

Article - 75 years - Special Edition

Analytic Hierarchy Process Algorithm Applied to Battery Energy Storage System Selection for Grid Applications

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Editor-in-Chief: Alexandre Rasi Aoki

Associate Editor: Clodomiro Unsuhay Vila

Received: 2021.03.10; Accepted: 2021.06.23.

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HIGHLIGHTS

- The Brazilian electricity regulatory agency calls for energy storage projects
- Electric utilities evaluate battery energy storage for power quality control
- The Analytic Hierarchy Process (AHP) algorithm for battery technology: a strategic choice
- Environmental, Technological, Regulatory and Financial AHP criteria

Abstract: The Brazilian Power Sector is preparing the introduction of battery energy storage in its distribution lines for energy quality control. The technical and financial viability of this new technology depends on several factors: battery technologies, geographical locations, environmental restrictions and the local regulation. One of the objectives of the present project was to create a methodology for helping technicians to choose the best battery technology for each particular application. The Analytic Hierarchy Process - AHP algorithm was selected to take into account all the above-mentioned factors. This methodology was applied to a case study considering four different commercially available battery energy storage systems (BESS) and the methodology was able to recommend the best choice by taking into account all the criteria and subcriteria considered. The second objective of the present project is to evaluate a real hybrid BESS operation composed of two different battery technologies. Up to the moment when this paper was submitted the BESS has not been installed yet. The installation place has already been selected, a feeder-line with 1,360 kW peak power, and monitored for energy quality. The BESS has been sized, a 250 kW/1 MWh flow battery together with a 250 kW/500 kWh lithium-ion battery and the purchase process has been initiated. Both battery technologies will work in separate and joint operations for power quality in on-grid and island cases.

Keywords: Battery Energy Storage; Brazilian Power Grids; Peak Shaving; Voltage-Sags Smoothing; Multicriteria decision-making Algorithm; Analytic Hierarchy Process; Battery Technology Selection.

INTRODUCTION

The population growth, the constant increase of per capita energy consumption in the developed world, and the democratization of energy provision in developing and poor countries are all contributing to the ever-growing need for power supply. At the same time, climate change and its relation to the global energy matrix is arguably one of the main issues currently faced by societies and decarbonization is mandatory. Fortunately, these issues have been addressed for some years now, and the world has witnessed a considerable increase in renewable energy. However, there is still a lot of work to be done. The intermittent nature of most renewable power sources limits their maximum potential as a basic source of energy in a national grid and some sort of storage system is necessary.

The other side of the power system, - distribution - is also undergoing a technological revolution. The “prosumers”, the deployment of microgrid systems and decentralized energy generation, are highly positive factors in the energy system, but also need storage facilities to solve the problem of desynchronization between generation and consumption and optimize their potential.

Energy storage in the power grid system is not a new phenomenon, as compressed air or pumped hydropower storage have been used for several decades [1,2], but current technological developments are making feasible another type of energy storage for the grid, which is much more flexible, scalable and involves the use of electrochemical batteries. Owing to the widespread use of portable electronic devices and the recent development of electric vehicles, batteries have attracted a good deal of attention and funding, and this has led to a great improvement in performance and innovative mature technology at a lower cost. It is worth mentioning that batteries have been used for the electricity grid for a long time, in both stationary and emergency applications, but the current scenario has allowed much larger systems to be employed and a wide range of new models have emerged. Several publications have carried out in-depth investigations of the variety of applications for power storage in the grid [3-6]. These might for example be used to attenuate wind power fluctuations and to provide centralized generation plants for photovoltaics. Alternatively, they can be used to store energy in periods when power generation is cheaper/scarcer so that it can be dispatched in a second period, as well as to benefit from arbitrage opportunities, or even increase the quality of the energy in critical loads. The purpose of this study is to examine this new type of energy storage and its applications.

Despite all the technical advantages of Battery Energy Storage Systems (BESS), their financial feasibility is still quite restricted and must be evaluated carefully [7-9]. Staffell and Rustomji conducted a study of different sources of revenue for BESS projects in the UK and found that BESS systems were not financially viable for hybrid wind generation and storage, or energy arbitrage [7]. Although the combined applications of arbitrage and the forward reserve market could triple the amount of this revenue, it would still not be sufficient to justify an investment. The authors draw this conclusion through simulations based on the 2013/2014 scenario [7]. Bradbury and co-workers analyzed the influence of energy storage technology on CAPEX and its technical features (roundtrip efficiency, self-discharge) on the economic viability of different storage technologies used for energy arbitrage [8]. The authors concluded that in 2008 the battery-based storage system was economically viable in Houston, the most volatile market and best-case scenario, but this was not the case for all the other markets and years.

Concerning another type of application, Bolanos and colleagues analyzed the viability of employing different battery technologies to replace diesel generators for the commercial energy consumers, which are normally used as peak power sources. The authors confirmed that this substitution was still not cost-effective, given the circumstances of Campinas/Brazil 2019. However, owing to the expected fall in battery prices, lead-acid and lithium-ion battery-based storage systems, it could be feasible in approximately 6 years [9].

Currently, the most promising application for storage can be found in the intermittent generation of power supply for isolated systems/remote areas [10,11]. In the case of on-grid applications, some recent work suggests all possible benefits should be taken into account, which is obvious, but some are difficult to quantify - like the social benefits of security and grid stability [12] – and it is thus hard to give an accurate estimate of their profits.

The World Bank published a guide that sets out the principles and practices of BESS economic analysis which are required for the institution's appraisal of investment projects. The guidelines emphasize that the main challenge is to estimate the benefits of a project involving BESS, in other words, to determine which

applications will be undertaken by BESS. In addition, the key decisions involve choosing a suitable storage technology and size [13].

Defining the ideal battery technology is not straightforward since there are many battery technologies available. **Table 1** provides information about the power storage systems around the world, which were operational at the end of 2019.

