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Energy Storage Technologies towards Brazilian Electrical System

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Abstract. Energy storage systems (ESS) have been attracted significant attention for improving the reliability of the entire power system (generation, transmission, and distribution), mainly when associated with electric generation from intermittent renewable energies (RE). In particular, ESS combined with RE can provided a set of grid services for future power grid operators, including tension and load level regulation, energy (from peak to off-peak) and contingency reserves management as well as providing power quality and reactive power support. In this work, some those storage technologies are considered for future Brazilian power system, such as (i) pumped hydro storage, (ii) compressed air energy storage, (iii) flywheel, (iv) battery, (v) regenerative fuel cell and (vi) supercapacitor. Hence, this paper presents a detailed conceptual map of EES technologies attractive for application in Brazil, supported by a range of ranking tools (Brazilian entire grid peculiarities, future grid design and ESS already demonstrated on site). The technologies are conceptualized in three large group: unsuitable, possible or suitable, considering its application. Before any deployment, however, there is need for further development and field tests to prove its feasibility and safety at power electrical system level.

Key words: Future Generation, Renewable Energy, Storage Energy, Power Quality.

1. Introduction

In the last five years in Brazil, the electricity consumption has increased at a rate of 1.6% p.a., even with conservative gross domestic product (GDP) growth (only 0.2% p.a. at same period) [1]. Even under the modesty GDP growth, the electricity demand is predicted to increase at 3.7% p.a. by 2026 [2]. To overcome this load-growth expectations, the Energy Research Company of the Ministry of Mines and Energy (MME) estimate that electric energy generation from novel renewable sources (Wind, biomass and solar), which are among the most abundant and potentially readily available to be used in Brazil, must growth at 13.0% p.a. at the same meantime [2].

On the large-scale power generation side, the Brazilian power grid is based on centralized generation by hydraulic power plant (HPP, 60.3 %), which are particularly installed far from away of the main consumption centers. While HPP system concept has demonstrated high reliability level, the grid operations require redundant and longer transmission grid assets. Therefore, the higher increase on demand, the higher capital cost occurs to improve the entire grid asset. Some estimates suggest that national grid infrastructure need increase at around 45% by 2026 to support the forecast demand [2]. Also, the transmission and distribution grid upgrading can be slow and not cost competitive.

As an alternative, the ESS units may potentially improve the economic efficiency of the electricity infrastructure [3, 4] providing value to the grid by entire utilization of the grid assets (optimization of the load factor). In addition, a grid tied established ESS may speed up the adoption of distributed RE along the power system, avoiding intermittence effects [5] as well as quality of the electric energy problems at distribution system level [4]. Taking solar energy and wind power as RE examples, there is an estimate growth from installed capacity of 6.7% (10 GW) to 17.9% (38 GW) by 2026 [2]. Therefore, the use of the decentralized ESS units can provide stability and reliability for future electrical power system in Brazil. Also, a set of grid services for power grid operators can be embedded, including tension and load level regulation, peak to off-peak and contingency reserves management as well as providing power quality and reactive power support [3].

In this context, the main purpose of this research is to analyze the most mature ESS technologies according to the profile of Brazilian electrical power system. A detailed conceptual map was obtained by using a range of ranking qualitative tools. Reliability and feasibility of ESS was main vector as storage technology. Brazilian entire grid peculiarities as well as future grid design combined with ESS were used as parameters.

2. Methodology

The method was based on reliability and feasibility of grid operation, supported by mature ESS technologies available in the market. By this way, qualitative and quantitative bibliographic review was carried out aiming to identify maturity level and feasible of application at short to medium term of the storage technology. Additionally, the ESS state-of-the-art was performed relying on the Brazilian electric sector.

The selection criteria used to recognize the potential application were as follows:

- Applicability and reliability of the ESS: (i) different sites were analyzed by focusing on a real support for the entire power system;
- Retrofit using ESS: (ii) replacements of the current technologies by advanced ESS which can deliver an efficiency, stability and/or power quality;
- Government Agencies and National Regulatory Agents: (iii) Market trends in agreement with the national agents involved, seeking out alignment with the projections and data base of other important agents in the energy sector, such as: National Electric Energy Agency (ANEEL), the Ministry of Mines and Energy (MME), Energy Research Company (EPE), besides as class associations, such as the Brazilian Association for the Storage and Quality of Electric Power (ABRAQUE).
- Government Entities and International Regulatory Agents: (iv) Market trends in accordance with international agents that address direct applications in the Brazilian context.

