly and seasonal pumped-storage plants. This is because Germany had an inflexible thermal electricity generation based on coal and Switzerland and Austria have a hydrothermal electricity grid, with greater needs for seasonal storage. Weekly PS capacity in Austria and Switzerland are expected to increase due to the growing needs to store wind energy from European countries.

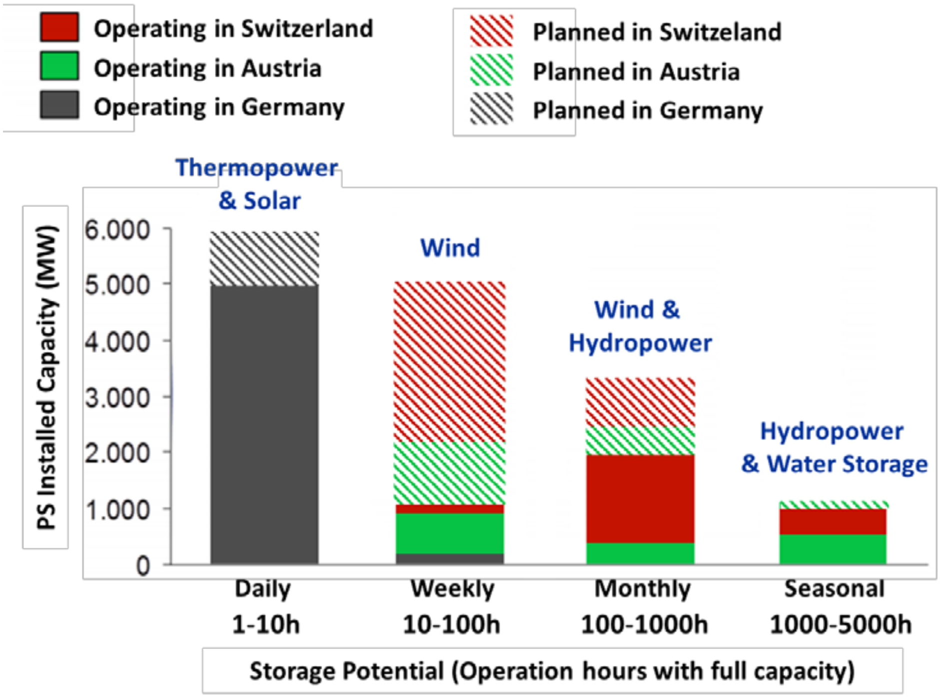


Figure 1: Operating and planned pumped-storage potential in Germany, Austria and Switzerland, including the main purposes of the storage cycles (adapted from [2]).

Table 2 compares the different pumped-storage cycles from a water perspective. The reservoir size for water storage purposes varies considerably with the storage requirements. For example, reservoirs can be planned to store water to regulate the flow of a main large river, or it can be built to supply water for a city or for industrial processes.

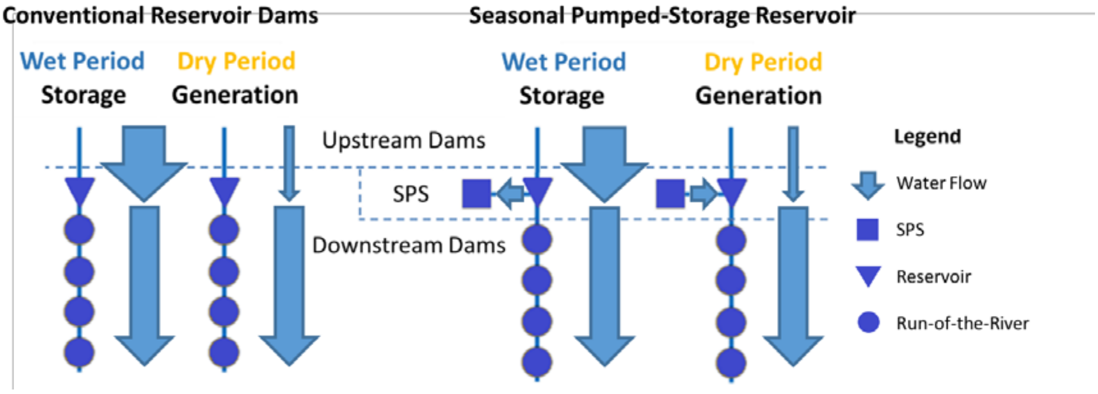
Table 2: Different pumped-storage cycles types for meeting water needs.