Table 1. BESS projects in operation sorted by types of battery technology. Data available in [14] and gathered before November 2019.

Battery technology	Nº of projects	Accumulated Power (kW)	Average power (kW by project)	Accumulated Energy (kWh)
Lithium ion	467	1,335,336.0	2,890.34	1,404,586.4
Sodium Sulphur	32	188,900.0	5,903.13	1,260,680.0
Lead acid	69	60,424.0	875.71	68,634.9
Supercaps	69	46,810.0	678.41	147,922.0
Nickel Cadmium	25	30,903.0	1,236.12	
Na-NiCl ₂ (ZEBRA)	2	30,000.0	15,000.00	9,150.0
Electrochemical ¹	27	14,481.0	579.24	52,127.3
Lead acid+Supercaps	20	13,054.0	652.70	15,943.4
Lead Carbon	12	6,732.0	561.00	
Sodium ion	3	1,016.0	338.67	798.0
Nickel Iron	11	971.0	88.27	3,181.8

¹ Not specified in the database.

As well as this, each technology encompasses several types of battery composition with distinct characteristics (for instance, lithium-ion could be “cobalt oxide”, “iron-phosphate”, “nickel-manganese-cobalt”, “titanate”, etc.), and their technical features [15] and prices [16] vary considerably.

A systematized approach is necessary to cover all the mentioned criteria and make a suitable selection of the battery technology required.

Electrochemical Energy Storage in the Brazilian Power Grid System

Compared with other leading countries in the world, Brazil still has little experience of Power Storage in its grid system. The most remarkable recent measure taken in this area was an initiative by ANEEL (Brazilian Electricity Regulatory Agency), which also regulates R&D programs for the power sector, and encourages projects to be carried out that are specifically devoted to this field. This call for projects, which is designated: “Technical and commercial arrangements for the incorporation of storage systems in the Brazilian electricity sector”, was launched in June 2016, and examined 29 R&D projects, of which 23 were finally approved by February 2017. The projects started in mid-2017 and are expected to be completed, by mid-2022. The 21 ongoing projects have a total budget of R\$ 370 MM, funded by 19 different institutions (utilities, R&D institutes, and universities), and it is expected that around 13.2 MWh batteries will be installed, divided into 63 pilot systems ranging from 2 kWh to 2 MWh [17].

This strategic plan is of the utmost importance and requires innovative projects to be provided for a very new sector, which is going to oversee several aspects of the Brazilian power storage system in the future. Each project has its objectives and characteristics, but ANEEL required that several key issues should be addressed. This means that even though the projects are still ongoing, (and a lot of them have experienced delays in scheduling on account of the COVID-19 pandemic), it is expected that this strategic call for projects will make a valuable contribution to the Brazilian power storage sector. The main strategic requirements made by ANEEL are listed below:

- Installation of a power storage pilot system. Monitoring its behavior and effects on the power grid system. Creation of databases. Conducting a technical and economic analysis, and making a comparison with different alternatives;
- Studying the impacts on the power grid operations and planning, and also the limits on connection limits, in light of the current infrastructure;
- Evaluation of environmental impacts;
- Design of business models that can enable and foster the use of power storage on the grid;

- Assessment of regulatory gaps and barriers for power storage dissemination and recommendations for improvements;
- Planning a technological roadmap and;
- Analysis of the cost and effort required to build a national technological database in this area.

The distributed application of resources, cited by the proponents of the project as the main reason for the respective storage system in response to ANEEL strategic call, is shown in **Figure 1**

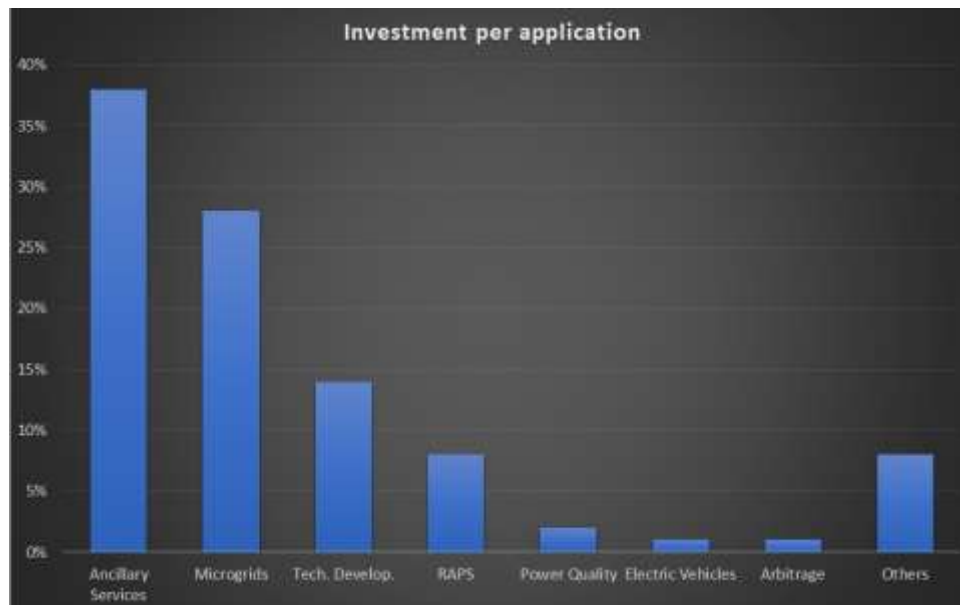


Figure 1. Investment by application in the ANEEL strategic call projects. “RAPS” stands for Remote Area Power Supply. Source [18].

It can be seen that the most common applications are ancillary services and the use of microgrids (often combined with renewable sources). Of course, the “Microgrids” and “Technological Development” can be split into more detailed categories, such as “capacity firming, load leveling and/or peak shaving”.

This paper examines an ongoing project which is a part of the above-described strategic call. The project was planned by the Parana State Energy Company – Copel and undertaken by the Institute of Technology for Development- LACTEC.