On basis of the collected data, a correlation matrix as the applicability potential for each ESS was obtained. It should be noted that the studies were restricted on the technical characteristics of the ESS's according to the pertinent needs of the applications, disregarding any type of economic analysis.

3. Energy Storage Systems

As electrical energy is usually converted into other form to be store, one of the most commonly criteria classification is based on the form in which the energy is stored [6-8]. In particular, we can arrange as potential, kinetics and chemical energies. [8-10].

A. Potential and Kinetics Storages

Electrical storage via potential and kinetics energy () can be addressed by pump hydro, compressed air energy storage and flywheel.

1) *Pumped hydro storage* (PHS)

The PHS is the largest and most mature ESS technology available in the market according to the DOE Global Energy Storage Database. Globally, the total installed PHS capacity reaches more than 160 GW (99%). This technology stores energy in the form of potential energy, where water is pumped from a lower reservoir to a higher reservoir. In this type of system, low-cost electric power (off-peak hours) is used to drive the pumps and then raise the water from the lower reservoir to the upper reservoir. Therefore, during periods of high energy demand, the stored water is released and through hydroelectric turbines produces electricity. This technique is currently the most economical means to store large amounts of energy, being quite widespread and commercially available, with powers up to 4,000 MW [9].

In Brazil, there are many places with favorable geographical characteristics to the PHS be installed. As most of these potential plants would be in the South-Southeast regions, near to the centers of large loads, transmission losses would be reduced [11]. It is pointed out that in the Brazil southeastern side; a set of PHS implantation along with higher falls is possible, being relatively economical. There is also the possibility of retrofitting the traditional hydroelectric power plants, thus reusing already built plants [11].

2) *Compressed Air Energy Storage* (CAES)

The general idea is to use low cost electric energy to store compressed air (40-70 bar), which a compressed air is used to generate peak hour electricity through combustion energy generation systems [7]. A typical plant is composed by five elements: (i) a multistage compressor equipped with an intercooler, (ii) a multi-stage gas turbine, (iii) a motor / generator with a clutch, the compressor and turbine at different times, (iv) underground storage for compressed air and (v) other auxiliary and control equipment [12, 13].

There are two types of CAES systems: diabatic and adiabatic. The diabatic cycle (D-CAES) is the only variation commercially implemented so far [7]. In this case, the heat generated during compression is dissipated into the atmosphere, and after the expansion, the compressed air must be reheated, typically with natural gas. In the adiabatic cycle (A-CAES), the heat that is created during compression, is stored and used to heat the air during expansion, reducing the need for fuel consumption

Compressed air can be stored in geological formations, such as salt caves or aquifers, or also in smaller-scale storage cylinders (SS-CAES) [10]. Compressed air energy storage systems with capacities between 50 and 300 MWe can store energy longer than other sources (up to more than one year) due to the small amount of losses involved [9]. Currently, due to the large volume required, storage in large volumes using rock formations is the only economically viable option [14]. However, the CAES installation is also limited by topographic conditions and the differences of the PHS, it was not found in the literature study of potential implantation of CAES in Brazil. As so far the only alternative of commercially implemented CAES is type D-CAES, will be the only one considered in this article.

3) *Flywheel* (FES)

It is a type of storage in the kinetic energy form, composed basically of 5 main elements (Fig. 1): (i) bearings, (ii) reversible electric generator / motor, (iii) inertia flywheel, (iv) and (v) a vacuum chamber. FESs store energy in rotating disks as kinetic energy. To "charge" this device, the power is used to starting the motor that turns the disk and the disk keeps turning until the power is needed. At that point, the disk can rotate a generator, which produces electricity. The speed of the flywheel increase during charging (adding energy) and decrease during discharge (loss of energy).

