

Analysis of Pumped Storage Plants (PSP) viability associated with other types of intermittent renewable energy

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Abstract. The energy generated by wind or solar photovoltaic (PV system) can be used by PSP to accumulate water in the upper reservoir, in the form of potential energy to be used later, during periods of high energy demand. This procedure offers the advantage of enabling the use of intermittent renewable energy source in times of growing needs of the electric power supply. The location of the PSP, the environmental aspects involved, their possible use for various purposes (stability of the power system at peak times, associate the turbine water for public supply purposes, among others) and the discussion of regulatory issues needs to be debated in the current context, where environmental issues require reliable sources of power generation and demand shows strong growth rates.

A dynamic model is used to analyze the behavior of a PSP proposal for a site in Brazil, analyzing a complete cycle of its operation as a pump or turbine. The existing difficulties to use this proposal based on existing regulatory policies are also discussed, and a list of recommended adjustments is provided to allow the penetrations of PSP projects in the Brazilian institutional framework, coupled with other intermittent energy sources.

1. Introduction

The growing penetration of fluctuating renewable energy requires flexibility to manage highly variable generation and grid control mechanisms. One technology which is ideally suited for increasing energy flexibility is energy storage. A wide range of energy storage technologies currently exists, each with its own advantages, constraints, applications, and potential. Among the existing technologies, pumped hydroelectric energy storage (PSP) is the largest and most mature form of energy storage available in the world.

The benefits of PSP to electrical system operations are well documented in textbooks and journals. Its flexible generation can provide both up and down regulation in the power system while its quick start capabilities make it suitable for black starts and provision of spinning and standing reserve.

This paper describes a PSP project that has been investigated in a research and development project (R&D) in the state of Sao Paulo, Brazil. The R&D project encompassed issues related to turbine-pump technology selection, the project capacity, the operational model, and changes in the regulatory



framework to allow the economic feasibility of PSP in Brazil. The results of preliminary design parameters, operational cycle data of a typical working schedule, and recommended regulatory changes are discussed in the paper.

2. Mathematics model to analyze pumped storage power plants

The analysis of the hydraulic behavior of a pumped storage power plant is done through the equations of continuity, momentum and the pump-turbine characteristics. The most utilized resolution method of the equations is Method of Characteristics (MOC), Andrade (2009) and (2010). The hydraulic machine is analyzed considering the representation of their characteristics in accordance with the proposed by Marchal, Flesh & Suter, adjusted by Fourier series Andrade (1992) and Koelle (1996), facilitating the use of these functions in mathematical computational models. The machine data used in this paper were experimentally determined at the Technical University of Munich, Martin (1986).

3. Pumped storage power plants analyzed

Figure 1 shows the schematic drawing of Pumped Storage Plant used to the simulations presented in this paper and Table 1 shows the parameters of the hydraulic system.