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

The interesting aspect of pluri-annual and seasonal pumped-storage projects is that they can provide both energy (daily, weekly and seasonal cycles) and water storage services in a single project, as show in storage.
Table 1 and Table 2. Given its low land requirements, SPS is an important alternative for balancing the water-energy-land nexus and should be given more focus.

3. SEASONAL PUMPED-STORAGE PLANTS

Some river basins have good water resources, but lack appropriate topography, or have other issues that impede the construction of effective storage reservoirs. In these cases, an alternative to store water and energy in the watershed is the creation of seasonal pumped-storage reservoirs. Figure 2 presents examples describing the comparison between the operation of conventional reservoir dams and seasonal pumped-storage plants. In conventional reservoir dams, all river flow is stored in the reservoir, if there is enough storage capacity. With SPS, on the other hand, the storage reservoir is parallel to the river basin and the inlet flow is limited to the SPS pumping capacity.



(a) (b)

Figure 2: Diagrams presenting (a) reservoir hydropower dams and (b) seasonal pumped-storage plant.

SPS consists of two reservoirs, a lower and an upper reservoir connected by a pump/turbine and tubes, as shown in Figure 3. The lower reservoir should be a storage reservoir, but does not need to have a large storage capacity, a weekly or monthly storage capacity is enough to store water from the main river into the upper reservoir. The upper reservoir should have a large storage capacity so that it can store most of the water from the main river during the wet period, and possibly store water for multiple years, in case of droughts. Thus, most water will be stored in the upper reservoir and the lower reservoir would reduce flow fluctuation in the main river so that the water can be pumped to the upper reservoir.

The water inflow in SPS reservoirs has two different sources. Either the water comes from the tributary river, due to precipitation and/or ice melting, as presented in Figure 3, or it can come from pumping water from the lower reservoir. The water inflow sources to the existing SPS projects cited in this paper varies a considerably. In Austria, Switzerland, Norway and Sweden, around 50% of the water is pumped and the other 50% of the water comes from natural flow [26]. At the SPS projects in the USA, Australia and Canary Island, most of the water that enters the seasonal pumped-storage reservoir is pumped into the reservoir.

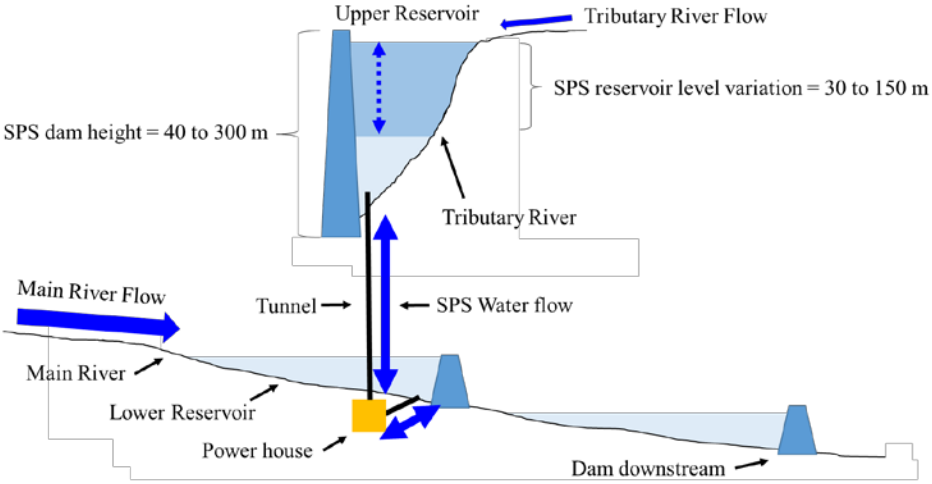


Figure 3: Diagram of a Seasonal Pumped-Storage plant.

The upper reservoir of a SPS plant, usually allows for a large level variation from 40 to 150 meters, with the intention of reducing the land requirement for water and energy storage. This low flooded and high level variation results in a low evaporation per water storage ratio. This makes SPS suitable for regions where evaporation has a large impact on water management.

Seasonal pumped-storage with high reservoir level variations became viable with the development of variable speed pump/turbines, as they allow greater variation on the pumping/generation head.

