Enhanced-Pumped-Storage: Combining pumped-storage in a yearly storage cycle with dams in cascade in Brazil

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**Abstract**

The new frontier for hydropower electricity generation in Brazil, the Amazon region, cannot be used for energy storage as the construction of storage reservoirs would have deep environmental and social impacts, thus run-of-the-river dams have been built instead. If Brazil still wants to generate 80% of its electricity from hydropower, there is the need to increase the country's energy storage capacity so that the excess generation coming from the dams in the Amazon region during the wet period can be used during the dry period. This article presents four ways to increase the storage capacity of a watershed. The most innovative alternative involves a large-scale pumped-storage site combined with a series of hydropower dams in cascade, which could store energy by pumping water to a new reservoir during the wet period and generate energy by releasing the stored water during the dry period. Even though pumped storage schemes have an average efficiency of around 75%, it has been calculated that the combination of a pumped storage site and a series of hydroelectric dams in cascade can increase the overall storage efficiency up to 90% and double the storage capacity of a watershed. This scheme was called EPS (Enhanced-Pumped-Storage).

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1. Introduction

Storing energy is a necessity that has come to the attention of various research groups and companies. New technologies such as the hydrogen fuel cell [1] and graphene ultracapacitors [2] are being developed but are not technically mature. Another approach proposed is to use electric car batteries to store electricity through a smart grid system [3]. Reviews of different energy storage technologies and their process description can be seen in Refs. [4,5]. However, almost all bulk generation capacity based on storage schemes, equivalent to over 130 GW [6], comes from PS (pumped-storage) due to its low cost and high energy conversion efficiency (70%–85%) [7,8] and this number is expected to further increase [9].

In Brazil around 80% of the electrical energy comes from hydroelectric power plants — unless there is a shortfall of rain [10]. This is because the combination of varying reservoir dams and run-of-the-river dams in the Brazilian watersheds was designed to generate a constant amount of electricity throughout the year. According to this scheme, during the wet period (December to April) some electricity is generated and some water is stored to fill up storage reservoirs. During the dry period (May to November), the stored water is used to generate electricity and the level of the dams is lowered. This design allows the river to generate a relatively constant amount of energy using the installed generation capacity at a high rate, reducing the cost of electricity.

The approach of relying on a constant hydroelectric generation in the Brazilian watersheds is reaching its feasible limit. Run-of-the-river dams that do not have storage capacity and generate power in proportion to the amount of water flowing in the river, are being built in the Amazon region [11]. This dam building approach is followed mainly because the geological formation of the rivers in the Amazon basin is relatively flat. A large flooded area would be required to store a small amount of energy and during the dry season the devastated area between the forest and the river will be so large that a severe impact to the environment and biosphere will result.

Apart from the lack of generation during the dry period, there is some electricity generation potential wasted as water bypasses dams not generating electricity during the wet period [12]. This waste is expected to increase with the development of the Amazon hydroelectric generation capacity (60% of the Brazilian hydropower potential), as there will be not enough storage capacity to store the
excess energy generated during the wet period. Fig. 1 shows the average monthly energy potential, without including storage, in different regions in Brazil and that the generation in the wet period will considerably increase with the construction of run-of-the-river dams in the Amazon water basin (North), when most reservoirs of the integrated national power grid (Interlinked National System — SIN) should be already full (Fig. 2). A detailed study of the hydro-power generation imbalance in Brazil is presented in Ref. [13].

Proposed solutions to reduce this seasonal generation imbalance have been studied. Some of these studies examine whether renewable energy sources could supplement the lack of hydroelectric generation during the dry period. For example, Da Silva et al. (2005) [15] and Riscosti and Sauer (2013) [16] show that wind power in the Brazilian Northeast could complement the lack of hydroelectric generation during the dry period in the region. CEBDS (Brazilian Business Council for Sustainable Development) (2013) [17] shows that the sugarcane harvest happens during the dry season and the combustion of its bagasse has the potential to generate around 15 GW of electricity. An increase in investment in intermittent renewable energy sources such as wind, biomass and solar is foreseen [11]. However, intermittent sources of energy cannot guarantee the supply of electricity and might increase the amount of energy wasted in the system.

This paper analyses four different approaches to increase the energy storage capacity of a watershed, focussing on Enhanced-Pumped-Storage schemes presented here. With these new techniques, the dams in the South, Southeast, Midwest and Northeast regions would generate more of their electricity during the dry period, in order to complement the new dams in the North, Amazon region, which would generate most of its electricity during the wet period.