This project has two main objectives. The first one is to develop a methodology to identify the most suited battery technology for a given set of applications and the second one is demonstrating the benefits of pilot-scale real BESS operation, installed in a county-side substation. Up to the moment when this paper was submitted the BESS has not been installed yet. The installation place has already been selected, a feeder-line with 1,360 kW peak power, and monitored for energy quality. The BESS has been sized, a 250 kW/1 MWh flow battery together with a 250 kW/500 kWh lithium-ion battery and the purchase process has been initiated. Besides the project objectives, another contribution of this paper is to disseminate energy storage activities in Brazil and its potentialities as well as provide a case study of a proper battery technology selection considering quantitative and qualitative parameters by a multicriteria AHP algorithm.

In the next section, it will be presented the AHP algorithm in detail with its criteria and subcriteria. The result section will present the algorithm applied to a case study, a previous electrical characterization of the substation bus where the BESS will be installed and also a simulation of BESS operation for peak sheaving. In the final section, a brief discussion of the results is presented.

MATERIAL AND METHODS

The project has two key objectives. The first is to employ a multicriteria methodology for battery technology selection and the second is to install and evaluate a commercial BESS connected to the Copel distribution grid.

Multicriteria decision methodology

The definition of the best battery technology was designed as a multicriteria problem, and employed the Analytic Hierarchy Process-AHP method; its development was divided into two phases: 1) Hierarchical

structuring and 2) Definition of weights. Each of these is examined in detail below. The AHP method was implemented in Matlab R2018b.

Phase 1 – The hierarchical structure: in this phase, the problem criteria and sub-criteria are established and the hierarchical structure that is defined, is based on bibliographic research and meetings with different specialists in the area. Four criteria were defined: Environmental, Technological, Regulatory, and Financial. Sub-criteria were listed for each of them, as shown in Figure 2.

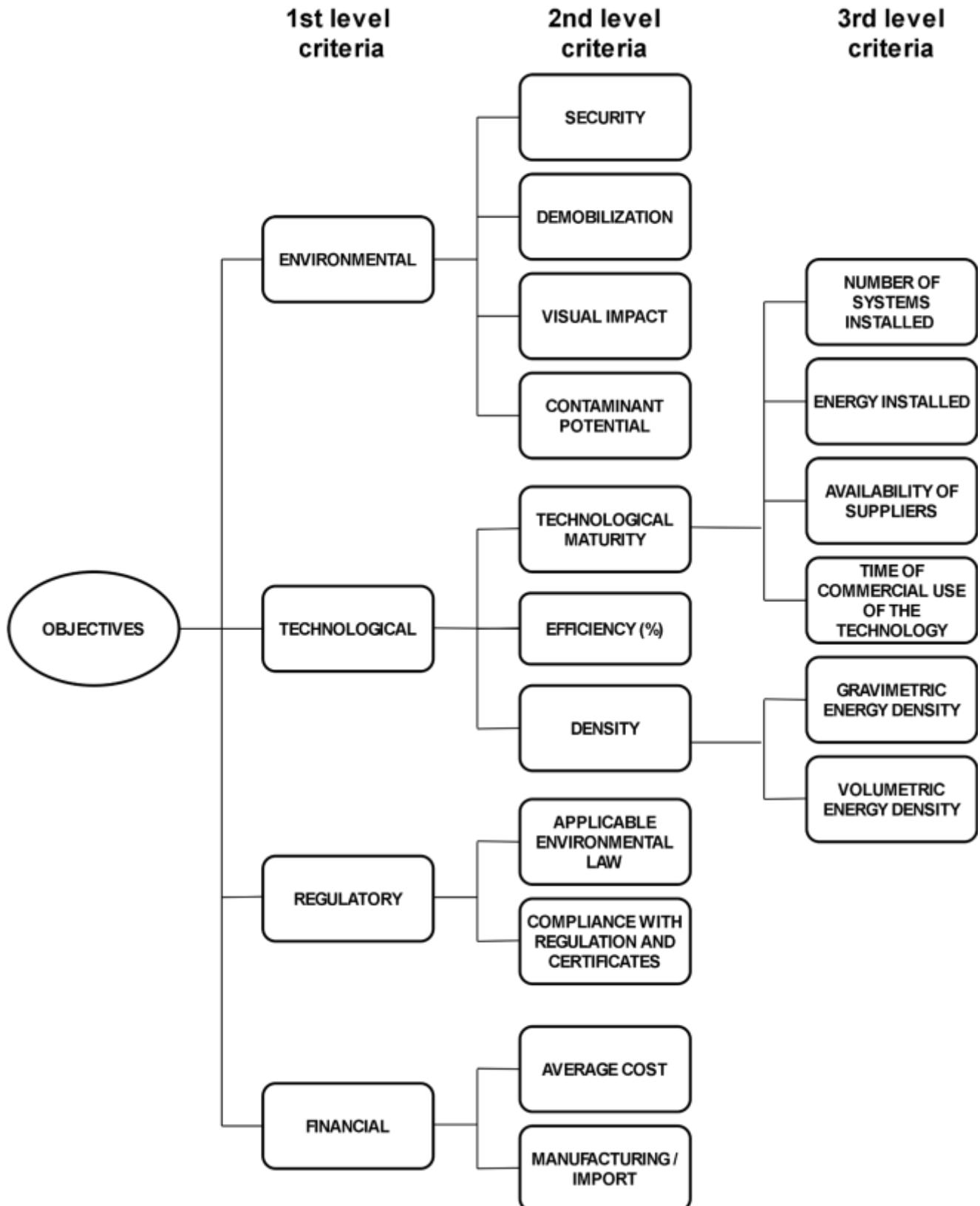


Figure 2. Hierarchical scheme. Source: the authors (2020).

