On Storage Technologies from the Perspective of Ancillary Services for Power Systems ⋆

Thais Rosa Rey * **Eduardo Lorenzetti Pellini** **
Eduardo C. Marques da Costa ***

* *Departamento de Engenharia de Energia e Automação Elétricas, Escola Politécnica da Universidade de São Paulo (USP), SP, (e-mail: thaisrrey@gmail.com).*
** *Departamento de Engenharia de Energia e Automação Elétricas, LPROT - Laboratório de Pesquisa em Proteção e Automação de Sistemas Elétricos, Escola Politécnica da Universidade de São Paulo (USP), SP, (e-mail: elpellini@usp.br)*
*** *Departamento de Engenharia de Sistemas Eletrônicos, LPS - Laboratório de Processamento de Sinais, Escola Politécnica da Universidade de São Paulo (USP), SP, (e-mail: educosta@usp.br)*

Abstract: This article presents an overview of the deployment of intermittent renewable energies. It shows the importance of planning the grid according to the energy storage capacity, frequency control, and other factors to which this type of solution contributes. This kind of planning prepares the system predicting solutions to provide required ancillary services for power systems. A state-of-the-art review is carried out on storage technologies applied to the optimization of power transmission systems, management of resources, power dispatch, resources integration management, and various other applications.

Keywords: Energy storage, ancillary services, power systems, optimization.

1. INTRODUCTION

Nowadays, it is increasingly difficult to carry out the activity of generating and supplying energy so that these two elements are balanced and still reduce the usage of pollutant resources. The demand for energy by consumers in a period of day, month or even year, is not exactly the same as it is generated by clean sources, which have a limited generation capacity, forcing the use of thermal power plants, which are more polluting, expensive and inefficient. The advent of new technologies, such as solar and wind generation, brought more challenges to maintain the balance between generation and consumption, since these types of generation are intermittent, i.e. dependent on the availability of renewable power resources, such as solar radiation and wind, which are somewhat unpredictable.

The stability and control of power systems with high permeability of distributed generation have been widely studied through the last decade, in which concerns the voltage instability resulted from intermittent energy sources and unpredictable load profiles (e.g. increasing number of electric vehicles). In this sense, several researches have been published on energy storage and new technologies for provision of ancillary services in power systems.

In this sense, the energy storage capacity in the world has doubled since 2017, increasing 3,3 GW in 2018 (1). According to recent forecasts, energy storage tends to increase even more through 2030, with installed power storage of 250 GW (2).

Furthermore, due to policies to support the development of storage technologies, this market is not only increasing, it is becoming less expensive and therefore more viable and flexible in the context of the distributed generation. In addition, according to reports from the World Energy Council, in 2016, there is a downward trend in the cost of energy storage systems at an annual rate of 8% per year on the horizon of 2030 (3).

This article proposes a technical survey on the state of the art of new storage technologies from the perspective of ancillary services applied to power systems, taken into account the increasing permeability of renewable energy sources and distributed generation. The manuscript is structured into five sections, in which section II introduces the definition of ancillary systems. Section III describes the main technologies of energy storage in power systems, section IV proposes a technical and economic discussion of the technologies presented in III *a priori*, and some conclusions on the applicability of such technologies are listed in section V.

2. DEFINITIONS OF ANCILLARY SYSTEMS

From the technical literature, ancillary services are defined as follows (4):

- primary frequency control;
- secondary frequency control;
- voltage control (primary or secondary);

⋆ T. R. Rey, E. L. Pellini and E. C. M. Costa are with POLI-USP - Polytechnic School of the University of São Paulo, SP, Brazil. e-mail: thaisrrey@gmail.com

- power reserve for primary control;
- power reserve for secondary control;
- standby reservation;
- reactive support;
- self-recovery (black start); and
- special protection systems (SPS, or SEP according to (4) Brazilian definition).