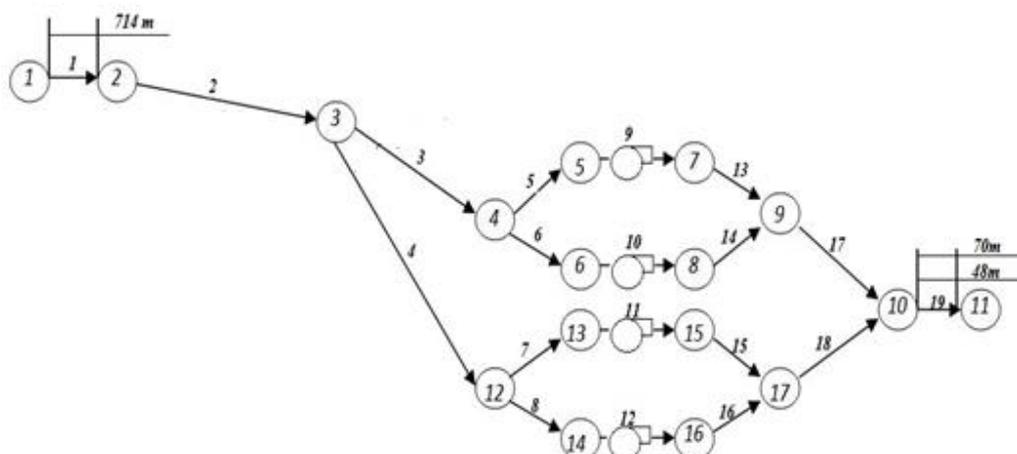


Figure 1: Schematic drawing of Pumped Storage Plant used to the simulations

4. Weekly cycle of operation of the pumped storage

The pumped storage scheme analysed in this paper has a discharge availability of $126.50 \text{ m}^3/\text{s}$ to be distributed in the four Francis turbines, resulting $31.62 \text{ m}^3/\text{s}$ in each. Also available for the two Pelton turbines a flow rate of $31.60 \text{ m}^3/\text{s}$, with $15.80 \text{ m}^3/\text{s}$ in each.

Considering all the machines running as turbines the output flow from upper reservoir will be of $158.10 \text{ m}^3/\text{s}$. In the operation as a pump, each machine can pump a flow of $23.33 \text{ m}^3/\text{s}$ to upper reservoir, resulting the total discharge of $93.30 \text{ m}^3/\text{s}$.

Thus, for each hour of the plant operation, a volume of 0.57 hm^3 flows through the four machines or a volume of 0.34 hm^3 through the two pumps. Knowing that the volume available in the lower reservoir is 7.55 hm^3 can write that:

$$Vol_{pumped} = 0,34.t \quad (1)$$

$$Vol_{turbined} = 0,57.t \quad (2)$$

$$Vol_{lower\ reservoir} = 7,55 + 0,57.t - 0,34.t \quad (3)$$

Table 1: The parameters of the hydraulic system.

Pipe Data						
Pipe	Upstream node	Downstream Node	L (m)	D (m)	A (m/s)	f
2	2	3	3930	6,5	1000	0.020
3	3	4	2485	3,2	1000	0.020
4	3	12	2485	3,2	1000	0.020
5	4	5	100	2,5	1000	0.020
6	4	6	100	2,5	1000	0.020
7	12	13	100	2,5	1000	0.020
8	12	14	100	2,5	1000	0.020
13	7	9	100	2,5	1000	0.020
14	8	9	100	2,5	1000	0.020
15	15	17	100	2,5	1000	0.020
16	16	17	100	2,5	1000	0.020
17	9	10	400	4,0	1000	0.010
18	17	10	400	4,0	1000	0.010
Reservoir Levels						
Res.			Nível (m)			
1			714			
19			48 a 70			
Pump-Turbine						
Number	Upstream node	Downstream Node	H _R (m)	Q _R (m ³ /s)	N _R (rpm)	
9	5	7	604.3	31.615	600	
10	6	8	604.3	31.615	600	
11	13	15	604.3	31.615	600	
12	14	16	604.3	31.615	600	

The intersection of the curves of pumped volume and lower reservoir volume show how many hours the plant can operate in pumping mode so as not to leak volume. From this intersection follows that $t_{\text{pumping}} = 73.50$ h and $Vol_{\text{pumping}} = 24.72$ hm³. This result can be shown in Figure 2.

The pumped storage plant is idealized to be a closed-loop cycle model that means the pumped volume must be equal to the turbined volume. With the pumping volume the turbined time can be calculated as $t_{\text{turbined}} = 43.43$ h