The characteristics of each of the criteria and sub-criteria used in the methodology are outlined below. In the environmental criteria, the main points must be examined from an environmental perspective, such as risk indicators, recycling, visual damage, and damage to the biota. Four sub-criteria are drawn on for this: safety, demobilization, visual impact, and potential contaminants.

Safety refers to sporadic environmental risks, the indicators of which are associated with potential damage. The alternatives were classified as the risk of explosions, corrosion, contamination by leaked fluid, and exposure to toxic agents. A numerical summary is defined to assess this item, in which the higher the risk, the less important is the technology.

Demobilization is divided into disposable, partially recyclable, and fully recyclable material. This item refers to recycling, which depends on how batteries are formed, as well as the types of waste that occur at the end of the useful life of the device. It is based on the hypothesis that the best alternative will be the one that allows full recycling, or as close to that as possible.

Visual Impact is caused by the size of the container used in the installation of the energy storage system. In this subcriteria, it is assumed that the larger the container, the greater the visual impact and, hence, the less the importance of the technology.

The Potential Contaminator represents the environmental damage to the biota caused by the chemical composition of the batteries. The evaluation of this criteria is based on the assumption that the less the damage, the greater the importance of the technology.

The specific features of each study are the determinants for the selection of the technological criteria [19]. The sub-criteria selected for this study were technological maturity, efficiency, and density. The technological maturity subcriteria were evaluated by the number of systems installed in the world, installed energy, availability of suppliers, and the time of the commercial use of the technology. The density subcriterion was divided into gravimetric and volumetric density.

Efficiency is defined in terms of the chemical process used by the battery and is the maximum percentage of charge and discharge of stored energy that can work with the minimum reflection in its useful life [20]. In measuring its criteria, the higher the percentage, the greater the degree of importance of the technology.

The number of systems installed in the world is a means of measuring the number of installed projects for each technology. An analysis of these subcriteria was conducted by carrying out, a global assessment with a set of 1596 energy storage projects. The information was extracted from the website of the Global Energy Storage Database - GESD [21]. As a form of measurement, this methodology attached the highest degree of importance to the number of projects in operation, that is, the greater the number of projects, the greater the importance of the technology.

Installed energy is the amount of power (MW) installed in projects worldwide. Data from the GESD website were used [21]. The amount of installed energy is adopted as the highest degree of importance, that is, the greater the amount, the greater the importance of the technology.

Supplier availability refers to the approximate number of suppliers available for each type of technology. When making this assessment, data from the GESD website [21] were also used. The degree of importance is linked to quantity, that is, the greater the number of suppliers, the greater the importance of the technology.

The time of commercial use indicates the time that the technology is commercially available for sale and, the longer this is, the greater the degree of its technological significance.

Volumetric energy density is measured in kWh/m³ where the higher the density, the greater the degree of importance of the technology, as it represents less volume for a greater amount of energy. The gravimetric energy density is the amount of energy stored per unit of volume or mass, expressed in kWh/kg. The higher the energy density, the more energy can be stored or transported by the same amount of mass.

In Brazil, there are still no regulations for the use of batteries in power systems; in this study, the regulatory criteria were divided into environmental legislation and compliance with regulations and issuing of certificates. Environmental legislation embodies legal provisions for the analysis of technologies concerning the operation since the existence of laws makes contracts legally binding. The absence of specific legal provisions means that the legislation is adaptable. Compliance with regulations and the issuing of certificates represents compliance with specific Brazilian standards and the laws that regulate the technology.

The timing of the implementation of storage technologies is affected by competitiveness, which, in turn, depends on the rising pattern of technological costs [22]. In this study, the sub-criteria average cost and the expenditure on manufacturing /imports were selected as the financial criteria. The higher the battery average cost, the lower the importance of the technology. Manufacturing /imports is a subcriteria that refers to the existence of battery factories in Brazil and the need for imported products. These subcriteria are defined to

cover the costs incurred for importing equipment and also the costs arising from maintenance and possible changes in the use of technology.

Phase 2 – Definition of weights: in this phase, consistency of the figures recommended by specialists in related areas are standardized and the interdependence of the criteria and sub-criteria are validated.

One of the advantages of the AHP is that it can rely on expert professional experience in each area for classifying the criteria and subcriteria. When determining the level of importance between the criteria and the sub-criteria, specialists in different areas answered a survey that is based on the Saaty scale [22]. A consistency test is conducted for each completed survey, which indicates whether the answers are valid or not.

Battery storage systems

The BESS pilot scheme is designed to install a 250 kW/1 MWh flow battery together with a 250 kW/500 kWh lithium-ion battery in a Copel power substation near Curitiba City in Parana State. The BESS will be connected to a real consumer feeder, to enable it to carry out load shifting, peak shaving, voltage sags smoothing, and reactive power control among other possible tasks in on-grid and island operations. The initial stage will be to analyze the feeder energy quality state before the installation of BESS so that it can be compared with the situation after the installation. Another objective is to analyze the joint operation of both battery technologies. This will be done in grid-connected and island operation in the same feeder.

RESULTS

Following the same pattern adopted in the methodology, the results will be divided into two parts. The first is related to the deployment of the multicriteria methodology and the second will be related to an assessment of the BESS pilot scheme.

Multicriteria decision algorithm

In line with the AHP methodology, specialists in the areas of energy, the environment, chemicals, materials, forestry, biology, and ecology answered the questions in the survey and their answers were submitted to the consistency test. Based on the consistent results, the weighted criteria were obtained, as shown in Table 2.

Table 2. Criteria weights defined from the responses of the specialists. Source: the authors (2020).