The analyses throughout the paper are mainly based on technical and economical issues on frequency and voltage stability, and mainly active power storage. Although the scope of the manuscript is to present some state-of-the-art information, an additional and enriching discussion is promoted about these main technologies on ancillary systems.

3. ELECTRIC ENERGY STORAGE PRINCIPLES

This section discusses the existing technologies for energy storage for electrical power systems. In addition, its basic operating concepts, assemblies and some details about each solution are presented.

3.1 Eletrochemical storage: Batteries and super-capacitors

Electrical energy can be stored electrochemically in batteries and capacitors. Batteries could be separated in two groups: flow batteries and secondary batteries (5), each one with a wide variety of electrolyte types and arrangements. Capacitors can be classified as electrostatic capacitors, electrolytic capacitors, and electrochemical capacitors (the last one also called as super-capacitors or ultra-capacitors) (6). Such technologies are described in more details in Fig. 1.

(1) *Secondary Batteries*: these are the well-known conventional batteries commercially available. These batteries basically work with an anode, where chemical components oxidation occurs, and reduction process in the cathodes. Such chemical components compose 6 types of batteries (Lead acid battery, nickel cadmium and nickel metal hybrid battery, lithium ion battery, metal air battery, sodium sulphur battery, as showed in Figure 1, and sodium nickel chloride battery), though electrolytes and battery components are constantly being updated, or even including new technologies (6). This technology is very mature, and the main challenge related with this kind of technology in power system is the arrangements to generate major installed capabilities. This is due to the complexity of installing storage systems along with the electrical system in operation and also because of the size and aggressive cycles imposed by the large dimensions of the system, it is very difficult to operate the storage. According to the technical literature, the larger the size of this type of system, the more difficult it is to identify the charge state (SoC) and health state (SoH) of the battery by conventional methods. This difficulty makes battery monitoring programs have a very complex management software for real-time assessment (7), as shown in figure 2.

(2) *Flow Batteries*: it is also a type of rechargeable batteries, but the energy is stored in one or more electroactive species which are dissolved in liquid electrolytes.

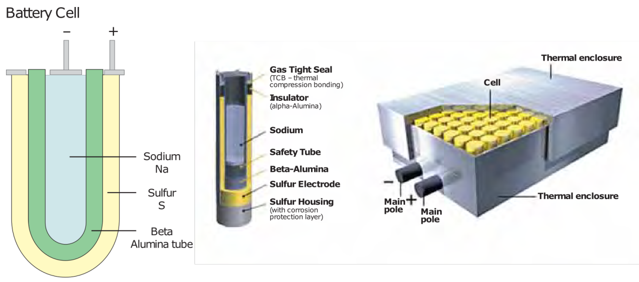

Figure 1. Construction principle of the Sodium/Sulfur battery(5).

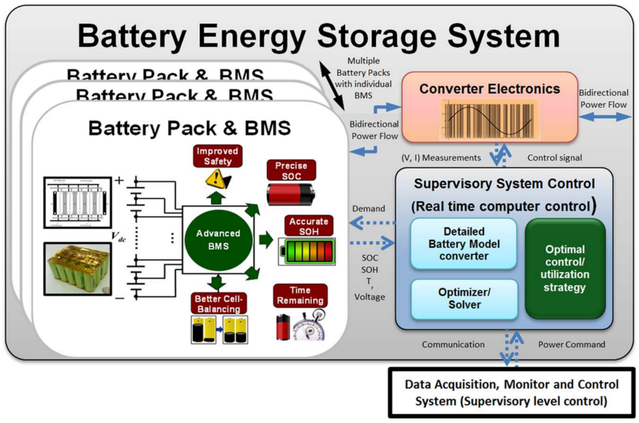

Figure 2. BESS and BMS arrangement to larger size battery storage (7).