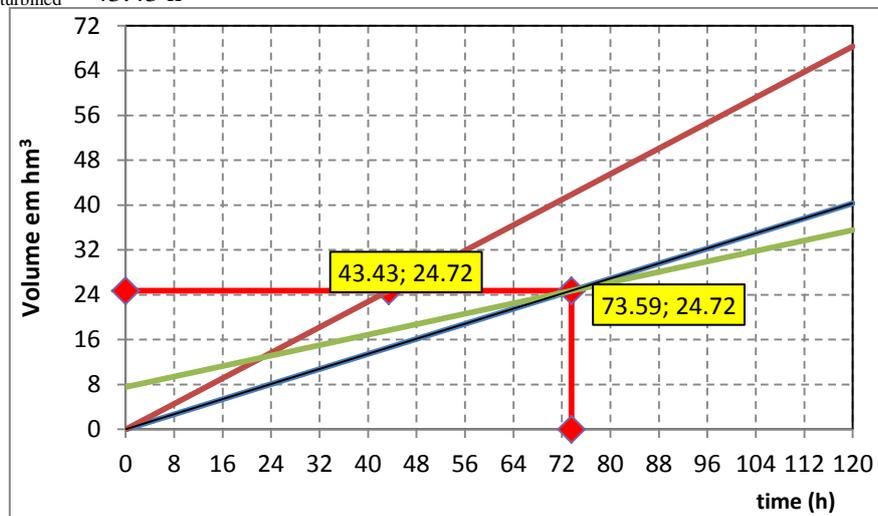


Figure 2: Pumped, turbined and lower reservoir volumes as function of plant operating time

To meet the energy demand profile of the network the following values were adopted: 47 h of working as turbine and 79 h working as a pump.

The available volume in the lower reservoir is 7.55 hm³, with levels ranging between 48m and 70m. The level of the lower reservoir can be calculated from the equation (4). The level of the upper reservoir will be considered constant at 714 m to be large.

$$h = 0,0155 Vol^3 - 0,3079 Vol^2 + 4,3634 Vol + 48 \tag{4}$$

The weekly operation proposed for the Pumped Storage Plant is presented in Table 2. Figure 3 represents the cumulative turbined, pumped and available at lower reservoir volumes. It is noticed that throughout the week no leakage occurs from the lower reservoir and the cumulative volume pumped and turbined are nearly identical, showing that the volume of the lower reservoir is suitable for this proposed operation in closed circuit.

Table 2: Weekly cycle of operation of the pumped storage

Week Days	Period	Pumping (hours)	Generating (hours)	Total	
				Pumping (hours)	Generating (hours)
Monday	14h - 21h	0	8	0	8
	23h - 24h	1	0	1	0
Tuesday	01h - 10h	10	0	33	24
Wednesday	14h - 21h	0	8		
Thursday	23h - 24h	1	0		
Friday	01h - 12h	12	0	13	8
	14h - 21h	0	8		
	23h - 24h	1	0		
Saturday	01h - 11h	11	0	14	7
	13h - 20h	0	7		
	21h - 24h	3	0		
Sunday	01h - 18h	18	0	18	0
Total=				79	47

