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# Sustainable use of spilled turbinable energy in Ecuador: Three different energy storage systems☆

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ABSTRACT

The incorporation of Energy Storage Systems (ESS) in an electrical power system is studied for the application of Energy Time Shift (ETS) or energy arbitrage, taking advantage of the turbinable energy discharged in hydroelectric plants. For this, three storage systems were selected: Lithium-Ion Batteries (LIB), Vanadium Redox Flow Battery (VRFB), and Hydrogen Storage Systems ($H_2SS$). The spilled turbinable energy available at the Paute Integral hydropower complex in the Republic of Ecuador is taken as the case study. Based on real data from the operation of these plants, a distinctive element of the study, the performance of the selected energy storage systems was analyzed applying the Analytic Hierarchy of Process for decision-making, where technical, economic, and environmental criteria were considered. Electrical energy stored during the early morning seeks to displace the thermal generation during peak hours, close to the demand centers. The results show that all the storage systems analyzed satisfy the required demand, although VRFB is recommended for the ETS. From an economic point of view, LIB represents the best alternative. From a technical point of view, $H_2SS$ is slightly superior, while prioritizing environmental aspects, VRFB technology prevails. However, the selection of the best ESS alternative must be continually evaluated, due to permanent technological changes. It is concluded that ESS represent a viable alternative to improve the operational performance of hydroelectric plants, meet the variability of demand, improve the quality of the electrical energy delivered, and displace the pollution-generation plants.

## 1. Introduction

Historically, the satisfaction of basic energy needs, the continuous search for economic and social development, and the improvement of people's standard of living have implied a constant growth of material consumption per capita. Together with the natural demographic growth, this material consumption has caused a sustained increase in energy demand, mainly fossil fuels and, consequently, a greater emission of greenhouse gases, whose global climate effects are undeniable. Thus, it is urgent to decarbonize the energy sector, especially the production of electricity, which has promoted the development and use of renewable energy sources. However, by nature, these sources are intermittent and do not always adapt to society's varying energy demand. Additionally, these technologies' conversion efficiency, in terms of the use of their installed capacity, is far from that desired. All this implies that the efficient use of these primary sources of energy must contemplate the incorporation of energy storage technologies to improve the performance of the existing infrastructure. This article compares various forms of energy storage that allow increased efficiency of renewable generation plants (mainly hydropower) and that improve the quality of the electrical energy distributed to sites with high power demand but that are distant from these plants. These storage technologies would make it possible to reduce, or displace, the use of fossil fuels for the generation of electricity in such places, with all the advantages that this substitution entails.

Worldwide, more and more investment is being made in renewable energy generation projects, mainly on hydroelectricity, solar energy, and wind power. Thus, in 2018 global investment in renewable energy reached US $289 billion and financing for new capacity was almost three times higher than in the coal and gas sector [1]. In the case of Latin America, investment in 2019 reached US $19.6 billion, the highest in the

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**List of abbreviations**

| | |
|---|---|
| AHP | Analytical Hierarchy Process |
| ESS | Energy Storage Systems |
| EPS | Electric Power System |
| ETS | Energy Time Shift |
| G2P | Gas to Power |
| $H_2SS$ | Hydrogen Storage System |
| REDOX | Reduction–oxidation flow battery |
| LIBs | Li-ion Batteries |
| MADM | Multi-Attribute Decision Making |
| MCDA | Multi-Criteria Decision Analysis |
| P2G | Power to Gas |
| P2P | Power to Power |
| STE | Spilled Turbinable Energy |
| VRFB | Vanadium Redox Flow Battery |
| CF | Carbon Footprint |
| FC | Fuel Cell |
| LCC | Life-cycle-cost |
| LCOE | Levelized Cost of Energy |
| GHG | Greenhouse Gas |
| LCA | Life Cycle Assessment |
| NCRE | Non-conventional Renewable Energies |
| T&D | Transmission and Distribution |

