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AMERICAN JOURNAL OF HYDROPOWER, WATER AND ENVIRONMENT SYSTEMS

Editorial

Demand for electricity is increasing rapidly in Latin America. Expanding and enhancing the current power generation infrastructure is thus a major concern for the region. In that context, renewable energy is bound to play a relevant role in the coming years and hydroelectric energy especially so in view of its relatively unexploited potential, which is estimated in around 690,000 MW in the region.

Our mission is to contribute to the regional integration by means of the production of knowledge in the field of hydroelectric power generation and hydromechanical systems, with focus on technological advance and the rise of quality standards, but with an eye on the priorities of a region where, well into the XXI century, millions of people find themselves deprived of electricity. That includes the topics such as the evaluation of the development of projects of low environmental impact, the role of hydroelectric powerplants in the face of the diversification of the energy matrix as well as mini- and small-hydro projects to meet the demand of areas with no access to the electrical network.

Three symposia have been held and six editions of this Journal have been published since the creation of this, the Latin Group, in 2012. Added to that are postgraduate courses and exchange programs that are being organized at present. Mexico, Brazil, Ecuador, Colombia, Uruguay and Argentina are the most active members of the Group and it is our goal to get more involved in the future.

We firmly believe in the ability of our universities to conduct the research in the field of hydraulic turbomachinery and that this knowledge will have a beneficial impact on the policy making of our countries, whether on matters related to existing infrastructure as well as the development of long-term projects and strategies.

We understand that keeping and strengthening the link between the nations currently participating is a major challenge in the framework of a constantly evolving reality, seen reflected in the availability of economic resources, the technological tools and the swings of institutional management. May this new edition of the Journal serve as evidence that, however difficult, such challenge is achievable.

Eng. Sergio O. Liscia
Presidente Latin Group 2017-2021

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Divide your article into clearly defined and numbered sections. Subsections should be numbered 1.1 (then 1.1.1, 1.1.2, ...), 1.2, etc. (the abstract is not included in section numbering). Use this numbering also for internal cross-referencing: do not just refer to 'the text'. Any subsection may be given a brief heading. Each heading should appear on its own separate line.

1.1.2 Format

All text of the manuscript must be located within a 170 mm by 252 mm rectangle of a white A4 page or within 170 mm by 240 mm for the letter format. The margins are given in Table 1. An example of the page format is given in Fig. 1

[Table 1]: Page margin for manuscripts.

Margin Position	Top	Bottom	Left	Right
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All text should be single spaced, black and in 12-point type. "Times News Roman" or a similar proportional font should be used. Total length 15 pages in Word.

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State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

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A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.

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Results should be clear and concise.

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This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

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The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

References

Within the text, references should be cited in numerical order according to their order of appearance. The numbered reference citation within text should be enclosed in brackets.

After the second edition all papers must have at least one reference of the American Journal of Hydropower, Water and Environment Systems.

Example: It was shown by Prusa [1] that the width of the plume decreases under these conditions.

In the case of two citations, the numbers should be separated by a comma [1,2]. In the case of more than two references, the numbers should be separated by a dash [5-7].

List of References. References to original sources for cited material should be listed together at the end of the paper; footnotes should not be used for this purpose. References should be arranged in numerical order according to the sequence of citations within the text. Each reference should include the last name of each author followed by his initials.

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Sample References

- [1] Ning, X., and Lovell, M. R., 2002, "On the Sliding Friction Characteristics of Unidirectional Continuous FRP Composites," *ASME J. Tribol.*, 124(1), pp. 5-13.
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Abbreviations

Define abbreviations that are not standard in this field in a footnote to be placed on the first page of the article. Such abbreviations that are unavoidable in the abstract must be defined at their first mention there, as well as in the footnote. Ensure consistency of abbreviations throughout the article.