Criteria		Sub-criteria					
Environmental	24.64%	Safety	37.39%				
		Demobilization	20.20%				
		Visual impact	5.3%				
		Contaminant potential	37.09%				
Technological	29.64%	Technological maturity	19.04%	Number of systems installed	12.92%		
			Density	36.90%	Installed energy	33.28%	
					Availability of suppliers	37.07%	
			Efficiency	44.04%	Time of commercial use	16.72%	
		Gravimetric energy density			54.65%		
		Regulatory	21.07%	Applicable environmental law	51.67%	Volumetric energy density	45.35%
Compliance with regulations and certificates	48.33%						
Financial	24.64%	Average cost	61.45%				
				Manufacturing/Imports	38.55%		

The results of the calculated scores from the answers given by the specialists to the four main criteria showed that the technological criteria were the most important with a score of 29.64%. Among the three sub-criteria, efficiency had the highest priority with a score of 44.04%. The second most important criterion was energy density with a score of 36.90% where the gravimetric density (54.65%) was more important than volumetric density (45.35%). Concerning the components of the technological maturity subcriteria, the supplier availability subcriteria had a higher priority with 37.07%.

In the case of regulatory criteria, the applicable environmental law subcriteria was the most important and achieved a score of 51.67%. In the distribution of the weights for the financial criteria, the average battery cost subcriterion was the most important with a score of 61.45%. Finally, in the case of the environmental criteria, the most important subcriteria was security with a score of 37.39%.

The next stage is to determine the features of each battery technology, that are related to the criteria and subcriteria used in the methodology.

A validation test was conducted that was based on four different types of battery devices (alternatives 1-4) in a simulated demand of 50 kWh. The features of each alternative, for the adopted criteria and sub-criteria, are shown in Table 3.

Table 3. Features of the battery technologies. Source: the authors (2020).

Sub-criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Safety	Corrosion, exposure to toxic agents	Corrosion, exposure to toxic agents	Corrosion, exposure to toxic agents	Explosions, exposure to toxic agents
Demobilization	Fully recyclable	Fully recyclable	Fully recyclable	Disposable
Visual impact	Equivalent to container up to 33 m ³	Equivalent to container up to 33 m ³	Equivalent to container up to 33 m ³	Equivalent to container up to 33 m ³
Contaminant potential	Little damage	Serious damage	Average damage	Little damage
Efficiency (%)	85	92	85	98
Number of systems installed	45	3	69	112
Installed energy (MW)	61.4	1.0	61.4	174.6
Availability of suppliers	More than 40	Between 5 and 20	More than 40	More than 40
Time of commercial use	Over 60 years	Up to 10 years	Over 60 years	Over 40 years
Volumetric energy density (kWh/m³)	37.60	62.72	55.50	115.04
Gravimetric energy density (kWh/kg)	0.01875	0.02353	0.03542	0.08780
Applicable environmental law	Law enacted and applicable to technology	Law can be adapted	Law enacted and applicable to technology	Law can be adapted
Compliance with regulations and issuing of certificates	Standard only	No standard	Standard only	Standard only
Manufacturing/Imports	Factory in Brazil	Factory abroad	Factory in Brazil	Factory abroad
Average cost	Between US\$ 500 and US\$ 1000	Between US\$ 500 and US\$ 1000	Between US\$ 100 and US\$ 500	Higher than US\$ 1000

With the battery features (see Table 3) and the classification of the criteria and sub-criteria (see **Table 2**), the AHP methodology ranked all the analyzed battery devices, according to [22]. The AHP results can be seen in Table 4.

Table 4. Final AHP results for each type of battery device. Source: the authors (2020).

Technology	Priority
Alternative 1	26.13%
Alternative 2	19.73%
Alternative 3	27.92%
Alternative 4	26.22%

The results of the final AHP showed that Alternative 3 was the best-ranked battery device with a priority of 27.92%, in terms of the basic assumptions of the study. The results show that alternatives 1, 3 and 4 has a minimum difference (around 2%), so they can be considered technically equivalents. For a better evaluation it's recommended analyze the detailed "priority result" of the criteria and sub-criteria given in **Table 5**.

Table 5. Detailed "priority result" of the criteria and sub-criteria. Source: the authors (2020).

Technology/Criteria	Environmental	Technological	Regulatory	Financial
Alternative 1	0.2371	0.1700	0.3415	0.3267
Alternative 2	0.2371	0.1819	0.1186	0.2433
Alternative 3	0.2527	0.2176	0.3415	0.3267
Alternative 4	0.2730	0.4305	0.1985	0.1033

With regard to three criteria, from an environmental perspective, the best-ranked battery device is Alternative 4 (27.30%), which is also the most appropriate from a technological standpoint (43.05%), in this case it is greatly superior to the others. In the case of the regulatory criteria, Alternatives 1 and 3 obtained the same result with 34.15%. There was also a tie concerning the financial criteria between the same alternatives (1 and 3), which both had 32.67%.

The results of the method must be evaluated by specialists to validate the choice, since they have greater knowledge of the particularities of each technology. The advantage of using AHP for this problem is the consideration of subjective criteria such as environmental and regulatory criteria, which cannot be used directly in the calculation of the cost-benefit of technologies.

Assessment of the BESS pilot scheme

When making the commercial evaluation of BESS, the initial stage was to choose a feeder energy line (where the BESS will be installed) and analyze its power and energy consumption before the installation of BESS. The chosen grid-line for the BESS installation was a feeder-line with 1,360 kW peak power. Figure 3 shows the feeder power peaks from September 2018 to September 2019 (one year).

The installed power capacity of BESS is about 500 kW, which is enough for testing all the planned BESS operational modes, including island operation in eight months of the year, from March to October (see Figure 3). In the other four months (from November to February), the BESS will be used in on-grid assisted operational mode (with no island operation). Another important piece of information for the BESS operation that is worth noting, is the energy consumption in the feeder. Figure 4 shows the monthly feeder energy consumption for the same period, from September 2018 to September 2019. As can be seen, from March to October, the monthly energy consumption is quite constant, (about 5 MWh per month), which represents a daily average energy consumption of about 167 kWh. This means that the 1,500 kWh BESS capacity could have autonomy for around 9 to 10 days in an island operation (for these months).