1.1. Energy storage shortage in Brazil

For Brazil to supply its electricity demand, it stores energy during the wet period for generation during the dry period. In the nineteen seventies, the energy stored in the reservoirs, when full, had the capacity to supply energy for three to four years. Today, with the current demand for energy, these reservoirs can store energy for around 5 months, when full. Fig. 2 shows that the total storage capacity increases with the increase in monthly demand for electricity. However, the total storage capacity will stop increasing but the monthly demand will continue increasing. Thus, the system will rely less on energy storage, resulting in a more volatile monthly hydro storage capacity and compromising the energy security of Brazil. The amount of months of hydropower storage is found by dividing the ‘Monthly Demand’ line by the ‘Monthly Hydro Storage’ line in Fig. 2. It should be noted that the ‘Monthly Demand’ is not only supplied with hydropower. Thermoelectric and other sources of energy also contribute to the supply.

As can be seen in Fig. 2, in July 2001, the monthly demand had to be considerably reduced, because there was not enough stored energy. This resulted in a deep energy crisis. This graph shows that this crisis impacted the economy so hard that the energy consumption only returned to the same level in January 2005.

In the beginning of March of 2014, a similar trend is appearing. In the Southeast, the volume of water in the reservoirs fell to the same level as in 2001, 34% [18]. However, since 2001 much has happened to reduce the risks of a new energy crisis. Transmission lines were installed, increasing the ability to transfer electricity from one region to another (in 2001, the energy that could have been generated in the South or in the North could not be transferred to the Southeast and Northeast due to lack of transmission lines). The country also received considerable generation capacity reinforcement, which totalled 33.8 GW in 2012, with thermoelectric power plants and...
other renewables [11]. Assuming a reasonable capacity factor of 70%, when there is no rain and there is an urgent need to generate electricity, this capacity will generate 24.3 TWh, which is only half of the monthly demand in 2012 and might not be enough to supply Brazil’s electricity demand. Hydroelectric generation capacity is predicted to increase 40% by 2022 but the energy storage capacity is expected to increase only 2% by 2022 [11], which will be equivalent to a generation of 49.16 GW for 6 months. One solution for the Brazilian electricity sector is to diversify the Brazilian generation capacity. However, if Brazil still wants to develop its hydropower capacity to keep generating around 80% of its electricity from hydropower, it will need to increase its storage capacity.

1.2. Centralized energy storage potential

Another potential problem with the Brazilian hydropower storage capacity is that the main hydroelectric dams with reservoirs are in the Southwest region. If there is a limited volume of rain in this area, the energy supply in Brazil might be compromised. Out of the Brazilian storage capacity, 70.1% is in the Southeast and Midwest regions, 18.0% is in the Northeast region, 6.9% is in the South region and 5% is in the North region. Fig. 3 shows the reservoir hydroelectric dams locations in Brazil with their respective storage capacities. This figure was created with the values of the reservoirs taken from Ref. [19]. This graph did not include reservoirs with the storage capacity smaller than 0.37 TWh.

It would be interesting to decentralize the Brazilian energy storage potential by building new energy storage sites in areas where there is limited storage capacity at present. This would reduce the risk of not having energy stored to supply the country during the dry period, if it does not rain enough in the Southwest region, and thus, increase the country’s energy security.

The issue of climate unpredictability is becoming increasingly important due to global warming. According to Soito and Freitas (2011) [20], changes in temperature lead to changes in atmospheric pressure and wind patterns, thus, changes in rainfall patterns are to be expected. It is important to carry out studies on predicting and evaluating climatic vulnerability in the generation of hydroelectricity in Brazil, with an emphasis on the anticipation of power shortages.¹

¹ It is convenient to make a distinction between climate change and natural climate variability: climate change is the systematic variation of climate parameters. It may occur due to changes in the climatic system or by anthropogenic action. For this, a great variety of data and results of atmospheric models must be utilized. Climate variability is inherent to the climatic system and presupposes alternation, that is, the superposition of cyclical or semi-cyclical variations.
Lucena et al. (2009) [21] used the IPCC (Intergovernmental Panel on Climate Change) long-term projections [22] to analyse the effect that global climate change will have on regional climates and concludes that there will be changes in Brazilian regions, especially in the Northeast. However, the effect on electricity generation will be stronger in the Amazon region as it has limited energy storage potential.

Given the rain pattern variability, assuming climate change or not, it would be advisable to decentralise the storage capacity of Brazil to increase its energy security. For example, Brazil is currently heavily reliant on rain in the Southeast region and as it has rained much less than the yearly average in this region during 2012, 2013 and the beginning of 2014, thermoelectric plants were running at full capacity, electricity prices will considerably increase and there is a risk of a new energy crisis by the end of 2014.