Acknowledgements

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PUMPED HYDROELECTRIC ENERGY STORAGE SYSTEMS (PHES): CHALLENGES AND PERSPECTIVES IN THE BRAZILIAN ENERGY SCENARIO

¹ Raimundo, Danielle Rodrigues; ²Filho, Geraldo Lúcio Tiago

ABSTRACT

The expansion of renewable energy sources, encouraged by the growing concern for the environment and for combating global warming effects, has raised the issue of energy storage to regulate the intermittent characteristic of alternative sources, such as solar and wind. In this way, pumped hydroelectric energy storage systems (PHES) emerge as the oldest storage technology on the planet, presenting high technological maturity, low environmental impacts and high efficiency. A PHES study is proposed in this article, showing its main characteristics and challenges in the world energy scenario, with a special focus on the Brazilian scenario. The presence of reversible plants already adds over 127 GW of installed power worldwide, with particular reference to countries such as Japan and USA. In Brazil, this type of enterprise still faces many barriers, such as lack of regulation, economic and environmental issues. However, the government has already made efforts to insert this technology in the energy market, establishing criteria, prospecting possible locations and proposing regulatory measures for tariff regulation. Pilot projects should be encouraged to observe in practice the effectiveness of government efforts and begin to expand this form of energy storage.

KEYWORDS: pumped hydro energy storage, energy storage, Brazilian energy market.

1. INTRODUCTION

The increase in renewable sources consumption, considered as intermittent sources, allied to demand fluctuations, has raised the issue of energy storage and its effects on the grid [1]. This increase has been motivated by concern about global warming and climate change, and, in this scenario, the development of energy storage systems is crucial to allow the expansion of renewable energy production, both in small and large scale. The function of these systems is to regulate and level the daily fluctuations of renewable energies, ensuring greater stability and reliability to the electrical system [2]. In addition, besides being technical managerial solutions of the network, the storage systems also contribute to the use of clean energies and their autonomy [3].

There are a number of energy storage systems, such as compressed air, batteries, flywheels, capacitors, hydrogen and pumped hydroelectric energy storage systems (PHES). PHES are a versatile type of hydroelectric plant, which use two reservoirs at different heights. At peak times, water flows from the upper reservoir to the lower, driving an electric generator through a hydraulic turbine. During periods of low consumption, the water is pumped to the upper reservoir in order to be used again in the hours of high consumption [4].

The present article aims to present a PHES' study, showing its main technical, environmental, operational and economical characteristics, beyond the challenges in the world energy scenario. In addition, special attention will be given to state of art of this technology in Brazil, the government's plans and the challenges of PHES in the Brazilian energy matrix.

2. LITERATURE REVIEW

2.1. PUMPED HYDROELECTRIC ENERGY STORAGE (PHES)

As already mentioned, pumped hydroelectric energy storage systems (PHES) are a versatile type of hydroelectric,

which have two reservoirs. During daytime, period of greatest energy consumption, PHES uses water from the upper reservoir to generate electricity and stores it in the lower reservoir. At night, when energy consumption is lower, PHES pump back the water stored in the lower reservoir to the upper reservoir, establishing a sort of closed loop, which continually reuses the water [5]. Figure (1) shows the operational scheme of a PHES.

[Figure 1: Operational scheme of a PHES (THE HEA, 2013) apud [4].]

As reported by Pasten and Santamarina [6], the bigger level difference between the two reservoirs and the bigger flow, the more energy will be produced. Reservoir planning is the most critical element of a reversible plant, and its construction can be by two forms, according to Schreiber (1978) apud [7]. The first form is the closed circuit plants, or also called "pure pumping plants". They are independent of the river, where water flow transits between the two reservoirs and, possibly, an additional flow is necessary to replace the losses by evaporation and infiltration. The second form is open or semi-open power plants, where the reservoirs are built on riverbed, being used as conventional hydroelectric plants during daytime, and at night, surplus renewable energies are used for pumping [7].

2.2. TECHNICAL ASPECTS

The technical characteristics of reversible hydroelectric plants are not only points of energy supply, but also electric

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grid execution tools [8]. A PHES can operate as much a charge source as a energy source. The PHES is used as a pump, consuming energy in hours of low demand, or as a generator, generating energy during peak hours, and this is not possessed by any other type of power plants [8].