*Nomenclature*

| | |
|---|---|
| *a, b* | Performance alternative |
| $C_{1i}$ | Criterion 1 value in cell *i* (from 0 to 10) |
| $C_{2i}$ | Criterion 2 value in cell *i* (from 0 to 10) |
| $C_{3i}$ | Criterion 3 value in cell *i* (from 0 to 10) |
| $C_{ni}$ | Values, for each criterion *n*, the best of three alternatives *i* |
| $E_E$ | Higher calorific value of $H_2$ HHV (3.54 $kWh/Nm^3$) |
| $E_{Elec}$ | Electrical energy to be supplied to the electrolytic system |
| $E_i$ | Input energy |
| $E_0$ | Output energy, 1 MWh for efficiency calculation |
| $F_p$ | Production factor in the Production component |
| $H_a$ | $H_2$ stored for the daily operation of the End Uses component, $Nm^3H_2$ |
| $H_{FC}$ | Hydrogen consumed in the fuel cell system, $Nm^3H_2$ |
| $H_p$ | $H_2$ produced by electrolysis |
| $H_{Storage}$ | Storage container capacity |
| $F_u$ | $H_2$ utilization factor, adim |
| $F_s$ | Overdesign Factor, adim |
| *i* | Criterion "*i*" |
| $P_i$ | Input power to the $H_2$ Production component |
| $P_o$ | Output power of the End Uses component or daily power |
| $R_{Total}$ | Ratio between the output and input energy of the overall system |
| $t_o$ | Operating time |
| $v_i(a)$ | Partial function value |
| *V(a)* | Total value score |
| $V_i$ | Prioritization index value in cell *i* |
| *W* | Weights |
| $W_1$ | Weight criterion 1 (%) |
| $W_2$ | Weight criterion 2 (%) |
| $W_3$ | Weight criterion 3 (%) |
| $\eta_e$ | Efficiency of the electrolytic process |
| $\eta_{fu}$ | Efficiency of the End Uses component |
| $\eta_e$ | Efficiency of the P2G conversion, = 0.75 |

last 5 years, led by Brazil with 35% contribution [2]. Ecuador is no stranger to this situation. During the last decade, the hydroelectric plants installed capacity increased by 148%. The contribution of renewable energy, which was 43.5% of the country's electricity demand in 2006 [3], became 78.13% in 2019 [4], although the gross demand for electric power approximately doubled in this period (from 16,384 GWh to 32,309 GWh) according to these same reports. The entry into operation of large hydroelectric plants, which had an installed capacity of 3000 MW in the last decade, has caused an increase in renewable generation capacity, such that Ecuador went from being a continuous importer of electricity to being an exporter. However, thermal power plants that burn fossil fuels, located at distant sites from the national electricity grid, are still necessary in order to increase the reliability of the system and deliver electricity with the legally established technical quality conditions.

Renewable sources of energy are not normally controllable. Key variables such as solar radiation, wind speed, and direction or river flow can be predicted with a certain accuracy; however, they cannot be controlled at will and their magnitudes have large seasonal and daily variations. Additionally, in certain situations, energy use must be immediate, as it is difficult, or impossible, to store it in its primitive state. In the case of some hydropower plants, water is accumulated, and its potential energy, in reservoirs but their capacity is limited and they can become full, particularly during the rainy season; thus, when for any operation reason the production of the hydropower plant is reduced while water is spilled by the spillway, energy ends up being wasted [5]. The concept associated with this condition is known as STE; that is, the water is returned to the river bed without going through the energy generation process. STE can be increased by operating conditions of the EPS, since energy demand tends to decrease in the early mornings, or by saturation of some element in the T&D network. This reduction in the generation of energy in plants with available renewable energy causes a deterioration in their productivity indicators and, above all, the advantage of having renewable energy for generation is wasted, which, in most cases, must be compensated by expensive energy from fossil fuels.

