Pumped Hydroelectric Energy Storage in Brazil: Challenges and Opportunities

F Libório¹, H T Firmo¹

¹Avenida Athos da Silveira Ramos, 149 – Bloco D, Sala 202. Cidade Universitária da Universidade Federal do Rio de Janeiro, Rio de Janeiro – RJ, 21941-909, Brasil.

E-mail: fliborio@poli.ufrj.br; hfirmo@poli.ufrj.br

Abstract. Motivated by growing concerns about the environment and the rising price of fossil fuels in recent years, many countries have started to diversify their energy sources, optig for renewables whenever feasible. Brazil, a country with a predominance of hydroelectric generation, has also experienced a greater participation of other renewable sources, such as wind, solar and biomass. However, even though they contribute for a lower dependence on water and fossil fuels for energy generation, their intermittence lead to an increase of operational complexity and may threaten the country's energy security. As an emerging economy with growing energy needs, the challenge now in Brazil is to identify ways to ensure efficient energy supply, compatible with demand and mindful of environmental issues. In this context, this work presents a compilation of the main studies and surveys related to Pumped Hydroelectric Energy Storage (PHES), while seeking to contribute in finding ways to reduce the unpredictability of renewable sources generation. Furthermore, the aim is to increase energy security in times of drought, especially when the inter-regional, seasonal and multimodal complementarity of energy generation in Brazil fails to avoid energy deficits. The methodology used draws upon a bibliographical review of the current PHES scenarios in Brazil and in the world. Advantages and opportunities of this type of energy storage are assessed at the national level, together with a presentation of the challenges faced by the implementation of this model in Brazil. Finally, we discuss the main challenges and present some suggestions for future work on this subject.

1. Introduction

The Paris Agreement drafted during the 21st United Nations Climate Change Conference in 2015 recognized the need for global responses and adjustments to reduce the consequences of climate change. As consequence, there has been a worldwide trend towards energy systems totally based on renewable energy sources, both in developed and developing countries. Moreover, it can be observed that even countries that have currently an energy matrix with high dependence on fossil fuels, such as Saudi Arabia, Iran and India, are seeking to make a transition to a less polluting form of electricity generation.

It is known, however, that the great majority of renewable sources have intermittent and variable availability. Therefore, the energy transition must take these factors into account so that reliability and energy security are not compromised, to guarantee operation flexibility of the electrical system to meet energy demand.

To achieve this goal, it is highly recommended the use of devices to store surplus energy when supply is greater than demand for later use. Cantane et al. (2018) [1] also indicates that the introduction of energy storage systems can increase the economic efficiency of the electric system, by optimizing the
capacity factor of Hydroelectric Power Plants (HPP), by allowing greater participation of renewable sources in the energy mix, and by ensuring stability, reliability and safety of the national electricity grid.

Several technologies were developed for energy storage, such as Li-ion batteries, Compressed Air Energy Storage (CAES) and Pumped Hydroelectric Energy Storage (PHES), but here we will focus on the latter, aiming to discuss the history and the current panorama of the development of this technology in Brazil and in the world, pointing out their main challenges and perspectives.

2. A Brief Review of the Literature on PHES

The use of renewable energies has been the main object of energy targets in different countries, which were driven by growing concerns on environmental issues, rising oil prices, population and energy demand growth, as well as technological innovations [2]. Actually, as Rogner and Troja (2018) [3] indicates, photovoltaic, wind and solar energy represented about 60% of the increase in electricity generation capacity in 2017.

Shafiullah et al. (2013) [4] remind that, given the intermittent characteristic of renewable energy, the increase of these sources may compromise the reliability of electrical systems. Zhang et al. (2010) [5] state that traditional power grids are not designed to handle large variations in electricity supply, and Vennemann et al. (2010) [6] add that the problem with the unpredictability of energy availability is that energy supply and demand must coincide at all times in distribution networks.

Many studies have discussed ways to enable energy transitions in different countries, always opting for non-polluting energy matrices, composed entirely of renewable sources [7, 8, 9 and 10]. In several cases the full use of renewable sources was presented as the most competitive and least expensive alternative to achieve zero polluting emissions. However, to deal with their intermittency, energy storage technologies are required.

In countries that currently have energy mixes based almost entirely on fossil fuels, such as Iran — the world's second largest natural gas reserve [7] — and Saudi Arabia [9] — the second largest oil reserve —, a complementarity between renewable sources and energy storage allows for an integration of seawater desalination systems, which contributes to the reduction of water stress in this arid region.