Reversible pump drops range from 100 to 800 meters. The turbines output power varies between 10 and 500 MW, not requiring high levels of water quality, can be operated even at sea [9]. The PHES' efficiency can reach from 70 to 85% [6]. Some PHES can pass from pumping stage to the maximum power generation in just 2 minutes, and the standby for maximum load in just 12 seconds. This advantage can bring numerous benefits to these plants when installed near the consumption centers, because it avoids investment in transmission lines and, consequently, reduces energy losses [10].

In comparison to other large-scale storage systems, such as battery banks and compressed air, investment in PHES is lower, with longer lifetime and greater stability. Therefore, pumped storage hydropower plants are considered the best tools for large-scale energy storage, and currently the most mature and practical technology [8], as shown in figure (2).

2.3. ADVANTAGES AND ENVIRONMENTAL IMPACTS

World energy systems are highly dependent on fossil fuels today, that causing greenhouse effect by emitting toxic substances. In this sense, PHES can be utilized to reduce the environmental emissions of CO_2 , SO_2 , and NO_2 , besides decreasing the dependency on thermal generating units [22].

Due to the similarity in reservoirs construction, environmental impacts of reversible plants are much closer to conventional hydroelectric plant, such as changes in the flow rate, widening of riverbed, impacts on flora and fauna, socioeconomic impacts, and others [7]. Reversible plants' construction has few negative consequences, in relation to conventional plants, such as no air pollution and small losses of land resources [11]. Moreover, the impact of hydroelectric plants is observed only at the local level, and it is possible to take mitigating measures to reduce damages to environment, making them tolerable, considering the benefits of this energy type [12], which also applies to PHES.

The positive effects, observed by [11] with data collected on-site in some European reversible plants, are intensification of water circulation, improvement of water quality due aeration, sedimentation, intensification of oxidation and mineralization of some organic and biogenic substances, improvement of self-purifying capacity of the reservoirs, among others. The increase of biogenic substances into the photic zone promotes an increase of planktonic organisms' reproduction. The greater

water aeration allows the elimination of oxygen stratification, which reduces the portion of blue-green algae.

Also in agreement with [11], some negative effects were also observed, such as fish death in pumping phase and turbidity increase. During operation of one of the plants observed, in a pump regime, up to 90% of zooplankton in the water being pumped dies. Death is most considerable in the spring, when rotifers dominate in the zooplankton. Despite high reproduction rates are characteristic for zooplankton, this factor is very significant. About fish death, in some of the observed PHES, the amount was not significant, and in other places, the diversity of organisms was higher in the reservoirs than in the river [11].

About socio-economic impacts, reservoirs used for hydropower purposes, both nature and artificial, has multiple uses and are important part of a nature. One of this multiple purposes is the recreational usage, where people can do fishing, swimming, kayaking, and many others. When introducing pumping, there will be changes which can affect the recreational and aesthetical values. This changes could lead to changes in water quality, visible changes in the shoreline zone and possibly significant areas of exposed littoral zone can cause undesirable odors [23].

About the advantages of reversible plants, a study by Companhia Energética de São Paulo [13], in partnership with Eletronorte, enumerated the benefits of this type of energy storage. Among them is the support for expansion of intermittent renewable sources, such as solar and wind power, as well as support to run-of-river power plants and increase reliability and quality of energy supply. There is still reactive power control, system stability, modulation of load variations, decrease of thermoelectric plants dispatch, better installed capacity utilization and cost reduction of acquiring energy at peak times, among other advantages.

3. METHODOLOGY

This study uses articles available in literature to build the state of art of PHES technology in the global energy scenario. For Brazil, in addition to articles, government documents and symposium presentations were used in order to know the plans of Brazilian government for PHES resumption in the national matrix.

3.1. DATA COLLECTION

To compose the study, scientific articles and works available in the literature were selected, which had the theme of energy storage from the reversible hydroelectric plants, their main characteristics, challenges and perspectives. The analysis was carried out both for worldwide scenario and for Brazil, in order to establish a comparison between the development stages of this technology type and to propose suggestions for PHES advancement in the national energy market.

4. RESULTS AND DISCUSSION

4.1. PUMPED HYDROELECTRIC ENERGY STORAGE IN THE WORLD

The hydraulic potential utilization through the reversible plants appeared around 1890 in Europe and today it reaches over 127 GW of power worldwide [2, 5]. At a country level, Japan has the largest installed capacity of PHES, with 25 GW, followed by China and USA [14], as shown in table (1) and figure (3) below.