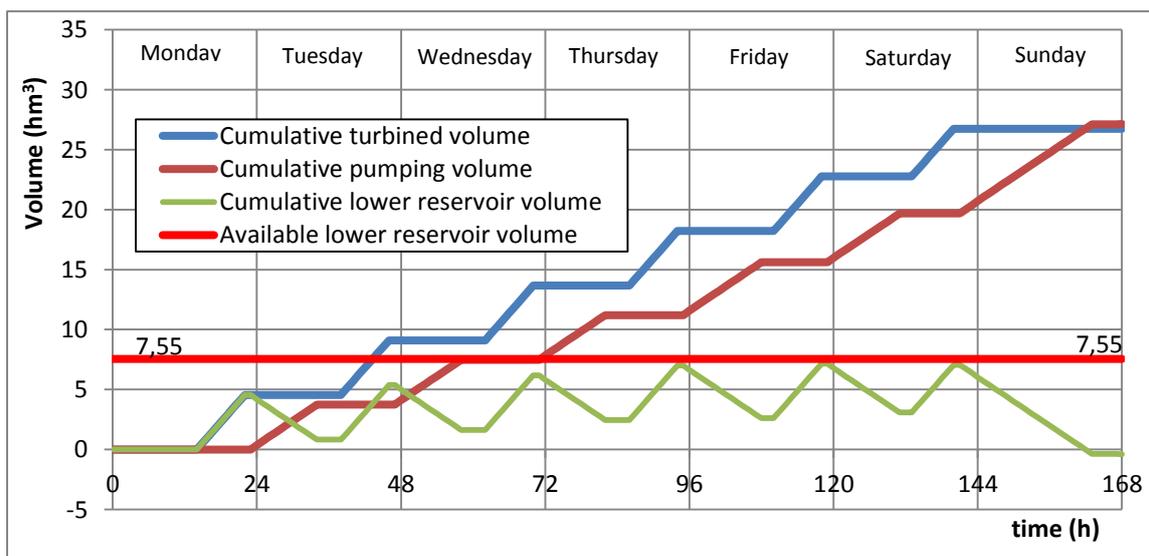


Figure 3: Cumulative turbined, pumped and available at lower reservoir volumes.

5. Energy Analysis of the Pumped Storage Plant Operation

The analysis of the operation of the plant began on a typical Monday, starting at 14 h with generation in the four turbines and lower reservoir in the elevation 48 m (empty). The simulations were developed using the extensive period with time step of 1h to cover a typical week. The operation of the plant was kept constant for one hour, allowing the calculation of the volumes pumped or turbined. With these volumes and using equation (4) (level x volume) it is possible calculate the new level of the lower reservoir, to be used in the simulation of the following hour. In addition to the pumped and turbined volumes on the machines was considered a volume withdrawal of the lower reservoir of 0.04 hm³ concentrate daily at 24 h, referring to the public water supply for a city.

Figure 4 shows the variation of the lower reservoir level for weekly operation adopted, showing that its level was within the permissible limits of 48 to 70m.

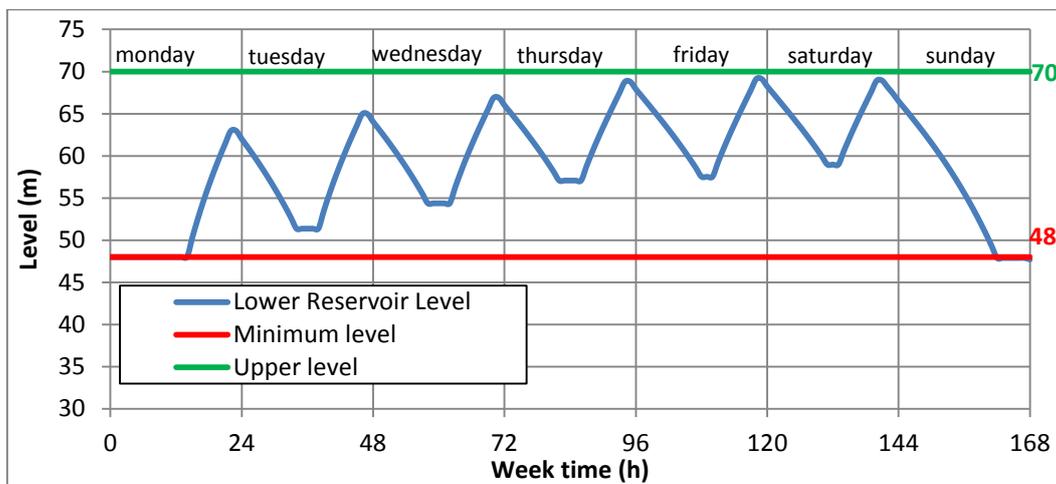


Figure 4: Weekly level variation of the lower reservoir.

Figure 5 shows that the volume available in the lower reservoir of 7.55 hm³ is sufficient to meet this proposed operation. We also emphasize that both the dimension and the volume of the lower reservoir at the end of the simulation period returned to baseline, showing it to be possible to restart the operation in the next week.