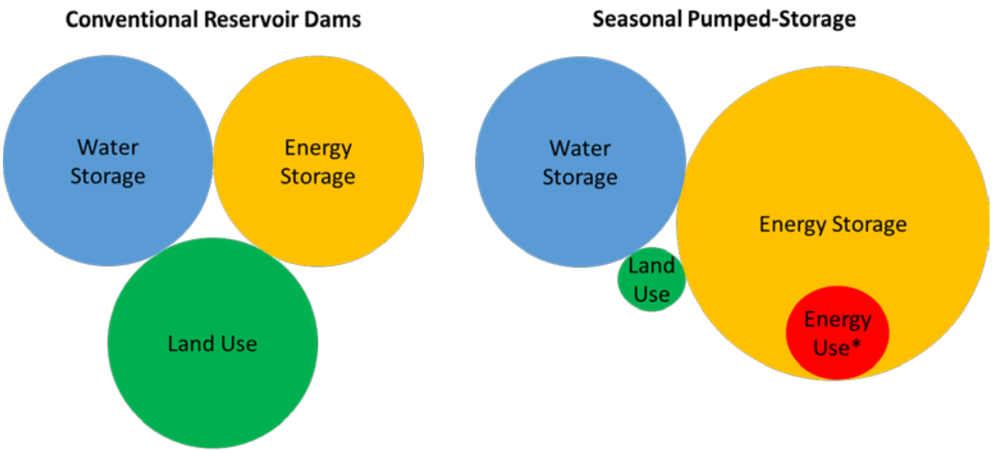
Table 3 presents pumped-storage sites with high pumping/generation head variations. The highest pumping/generation head variation percentage in
Table 3 is 42.5%. This paper assumes pumping/generation head variation percentage of 50% in the development of SPS projects. This is a large value and could be reduced, however a reduction would affect the designed parameters, specially storage capacity and the operational flexibility of the SPS plants. The increase in variable speed pump/turbine manufacturing due to the increase in intermittent renewable sources of energy could contribute to the improvement of the technology and lower its cost, which would also increase the viability of SPS. Another alternative to further increase the head variation of a SPS plant is to arrange two pump-turbines to operate in series when pumping head in small and operated them in parallel when pumping head is high [27].

Table 3: Pumped-storage sites with high pumping/generation head variation [28], [29].

Name	Units	Head (m)	Head Variation (m)	Variation Percent (%)	Power (MW)	Speed (rpm)	Country
Nant de Drance	6	250 - 390	140	35.9	157	428.6 +/- 7%	Switzerland
Linthal	4	560 – 724	164	22.7	250	500 +/- 6%	Switzerland
Tehri	4	127 – 221	94	42.5	255	230.8 +/- 7.5%	India

Limberg II	2	273 - 432	159	36.8	240	428.6	Austria

Figure 4 presents a comparison of the water, energy and land nexus between CRD and SPS. Assuming the same water availability in the river, SPS would require less land to store the same amount of water. In addition, the energy storage potential of the water would increase with SPS as the water has to the pumped up during the storage process, further increasing the potential energy of the water.



*Depending on the setup, SPS can increase hydropower on the cascade, generating more energy than it consumes.

Figure 4: Water, energy, land nexus comparison between CRD and SPS.

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

Table 4 presents examples of the water flows which demands 100 MW pumping capacity with different pumping/generation heads, assuming a 90% generation efficiency. This water flow could be stored in a reservoir or transposed to another river. Equation 1 presents the relation between the energy required for pumping and the water flow into the storage reservoir.

Eq. 1: $$Pumping\ Capcity\ (MW) = Water\ Storage\ Flow\left(\frac{kg}{s}\right) \times Head\ (m) \times g\ \left(\frac{m}{s^2}\right) \times \eta\ (\%)\ \times 10^6$$

Where g is the acceleration of gravity (9.81 m/s2) and e is the pumping efficiency, which is assumed to be 90% [30].