2. Methodology

This section presents a strategy to resolve the Brazilian hydroelectric generation seasonal imbalance and four techniques to increase the storage capacity of watersheds so that the Brazilian watersheds, other than the Amazon watershed, can generate most of its hydroelectricity during the dry period. These techniques are EPS (Enhanced-Pumped-Storage); Pumped-Storage in Cascade; Additional Storage Reservoir Dams and the Retrofit of run-of-the-river dams into Storage Reservoir Dams.

2.1. Resolving the hydropower generation imbalance in Brazil

The Amazon water basin hydropower potential of 106 GW, if developed, would generate most of its energy during the wet period with run-of-the-river dams. This is equivalent to 60% of the total Brazilian hydropower capacity [11]. However, if all this capacity were developed, there would be a massive hydropower generation imbalance in Brazil as more than half of the Brazilian capacity will generate most of its electricity during the wet period. If the Amazon hydropower potential were built and Brazil desires to keep generating around 80% of its electricity from hydropower, there would be the need to increase storage capacity in Brazil.

However, the Brazilian Government and energy sector agencies (EPE, ANEEL and ELETROBRAS) are not planning to increase the Brazilian energy storage capacity [11]. It has been highlighted that hydropower plants with storage reservoirs are not appropriate for the Amazon watershed. Apart from the reasons mentioned in Refs. [20,23], the fact that the region has a very flat geology impedes the construction of storage reservoirs. A huge flooded area will result in a very low storage capacity per square kilometre of reservoir. Another important fact, which has not been mentioned in the literature, is that the variation of around 5 m depth in a reservoir in most parts of the Amazon watershed would result in a huge devastated area. When the level of the reservoir is lowered during the dry season, an extensive area of devastated forest will appear. This devastated land between the reservoir, during the dry season, and the forest will deeply impact the fauna and flora of the area. For example, native Indian communities and wild animals would have to travel around 1–5 km to drink water from the river or to fish.

The geology of the South, Southeast, Midwest and some areas in the Northeast of Brazil are appropriate for the creation of hydroelectric dams with storage reservoirs. This is because their rivers have the geological formation of a valley. This shape considerably reduces the varying flooded area between full and empty reservoirs, reducing the environmental and social impact of Storage Reservoir Dams.

This paper proposes that the watersheds in these regions should have their storage capacity increased. Even though their hydropower generation would decrease during the wet period, they would increase during the dry period. This concept goes against the usual approach of minimising the cost of electricity in watersheds. But as there is the need to increase energy storage, there is the need for more investment in these watersheds.

A good strategy to effectively use the Brazilian hydroelectric potential is to use the Amazon water basin to generate electricity during the wet period and increase the storage capacity of the other water basins so that they generate most of their electricity during the dry period.

2.2. Enhanced-Pumped-Storage

Pumped-storage sites are widely used in various countries, they allow electricity to be supplied efficiently when the demand is high. As the demand for electricity is lower at night, the excess generation is stored so that it can be used during the day when demand is higher. This enables, for example, nuclear reactors to operate at full capacity at night when the demand for electricity is low as the energy is stored. For example, around 9% of Japan's electricity generation capacity is pumped-storage as Japan relied heavily on nuclear power in the past [24].

The storage process consists of pumping water from a lower reservoir to an upper reservoir, where the potential energy of the water is higher. When electricity generation is needed, water in the upper reservoir flows to the lower reservoir through a turbine which generates electricity. There is a loss of 15%–30% during this storage and energy conversion process. It should be noted that, in most cases, for the construction of a pumped-storage site, only one turbine and generator are needed. The turbine and generator will be used to pump water during one part of the cycle and generate electricity at another part of the cycle.

Recently, a proposal to combine the operation of dams in series (the so called generation in cascade [25]) with pumped-storage was mentioned in Refs. [26,27]. Their work discusses the use of a pumped storage site to reduce the amount of water bypassed in dams and to increase the amount of electricity generated in dams in cascade. When there is a rainy period and the hydro reservoir is almost full, the dam may spill over some of the water as it cannot use it to generate electricity. Either because there is not enough generation capacity to transform the water flow into electricity or because there is not enough demand to use the energy. Thus, a pumped storage site may be built to increase the water storage capacity and to utilize the extra capacity of the dams to pump the water to an upper reservoir, in this way improving the operation of the dams in cascade.

The combination of a pumped-storage site and series of dams in cascade as proposed in this paper was called Enhanced-Pumped-Storage. It can be used not only to improve the operation of the dams in cascade, but it can considerably increase the very much needed energy storage capacity of Brazil.