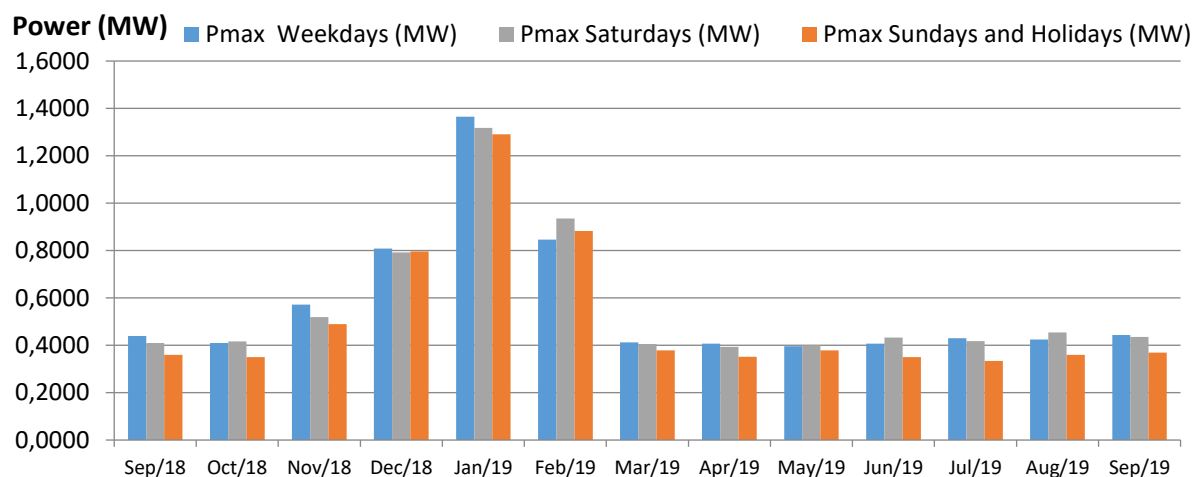


Figure 3. Feeder power peaks from September 2018 to September 2019 (before the installation of BESS). Source: Parana State Energy Company.

Before analyzing whether it is possible to have on-grid BESS application modes (like peak shaving, load shifting, and voltage sags smoothing), information about hourly consumption is required. Devices were installed for power, voltage, and measuring energy to access this information before BESS was installed to provide information about the state of the power grid (and to make future comparisons, after the installation of BESS). Hourly power consumption measurements, for a typical weekday, between March and October, are given in Figure 5. This power profile shows a sharp power peak between 18:00 and 20:00 h. For example, one of the BESS on-grid operational modes that can be applied to this feeder, based on this power consumption profile, is peak shaving.

Figure 6 shows a simulation of the peak shaving application for this feeder. In this figure, the red line represents the defined maximum power - P_{max} , that will be determined by the state energy company power grid only during the period of peak demand (between 18:00 and 20:00 h). The difference between this chosen limit and the actual power consumption during the peak time will be provided by the BESS. The yellow vertical lines in the figure represent the BESS charge (between 0:00 and 16:40 h) and discharge (between 18:00 and 20:00 h). The simulation assumed a low power recharge regime and stand-by periods between recharges and discharges to minimize battery degradation. The solid blue line represents the new power profile - P_{new} , calculated by energy balance considering 100% roundtrip efficiency and the battery in fully recharged state before the peak demand period.

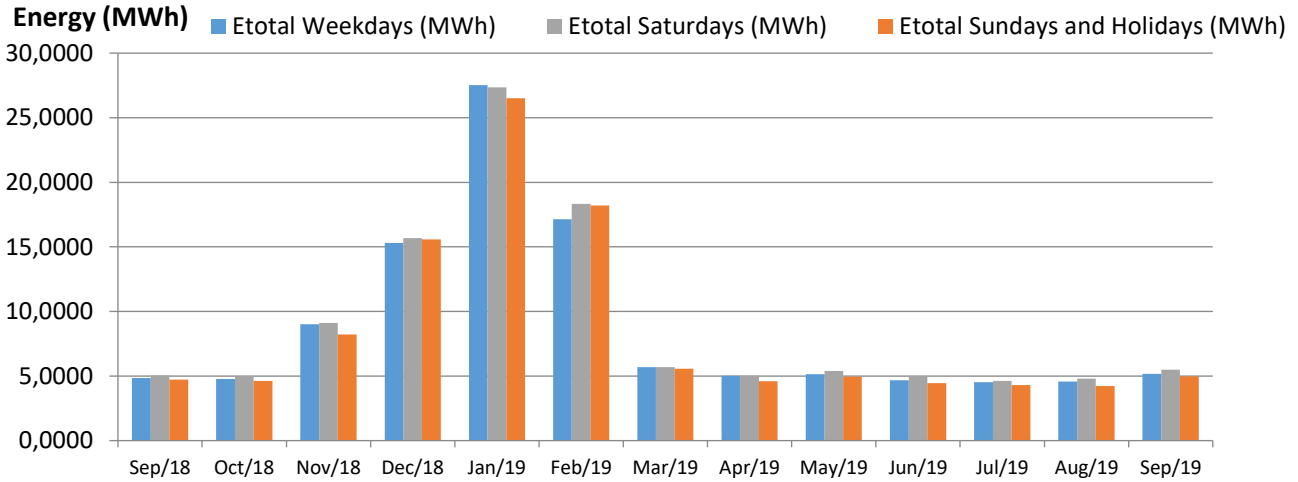


Figure 4. Feeder energy consumption from September 2018 to September 2019 (before the installation of BESS). Source: Parana State Energy Company.