The alternative to reduce STE is precisely to generate electricity with the resources available at that time, despite not being required in the EPS, and to store it (into an ESS) to be used when necessary. This work would allow the application of the concept of ETS, load balancing, or energy arbitrage, which consists of storing energy during periods where the price of electricity production is low and unloading it during periods of high prices (which coincide with the hours of greatest demand). At present, several technologies for ESS are being investigated and their importance is fundamental, as much or more than the technological development of energy generation with renewable sources itself. These storage technologies can be classified, mainly, into mechanical, electrochemical, chemical, thermal and electrical [6].

A classification of energy storage systems, according to their origin, is observed in Fig. 1, where the option of mechanical origin, Pumped Hydroelectric Energy Storage, is widely used for applications such as those in this study due to its low cost [6]. However, this option has an important geographical limitation since it requires large volumes of water and two adjacent reservoirs with differences in height. Today, electrochemical storage technologies, such as Lithium-Ion, have taken an important role mainly because of their cost reduction and their high energy density [7]. However, certain environmental impacts related to the waste management from this type of ESS at the end of its useful life, are promoting cleaner technologies such as those of chemical origin, where hydrogen fuel cells stand out [8].

This article analyzes three ESS technologies (LIBs, VRFB, and $H_2SS$) and contextualizes them in a real case study in Ecuador, comparing the viability of these alternatives through a MCDA. The multi-criteria method used is the AHP that allows the alternatives to be compared

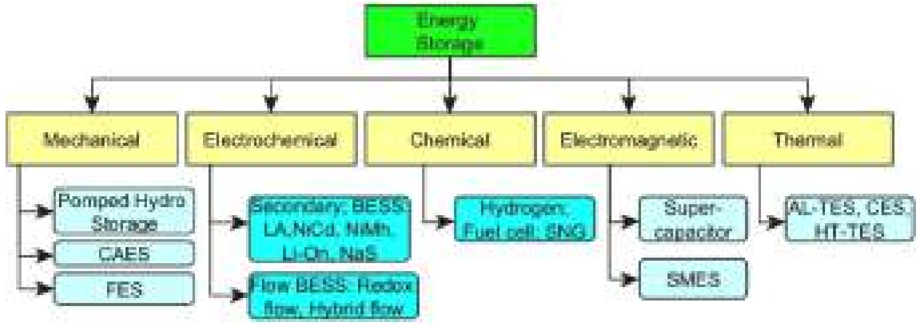


**Fig. 1.** Classification of energy storage systems based on the form of energy stored. Adapted from Ref. [6].

with respect to the various selected criteria and to estimate the weights of that criteria. The proposal is to locate an ESS in a place close to the consumption centers so it provides energy into the electricity grid during the hours of greatest demand. For the case studied, it would displace the energy generated in the Miraflores Thermal Power Plant (UTM: −0.958538, −80.722211) or in the Manta 2 Thermal Power Plant (UTM: −0.961589, −80.67902), both located in the coastal Province of Manabí. To charge the ESS, the STE available during the early mornings at the Paute Integral Hydropower Complex (UTM: −2.575393, −78.505375) would be used (see Fig. 2). This application would have multiple benefits: first, improve the use of the infrastructure installed in the power plants of renewable generation (e.g., hydropower); second, reduce STE due to lack of demand; third, displace polluting thermal generation by generation which is friendly to the environment; and fourth, improve the reliability and quality of energy at consumption points, including reducing losses along the T&D lines.

The article is organized as follows: Section 2 presents the state of the art of ESS and justifies the selection of the three considered in this study. In Section 3, the methodology applied for the study is described and the variables and parameters of the model that describe the operation of the electrolytic hydrogen option are identified. Section 4 presents the application case, which, although it corresponds to the Ecuadorian reality, represents an increasingly global problem, especially in countries with high penetration of renewable energies in their energy matrix; thus, the focus and the method developed could be replicated in other geographic contexts with a similar situation. Next, Section 5 analyzes the criteria and results, and finally Section 6 presents the conclusions and recommendations for future work.