The electrolytes liquids are stored externally in tanks and pumped through the electrochemical cell, which converts chemical energy directly to electricity (discharge process), or use electricity to stimulate cell reverse reactions to generate electrolyte liquids again (charge process). This type of batteries can be classified as Redox flow battery (RFB), as figure 3, and Hybrid flow battery (HFB). The difference between both is where the masses of electrolyte are. In the RFB case, both electrolytes are in external tanks, and in HFB, one of the active masses is internally stored within the electrochemical cell, whereas the other remains in the liquid electrolyte and is stored externally in a tank (5).

(3) *Electrostatic capacitors*: consist of two identical and parallel metal plates, separated by a dielectric material (mica, glass, ceramic, polyester, polyethylene or paper). Upon applying a voltage across the capacitor's terminals, the plates accumulate electrical charges of opposite signs, which use a solid dielectric material to accumulate energy.

(4) *Electrolytic capacitors*: accumulate charges on two electrodes separated by a solid dielectric. The big difference is in the fact that the cathode of the electrolytic capacitor is a liquid electrolytic solution (electrolyte), and the anode is a metallic plate with a thin layer of aluminum oxide, which is an electrical insulator (dielectric). The electrolyte in contact with an aluminum foil does not oxidize.

(5) *Electrochemical capacitors*: combines the functioning of normal capacitors with an ordinary battery. Instead of using a conventional dielectric, capacitors use

ISSN: 2525-8311

DOI: 10.20906/CBA2022/3497

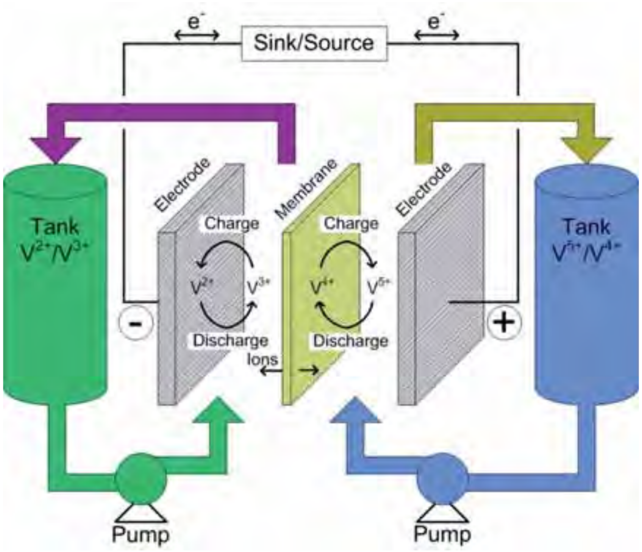

Figure 3. Construction principle of the redox Vanadium battery(5).

two mechanisms to store electrical energy: double-layer capacitance and pseudo capacitance. Double-layer capacitance has electrostatic characteristics, while pseudo capacitance is electrochemical. The construction of super-capacitors is similar to electrolytic capacitors, both consisting of two sheet electrodes, an electrolyte and a sheet separator. The separator is located between the electrodes and the sheet, and rolled or folded into a shape, usually cylindrical or rectangular. This folded form is placed in a casing, impregnated with electrolyte and hermetically sealed. The electrolyte used in the construction of super-capacitors, as well as the electrodes, are different from those employed in common electrolytic capacitors. To store electrical charge, a super capacitor uses porous material as separator to store ions in these pores at the atomic level. The material most commonly used in modern super-capacitors is activated carbon.

3.2 Compressed Air

This type of energy storage has been used since the 19th century. It consists of using energy to compress air in compartments (usually underground) and pipes, storing it at high pressure, and then mixing it with natural gas to burn and expand it in a modified gas turbine. Despite being able to store large amounts of energy, the air compression system is usually inefficient (about 50% in adiabatic systems), thus being unattractive for large storage (5). Furthermore, depending on the type of gas it is mixed with, there can be serious environmental damage or risk of explosions.