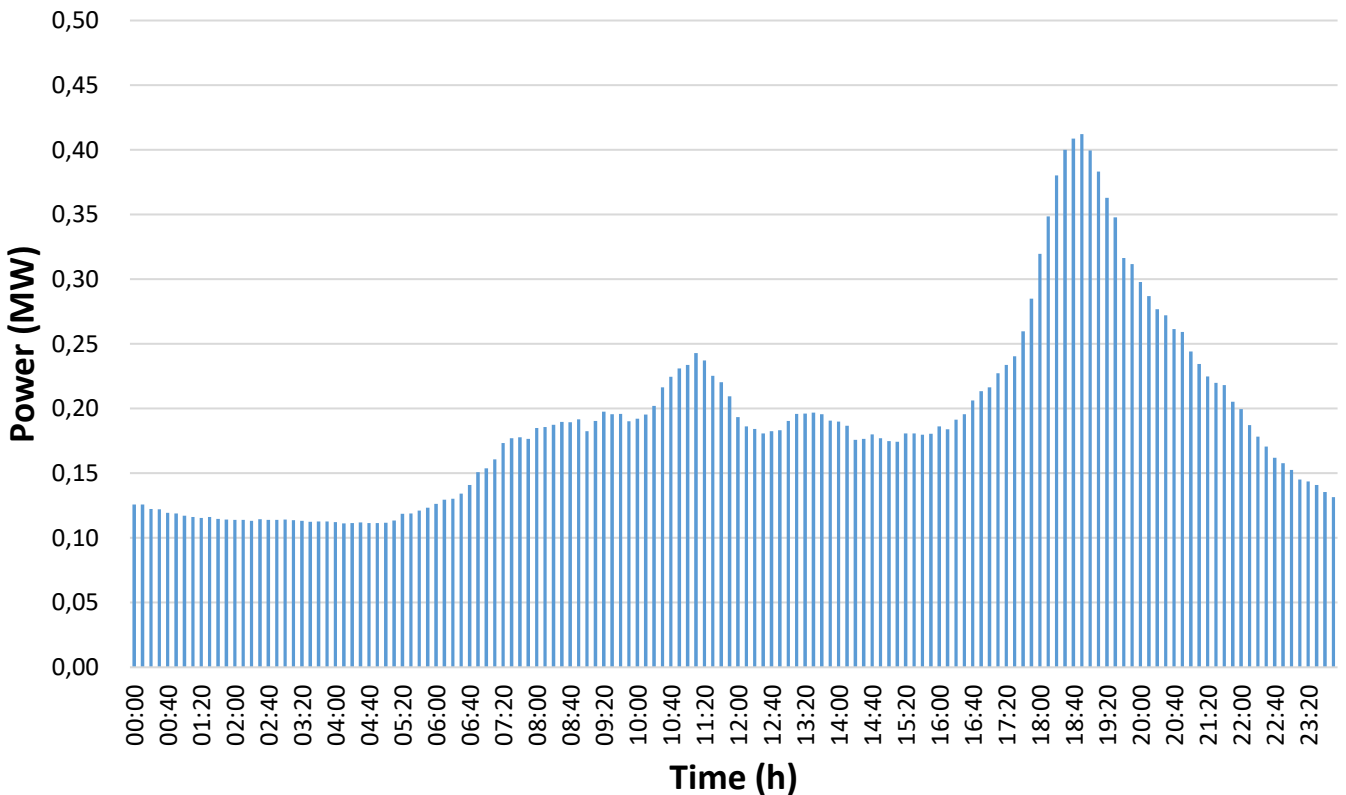


Figure 5. Hourly feeder power consumption on a typical weekday between March and October. Source: Parana State Energy Company

Another important application that must be tested will be the voltage sags smoothing. Voltage sags were observed in the chosen feeder. Figure 7 shows a typically measured voltage sag in this feeder (medium

voltage line). In a simulation, the yellow lines represent the planned BESS discharge, to smooth the voltage sag. In this way, the BESS will be tested in different applications (as many as possible and most of them in parallel) to take advantage of their potential and contribute to the payout system. And more important, different battery technologies (lithium-ion and flow battery technologies) will be used to test these operational applications to reveal their strengths and weaknesses.