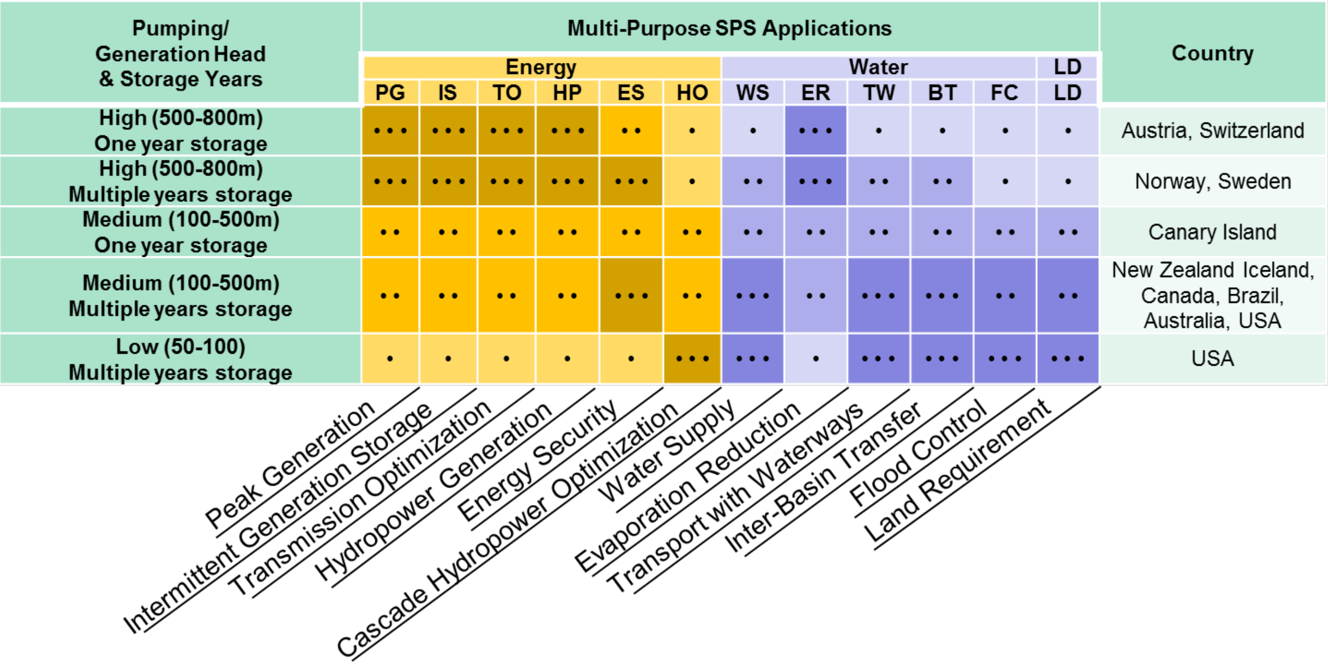
Table 4: Comparison between water flow and pumping capacity in SPS plants.

	Pumping/Generation Head				
	50 m	100 m	200 m	500 m	800 m
Pumping Capacity (MW)	100	100	100	100	100
Water Storage Flow (m3/s)	226	113	56.6	22.7	14.2

A SPS plant built mainly for water management services, such as, flood control, water supply, waterway transport, inter-basin transfer, and hydropower optimization should have a low pumping/generation head so that it can pump large amounts of water with little energy. A SPS plant built mainly for peak hour generation, renewable energy intermittency storage, transmission optimization, energy supply security and hydropower generation should have a high pumping/generation head so that it can store large amounts of energy with little water, land and lower costs. Note that for hydropower optimization the pumping/generation head should be small because pumping losses should be minimized and most of the hydroelectric gain should happen in the dams in cascade downstream of the SPS plant. Evaporation reduction requires a high reservoir level variation with the intent of reducing the evaporation area/water stored ratio. In order to design multi-purpose optimal SPS projects, all services should be included into the SPS design in order to find the appropriate pumping/generation head. Alternatively, two or more smaller SPS plants could be built, some with high pumping/generation head and others with low pumping/generation head for a better combination of these services.

Table 5 presents examples of multi-purpose SPS applications and how well they work with different pumping/generation heads. Some of these applications need not involve a strictly seasonal operation, i.e. filling up in six months and emptying in the other six months. It also considers applications in which the upper reservoir stores larges amount of water for several years, in case of a drought, and other applications. Note that medium and low pumping/generation heads can also be used for intermittent renewable generation storage or peak generation, however with a small and medium contribution, respectively. Examples of SPS projects are found in Austria [1]–[4] Switzerland [5]–[8]. Norway [9], [10], Sweden [11], [12] Canary Island [13], [14], New Zealand [31], Iceland [32], Canada [33], [34] and Brazil [35]–[37], Australia [15], USA [12], [16].