The main operational characteristic of ESS is that they are extremely fast in response time and high efficiency for short storage durations, with disadvantages being the high self-discharge rate due to friction losses. Most flywheels are designed to provide high output power for short periods, on the order of 5 to 50 seconds [9, 15].

The FES does not depend on geographical conditions and is modular and can be installed according to the energy needs of the application. FES's are marketed in the power range from 100 to 300kW. Therefore it has a high potential of application while scalability and availability [7].

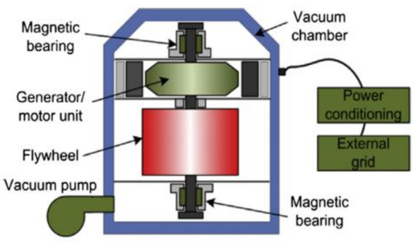

Fig. 1. Basic scheme of the FES [7].

B. Chemical Storage

Electrochemical systems, such as battery and regenerative fuel cells, can efficiently store electricity in the chemical form. Reversibly, the chemical energy can be release into electric energy on demand.

A battery is basically consists by two (or more) connected electrochemical cells (serial and/or parallel). The electrochemical cells are composed by two electrodes (anode and cathode) into an electrolyte, which are electrically insulated by a separator that acts as selective ions-exchange. In general, batteries are fast-responding time and can be modular,[8] widening the range of applicability for power grid support. These electrochemical systems exhibit relatively low self-discharge losses and high faradaic efficiency. Due to the favorable deliverable of power and higher energy densities, the use of batteries as ESS is attractive. However, disposal and/or recycling of their materials at the end of life are still drawbacks to be overcome.

Taking in account many available chemical elements to acts as electrode, along with different electrolytes and/or separators, a wide range of battery technology is provided. In particular, lead acid (LA), lithium ion (Li-ion), nickel metal (nickel metal hydride - NiMH or nickel-cadmium - NiCd), sodium-sulfur (NaS), sodium-nickel chloride ($Na-NiCl_2$) and redox flow battery (RFB) can be addressed as potential stationary batteries for electrical power grid applications. According to the DOE Global Energy Storage Database, for example, the currently worldwide battery ESS pilot-projects are estimated to be about 841 with an installed capacity of 2.10 GW. Approximately, 82.7% of current projects are under operation (1.64 GW), 1.2% under construction (0.07 GW) and the remaining 16.1% were already announced (0.4 GW). From these projects, LA, Li-ion, NaS, $NaNiCl_2$ and RFB batteries are founded as dominant technologies. Therefore, herein the battery ESS technologies already applied (under operations) in the electrical power grid, i.e., presents a maturity on operative system, are considered for the present analysis.

LA type batteries are low cost and the most common in the Brazilian domestic market. However, most of them are not specifically developed for stationary storage applications. LA batteries have short cycle life (deep cycles) and high maintenance needs, which made its life-cycle cost impracticable for large-scale storage applications. Alternatively, lead-carbon battery, which is a LA battery combined with carbon supercapacitors, may be a promise option for improving the cycle life. On other hand, the capital costs per cycle of lead-carbon battery may be abruptly increased, because a battery management system should be needed. Another mature technology is nickel-based battery (NiMH and NiCd). However, these batteries have low efficiency (<70%, round-trip efficiency). In particular, NiCd batteries depend heavily on the depth of discharge - which significantly reduces the life-cycle. Also, inherent issues to the environment, by using cadmium into its composition, are difficulties to wide applications.[8]. Thus, nickel-based batteries are preferably applied as an uninterruptible power supply for machines and equipment connected to the EPS.

Although developed for applications in small portable systems and recently for electric vehicles, Li ion batteries are of paramount interest because of highest power technology, which can be used potentially for frequency regulation. However, the short discharge times (~ 4h) and an abrupt decrease on life-cycles at temperatures above 35 °C are still the main drawbacks for this technology, mainly when the focus is higher energy density to be employed in isolated tropical regions.

Another interesting type is the high energy density batteries, such as NaS and $Na-NiCl_2$. These batteries show the largest discharge times (~ 8h) and can be an economical solution for power quality improvements (voltage regulation and peak load reduction). However, as electrochemical cells are internally operate at high temperatures (250 - 330 °C) applications where the intermittent are frequently will impact on overall efficiency [10].