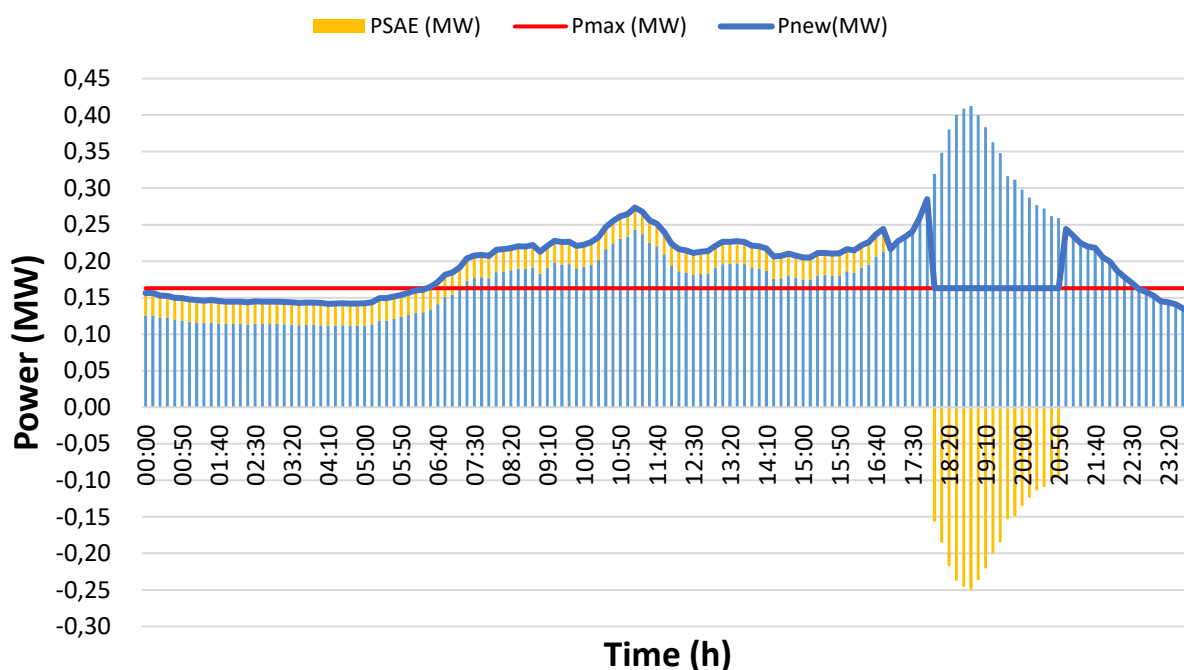


Figure 6. Simulation of peak shaving in the BESS applications. The red line represents the maximum power - P_{max} , provided by the company power grid during the period of peak demand (between 18:00 and 20:00 h). The yellow vertical lines represent the BESS charge (between 0:00 and 16:40 h) and discharge (between 18:00 and 20:00 h). The solid blue line represents the new power profile P_{new} due to the BESS charge and discharge operation. Source: Parana State Energy Company.

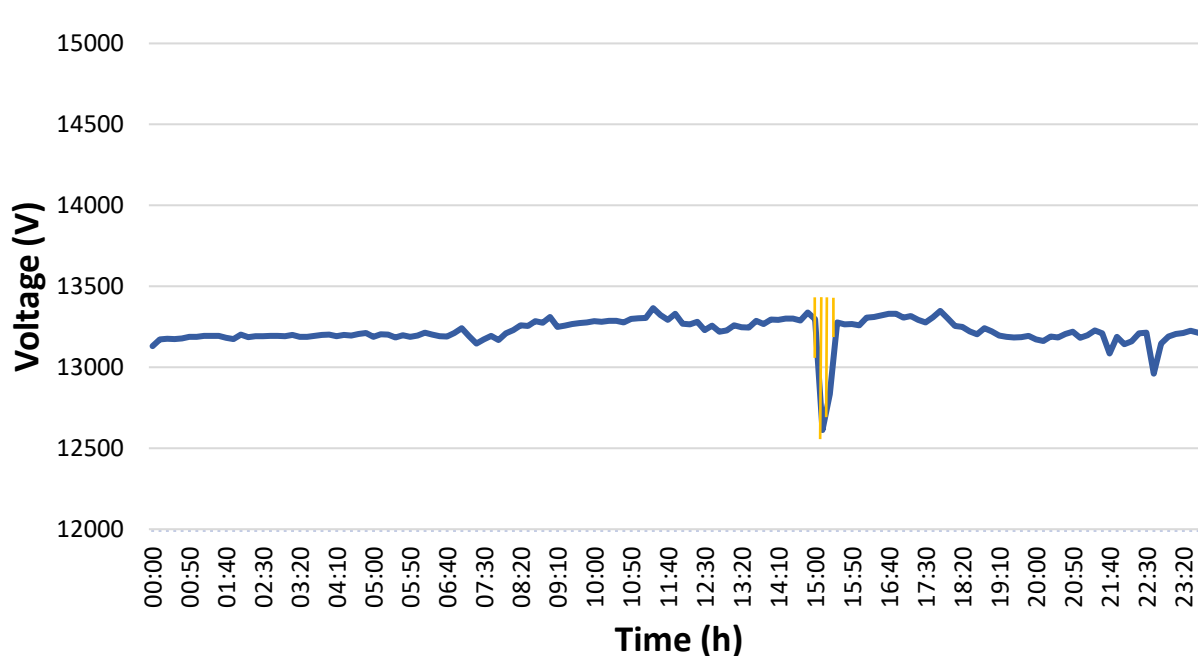


Figure 7. The solid line is a measured feeder voltage. The yellow lines represent the expected BESS discharge, to smooth the voltage sag (simulation). Source: Parana State Energy Company.

This project is still ongoing. Batteries are now being purchased and will be operational in 10-12 months to test the planned operational regimes. The results of the lithium-ion and flow batteries operation in real-world conditions will be available in the future.

DISCUSSION

The Brazilian Power Sector is preparing the introduction of battery energy storage in its distribution lines for energy quality control. The success or failure of this new technology (from a financial and technical standpoint) depends on many factors. Different kinds of battery technologies have advantages and disadvantages depending on the operational regimes adopted. Different geographical locations, accessibility, spare parts availability, and other related factors may play a significant role in giving priority to one technology rather than another, and even environmental restrictions and the local regulatory framework can affect the results. The AHP algorithm is designed to take into account all these factors. It should be pointed out that the results of the algorithm results depend a great deal on the evaluations of the specialists. In view of this, as many experts as possible must be consulted for each evaluated criteria and subcriteria to overcome this subjectivity. In this case, the survey results of 19 specialists and 4 alternative battery devices were analyzed.

It's important to note the useful life of the alternatives was used to calculate the batteries dimensioning, however it was not considered as a criteria in AHP method. In the future work is expected to use the useful life with the real prices of the technologies to replace the average price subcriteria. The real evaluation of BESS for two different battery devices is only now starting. Preliminary results showed the chosen feeder-line situation before the installation of BESS. The feeder was chosen to allow almost all the possible BESS applications to be assessed, in a battery joint operation (flow battery together with the lithium-ion battery) or in a separate way, both for on-grid or island systems. The question about the joint operation of different battery devices in the same grid-line is a matter of concern. In the future, it is expected that different kinds of batteries will be installed in the same feeder, which will make their joint operation necessary. This possibility gives rise to many questions, in particular about their island joint operation which is caused by their similar power capabilities. This project seeks to address this question and others related to joint operation, by identifying critical key issues and differentiated demands for operational control.

Funding: This research is being funding by the R&D project PD-2866-0444/2016 sponsored by Parana State Energy Company - Copel, under the auspices of the R&D Program of the Brazilian Electricity Regulatory Agency – ANEEL. The authors are also grateful to the National Council for Scientific and Technological Development (CNPq) for providing grants through Law No. 8010/1990, I.I. 17/3098290-0.

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