Table 5: Main characteristics of multi-purpose SPS applications and their respective ideal pumping/generation heads.



Pumping/ Generation Head & Storage Years	Multi-Purpose SPS Applications												Country
	Energy						Water					LD	
	PG	IS	TO	HP	ES	HO	WS	ER	TW	BT	FC	LD	
High (500-800m) One year storage	•••	•••	•••	•••	••	•	•	•••	•	•	•	•	Austria, Switzerland
High (500-800m) Multiple years storage	•••	•••	•••	•••	•••	•	••	•••	••	••	•	•	Norway, Sweden
Medium (100-500m) One year storage	••	••	••	••	••	••	••	••	••	••	••	••	Canary Island
Medium (100-500m) Multiple years storage	••	••	••	••	•••	••	•••	••	•••	•••	••	••	New Zealand Iceland, Canada, Brazil, Australia, USA
Low (50-100) Multiple years storage	•	•	•	•	•	•••	•••	•	•••	•••	•••	•••	USA

* The number of "•" represents the importance of the aspect in the SPS project. Where, "•" represents a small contribution, "••" represents a medium contribution, "•••" represents a high contribution.

4. COMPARISON OF CUANDO CRD AND SPS

This section compares the proposal of a conventional reservoir dam (Cuando CRD) and a seasonal pumped-storage plant (Cuando SPS) in the Zambezi watershed, in Angola (Figure 5). The Cuando River has high seasonal flow and annual precipitation varies considerably, thus a large pluri-annual storage is required for better water management of the basin. Both proposed reservoirs were designed to store the same amount of water with the intention of storing water from years with high precipitation for drought years.

Figure 5: Cuando CRD and SPS plats at the Zambezi region [38].

The proposed Cuando SPS plant consists of 12 km tunnel, 5 km of channels that takes water from Cuando River, at an altitude of 1090 meters, and stores it in the Cuando SPS reservoir, as shown in Figure 6. The reservoir requires a dam 2 km long and 90 m high and has a water level variation of 60 meters. The Cuando CRD consist of a dam 40 meters high and 4 km long and has a water level variation of 20 meters.

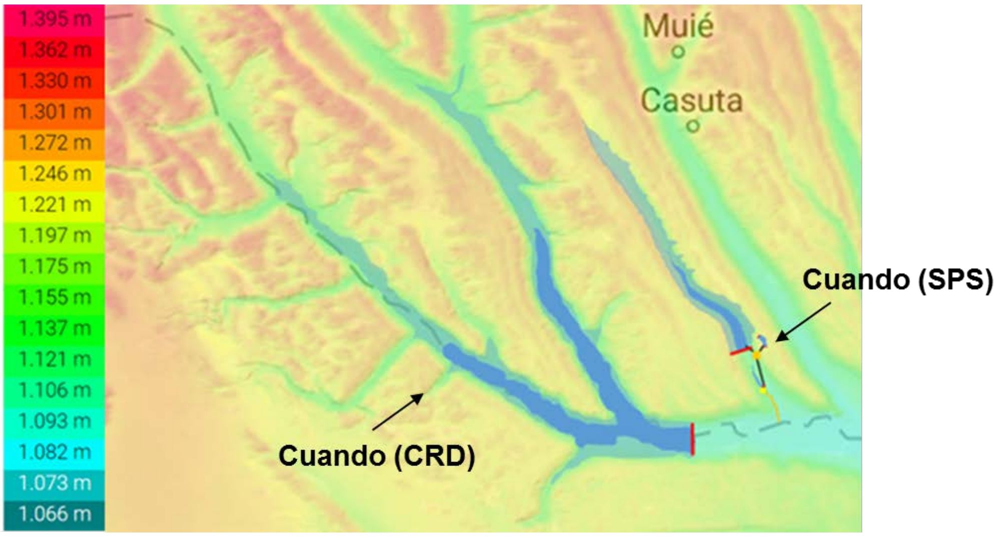


Figure 6: Proposed Cuando CRD and SPS in the Cuando River.