3.3 Flywheel systems

Flywheel energy storage, also known as kinetic energy storage, is a form of mechanical energy storage. In flywheels, kinetic energy is transferred in and out of the flywheel with an electric machine acting as a motor or generator, depending on the charge/discharge mode (6). The kinetic energy can be provided by mass transportation systems

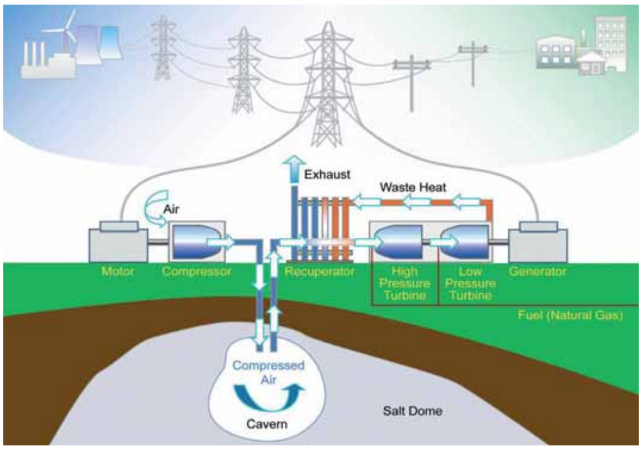

Figure 4. Diagram of operation of compressed air storage plant(5).

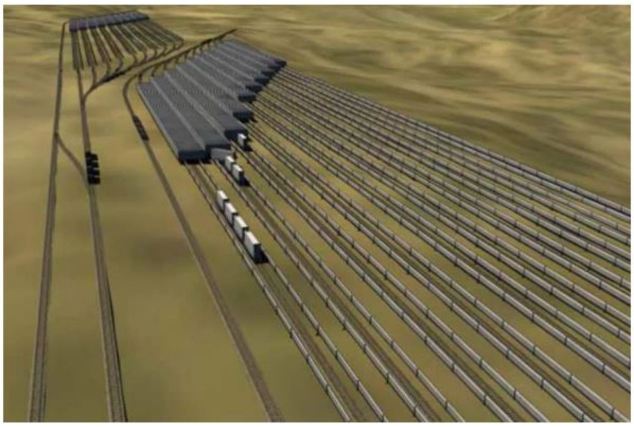

Figure 5. ARES project in California(8).

like The Car Systems Tested in California (figure 5) (8) or the system project using steel cables to lift concrete blocks weighing from 30 up to 35 tons in Rio Grande do Norte, Brazil (9).

3.4 Pumped Storage Power Plants

Conventional pumped hydro storage systems use two water reservoirs, at different elevations, to pump water during off-peak hours from the lower to the upper reservoir (charging) or, when required, to flow back water from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging) (5), as can be seen in Figure 6.

Pumped Storage power plants can have pumps and turbines in the same machine, or separated machines, as well as generators and motors. The choices associated with horizontal or vertical configuration, the size of the reservoir and the type of generating/pumping speed (fixed or variable) influence the overall efficiency of the system.

If we analyse pumped storage power plants only considering efficiency, it is possible to conclude that the maximum installed and more efficient pumped storage power plants are that ones that uses vertical configurations with variable velocity, controlled by electronic converters either in double excited machines or full power converters.

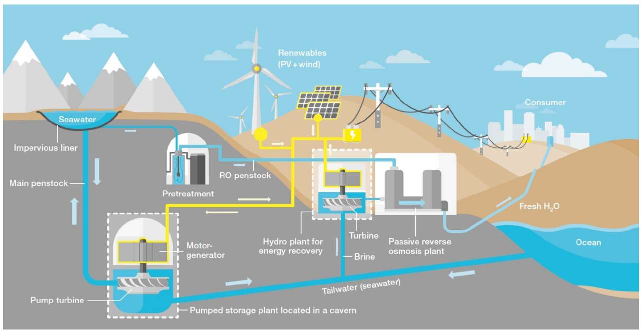

Figure 6. Diagram of operation of compressed air storage plant(5).