[Table 1]: Installed PHES capacity by country in 2014.

Country	Installed PHS capacity (GW)	Under construction (GW)	PHES power capacity as a % of installed electrical generating capacity
Japan	24.5	3.3	8.5
China	22.6	11.6	1.8
USA	20.5	-	1.9
Italy	7.1	-	5.7
Spain	6.8	-	6.6
Germany	6.3	-	3.5
France	5.8	-	4.4
India	5.0	1.7	2.2
Austria	4.8	0.2	21
Great Britain	2.7	-	3.0
Switzerland	2.5	2.1	12
Portugal	1.1	1.5	6.1

[Figure 3: Figure (3) – Global installed PHES capacity [15].]

At the beginning of its development, the reversible hydroelectric plants were built up only in geographically favorable locations. The most significant expansion occurred in the post-war period of World War II, when economies began to recover and there was an increase in the complexity of electric power systems. The 1990s saw an abrupt decline in the number of new PHES installed worldwide, but in the beginning of 21st century, there has been a renewed worldwide interest in the PHES technology, as an integrator for intermittent solar and wind power production [15].

4.2. PUMPED HYDROELECTRIC ENERGY STORAGE IN BRAZIL

In Brazil, there are only two plants that could be classified as reversible, but do not act as such PHES: the Pedreira Elevatory Plant and the Traição Plant, both in the state of São Paulo [10]. A study [16] of the EPE (Energy Research Company) carried out a survey of the potential of PHES in Brazil, presented at the X Symposium on Small and Medium Hydroelectric Plants and Reversible Plants, occurred in 2016. As stated in the study, the regions with the greatest potential for reversible plants installation are São Paulo, Rio de Janeiro, Minas Gerais, Ceará and Pernambuco [16].

4.3. CHALLENGES OF PUMPED HYDROELECTRIC ENERGY STORAGE

Pumped storage hydropower plants have many advantages, already described in the course of this paper, as reducing the instability due to intermittent renewable sources. However, this type of energy storage technology also has its challenges. In accordance with [17], reservoirs are under water flow variation, which makes them vulnerable to rain, melting,

evaporation, infiltration, etc. Climate change also affects the reversible system when exposed to years of drought and higher temperatures, as well as environmental issues that must be taken into account during the installation and operation phase. However, the author [17] argues that these challenges can be considered insignificant, since well-planned and executed projects can solve these problems.

In relation of the operation of PHES, Pérez-Díaz et.al. [18] discusses three main challenges: uncertainties of real-time use, revision of long-term guidelines and definition of optimal strategies for the operation of PHES, according to their characteristics. Uncertainties in energy delivery are an ongoing and current challenge, which if it is solved, could increase the participation of PHES and intermittent sources, consequently improving the economic viability of reversible plants [18]. As reported by the authors, there are several models of price forecasting, but none of them were applied in real time in the energy reserves. In addition, around the world, backup power services are remunerated by two different concepts: availability and delivery. The amount of energy, in real time, for system equilibrium purposes depends on the system imbalances themselves. In places with large amounts of non-dispatchable energy, the need for balancing services is higher, and the opposite is also true.

The concern about uncertainties in energy prices in short-term generation has been a much discussed topic during the last decade, as said in [19]. In this article, more sophisticated forecasting methods in the USA are mentioned, such as Conejo et.al (2002, apud [19]), where market compensation prices for the following day are modeled by a density function of probability. And the offers of energy sales are obtained by the MILP, deterministic mixed integer linear programming. This model aims to maximize the weekly profit of a PHES. The uncertainty of hourly prices of energy market and regulation are considered through the variation of the corresponding forecasts errors. The uncertainty of the energy delivery and its use in real time is modeled by means of a probability parameter, included in the equation of the upper reservoir water balance. Although it is an approximate approach, it is the first attempt to model the use of water for the purposes of load frequency control [19].