Finally, redox flow batteries can be an attractive choice due to the flexibility of increasing the storage capacity. Briefly, two external tanks contain active chemical species for chemical storage (Fig. 2). Thus, the energy capacity can be improved either by increasing the volume of the tank or by increasing the concentration of electrolyte [16]. Vanadium redox (VRB), polysulfide-bromide (PSB) and zinc-bromine (ZnBr) are types of flow battery. However, inherent issues to the environmental impacts due to the electrolyte toxic are still worries for large applications.

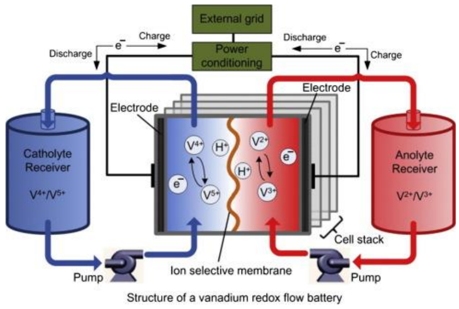

Fig. 2. Schematic diagram of a flow battery [4].

In addition to batteries, chemical storage can be made by means of molecules such as hydrogen, methanol, ethanol, etc. For example, hydrogen can be obtained through the electrolysis of water and subsequently converted into electrical energy through regenerative fuel cells (RFC). Briefly, from a practical point of view, electrolysis consumes off-peak electricity to produce hydrogen, and the fuel cell uses that hydrogen, along with oxygen from the air, to generate electricity when needed. A schematic of regenerative fuel cell is shown in Fig. 3.

There are different types of RFCs, which is classified by the type of electrolyte, as well as operating temperature [7]. The RFC can addressed as alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). The present study will consider only regenerative PEMFC system, because it presents good technological maturity.

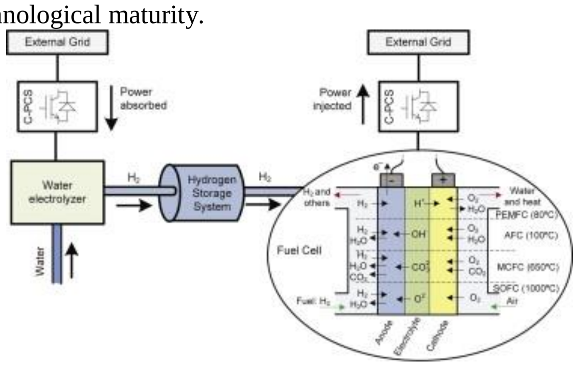

Fig. 3. Regenerative fuel cell topology [16].

C. Electrical Storage

For electrical storage, supercapacitors (SC) and superconducting magnetic energy storage (SMES) are considered. Supercapacitors, so-called as double-layer capacitors [9, 10], are electrochemical cells which the electrical charge is stored at the solid-liquid interface (electric double layer region) without electrochemical reaction. This system provide fast-responding time, shortly charge or discharge time and longer life-cycle [15]. SMES stores energy employing superconducting material by cooling the superconductor coil below the critical temperature, where a negligible resistance takes place. The SMES may be considered similar to capacitors by a fast-responding time on demand, but is limited by the energy storage capacity. This also restricted SMES to "power" applications with extremely low discharged times. However, the superconducting coil is very sensitive to temperature changes and because of this; operational reliability is crucially dependent on the refrigeration system.

Until now, several demonstration projects have been deployed, but few SMES with small capacity are commercially available [8]. Thus, SMES is not considered for the present analysis.

D. A Summary of Selected Technologies

Throughout the generated performance parameters for feasible stationary storage applications, the Table I reveal these information/parameters for the selected technologies.

Table I - Selected ESS by different parameters [9, 13]

Technologies		Capacity [MWh]	Power [MW]	Discharge time	Response time
Mechanical	PHE	<14000	50-4000	hrs-weeks	s ~ min
	D-CAES	<2700	50-300	1-24 hrs	<15min
	FES	<10	<20	1s-15 min	<10 ms
Chemical	Lead-acid	0.25-50	<20	<4h	ms
	Lithium-ion	0.25-50	<50	<1 h	ms
	NaS	<245	<80	<8h	ms
	Na-NiCl2	<75	<50	<8h	ms
	VRB	<250	0.5-40	<10 h	<10 min
	PEM	0.3-5	<50	s-days	s
Electrical	SC	0.1-0.5	<1	1 ms-1 h	<10 ms

4. State-of-Art for ESS in Brazil

Several studies have been published that estimate the energy storage potential based on technical characteristics in several applications and highlight the role of ESSs in modern electrical networks [3, 7, 9].