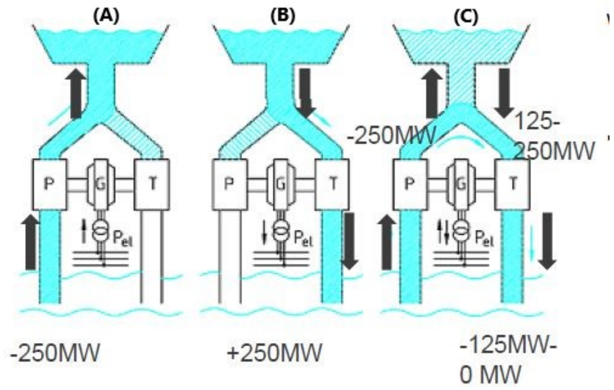

Figure 7. Hydraulic short-circuit (10).

- Hydraulic short-circuit
  Thinking about improving the efficiency of variable speed machines, a specific type of operation for the topology of hydro mechanical components has been used recently in some pumped storage power plants. This operation is known as hydraulic short circuit, which, within the possible operations of pumped storage power plants, optimizes the response time of the machines in the transition of operating state between turbine and pumping and also the reverse path. For this type of operation to be possible, the hydraulic machines, turbine, and pump must be separated.
  The hydraulic short circuit works in the following way: he turbine and the pump work continuously so that both are equal in the transfer of power to the grid, that is, the incoming power is equal to the outgoing one and there is no exchange of water between the lower and upper reservoirs (part (C) of the figure 7). For generation to occur, the water flow is increased in the turbine, with water exchange between the reservoirs and supply of active power to the grid (part (B) of the figure 7). Pumping takes place when the water flow is increased in the pump, causing active power absorption by the machine of grid (part (A) of the figure 7).

4. TECHNICAL AND ECONOMIC COMPARISON

In view of the main characteristics of each technology described previously, we can analyze the economic and technical differences between storage solutions. Such comparison allows us an appropriate evaluation of each solution based on advantages and restrictions for each case.

Table 1. Comparison data between solution - Power density and installed capability.

Technology	Range of Absolute capability (installed)	Range of energy density
Secondary Batteries	100MW (12), South Australia's	20-750 kWh/m^3 (6)
Flow Batteries	-	16-70 kWh/m^3 (6)
Capacitor/ SuperCapacitors	1000F, Sunvault	1-35kWh/m^3 (6)
Compressed air	110MW, Alabama-EUA	0.8-20 kWh/m^3 (6)
Flywheel systems	20MW, Stephentown, Nova York	0.3-400 kWh/m^3 \cite{ref6}
Pumped Storage	3000 MW (installed) (10)	0.2-1.5 kWh/m^3 (6)

Here, storage technologies will be compared based in three characteristics, which are described as follows.

4.1 Capacity: Power reserve control

For storage technologies, the capacity can be measured in two different ways: using the absolute values of capacity or the energy density. When the capacity is analyzed from the perspective of absolute values, it is possible to verify the order of magnitude that the solution provides for the analyzed application, in some scenarios. However, when the capacity is analyzed from the perspective of energy density, the relationship is given between the absolute storage capacity with the proportions of the solutions, such as volume or weight.

In matter of absolute capacity, the storage system of flywheel, compressed air and pumped storage power plants have advantage when compared to other technologies (6). These type of technologies can easily surpass the maximum values of 100 MW of power of the largest battery storage park in the world today (12).

Nevertheless, if the analysis is shifted to the perspective of power density, super-capacitors and some types of batteries are have superior benefits(6). This indicates that even nowadays these kinds of technologies are not able to overtake others in a matter of absolute capacity. High energy density solutions may be better options in the future if they achieve higher absolute capacity, because such solutions can store the same value of energy using less volume and weight (6), which means less material and space to provide storage solutions, reflecting in parameters like cost and adaptability of storage plants. All this information can be better analysed in table 1.