For the review of the long-term guidelines, the authors [18] consider a new operating strategy, executing the short-term scheduling models for longer periods of one or more weeks. Thus, several historical scenarios characteristic of each enterprise would be run, beginning on different days, to obtain the periods of greater profit, within the conditions of each model. For the strategies definition, the authors [18] commented that new operating models are mandatory, such as those of variable speed equipment and plants that operate in a hydraulic short-circuit. The hydraulic short-circuit was defined by [19] when the operation allows to provide load frequency control through simultaneous pumping with rated power and turbine power generation control.

In addition to uncertainties of PHES operational schemes, there are also the competitive challenges, which contribute to the uncertain outlook of PHES development in the United States, for example. In recent years, natural gas production in the USA has been expanding quickly, which causes a decrease of its price and render PHES uncompetitive. On the other hand, the carbon dioxide emissions and the advance of intermittent renewable power can increase the development of PHES [24]. Another impasse is the question of how hydroelectric are still seen by the population. Many people don't consider it as a "green energy". In this way, much research is still needed in the area, but these changes of vision take time [25].

In terms of costs, a study in [26] shows that in a few years, from the specialists' point of view, the cost trend of a PHES system would be as profitable as diesel, overcoming the competitiveness of batteries, which today constitute the most common form of energy storage.

4.4. CHALLENGES OF PUMPED HYDROELECTRIC ENERGY STORAGE IN BRAZIL

As already seen in this article, the hydroelectric reversible plants have numerous challenges of operation and control, within an energy market. The potential of PHES on the planet is significant and several countries, such as Japan, China and USA, are already able to develop methods and technologies that can get around the difficulties of this storage system and expand its facilities. Unfortunately, this type of enterprise has not been explored yet very well in Brazil, although many studies of the federal government point to great potential throughout the country [4, 5, 7, 10, 13, 16 e 20].

Brazil was the first country in the world to install a reversible turbine, but the vast amount of water resources provided greater conditions for the development of conventional hydroelectric plants [4]. Some authors argue that the main challenges for reversible plants in Brazil are economic viability and lack of regulation [16, 20].

Other challenges of the PHES in the Brazilian energy scenario are the geographic question, for implantation of the two reservoirs; difficulty in allocating reversible plants in an energy category, since it presents generation and consumption within the same enterprise; differentiated tariffs that allow their viability [4]. About environmental regulation, the study in [20] proposes that the PHES in Brazil are under the application of the norms of the National Policy of Environment and National Policy of Water Resources, including granting water use and all the resulting environmental licenses of each phase of the project, with due regard to the type of plant.

The study in [10] proposes that the PHES be dispatched by ONS - National System Operator, and that a regulatory model be created to make economically this type of plant, in addition to considering the various possible arrangements, as isolated or allied reversible plants sources such as solar, wind or even thermal.

There is also the possibility of a generation link between wind power and reversible hydroelectric plants (figure 4), presented by [4, 10]. In this case, wind energy would serve as an energy supply for the pumping hours at the reversible plant, managing to reuse from 70% to 85% of electricity. The advantage of these systems is the cost savings, as well as the environmental benefits, since no fuel is needed, considerably reducing the emission of pollutants [21].

[Figure 4: Model of wind-hydro pump storage systems [21].]

5. CONCLUSION

Pumped hydroelectric energy storage is a mature energy storage technology with great potential for use throughout the world. Its expansion will benefit not only the grid systems, but also the evolution of renewable sources, ensuring greater reliability and energy stability. As the oldest form of storage on the planet, PHES are well established in developed countries, such as the USA and Japan, which allows new methods and innovations to be available and getting around the difficulties in the operation of these enterprises. In Brazil, there is already a concern for the insertion of PHES in the energy market, but the lack of regulation, feasibility and economic incentives and the difficulty of obtaining fast and consistent environmental assessments are still a barrier. However, there are already solutions and examples of methods used by other countries, in addition to attempts by the government to frame the PHES within the Brazilian scenario. In this sense, pilot projects should be encouraged in order to observe in practice the effectiveness of suggested models and begin to expand this form of energy storage. In this way, Brazil will also be able to use the reversible hydroelectric plants, ensuring the expansion of wind and solar energy in a stable way, contributing to an increasingly clean and sustainable electric matrix.

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