A large-scale pumped-storage site, built close to the top of a river, can change the flow regime of the river and thus change the seasonal hydroelectric power generation of the whole river. Instead of storing energy at night and generating energy during the day, as most pumped-storage sites do, Enhanced-Pumped-Storage schemes would store energy during the wet season and generate electricity during the dry season. Apart from using the excess energy generated in the Amazon run-of-the river dams during the wet period, the reservoir could be used to store the surplus generation coming from intermittent renewable sources such as wind and solar power.

This scheme consists of creating a new artificial reservoir which has a height 200 m or higher than the lower reservoir, which allows for a variation in the upper reservoir height higher than 50 m or...
more. In addition, the distance between the two reservoirs should be smaller than 12 km, should be followed by dams in cascade and have an impermeable and stable geological formation. The bigger the elevation difference between the two reservoirs the thinner the tubes will need to be to generate the same amount of energy, and the smaller will be the flooded area. The bigger the height variation of the upper reservoir, the less area flooded required and the less evaporation will occur in the reservoir. The lower reservoir is connected to a major river with a series of hydroelectric dams following it. It should have a bigger water storage capacity than the upper reservoir so that the pumps could operate at maximum capacity during the wet period. Alternatively, the lower reservoir should have a flow big enough so that water can be pumped to the upper reservoir during the wet period without altering the level of the reservoir.

The equation used to estimate the energy stored in the Enhanced-Pumped-Storage sites is shown below:

\[
\text{Energy Stored} = \sum_{i=1}^{n} h_i f_i g \rho
\]

where, Energy Stored is calculated in (J), \( h_i \) is the height difference between the upper and the lower reservoirs in (m), \( n \) is number of iterations of filling or emptying the upper reservoir, \( f_i \) is each iteration step, \( g \) is the flow of water equivalent to each iteration step (kg), \( g \) is the acceleration of gravity (m/s²), \( \rho \) is the density of water (kg/m³).

An example of the operation of Enhanced-Pumped-Storage schemes can be seen in the Paraná Basin, as shown in Fig. 4. During the wet period, some of the water in the lower reservoir dam (Serra do Façan and Furnas) would be pumped to the upper reservoir of the pumped-storage site (Catalão and Canastra). This will reduce the generation of the lower reservoir and the dams in cascade in the river (Grande, Paranaiba and Paraná). During the dry period, the water stored in the upper reservoir will flow to the lower reservoir generating electricity and increase the generation of the dams in cascade.

The terminology used in this paper, refers ‘EPS site’ to the large-scale pumped-storage site used to store energy and water, for example the Serra do Façan — Catalão site and the Furnas — Canastra site. EPS scheme refers to the combination of the EPS site and the dams in cascade that follows the EPS site.

More specifically, the Canastra Sierra EPS scheme consists of an artificial upper reservoir in the Canastra Sierra which can vary from 1050 m to 1120 m high and the Furnas reservoir at 760 m above sea level as the lower reservoir (biggest energy storage reservoir of the SIN). This site would require a series of pipes 12 km long and a dam greater than 170 m in height. During the wet period the reservoir would fill following the sequence from Fig. 5(a)–(b). During the dry period the reservoir would empty following the sequence from Fig. 5(b)–(a). The calculations to estimate the storage capacity were made with the difference in volume between the topology of the varying height of the reservoirs.

Following the Furnas reservoir there are 12 dams which generate electricity from a height of 760 m above sea level with the Furnas dam to 100 m above sea level with the Itaipu dam, as shown in Fig. 4. This consists of a total height difference of 1150 m. During the wet period, most of the water in the Furnas reservoir will be pumped to the Canastra reservoir considerably reducing the flow of the Rio Grande and thus the electricity being generated during the wet period in the 12 dams that follows the Furnas dam. During the dry period, however, the water will flow from the Canastra reservoir to the Furnas reservoir generating electricity and allowing the 12 dams that follow the Furnas dam to generate considerably more energy during the dry period.

The most important aspects of EPS schemes are 1) smaller flooded area to store the same amount of energy and, with the smaller flooded area, there is considerably less losses with evaporation; 2) high overall efficiency, around 90%, which could be beneficial to store energy from intermittent renewable sources; 3) additional peak load generation capacity; 4) the new generation capacity required is around half the generation increased during the dry period; 5) reduce transmission costs for connecting new run-of-the-river dams in the Amazon region to the consumption areas (Southeast). However, it should be noted that EPS schemes are only used to store energy, they do not contribute to extra energy generation to the system.