Analyzing those attributes, it is possible to classify the storage technologies according to their discharge time and their capacity, as showed in figure 8. Depending on the system power ratings, to offer better implementations and services to the Grid, the National Hydropower Associantion (NHA) (11), recommend a specific storage solution. For example, the pumped hydro (PSH) is used normally to bulk power management while the NiCd batteries are used as UPS Power Quality.

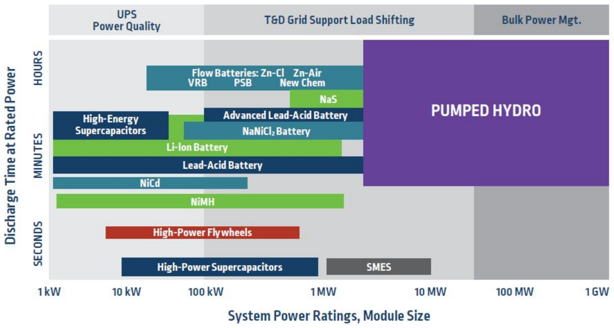

Figure 8. Various capabilities of different energy storage technologies, from the Energy Storage Association (ESA).(11).

4.2 Frequency and voltage control

Normally technologies such as pumped hydro, flywheel and compressed air, have a technical maturity higher than other technologies. This technologies can provide frequency, voltage and active power control due to the electromechanical nature, which provides rotating reserve to the system, and voltage and frequency reference levels to be followed by the electronic regulators connected to the grid (13).

However, power electronics have been developed because of the high penetration of intermittent sources in the grids. With the new features of the regulators and governors in this kind of plant, which could be applied in batteries an capacitors storage plants, these plants do not depend on rotating reserve an voltage and frequency reference level of electromechanical power or storage plants. That means plants controlled with power electronics will be able to provide ancillary services and also help in the system stability.

4.3 Efficiency, lifetime and costs

To compare technologies from the perspective of ancillary services, it is important to analyse three aspects: efficiency, lifetime and costs; since such aspects, together with the characteristics previously described, will define the more adequate solution for each case.

Looking only towards efficiency, super-capacitors and some kinds of batteries (like NaS and HFB batteries) have a cycle efficiency superior to 90% comparing to 85% of pumped hydro and 75% of compressed air (6). However, if the efficiency is compared to the lifetime pumped hydro, compressed air and even flywheel technologies have more cycles than batteries and super-capacitors. Furthermore, it is important to mention the maintenance of these plants, which would extend the operating cycles, although batteries and super-capacitors require more maintenance, which increases the operating cost.

In terms of cost, eletromechanical technologies have a higher CAPEX than other technologies, even though nowadays when batteries and super-capacitor technologies have been increasingly used. Even if these plants OPEX are analyzed separately, these kinds of technologies are still very expensive. However, if the OPEX ($/kW or $/kWh) is analyzed together with plants maintenance and lifetime, the eletromechanical technologies become more attractive (6). All this information can be better analysed in table 2.

Table 2. Comparison data between solution - Comparison data between solution - Capital investment and efficiency.

Technology	**Average of Capital (energy based)**	**Range of efficiency (per cycle)**
Secondary Batteries	300$/kWh (6)	60-95% (6)
Flow Batteries	150-1000$/kWh (6)	65-90% (6)
Capacitors/ supercapacitors	300-2000$/kWh (6)	60-99% (6)
Compressed air	2-30$/kWh (6)	41-90% (6)
Flywheel systems	1000-8800$/kWh (6)	80-96% (6)
Pumped Storage	5-300$/kWh (6)	50-90% (6)

5. CONCLUSION

A comparison was carried out on the main types of electrical energy storage for power systems, in terms of providing ancillary services. In section 2 the definition of ancillary used for the analysis performed was presented. A short description of features and functioning of each type of storage technology was introduced in Section 3. Section 4 compares the technologies presented in Section 3, from technical and economic perspectives, emphasizing ancillary services supply and storage plants implementation.