In 2015, India had coal as its main energy source, which caused great health problems to the population, besides contributing to the emission of pollutants and the presence of heavy metals. Data from 2014 reveals that 840 million Indians used wood and biomass for cooking, making it the leading cause of indoor air pollution and premature death. Fortunately, the country has sought to universalize access to electricity and to have a less polluting energy matrix [11].

According to Anagnostopoulos and Papantonis (2012) [12], in addition to energy storage technologies, a greater integration of renewable sources can be achieved through connections to the national grid and more flexibility in the management of the electrical system. In the case of Greece, for example, studies [12 and 13] have shown that while photovoltaics may have enough power to meet peak demand during the day, a joint operation with wind-powered PHES can provide a better solution for the country, as the latter technology is more mature and economically efficient [ibid.ref.12]. These authors report that a 400MW PHES arrangement might increase the annual energy output by more than 500%, but emphasize however that the amount of stored energy must be compatible and chronologically aligned with the inclusion of renewables in the energy mix, so as to avoid mismatches and a consequent non-economic solution.

Currently, PHES is the most mature and the largest capacity form of grid energy storage technology available on the market [14]. Data from 2018 indicate that there are about 161GW of PHES installed capacity around the world, which correspond to 99% of worldwide energy storage [3].

Presently, PHES have capacities up to 4,000MW and can generate up to 14,000MWh. Their discharge time usually ranges from a few hours to as much as weeks, and the response time between pumping and generation at full power is about 2 minutes [6].

According to a recently released Australian Global Pumped Hydro Atlas [15] there exists a total of about 530,000 potentially feasible pumped hydro energy storage sites worldwide, with a total storage potential of about 22 million GWh. China is the country that has deployed most of the world’s PHES,
with about 15GW being installed between 2010 and 2017, which corresponds to almost 10% of global installed capacity [3]. By the year 2030, it is expected a global growth of 78GW (about 48% of the current total capacity), with 50GW only in China. Europe, in turn, should be responsible for a capacity increase between 8 and 11GW. China’s intense development and consequent growth in energy demand make PHES an important alternative to bring energy security to the grid, especially because of the fast increase of wind generation. The current challenge, however, rests no longer on the location of PHES stations, but revolves around the economic issues surrounding their construction and operation, especially regarding the profitability of the projects [16]. The non-uniformity of prices and technological solutions adopted, as well as different PHES management models limits investments in these devices. As Filho et al. (2017) [17] conclude, the determination of the best technology to be used is a function of cost, storage capacity and unloading time.

3. PHES in Brazil
Data from the Energy Research Company (EPE) of the Brazilian Ministry of Mines and Energy (MME) forecast a growth of wind, solar and biomass energy sources by around 13% per year until 2026, as these are some of the most abundant energy sources in Brazil [18].

Cantane et al. (2018) [1] reminds that the country has several suitable locations for PHES, especially in the South and Southeast regions, where favorable topography and wide water supply facilitates deployment. Another positive point is the proximity to major consumption centers, which should decrease power transmission losses. On the other hand, Brazil has currently only four PHES, all built between 1939 and 1955, which together add to 191.4MW of turbine power and 137.3MW of pump power. PHES projects were abandoned in the 1970s, mainly because the nationwide supply of natural resources made it possible to meet demand without the need for greater investments in storage [2].

Studies such as [12] have found that wind farms perform better when combined with PHES, given their complementarity. Thus, it is believed that such arrangement is a good solution to deal with sudden variations of wind energy, while contributing to the country’s energy storage capacity. Additionally, Hunt et al. (2016) [19] proposes the construction of Seasonal PHES (SPHES) to balance seasonal variations in hydroelectric production and to increase the total storage efficiency of cascade hydropower systems.

However, EPE and MME (2013) [20] point out that although the country is reaching the limit of the relation established by hydroelectric projects to use energy reserves obtained during the wet season for generation in the dry season, the Brazilian government and its energy agencies do not seem keen to increase the country's energy storage capacity in the coming years. In this context, Hunt et al. (2014) [21] estimates that while power generation in the country should grow by 40% by the year 2022, energy storage will increase by 2% only, in the same period. As presented by Godei (2013) [22], completely filled reservoirs in Brazil can only store water (and therefore energy) for four months, with 70% of the country's energy storage capacity concentrated in the Southeast and Midwest [ibid]. So, it can be concluded that an unfavorable rainfall regime in these regions may compromise the country's energy supply. To avoid such a situation, the same author proposes the construction of PHES in places where there is currently low energy storage capacity, so that Brazil could rely less on the Paranáiba and Grande river basins, which account for 45% of the national energy storage.