The required pumping/generation capacity, to store 50% of the average annual flow of the main river in 6 months, operating at 70% capacity, is 103 MW. This would allow the reservoir to fill up around 36% in the wet period. If the Cuando SPS plant were also designed to store energy from intermittent renewable energy sources and/or for peak hour generation, the capacity of the plant would have to increase to, for example, 600 MW in order to give it more operational flexibility to the plant. The pump-turbines would then be used for seasonal, weekly and daily storage cycles according to the energy and water storage needs. Table 6 presents a comparison between the Cuando CRD and Cuando SPS.

As the Cuando SPS does not have a reservoir dam in the main river and the plant would also be used to store intermittent renewable sources, a lower regulating reservoir, with a small water storage volume, is required for daily and weekly storage cycles. This reduces the impact of the SPS operation on the Cuando river flow, i.e., the seasonal storage cycle between the upper reservoir and the river will not be affected by the daily and weekly cycles between the upper and lower reservoirs of the SPS plant.

Table 6: Comparison between Cuando CRD and SPS reservoirs

Characteristics	Cuando CRD	Cuando SPS
Maximum level (m)	1140	1210
Minimum level (m)	1120	1150
Level variation (m)	20	60
Downstream level (m)	1100	1120
Upstream level (m)	-	1240
Minimum pumping height (m)	20	75
Dam height (m)	40	90
Dam Lenght (km)	4	2
Tube (km)	-	12 + 5 Chan
Maximum Flooded area (km^2)	559.8	131.7
Minimum Flooded area (km^2)	279.9	73.2
Floded area variation ratio	2	1.8
Useful stored volume (km^3)	4.4784	4.48
Average flow (m^3/s)	80.0	82.6
50% of Total Flow (km^3/year)	1.23	1.27
Ratio with useful stored volume	3.64	3.52
100% of flow (km^3/year)	2.46	2.54
Ratio with seful stored volume	1.82	1.76
Catchment (km^2)	30509	30509
Power capacity (MW)	26	103

Figure 7 presents an extended comparison of the costs and gains from the Cuando CRD and SPS plants. This analysis compares costs in both storage alternatives if they were built from scratch. It should be noted that other gains such as transmission optimization, electricity grid ancillary services (frequency adjustment, harmonics reduction) was not included in the analysis and would additionally contribute to the viability of the projects.

As the costs of Cuando CRD adds up to $USD 1.13 billion and the revenues to $USD 1.27 b, the overall revenues of Cuando CRD are higher than its costs only by $USD 0.13 b. A profitable and sustainable solution would be to construct Cuando SPS operating with only seasonal cycle or with seasonal, weekly and daily cycles. This would provide water supply, store energy from intermittent source and for peak generation and greatly reduce surrounding environmental impacts. Comparing the costs ($USD 0.73 b) and revenues ($USD 1.17 b) of the Cuando SPS project with only seasonal cycle, it was found an overall profit of $USD 0.43 b. On the other hand, Cuando SPS with seasonal, weekly and daily cycles costs $USD 1.70 b and has $USD 3.18 b which results in an overall profit of $USD 1.48 b. This shows that SPS is a more viable alternative to store energy and water in the Cuando River at the Zambezi River Basin then CRD.