### 2.2.1. Higher overall storage efficiency

The efficiency of EPS schemes is higher than in conventional pumped-storage sites because the height difference for pumping water in the EPS site, is smaller than the overall generation height of the EPS scheme (which includes pumped-storage and the dams in cascade). The energy lost in the EPS scheme would be equivalent to a conventional pumped-storage site, however, as the energy generated will include the EPS site and the dams in cascade, the ratio between the energy loss and the energy generated becomes smaller, thus increasing the overall efficiency.

For example, considering Canastra Sierra (1120 m) EPS scheme, energy will be lost for pumping water to the Canastra dam (352 m higher), storing energy and water from the wet to the dry period. However, the energy will be generated in the Canastra dam, Furnas dam and the dams in cascade (equivalent to 1020 m). Assuming the efficiencies of the dams in cascade are not affected, a rough estimate for the OE (overall efficiency) of the EPS scheme is found with the two equations below.

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Fig. 4. Diagram of the dams in the Paraná, Paranaíba and Grande Watersheds with two proposed Enhanced-Pumped-Storage schemes. Source: Authors’ own material.
Fig. 5. Canasta reservoir, (a) empty at 1070 m above sea level and (b) full at 1250 m. Source: Authors’ own material.
2.3. Other energy storage techniques. Apart from the main techniques discussed in this paper, Enhanced-Pumped-Storage, this subsection briefly presents three other techniques to increase the Brazilian energy storage capacity.

2.3.1. Pumped-Storage in Cascade. Pumped-Storage in Cascade is a concept to increase the storage capacity of a watershed, reducing costs and environmental impacts. It requires a series of hydroelectric dams in cascade where at the top of the cascade there is a reservoir with two or more rivers flowing into it, as shown in Fig. 6(a).

In this design, a new Reservoir 2, as shown in Fig. 6(b), has enough storage capacity to store the water flowing in River 1 and River 2, where the water in River 1 is pumped to the Reservoir 2 during the wet period. In this way, the Dam 2 would be able to generate energy during the dry period using the water that flows in River 1 and River 2.

Pumped-Storage in Cascade increases the hydroelectric generation capacity of a watershed and its storage capacity.

2.3.2. Additional Storage Reservoir Dams

This option does not involve pumped-storage, however, it can be used to increase the storage capacity of the watershed just by simply building more dams with storage reservoirs upstream of the river. In this way, the watershed will be able to store more water during the wet period and generate more energy during the dry period.

2.3.3. Retrofit run-of-the-river dams into Storage Reservoir Dams

Run-of-the-river dams are usually built downstream Storage Reservoir Dams as the latter is used to keep the level of the run-of-the-river reservoir at a constant level so they can operate optimally. However, as there is need to increase storage capacity, there is a possibility to retrofit run-of-the-river dams into Storage Reservoir Dams. This option has not been mentioned in the literature. It should be considered for dams that already need to be retrofitted and that are closer to the top of the cascade. This is because the higher the storage reservoir, the more energy it will store with the same amount of water. In this case, the dam height should not vary, but additional turbines that can operate at different heads should be installed.

3. Results

This section presents the characteristics and the benefits of using Enhanced-Pumped-Storage schemes to increase the Brazilian storage capacity. It focuses on the environmental impacts, with focus on the flooded area used to store energy, costs of the technique and gives an example of how EPS could be used to store energy from intermittent renewable energy sources. The characteristics of five Enhanced-Pumped-Storage schemes are shown in Table 1.

3.1. Smaller flooded area and evaporation

Enhanced-pumped-storage sites can require a reservoir with an area 10 times smaller than conventional dams to store the same amount of energy. This is because, the difference in altitude between the two reservoirs is bigger than dams in cascade and because the reservoir allows for a greater variation in the level of the upper reservoir. For example, Tres Marias dam, Table 2, with a maximum height of 75 m allows for a variation of 23.3 m of its reservoir. Following the same ratio, an EPS scheme with 500 m difference between the upper and lower reservoirs, would allow for
a variation of 155.3 m in the upper reservoir. This would considerably reduce the flooded area per energy stored. The smaller the reservoir area required, the smaller is the environmental impact and losses through evaporation.

The total flooded area in Brazil, including both run-of-the-river and reservoir dams, is estimated to equal 37,943.44 km² in 2010 and the total storage capacity (ERAm\textsubscript{max}) in TWh is 210.2 \cite{19}.