## 2. State of the art

### *2.1. Importance and selection of ESS*

Currently, the ESS are of great importance because of their

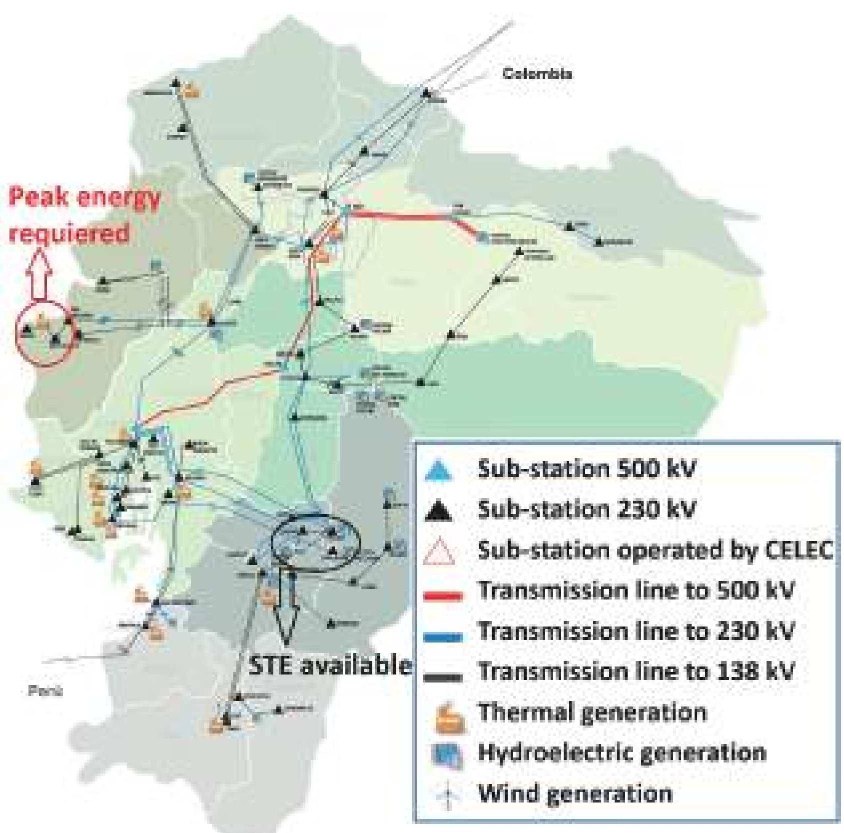


**Fig. 2.** Transmission system of Ecuador. Adapted from Ref. [9]. Use of STE from eastern hydroelectric plants (green circle) during the early hours of the morning to charge ESS located at consumption centers (red circle) and unload during peak hours.

contribution to having a more flexible and reliable EPS. The balance between generation and consumption, with its non-deterministic dynamics, implies challenges that can be approached from different points of view. The traditional approach proposes increasing power and capacity in generation, transmission, and distribution, which implies indiscriminately increasing the electrical infrastructure, to the point where its application has weakened over time, due to economic, social and environmental limitations. Additionally, primary non-renewable energy resources, such as oil and its derivatives, are increasingly scarce or are in sharp decline, largely because of their negative impacts on people's health and the environment in general. The classic paradigm of having a "just-in-time" energy production system entails having a generation and T&D infrastructure that can supply energy when demand requires it with the required quality standards. Generally, the EPS is dimensioned for the most demanding operating conditions, also including a safety factor which means having an infrastructure that will always be under-used.

New approaches to integrating ESS into EPS have aroused particular interest in recent decades. The ESS are mainly aimed at: 1. Reducing the gap between generation and transmission capacity and energy demand, 2. Improving the efficiency of power generation equipment, 3. Avoiding frequent starts and stops of thermal generation plants, 4. Reducing or deferring investment in expanding the electrical T&D network, and 5. Guaranteeing the safety and stable operation of the EPS, among others. In addition, some of these storage systems can contribute to improving the quality of energy with the use of voltage regulators, primary and secondary frequency control, due to their short response times, and even contribute to seasonal solutions (prolonged use, from days to months) [7]. Ultimately, ESS seek to achieve a more efficient and reliable EPS.