Making a review of recent research it is possible to conclude that modern power systems require all the different types of storage solutions to support the development and implementation of technologies for renewable energy generation and integration. From short- and medium-term solutions, the best providers of ancillary services and capacity of storage are the electromechanical technologies (pumped hydro, flywheel and compressed air), because of the highest installed capabilities and possibility to manage primare resources, e.g. water and fossil fuels. However, if batteries and super-capacitors are considered in terms of efficiency, absolute capacity, costs and power electronics, probably in a long time term, the electrochemical solutions will be more competitive in high power markets. Batteries and super capacitors can be applied for local solutions during emergency cases.

The issues and informative concerns raised in this article can justify new studies to improve storage technologies efficiency, costs, lifetime, capacity and the integration between storage plants and intermittent renewable energy generation. This article aims to show other advantages that storage plants could provide to the grids, which are explored in the current research, beyond dispatch control.

REFERENCES

[1] *Energy storage.* International Energy Agency (IEA), Paris. [Online]. Available: https://www.iea.org/reports/energy-storage-2
[2] *E-Storage: Shifting from cost to value Wind and Solar applications.* World Energy Council, London. [Online]. Available: https://www.worldenergy.org/publications/entry/e-storage-shifting-from-cost-to-value-2016
[3] Energy Storage Monitor - Lastest Trends in Energy Storage, World Energy Council, 2016.

ISSN: 2525-8311 DOI: 10.20906/CBA2022/3497

[4] *Procedimentos de Rede: Módulo 3.11.* Operador Nacional do Sistema (ONS), Brazil. [Online]. Available: http://www.ons.org.br/paginas/sobre-o-ons/procedimentos-de-rede/vigentes

[5] *White paper: Energy storage.* International Electrotechnical Commission (IEC),Geneva, Switzerland, 2011. Techinical Report.

[6] S. Koohi-Fayegh, M.A. Rosen, "A review of energy storage types, applications and recent developments", *Journal of Energy Storage*, Volume 27, 2020, Available: https://doi.org/10.1016/j.est.2019.101047. (https://www.sciencedirect.com/science/article/pii/S2352152X19306012)

[7] M. T. Lawder et al., "Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications," in *Proceedings of the IEEE*, vol. 102, no. 6, pp. 1014-1030, June 2014, doi: 10.1109/JPROC.2014.2317451.

[8] *The train goes up, the train goes down: a simple new way to store energy.* David Roberts. [Online]. Available: https://www.vox.com/2016/4/28/11524958/energy-storage-rail

[9] *Maior produtor do país na área, RN vai estocar energia eólica.* Igor Jácome, G1 RN, Brazil. [Online]. Available: https://g1.globo.com/rn/rio-grande-do-norte/noticia/2021/09/21/maior-produtor-do-pais-na-area-rn-vai-estocar-energia-eolica.ghtml

[10] *Pumped Storage Plants.* Voith Hydro. [Online]. Available: https://voith.com/uk-en/industry-solutions/hydropower/pumped-storage-plants.html

[11] *Pumped Storage Report.* National Hydropower Association's Pumped Storage Development Council, 2018.

[12] *Hornsdale Power Reserve.* Hornsdale Power Reserve website, 2017. [Online]. Available:https://hornsdalepowerreserve.com.au/

[13] J. MacDowell, S. Dutta, M. Richwine, S. Achilles and N. Miller, *"Serving the Future: Advanced Wind Generation Technology Supports Ancillary Services,"* in IEEE Power and Energy Magazine, vol. 13, no. 6, pp. 22-30, Nov.-Dec. 2015, doi: 10.1109/MPE.2015.2461331.

[14] *1.5GW offshore wind plant in South Korea to use 'next generation' lithium-ion battery energy storage.* Andy Colthorpe January 7, 2022. [Online]. Available: https://www.energy-storage.news/1-5gw-offshore-wind-plant-in-south-korea-to-use-next-generation-lithium-ion-battery-energy-storage/

ISSN: 2525-8311

DOI: 10.20906/CBA2022/3497