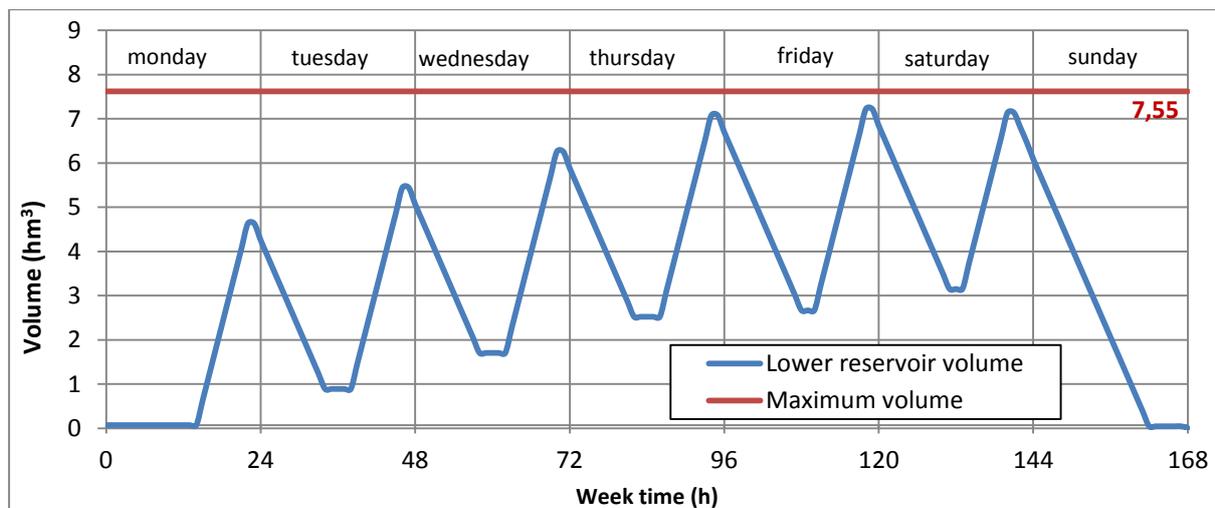


Figure 5: Volume available in the lower reservoir.

Figure 6 shows the power history of the Pumped Storage Plant considering the four machines working as a turbine or pump and, in the generation mode, when is added the two Pelton machines. Thus, totals approximately 792 MW in generation and 643 MW of consumption in pumping.

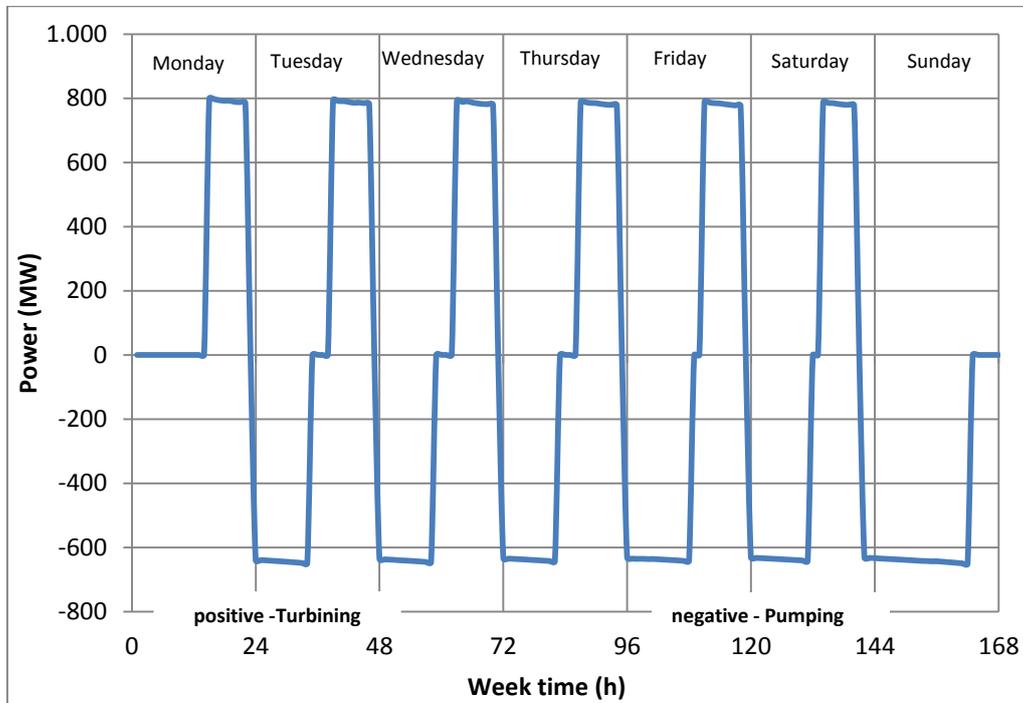


Figure 6: Weekly variation of the power generated or consumed considering four Francis turbines and two Pelton turbines

Assuming power as constant for a period of one hour is possible to do an energy balance for the weekly plant operation.