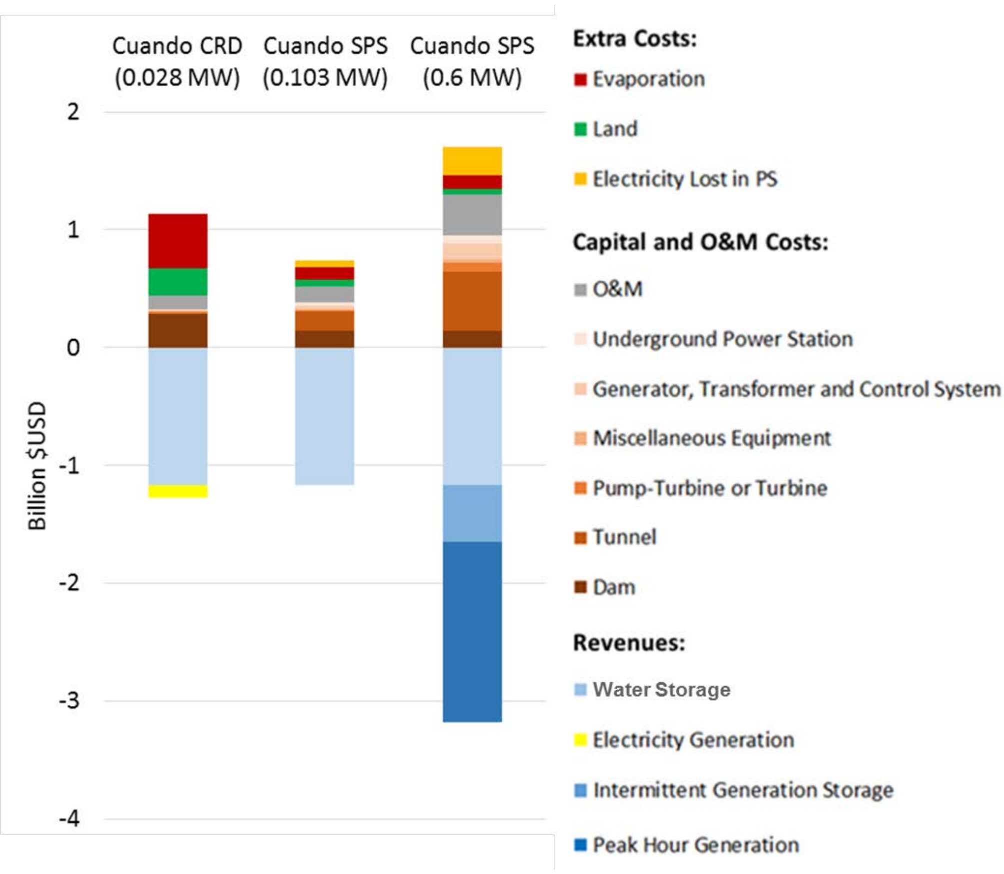


Figure 7: Overall cost estimates for Cuando CRD and SPS after 40 years.

The assumptions applied in Figure 7 are detailed below:

- Capital costs estimates, such as dam, tunnel, pump-turbines, generator, transformer, control systems, miscellaneous equipment, underground power station, were calculated using [39].
- O&M costs were assumed to be 2% of the investment costs per year of operation, not including land costs [40].
- It is assumed a 40 years plant operation, 4.5% interest rate, which accounts to a discount factor of 18.4 years. The discount factor is applied to “Electricity Generation”, “Peak Hour Generation”, “Intermittent Generation Storage”, “Water Storage”, “Electricity Lost in PS”, “Evaporation” and “O&M” costs.
- Land cost is estimated to be 4,100 $USD/ha, which also includes reservoir preparation.
- Electricity cost outside peak hours is estimated to be $USD 40/MWh.
- Electricity cost during peak hours is estimated to be $USD 160/MWh.
- Efficiency of the pumped storage process is 80%.
- The Cuando SPS with 600 MW operation integrates several applications. The capacity factor is divided in: 0.35 for seasonal storage, 0.163 for intermittent renewables storage and 0.13 for peak hour generation, which results in a 0.64 final capacity factor.
- The water cost assumed in this analysis is 0.05 $USD/m^3. For comparison reasons, note that the cost of desalinated water is in the order of 1.00 $USD/m^3.
- The yearly average evaporation is assumed to be 168 mm/m^2.month and the operational flooded area is assumed to be the average between the minimum and maximum flooded areas.

5. CONCLUSIONS

This article presented a comparison of conventional reservoir dams and seasonal pumped-storage dams. It was found that the main benefits of seasonal pumped-storage reservoirs are the small flooded areas and evaporative losses, whilst providing water and energy storage in locations where conventional reservoir dams are not viable. The main challenge for SPS plants is the inlet flow limitation of the SPS pumping capacity, the tunneling for pipelines, and the larger dam required, which might result in higher investment costs than CRD. However, the considerable reduction in land and evaporation costs can make SPS plants viable. In our analysis, we concluded that the Cuando CRD contributes to smaller overall gains when compared to Cuando SPS with seasonal cycle and Cuando SPS with multiple storage cycles.

Given the increased awareness and understanding of important water-energy-land nexus interactions, our findings suggest that seasonal pumped-storage can be a favorable and sustainable alternative for managing water and energy systems with low land requirements and evaporation losses.

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