The services provided by the ESS may be at the level of generation, transmission and distribution systems, as well as at the level of the consumer [3, 17].

In the case of transmission or distribution, the ESS application can postpone or even reducing the investments in expansion of the infrastructure or upgrade, as well as providing voltage support [3].

Renewable energy systems, such as wind or solar, can be integrated into the electricity grid supported by ESS, reducing the issues related to the intermittent power injection [17].

The storage of energy can also aid or support in the improvement of energy quality and the reliability of the electric network [3]. In Table II are presented some applications, divided in groups, and their respective characteristics.

Specifically, in the Brazilian context, based on the collection of information bibliographic carried out, a series of services were identified that the ESS can provide, being the applications identified were:

- Peak load reduction and energy arbitrage;
- Ancillary service, such spinning reserve, frequency regulation, voltage support;
- Continuous supply in isolated systems;
- Alternative energy integration;
- Support for DG integration;
- Assistance to the fleet of electric cars.

Table II – Characteristics of ESS applications [3, 4, 9]

Applications		Rated power [MW]	Duration	Response	Cycle/yr
Bulk energy	Electrical energytime-shift	0.1-500	2 –6h	ms–min	300-400
	Power supply capacity	1 -500	2 –6h	min	50-365
Ancillary Services	Load following	1 -100	15 m -1h	~ 1s	250-10000
	Regulation	10 -40	sec -hrs	~ 1s	250-10000
	Frequency response	10 -40	2 min-1h	ms	1000-10000
	Reserve	10 -100	min-h	ms	10-1000
	Voltage support	1 –10 MVAr	min–1 h	s	N/A
	Black start	5 -50	sec -hrs	min	10-20
Transmission infrastructure	Upgrade deferral	10 -100	1 -8 h	sec	10-50
Distribution infrastructure	Upgrade deferral	0.4 -10	1 -4 h	sec	50-365
Customer energy management service	Power quality	0.1 -10	ms-15min	ms	100-10000
	Power reliability	0.05 –10	1 -8 h	ms	<10
	Retail electricity time-shift	0.001 -1	1 -6 h	ms	50-250
	Demand charge management	0.05 -10	1 -4 h	sec	50-500
Renewables integration	Smoothing output	0.1-500	15min-6 h	ms-s	250-10000

For peak load reduction, Hong & Radcliffe [17] estimated based on the difference between the highest and lowest point of the EPS load curve, that it would be necessary to inject between 5 and 10 GW of energy storage over eight hours. As a result, ESS can be used to reduce the daily peak of electricity or the generation of seasonal electricity.

On ancillary service, Hong & Radcliffe [17] assumes that 5% of the reserve margin in relation to the average load is required for the Brazilian grid. Then approximately 8.5 GW in ESS can be used for ancillary service. However, due to the high participation of hydroelectric energy in Brazil, it is probable that energy storage has a more limited role in this type of application [17].

Relative to the use of the so-called alternative energies, specifically solar and wind, Brazil has very promising future prospects in terms of installed capacity. Presently, installed capacity for wind power is 11,513 MW, with expansion of 6,243 MW in the coming years (projects under construction + under construction not started) [18].

The cause of it, another immediate application for energy storage would be its joint use of wind farms in the Brazilian northeast (region with the highest concentration of wind farms). When the winds stop abruptly, which are not uncommon, complex and difficult maneuvers must be completed in a few minutes so that volume of power is replaced by other generating source, often located thousands of miles distance. A study carried out by EPE on wind generation in the northeast shows that due to the high frequency of occurrence and the duration of the calms, it is evident the need of a complementary source of generation to guarantee the demand of energy [19].