Thus, a wide variety of ESS technologies have been developed to satisfy different requirements of an EPS, such as energy density, specific capacity, performance, power output, response time, life cycle, safety and cost [10]. Other studies have included environmental and social aspects, in which human health has been one of the highest weightings for decision making, followed by the levelized cost of energy [11]. Social acceptance, despite being one of the relevant decision-making aspects, is a topic with high subjectivity and difficult to measure, which is why few studies analyze it in detail. ESS can be used throughout the electricity supply chain, from generation to distribution systems to consumers. The selection of an ESS depends on the combination of different technical and usage aspects; consequently, no ESS is suitable for all applications [12], which are often grouped according to the duration of the discharge: power quality (short and medium term) and energy management (medium and long term). Fig. 3 shows the main applications of ESS according to the discharge duration and nominal power. Therefore, ESS comparisons should be made under the same application segment [13], also the selection of different battery types, depend of each distinguished characteristics in power and energy, which then depends on the nature of power required and delivered [14].

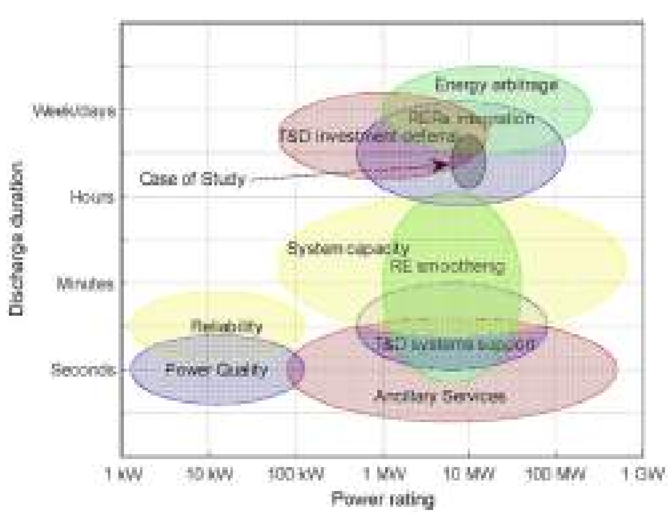


**Fig. 3.** Comparison of power rating with discharge time duration of different ESS. Adapted from Ref. [13].

Baumann et al. [15] study a classification of ESS similar to that found in Ref. [13]. They show the storage technologies based on power and operating time. In the range of tens of MW and hours of operation, the following stand out: PHES, air compression, hydrogen, and electrochemical batteries. On the other hand, Schmidt et al. [12] study the levelized cost of energy for different ESS, classifying them according to the frequency of discharge and their duration. In the application segment of the current study (T&D investment deferral and energy arbitrage), the PHES technologies stand out because of their low cost. However, as stated in Section 1, these technologies depend to a great extent on favorable geographical conditions, which are not always possible to achieve near the large centers of energy consumption (especially in the Ecuadorian coastal area). The present study takes this restriction into consideration and focuses on three technologies that might also apply to energy arbitrage: $H_2$SS, LIB, and VRFB.

Fig. 4 shows the relevance of the ESS based on their operation, where numbers 8, 1, and 9 belong to applications of ETS, T&D Investment Deferral, Energy Arbitrage, and Congestion Management, respectively. For power arbitrage applications, the three technologies mentioned converge.

For the selection of an ESS integrated into an EPS, multiple factors must be taken into account. A technique commonly used to solve this problem is called MCDA, where economic aspects are analyzed and weighted, in an integrated way, as well as social, technical and environmental aspects of each of the technologies under study [11]. In Section 3, the application of the MCDA for the case study is explained.