For a typical week the Figure 7 shows the cumulative energy generated when the operation as a turbine, the energy consumed when in operation as a pump and the energy balance in the plant.

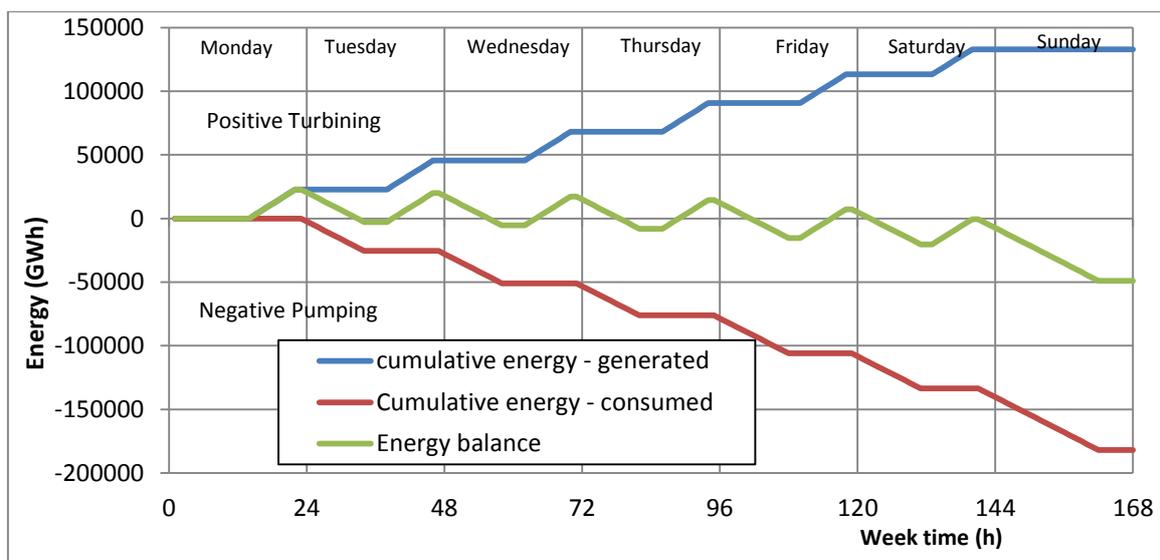


Figure 7: Cumulative generated and consumed energy and energy balance in the plant.

We notice that at the end of the weekly period the plant has produced an energy equal to 132,949.0 GWh (four Francis and two Pelton) and consumed an energy equal to 181,980.0 GWh in pumping water to the upper reservoir using four pumps (Francis). This operation weekly shows, as expected for the Pumped Storage Plant, a weekly energy deficit of 49,030 GWh.

It is noteworthy that the existing deficit should be compensated for the difference that must exist between the rate of purchase and sale of energy in a Pumped Storage Plant, remembering that buying energy for pumping occurs in periods of low demand and the sales of the generated energy occurs during periods peak consumption. This fact helps in justifying the economic feasibility of Pumped Storage Plant and will be presented following one regulatory model for the Brazilian reality.

6. Adjustments in the Brazilian Regulatory Framework to Allow Competitive PSP Projects

The proposal presented below considers the Brazilian framework for the power sector and its regulatory conditions. We must recognize at least three difficulties in the existing regulatory framework aiming at introducing PSP projects:

- a) the lack of market for balancing power or ancillary services in Brazil, which could be a reference to enable PSP projects;
- b) the small difference, if any, of the short-term price (spot price) between the on-peak and off-peak energy, which prevents economic return of PSP;
- c) the absence in Brazil, of vertical companies, where there would be financial compensation for investments in PSP projects from their benefits not only from the generation component, but also from revenues of the other segments as energy transmission and energy distribution. Vertically integrated companies have potential to capture these benefits, as with most projects of PSPs in the U.S., prior to the competitive market or even existing vertical companies owned by federal government.