4. Opportunities and Challenges
According to Yang and Jackson (2011) [23] and Droste-Franke et al. (2012) [24], of the currently available large-scale storage options (PHES and CAES greater than 100MW), only PHES are widely used. Moreover, Chu and Majumdar (2012) [25] affirm that these two technologies are the most economical and efficient long term storage technologies. Moreover, they do not burn fossil fuels, which is an advantage over other possible options.

In addition, Kapsali and Kaldellis (2010) [26] conclude that the PHES and wind arrangements have excellent technical and economic performance and can double generation by renewables. Katsaprakakis et al. (2008) [27] found that the introduction of a PHES station on the island of Crete decreased by about
10% the annual cost of electrical production in this isolated system, besides creating new possibilities, such as the harnessing of seawater as a lower reservoir in PHES arrangements. The first and so far the only time this has been done before was in the Okinawa Yanbaru Station, inaugurated in 1999 in Japan [28]. However, as highlighted in Geth et al. (2015) [29], the Muuga PHES Project in Estonia promises to be the second in the world to use this arrangement. Another interesting point is underlined in Rehman et al. (2015) [30], namely the joint use of renewables and energy storage systems to promote seawater desalination, which can be very useful in reducing water stress in arid regions as well as in isolated islands with limited water resources.

Brazil, a country of continental dimensions, has six different types of climatic regions [31], which contributes to inter-seasonality among them. Additionally, a complementarity between wind and solar generation was observed in Brazil [32], similarly to other countries such as Japan [8], Ukraine [10] and India [11].

Taking into consideration these aspects, as well as the large scale integration of energy sources provided by the National Interconnected System and the limitation of the construction of large reservoirs in the Amazon region, Hunt et al. (2016) [19] proposed the construction of SPHES to increase water and energy storage for the surplus energy produced during the wet period in the Amazonian hydroelectric power plants. In this way, the energy wasted today could be harnessed to supply PHES reservoirs in the rest of the country. Hunt et al. (2016) [33] also argues that this could be a possible solution for the water and energy storage of the São Francisco river basin, given the alarming water crisis that the region has faced in recent years [34].

Cantane et al. (2018) [1] and Arantégui et al. (2012) [35] consider the restructuring of existing Hydro Power Plants (HPP) to convert them into PHES as an interesting option for increasing the country's energy storage as an environmental friendly and low cost solution. The combination of pumped storage and HPP could make the Hoover dam the world's first hydro plant to combine both conventional and pumped hydro [36].

As mentioned in [1], when dealing with isolated grids, energy storage is of preeminent importance to reduce diesel costs in power generators, which currently guarantee the stability of the grid in isolated electricity systems, still very common in the Northern region of Brazil. This could reduce significantly the economic and environmental impacts generated by diesel, both in the purchase and use of fuel in generators as well as in its transportation, often necessary in remote places. Similar aspects were noted in Greek islands, where the costs of deploying PHES and wind would be comparable to those of fuel purchases and transportation [37].

Another remarkable example of PHES is the California Mulqueeney Ranch project, which aims to use recycled wastewater to operate an off-stream PHES station (280MW). This project, in addition to diverting wastewater that would go otherwise into watercourses and affect aquatic biota, might improve the quality of the water used in the pumping and generation phases through its aeration. Furthermore, as the station is located near the metropolitan region of San Francisco, there is no need for large transmission lines, reducing energy losses [23].

Among the benefits of energy storage, Filho et al. (2017) [17] mentions the following: greater efficiency in the use of electrical system resources; greater access to energy; and greater stability, flexibility and resilience of the grid. In [30] further gains are listed, such as: high response speed; flexibility to start and stop engines; and the maintenance of voltage stability. Ming et al. (2013) [16] adds the energy supply in times of high demand and flexible generation. When compared to Li-ion batteries, Rogner and Troja (2018) [3] highlights these aspects: large range of power and energy; discharge time of up to 12h or more (compared to about 2h of batteries); long lifetime (around 100 years, compared to about 10 years on the battery); and the global warming potential, which represents half of batteries. Finally, Dmitrieva et al. (1992) [38] describes the positive impacts of PHES, highlighting the higher rate of dissolved oxygen, the lower thermal stratification and the intensification of oxidation and mineralization processes of organic and biogenic substances.

