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A review of seasonal pumped-storage combined with dams in cascade in Brazil

Julian David Hunt*, Marcos Aurélio Vasconcelos de Freitas, Amaro Olímpio Pereira Junior

Energy Planning Program/COPPE/UFRJ, Brazil

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ABSTRACT

In order to maintain greater control over the country's water resources and reduce the vulnerability of the Brazilian electricity sector, this paper presents a review of the Seasonal-Pumped-Storage (SPS) potential in Brazil, its benefits and the different ways in which SPS can be integrated with hydroelectric dams in cascade downstream. In addition to increasing the Brazilian energy storage potential, SPS has the potential to: regulate river flows allowing the control of hydropower generation; reduce the spillage and increase power generation in the hydroelectric dams in cascade; turn the construction of new dams more viable where there is no suitable geology for the construction of conventional storage reservoirs; control floods when the geology does not permit the construction of storage reservoirs; decrease the evaporation of accumulation reservoirs; store the electricity generated from intermittent renewable sources; store energy for peak generation; reduce transmission bottlenecks; decrease the cost of electricity transmission from hydroelectric plants in the Amazon; decentralize the energy storage capacity in Brazil to increase energy security and to reduce the risk of electricity rationing.

1. Introduction

Brazil has just came out of a severe energy crisis and several regional water crisis, which started in 2013 and lasted until the end of 2015. The level of the stored energy in the reservoirs was reduced to 19% of total capacity in January 2015 [1]. The energy crisis resulted in an average 52% increase in electricity prices between October 2014 and October 2015 [2], which influenced on worsening the economic crisis in the country. In the end of 2015, the rain returned to the South of Brazil and an average of 3 GWmed[1] of hydropower potential bypassed the dams without generating electricity in the Iguaçu River during 4 months. As the economic crisis reduced the electricity consumption in 2015 by 0.6% in comparison to 2014 [1], it is expected that more water will bypass the dams in 2016 without generating electricity due to the low electricity demand during the next few years. The electricity supply and demand imbalance will worsen with the operation of new dams in the Amazon that will generate most of their energy during the wet period [3]. The Government has stated that there is the need to increase the storage capacity [4], however no viable solution to increase the countries energy storage potential has been proposed. Electricity demand is set to increase by 44.9% and energy storage will increase by only 0.9% over the next 10 years [4].

An efficient solution to the frequent variation between low electricity generation and excess of energy for any country is to increase its energy storage capacity. This paper develops and discusses different projects for the implementation of Seasonal-Pumped-Storage (SPS). SPS is an innovative technology, firstly proposed in Hunt et al. 2014 [5,6], to increase energy storage in a seasonal fashion. It stores potential energy during the wet season, when there is excess flow in the river, or when there is excess energy in the grid, pumping water to an upper reservoir. During the dry season, or when there is lack of flow in the river, or when there is lack of energy in the grid, the stored water generates electricity in the SPS and in the dams in cascade (two or more hydroelectric dams in series). Although, a conventional pumped-storage plant has an average energy efficiency of 75%, the combination of a SPS with hydropower dams in cascade, can increase the total storage efficiency to around 90%, without including the reduction of spillage in the dams in cascade. In cases where a SPS decreases the spillage or evaporation in the hydropower dams in cascade, the SPS may result in an overall energy gain, rather than a loss, to the system.

The aim of this paper is to review the potential of SPS in Brazil, the different approaches of combining SPS and dams in cascade, and further benefits of SPS, such as, reduce the vulnerability of a country's energy and water sectors, increasing its energy and water storage capacity; decentralize the storage potential of Brazil, increase the security of the electricity sector, remove the intermittency of renewable

* Corresponding author.
E-mail addresses: julian.hunt@ppe.ufrj.br (J.D. Hunt), mfreitas@ppe.ufrj.br (M.A.V.d. Freitas), amaro@ppe.ufrj.br (A.O. Pereira Junior).

[1] 1GWmed is equivalent to an average generation of 1GW during a month.

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sources, generate electricity during peak hours, decrease transmission line costs and reduce de spillage in the dams in cascade. Further benefits of SPS are presented in the following sections.

This article is structured as follows. Section 2 presents a review of existing pumped-storage and seasonal-pumped-storage schemes in the world, pointing out the differences between conventional and seasonal pumped-storage schemes. Section 3 explains in details the SPS methodology, reviews the seven different SPS types, gives an example of SPS project and shows how the efficiency of these systems are calculated. Section 4 reviews the potential of SPS projects in Brazil with the intention to resolve the energy imbalance, which resulted in the crisis in Brazil. It also presents the projects located in environmental protected areas, where SPS projects should not be constructed. Section 5 reviews the many benefits of SPS: low storage costs, multiple uses of water, decentralize energy storage, reduce transmission costs, reduce spillage and evaporation in downstream dams and reduced flooded area to store energy. Section 6 concludes the paper.