### Table 1

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Canastra (1120)</th>
<th>Canastra (1250)</th>
<th>Catalão</th>
<th>Lajeado</th>
<th>Morro da Mesa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical aspects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum altitude (m)</td>
<td>1050</td>
<td>1050</td>
<td>900</td>
<td>500</td>
<td>930</td>
</tr>
<tr>
<td>Maximum altitude (m)</td>
<td>1120</td>
<td>1250</td>
<td>950</td>
<td>635</td>
<td>980</td>
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<tr>
<td>Lower reservoir altitude (m)</td>
<td>768</td>
<td>768</td>
<td>756</td>
<td>195</td>
<td>800</td>
</tr>
<tr>
<td>Useful volume (km\textsuperscript{3})</td>
<td>3.72</td>
<td>17.22</td>
<td>5.22</td>
<td>3.12</td>
<td>0.34</td>
</tr>
<tr>
<td>Energetic aspects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall efficiency (%)</td>
<td>90.5</td>
<td>89.22</td>
<td>91.37</td>
<td>78.49</td>
<td>91.86</td>
</tr>
<tr>
<td>Storage capacity (TWh)</td>
<td>3.36</td>
<td>19.83</td>
<td>2.51</td>
<td>3.35</td>
<td>0.141</td>
</tr>
<tr>
<td>ERAm\textsubscript{max} (TWh)</td>
<td>8.959</td>
<td>45.83</td>
<td>7.374</td>
<td>3.950</td>
<td>0.751</td>
</tr>
<tr>
<td>SIN storage ratio (%)</td>
<td>4.25</td>
<td>22.16</td>
<td>3.50</td>
<td>1.88</td>
<td>0.36</td>
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<tr>
<td>6 months generation (GW)</td>
<td>2.05</td>
<td>10.65</td>
<td>1.68</td>
<td>0.90</td>
<td>0.17</td>
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<tr>
<td>Belo Monte distance (km)</td>
<td>2242</td>
<td>2242</td>
<td>1855</td>
<td>966</td>
<td>1821</td>
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<tr>
<td>Environmental aspects</td>
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<td></td>
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</tr>
<tr>
<td>Flooded area (km\textsuperscript{2})</td>
<td>77.88</td>
<td>132.2</td>
<td>228.79</td>
<td>66.00</td>
<td>17.00</td>
</tr>
<tr>
<td>Energy storage required (MWh/m\textsuperscript{2})</td>
<td>0.1150</td>
<td>0.3467</td>
<td>0.0322</td>
<td>0.0598</td>
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<td>Natural reserve</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

![Fig. 6. Pumped-Storage in Cascade diagram (a) before construction (b) after construction. Source: Authors' own material.](image)

Table 2 shows some of the existing conventional dams of the SIN that have the most effective storage reservoirs in Brazil. This is because they are located near the top of the river and thus will store energy to be generated in the whole river. The higher the reservoir above sea level, the bigger its potential to store energy per volume of water (assuming that there are hydroelectric plants following the reservoir’s dam). Comparing the flooded area of Nova Ponte, which is the most effective storage site in the SIN, to the Canastra Sierra EPS scheme at 1250 m, the Canastra site will flood an area 9 times smaller. Comparing the criterion ‘Area/ERAm\textsubscript{max} (MWh/m\textsuperscript{2})’ of the Enhanced-Pumped-Storage reservoirs in Table 1 and the most effective conventional storage reservoirs of the SIN in Table 2, shows that EPS require considerably less area to store energy seasonally.

The new frontier for hydropower development in Brazil, the Amazon region, is flat and it would require a very large flooded area to store energy. For example, if instead of the construction of Belo Monte, the previous project, developed in the seventies, for the development of hydroelectricity in the Xingu River \cite{28} was implemented, it would have flooded an area of 18,300 km² and generated an average generation of 9.5 GW. In this project, the area flooded for storage would be equivalent to 0.0015 MWh/m². This is equivalent to an area 25 times bigger than the flooded area in Nova Ponte (Table 2).

#### 3.2. Storage costs

The estimated costs for Enhanced-Pumped-Storage schemes vary considerably from site to site. This estimate depends principally on the height, length and volume of the dams, the length and diameter of the tubes and penstocks, the turbines and generators, the preparation of the reservoir and the transmission lines required to connect the site to the grid. The cost estimations are higher than conventional pumped-storage schemes because the dams are considerably bigger and the tubes connecting both reservoirs are usually longer. This results in an average cost 2—4 times higher than conventional pumped-storage sites per GW of turbines and generators installed. In other words, if you build a pumped-storage site to store energy during the night and generate 1 GW during the day it will cost around 1 billion dollars per 1 GW. However, if you build an Enhanced-Pumped—Storage site to store energy during 6 wet months and generate electricity during 6 dry months it will cost around 2 billion dollars per 1 GW to compensate the bigger dam and longer tubes. As Enhanced-Pumped-Storage schemes are designed to store energy in a yearly cycle, the storage capacity will be 365 times bigger than conventional pumped storage sites for the same pumping/generation capacity. Thus, the cost of storage per TWh will be 132.5 times smaller than conventional pumped-storage sites.