It is believed that there are some key challenges for deploying PHES today, both in Brazil and worldwide. Economic viability issues should be considered, given the effects of energy storage in the
national grid and the costs of construction and operation. From the environmental point of view there are also positive and negative impacts caused by PHES, which should assess in comparison to other alternatives.

Although Brazil has hydroelectric power plants as the basis of its energy mix, they are in general distant from demand centers, thus requiring long power transmission lines and, consequently, associated losses. This influences the arrangement of PHES and wind power as well, since the country, has its potential locations of the two sources usually very far apart [1]. In addition, it has been observed that environmental issues have increasingly delayed and even prevented the construction of new reservoir plants, likewise hindering the deployment of new PHES.

In Germany, Europe's largest energy market, energy storage is considered to have high impact across national borders due to regional integration. However, even with political support for energy transitions in the enthusiastic German energy market, the profitability of new projects is still uncertain, mainly because of environmental issues. As an attempt to bypass obstacles and impediments, alternatives such as the use of rivers as lower reservoirs, besides the allocation of machines in underground caves, among others, have been sought, as a way to reduce interference with nature and social and environmental well-being [39]. Similar cases occur in the United States, where PHES projects seek to minimize impacts, by avoiding river dams, and opting for artificial reservoirs outside the riverbed, as well as in abandoned mines, caves, etc. [23]. The authors also recall the case of Bear Lake, where the lack of awareness of the local population about the benefits of energy storage presented as a considerable barrier to the project.

Papaefthymiou et al. (2014) [40] points out that grid system operators must ensure the flexibility of operation, guaranteeing continuity in power generation services despite the rapid and unpredictable variations in supply and demand. In this context, it is clear that the high penetration of renewables in the electrical systems brings considerable volatility to the energy supply, so that it can considerably affect the economic conditions of the system operation, causing even negative prices, when hydro operators are paid to fill their reservoirs, since this is cheaper than turning off inflexible generations [41].

In general, investments in energy storage sources are very volatile and have to be given profitability guarantees. As mentioned in Joskow (2006) [42] the decrease in the profitability of energy storage systems in most European markets explains the lack of interest in further development of storage capacity in these markets. In other words, favorable market conditions are fundamental for the development of storage technologies. As Filho et al. (2017) [17] highlights, public policies and market incentives are fundamental to increase the feasibility of storage technologies and their applications, as well as setting tariffs, which is a critical issue in reducing the uncertainty of PHES investments [13]. Another difficulty is the operation of the PHES, which is very elastic in terms of the imposed tariffs Dena (2008) [43], making issues such as grid fees and water fees to strongly compromise the operation in terms of economic feasibility. Trussart et al. (2012) [44] also mentions mitigating and compensatory measures as determinants of profitability.

In Brazil, there are some regulatory hurdles that may hinder the development of PHES. Zuculin et al. (2014) [45] indicate three of them: the lack of an ancillary services energy market; the lack of verticalized companies, where there could be financial compensation for investments in PHES; and the small difference, if any, between low, medium and high load prices.

When addressing the construction of PHES stations, the first issue is the geographical limitations of favorable topography places [29], which can be facilitated by adopting closed loop PHES that provide more freedom in choosing a location [2]. In addition, there is the high cost of construction, which is comparable to that of a traditional dam [21] and is dependent on the characteristics of the terrain where it will be built [46]. Taking into account that this type of arrangement does not generate energy, but only storage, it can be more difficult to classify it in the regulatory framework of energy markets. However, it should also be considered that PHES supply energy precisely in periods of high demand, which may contribute to their viability. Despite these drawbacks, this technology is still the most mature and cost-effective energy storage in existence, especially when it comes to large scale. Thus, it can be concluded
that PHES need to achieve long-term reliability and yield in order to become more viable and so attract the investments needed for their development, especially in liberalized energy markets [3].

5. Conclusion and suggestions for future studies

This paper presented a brief profile of PHES today, with emphasis on the Brazilian system. The growing relevance of this form of energy storage can be especially noticed with the increasing use of renewable energy sources. However, improvements in the regulatory framework are necessary to consolidate its implementation.

For future studies, it is important to investigate the possibility of implementation and application of PHES and SPHES taking into account not only the values observed in energy markets, but the following issues as well: legal procedures; the duration of environmental licensing involving large energy projects; site conditions; environmental constraints and implied positive and negative impacts; safety and operation conditions of possible alternatives, especially in terms of the environmental factor, a paramount factor in a world increasingly craving for clean and renewable energy.

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