Given the aforementioned context, the proposal that is presented is based on the following assumptions:

Premise P1: The PSP projects should have centralized dispatch by the Brazilian ISO (centralized dispatching for all generators of the country), like the other types of hydro or thermal plants;

Premise P2: The relevance and attractiveness of PSP projects should be assessed from a systemic point of view, considering the regional benefits to the reliability and the overall effect for the national grid, reducing the need for transmission and others. The assessment must be made by the Brazilian ISO, comparing with other alternatives;

Premise P3: The adequacy should make the most of the current regulatory and institutional framework. In other words, efforts have to be addressed to avoid major regulatory changes that potentially represent barriers to implementation;

Premise P4: The regulatory model is to ensure the economic viability of PSP projects taking into account the strengths and uniqueness of PSPs such as:

- quick dispatch or adjustments to variations in load;
- contribution to control frequency and voltage in the grid.

Premise P5 : The regulatory model must consider several arrangements for proposition PSP projects, such as:

- A single PSP project
- PSP associated with wind farm
- PSP associated with solar photovoltaic plants
- PSP associated with thermal plant running to meet the base load, with constant generation at the point of maximum efficiency
- PSP associated partial combinations among the previous alternatives

Premise P6 : Once a PSP project is considered a relevant and timely option at a given location, with recognition of the value of their services and there is no market mechanism (ex1. enough price differential between on-peak and off-peak prices; ex.2 auctions for formation of spot price) to make it attractive to investors, the selection of the most interesting applicant using auctions, with sales associated to contracts is a legitimate regulatory manner to the public interest Rangoni (2012).

Once the location of one or more PSP is identified, an auction mechanism coordinated by government will select the most competitive proposal, based on the lower selling price. The winner generation company will sign a 20 years contract that guarantees selling the production along the entire period of the contract.

In this regulatory adjustment it is assumed that the economic feasibility of the PSP project is based on the production in periods of on-peak load (heavy and medium level), when the PSP plant works as generating unit, and that the purchase of electricity for pumping occurs through supply special rates. Special rates play the role of the pursuit of economy, necessary for the feasibility of the project.

The Call Auction set for each plant UHR will require the definition of the following parameters:

- a) Ceiling Price for energy produced during on-peak hours (heavy load);
- b) Supply rate of purchasing power for pumping purposes (from 0h to 7h every working day, and also during all hours of Sundays);
- c) Operational limits and conditions of dispatch, such as the minimum dispatching days along the year, particularly in the summer; regional time of the on-peak periods (eg 6pm to 12 pm); daily and weekly operating cycle;
- d) Order of merit for selecting the winner of the auction

When compared to the amount of energy derived from an auction from a traditional hydropower plant, there is less risk to the PSP generator, since the product (energy in on-peak hours) has much higher production regularity (daily production cycle), with small exposure to the effect of head variation due to flow increase in the tailrace channel, and neither the seasonal variability of inflows.

7. Conclusions

A dynamic operational model is presented in this paper, describing a Pumped Hydro Storage Project (PSP) in Brazil. The main technical information about the project is provided. The working schedule as pump and turbine is described based on a simulation model, which allowed defining the design and operational parameters. Like many other regions across the World, the growing interest on PSP projects in Brazil is based on the potentially competitive advantages of this energy storage option to be coupled to energy systems with growing penetration of intermittent generation. A critical problem in Brazil is the need of adjustments in the regulatory framework in order to be feasible and economically competitive the introduction of Pumped Storage Projects. Therefore, several guidelines are suggested in the paper in order to go further in the regulatory framework aiming at achieving better conditions to PSP become competitive and attractive to investors.

8. References

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