2. Pumped-storage and seasonal-pumped-storage

Pumped-storage plants (PS) are widely used to store energy [7,8]. At night, when electricity demand is low, excess generation is stored by pumping water from a lower reservoir to a higher reservoir. During the day, when demand increases, the stored energy is transformed into electricity. However, there is an energy loss of 15–30% during the storing process and electrical generation systems. These losses are usually 13,6% for pumping, where 0,5% is lost in the transformer, 3% in the motor, 9,6% in the pump, 0,5% in the pipes, and 9,1% for generation, where 0,4% is lost in the transformer, 1,4% in the generator, 6,5% in the turbine and 0,8% in the pipes [9].

Pumped-storage has been used in China [10,11], India [12,13], Japan [14], Europe [15–17] and the United States [18,19]. Table 1 shows the installed and under construction Pumped-Storage capacity. Underdeveloped countries, which have less strict energy security policies, are still sluggish on the development of pumped-storage potential. There is a proportionally higher concentration of pumped-storage plants in countries with a high share of Nuclear (France and Japan) and Coal (USA, China) power generation. Nuclear and Coal are inflexible, base load generation sources and generate a constant amount of electricity throughout the day [20]. In order to adjust the changes in demand between night-time and daytime, conventional pumped-storage schemes where installed with the intent to store energy during the night, when demand is low, and generate energy during the day, when demand is higher. Fig. 1 presents a typical power generation load curve in countries with high Nuclear and Coal generation share. Pumped-storage turbines operate at low capacity factors with the intent to guarantee the supply of electricity.

The last decade had an increase in pumped-storage plants with the

Table 1
Pumped-storage capacity installed and under construction in 2013 [21].

PS projects around the world	Installed PS capacity in 2013 (GW)	PS capacity under construction in 2013 (GW)
Africa	1.6	1.3
Middle East & North Africa	1.5	0
Latin America	1.0	0
North America	20.6	0
Europe	51.4	9.0
Asia – South & Central	5.1	1.7
Asia – East	56.3	12.8
Asia – Southeast & Pacific	4.6	0
Total	**142.1**	**24.8**

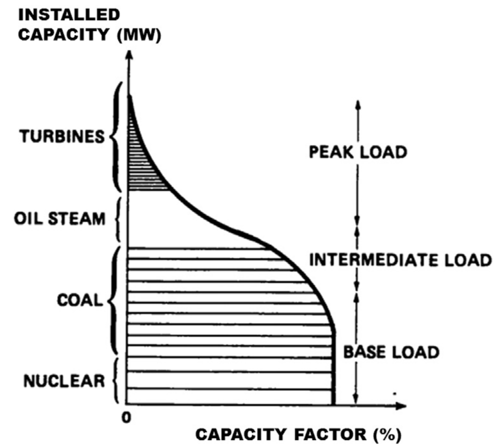

Fig. 1. Power generation load curve in countries with high nuclear and coal generation share [20].

intention to store energy coming from intermitted sources such as wind [22–24] and solar [25] in a gird scale [26] and in the insular scale (wind power [27–29] and solar power [30–32]). These schemes have the intent to optimise the operation of intermittent renewable sources, reducing losses when there is excess generation and complementing the supply of electricity when there is lack of wind and solar generation. Pumped-storage has proven to be a viable alternative to store energy on a grid scale [33] and 97% of the energy storage capacity (in MW) in the world consists of pumped-storage [34].

There are innovative approaches to apply pumped-storage, for example, using underground reservoirs, which brings the benefit of not flooding new areas, as the water reservoir is located underground [35]. Another innovative approach is to use seawater in the pumped-storage system [36]. Using seawater increases the possibility of implementing pumped-storage systems, where there is water shortage, close to the coast.

The Seasonal-Pumped-Storage concept, which consist of operating a pumped-storage plant in a yearly cycle instead of a daily cycle, was firstly presented in (Hunt et al. 2014) [5] and has the objective to store energy during months of high electricity generation or low energy demand and generate electricity during months of low electricity generation or high energy demand. For example, it can be used in countries where power generation is based on hydropower, biomass, wind or solar sources, with high seasonality variations. Alternatively, it can reduce the consumption of fuel during months when prices are usually higher. On the demand side, energy can be stored during the summer, when the demand is lower and generate electricity during the winter, when demand increases, or vice-versa.

One pumped-storage plants, which operates similarly to a SPS plant, is the Tonstad III plant located in South Norway. The power plant is an intermingled connection between several lakes, rivers and reservoirs, with eight hydropower plants (each with several turbines). The overall storage capacity of this complex is of 6 TWh, equivalent to a 5% of Norway's yearly electricity production [37]. The pumped-storage facility intends to store energy during years with high hydropower generation and generate electricity in years with low hydropower generation.

A project that would result in several plants similar to Tonstad III is the North Seas Countries Offshore Grid Initiative (NSCOGI). The NSCOGI intends to promote de implementation of wind power in the North Sea and use the hydropower and pumped-storage potential of Norway to reduce the intermittency from wind power generation [38–41].

Another interesting existing arrangement for pumped-storage, which has similarities with seasonal-pumped-storage sites, is the Shoalhaven Hydro Pump Storage Scheme, NSW, Australia, which has a capacity of 240 MW and generates electricity during peak hours. The

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