According to EPE, an auxiliary power source with a power of 2,345 MW and a 1,510 GWh accumulation capacity would be able to maintain constant a power supply equal to the average produced by all wind farms of 2015 [19]. Based on this result and the rapid expansion of wind power generation, it could be estimated that a 2 to 3 times greater ESS capacity would be required over the next 10 years.

With respect to DG, it is observed that the solar photovoltaic source represents 99% of the installations, followed by the wind source [20]. The increase in the number of consumer units, residential and commercial, with photovoltaic panels started in 2014 with growth rates between 200% and 300% p.a., reaching a total of 8,818 units and 67 MWp of installed capacity by February 2017 [21].

According to Nacimento, 886,700 consumers units powered by photovoltaic systems will be reached by 2024, which 808,300 are residential units and 78,400 commercial units, totaling an installed power of 3.2 GW [20]. Increased distributed generation will afford opportunities for energy storage deployment.

On the other hand, Brazil currently accounts for approximately 0.4% of its non-universalized potential customers market, with a base of about 63 million low-voltage customers, representing approximately 252,000 customers without access to the grid. The vast majority of them are in the isolated system in the north of the country [22]. The association of solar or wind generation with energy storage technologies can can reduce the very high costs of used diesel generators used to meet this type of customer, as well as reduce practically to zero the environmental impacts [23].

According to Bueno & Brandão, they estimate that a storage capacity of 4,600 MWh would be required, considering 48-hour autonomy, to serve customers in remote or isolated locations [22]. In economic terms, the use of ESS can represent a savings of around US$ 2 billion per year, related to fuel and transportation costs in regions that are difficult to access [23].

In the transport sector, the greatest use of ESS can come from the electric car side [22]. Today, Brazil has just over 3,500 hybrid and electric vehicles. , EPE projects that the electric car fleet it will reach 360,000 units, with a 2.5% share in 2026 [2]. It is emphasized that, only hybrid vehicles are considered, and they are assumed as flexfuel hybrids as of 2021.

5. Results and Discussion

The choice of energy storage technology depends directly on the application where will be employed. In order to choose the correct technology, it is necessary to distinguish the four parameters that characterize a technology: (i) power, (ii) energy, (iii) discharge time and (iv) response time [8]. These parameters, which were presented in Table I, should be compatible with the application requirements for which it will be used (Table II). It is showed in Fig. 4 this relation. For purposes of comparison, the characteristics of the selected ESS technologies and their possible applications in term of rated system power and discharge time are also included.

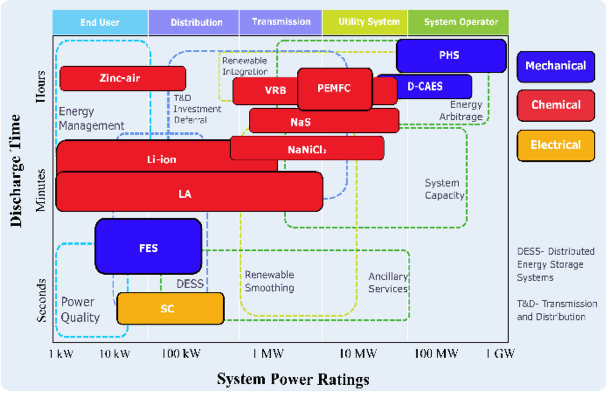

Fig. 4. Comparison between selected ESS technologies (own authorship)

Considering the contents of Tab. I and II, and based on [3, 8], a Tab. III was developed by relating the available energy storage technologies and their application in the Brazilian EPS.

The mechanical energy storage techniques, such as CAES and PHS, can allow the storage of energy at a large level of capacity (Tab. I), being suitable for bulk energy application and frequency regulation [9]. In [3, 9, 10], the PHS technology is classified as suitable for integration of alternative energy, but in the specific case of Brazil, the geographic regions propitious [11] for the PHS installation are far from away of most wind or photovoltaic parks. In this way, it would be inefficient, due to the long distance between the ESS and the application, for using the PHS on this type of application. Therefore, PHS was classified as "possible".