It was found that the cost of construction of large-scale pumped-storage sites for EPS schemes can be in the range of 0.5—1 B$/TWh or 2—4.2 M$/MW. However, it should be noted that the EPS site would change the flow regime of the river and the other half of the electricity will be generated in already built dams in cascade, so the cost of generation capacity from storage can reduce to 0.25—0.625 B$/TWh or 1—2.5 M$/MW. The reference used to estimate the costs of Enhanced-Pumped-Storage sites were taken from Refs. \cite{29,30}.

It is noted that Enhanced-Pumped-Storage sites have a maximum capacity factor less than 50% as water has to be pumped, before energy can be generated. This is not a problem as water is pumped during the six months of wet season and generated during the other six months of dry season.

The Canastra Sierra EPS scheme at 1250 m, for example, could increase the generation of the Grande and Paraná rivers during the
dry period by around 10 GW. However, this might result in a reduction of generation of around 11.2 GW during the wet period. Out of the 11.2 GW, only around 5.5 GW would need to be installed as most of the electricity would be generated the dams in cascade, which are already built. Thus, the Canastra PS site would therefore be able to resolve the imbalance of generation from the wet period to the dry period in Brazil with half the cost of storing energy with conventional pumped-storage schemes.

### 3.3. Intermittent renewables and peak-load supply

The presence of cascade generation, together with the construction of a pumped storage site will increase the efficiency of storing energy from intermittent renewable with pumped storage from round 75% to around 90%. Having a system to store energy with efficiency around 90% is important for Brazil to balance its seasonal differences in generation. In addition, if more capacity was added to the EPS site to remove the fluctuations of intermittent renewable energy sources, the investment in renewable energy in Brazil would become much more viable.

In order to increase the storage efficiency from intermittent renewable sources, the pumped storage site would have to operate differently to ordinary pumped storage sites, combining the need to store the energy from intermittent sources with the need to store energy from the wet period to the dry period.

For example, during the wet period, without taking into account intermittent renewable sources, there would be a reduction in generation resulted from several EPS schemes equivalent to, for example, 7 GW. However, in order to make use of the excess energy generated from intermittent sources, an additional 10 GW pumping/generation capacity would have to be included, so that a variable amount of energy should be generated or used for pumping, depending on the amount of renewable energy available in the grid. This 17 GW total energy storage capacity would store the same amount of energy equivalent to an EPS scheme with 7 GW operating at full capacity in a yearly cycle. The efficiency of these systems would be around 90%.

During the wet period, if there is low generation from renewables then the EPS sites would pumped around 3 GW of water, which would reduce the overall generation in the system (pump-storage plus dams in cascade) to 7 GW, if there is a high generation from renewables then the pumping will increase to 13 GW of water which will reduce the overall generation to 17 GW. Fig. 7 presents an example of wind generation time series (taken from the UK) and Fig. 8 shows how the EPS schemes could operate in order to remove the intermittence of the wind generation presented in Fig. 7. Similarly, during the dry period, the amount of energy generated will vary with the amount of excess energy from renewables. If there is a low generation from renewables then the EPS scheme would generate 15 GW of energy, if there is high generation from renewables then the EPS scheme could generate as low as 1 GW. For further analysis, Sousa et al. (2014) and Boer et al. (2014) propose methodologies to estimate the impact of the integration of wind energy and PS in electricity prices.

Similarly to intermittent renewables, the capacity of an EPS scheme could be increased to improve peak-load generation. During the wet period, the EPS site would pump more water during the night and would pump less water during peak hours. During the dry period, the EPS site would generate less energy at night and would generate more energy during peak hours.

### 4. Discussion

Apart from increasing the energy storage capacity of Brazil, Enhanced-Pumped-Storage schemes will reduce the amount of transmission lines in the country. With the new dams built in the

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**Table 2**

Effective storage reservoirs in Brazil.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Furnas</th>
<th>Serra do Fácil</th>
<th>Nova Ponte</th>
<th>Três Marias</th>
<th>Bento Munhoz</th>
<th>Serra da Mesa</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical aspects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average height (m)</td>
<td>761.1</td>
<td>747</td>
<td>800.8</td>
<td>563.6</td>
<td>725.2</td>
<td>445.7</td>
</tr>
<tr>
<td>Height variation (m)</td>
<td>18.0</td>
<td>23.5</td>
<td>39.6</td>
<td>23.3</td>
<td>42.0</td>
<td>42.7</td>
</tr>
<tr>
<td>Dam height (m)</td>
<td>127</td>
<td>92</td>
<td>141</td>
<td>75</td>
<td>160</td>
<td>154</td>
</tr>
<tr>
<td>Useful volume (km³)</td>
<td>17.22</td>
<td>5.20</td>
<td>10.38</td>
<td>13.5</td>
<td>5.6</td>
<td>43.25</td>
</tr>
<tr>
<td><strong>Energetic aspects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EERmax (TWh)</td>
<td>25.716</td>
<td>4.827</td>
<td>16.773</td>
<td>11.742</td>
<td>4.406</td>
<td>4.723</td>
</tr>
<tr>
<td>SIN storage ratio (%)</td>
<td>12.24</td>
<td>2.3</td>
<td>7.99</td>
<td>5.59</td>
<td>2.10</td>
<td>2.25</td>
</tr>
<tr>
<td><strong>Environmental aspects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floored area (km²)</td>
<td>1440</td>
<td>219</td>
<td>442</td>
<td>1040</td>
<td>167</td>
<td>1784</td>
</tr>
<tr>
<td>Energy stored seasonally/area required (MWh/m²)</td>
<td>0.0179</td>
<td>0.0220</td>
<td>0.0379</td>
<td>0.0113</td>
<td>0.0264</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

*Source: ONS (National System Operator) (2004).*

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Fig. 7. Example of wind power generation to be stored, taken from England.
Amazon region, there will be the need to build transmission lines to where the energy will be consumed (Southeast region). However, as the EPS site will consume a considerable amount of energy during the wet period, the amount of transmission lines from the EPS site to where the energy is consumed will reduce.

For example, if the Canastra Sierra EPS scheme (1250 m) is built, the transmission line from Belo Monte to the EPS site will require a capacity to transmit 11 GW of energy (equivalent to the maximum electricity generated during the wet period in Belo Monte), however, as some of this energy is stored, the transmission line from the EPS site to the consumption area (e.g. Sao Paulo) would have to be only around 8 GW, which is equal to 11 GW minus the 3 GW pumping capacity in the Canastra 1250 EPS site. In addition, the Canastra EPS site is well located as it is close to the transmission lines sub-stations which connect the North, Northeast and Southeast regions.

Regarding environmental impacts, EPS sites have similar impacts from pumped-storage sites [34] and large reservoir dams [23]. As mentioned previously, EPS sites require a considerably smaller flooded area than conventional Storage Reservoir Dams. However, as EPS sites require a big height difference, it turns out that most appropriate EPS sites are located in environmentally protected areas, such as public forests, ecological reserves, national parks, etc. In addition, EPS schemes would be favourable to the management of water in the watersheds as it would increase the water storage capacity and thus reduce the water wasted during the wet period and increase the water available during the dry period.

5. Conclusion

This paper pointed out some problems in the Brazilian energy sector to store hydroelectric energy from the wet period to the dry period. It showed the need to increase the Brazilian energy storage capacity if the country still wants to generate 80% of its energy from hydropower and it argues that, to increase the energy security in the country, the new storage capacity should be distributed to regions other than the Southeast region, which has around 70% of the Brazilian storage capacity.

The proposed solution to the hydroelectric generation imbalance is to increase the energy storage capacity of the regions other than the Amazon region, so that these regions will generate most of their energy during the dry period in order to complement the increased generation in the Amazon region during the wet period. Four alternatives to increase the storage capacity in watersheds were presented, giving special attention to the Enhanced-Pumped-Storage scheme presented in this article. EPS is the combination of a large-scale pumped-storage site with hydroelectric dams in cascade. They require a considerably smaller flooded area to store the same amount of energy, reduce losses through evaporation, have an overall storage efficiency of 90% in some cases, can be used to store energy from intermittent sources and would greatly increase the storage capacity of Brazil.

Future work will involve a MCDA (Multi-Criteria Decision Analysis) method to compare locations to develop EPS schemes [35,36]. The criteria of comparison will be relative to the storage capacity and will take into account the flooded area; basic cost; cost to increase pumping/generation capacity to remove the intermittence of renewable sources; potential environmental and social impacts; number of people to be displaced; overall storage efficiency; distance from the Amazon to reduce transmission costs; and distribute the Brazilian energy storage capacity to other regions other than the Southeast region to increase energy security. Once the most suitable EPS scheme is selected, a preliminary feasibility analysis and environmental impact assessment will be performed. In addition, this paper did not attempt to predict how much energy storage will be required in the future. For this a detailed study using a program such as NEWAVE [37] would be required and will be part of future work.

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