The SC and FES techniques, due to be based on shorter discharge times and higher power, can be used manly as emergency devices or applications for faster time responses [7]. On the other hand, batteries can be modular, easy scalable and used in many different applications [9]. According to the Table III, battery power storage can be applied into the entire system from ancillary services to support a smart network at level of generation, transmission, and distribution. In accordance with the time of response and the power capacity, most of batteries can be used to integrate RE. In particular, slow response time may limit the use of VRB batteries. However, the reduced discharge time limits the use of lead-acid batteries for applications that require high energy capacity [8].

Even though ancillary services are considered as possible for ESS application in the Brazilian electric sector, it is worth to note that there are no mechanisms in the Brazilian regulation for the remuneration of these services. There is also no provision in the regulation for passing on the costs of these services to the tariffs [22]. The poor market structure is one of the major obstacles to the development of energy storage in Brazil [24].

Table III -ESS technologies and their applicability in the Brazilian electric sector.

		Mechanical			Chemical						Elec.
Applications	**Example**	PHE	D-CAES	FES	LA	Li-ion	NaS	Na-NiCl₂	PEM	VRB	SC
Bulk Energy	Arbitrage	Green	Yellow	Red	Red	Red	Red	Red	Red	Red	Red
	Peak shaving	Green	Yellow	Red	Red	Red	Yellow	Yellow	Red	Yellow	Red
AncillaryService	Voltage Support	Red	Red	Green	Green	Green	Green	Green	Yellow	Yellow	Green
	Frequency regulation	Yellow	Green	Yellow	Green	Green	Green	Green	Yellow	Yellow	Red
	Exchange control	Yellow	Yellow	Red	Red	Yellow	Green	Green	Yellow	Green	Red
	Spinning Reserve	Red	Green	Yellow	Yellow	Red	Yellow	Yellow	Red	Red	Red
	Load following	Red	Yellow	Green	Green	Yellow	Green	Green	Green	Green	Red
Integration of RES (intermittent generation)	Wind generation in northeast of Brazil.	Yellow	Yellow	Yellow	Red	Green	Green	Green	Yellow	Green	Green
	Photovoltaic parks in the center and northeast	Yellow	Yellow	Red	Red	Green	Yellow	Green	Red	Green	Red
Distribution Network	Support for intelligent network integration and distributed generation.	Red	Red	Red	Yellow	Green	Green	Green	Yellow	Yellow	Red
	Detection of defects and supplies of priority loads.	Yellow	Yellow	Green	Yellow	Green	Green	Yellow	Yellow	Yellow	Red
	Unbalanced phase compensation	Red	Red	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Green
Island Systems	Continuous supply of energy in isolated systems in the north of Brazil.	Red	Red	Red	Red	Green	Green	Green	Green	Yellow	Red
Transport	Electric vehicles	Red	Red	Red	Green	Green	Red	Yellow	Yellow	Red	Yellow
Applicability		Red: Unsuitable (null)			Yellow: Possible (Low)				Green: Suitable (High)		

6. Conclusions

This research had as objective to map the main niches of application of ESS in the Brazilian electrical system and consequently also for automotive use.

Although there are benefits brought by energy storage, it is still an incipient technology with limited use in Brazil. Therefore, it was difficult to find studies and researches that cover applications in the Brazilian scenario.

However, due to the variation in generation and the need to balance power and regulate voltage and frequency, the use of energy storage systems is inevitable in the modern network.

For that reason, the results brought by the present work, although they come from a simple analysis, mark the guideline to be taken by governmental organs and regulatory agents referring to ESS its applications.

The present study found that technologies such as batteries, PHS, D-CAES, FES were the ones that present the best applicability to meet emerging Brazilian needs and are expected to be the most prominent at the national level. Supercapacitors have a limited number of potential applications, only on transient issues, such as improving energy quality. The PHS and D-CAES technologies have great potential in application that requires high energy such as arbitrage. Particularly, relative the integration of wind farms and solar power plants, battery storage is the most appropriate because it has the required power and energy density, as well as the appropriate response time. For isolated systems, the association of solar generation with Li-ion batteries and $Na\text{-}NiCl_2$can be a solution to reduce the operating costs of diesel generators used today.

It should also be noted that the analysis presented was performed only from the technical point of view and can be used for future work that consider economic factors in the choice of a technology.

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