### 2.2. Flow battery (REDOX)

Energy storage with REDOX flow technologies is an electrochemical system that consists of the reduction and oxidation of two active materials, hence the name REDOX [16]. The most common of these technologies is the one that uses vanadium in its electrolyte; the battery has two electrodes, active materials permanently immersed in the electrolyte in solution. The advantage of flow technologies over conventional battery types lies in the possibility of designing the system with an optimal power/energy ratio, without the need to maximize energy density [7]. The VRFB is the most commercially successful, presenting the highest number of charge-discharge cycles and a lower levelized cost of energy compared to the others in its category [17]. This ESS also has a fast response and can be overloaded or deeply discharged without permanent damage to the system. However, an overload gives rise to possible secondary reactions, such as hydrogen production, affecting the proton exchange membrane [17]. In addition, VRFB offer an important

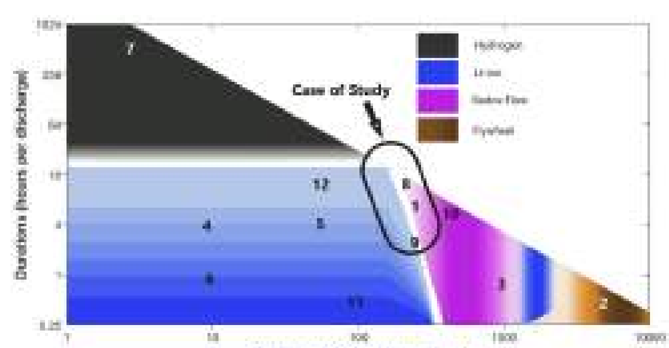


**Fig. 4.** Selection of storage systems, depending on the duration and frequency of loading/unloading. Adapted from Ref. [12].

advantage: the output power and the energy storage capacity are independent variables, since the first is determined by the size of the membranes and the second depends on the chosen electrolytes, their concentration, and volume [18]. Consequently, the design can be scalable, both in power and in storage capacity, in a technically simple way.

VRFB are one of the more suited batteries for stationary usage, as they can be built with a high degree of modularity, have no cross-contamination problems and have an extended system lifetime of up to 20 years and [19]. In other study it is concluded that VRFB produced the smallest environmental impact and it is considered the benchmark battery technology in comparison with electrochemical batteries [20].

Wingren and Johnsson [21] state that ESS from VRFB are emerging as an important alternative for power quality applications, mainly because of their low price, high robustness, and low degradation rate. The study also shows that future prices and performance of VRFB are highly uncertain, although performance is expected to increase and prices to decrease. The study even compares the 100 largest ESS, of which 74 are greater than 10 MW, 65 of them belong to LIB, 2 to vanadium flux, 5 to NaS, 1 to ZCF, and 1 to NiCd.

In the last decade there have been several large-scale projects with VRFB technology, such as the one developed in 2015 by Sumitomo Electric Industries, Ltd., incorporating a flow battery to suppress the fluctuations of renewable energies in the energy systems, and therefore, contribute to the EPS' stabilization [22]. This ESS has a capacity of 60 MWh (15 MW × 4 h) and was installed in a building with a land area of 5000 $m^2$ in the substation of Hokkaido Electric Power Co., Inc. (HEPCO), Japan. Another prominent case study is the construction of a vanadium flow battery with power and capacity of 800 MWh (200 MW × 4 h) in Dalian, China. At the time, the project was cataloged as the largest battery in the world, being the only one with a power greater than 100 MW, made up of VRFB instead of LIB. Its construction began in 2016 [23]; however, there is no information on its progress in recent years.

### *2.3. Lithium-ion family batteries*

Lithium-ion electrochemical battery technology is the most widely used on a large scale and represents over 90% of the total capacity of the electrochemical ESS installed in the world, because of its high efficiency and cost reduction of around 80% between 2010 and 2017 [24]. Its efficiency can vary between 85% and 94% [25], and it has an energy density from 200 Wh/kg [26]. ESS using lithium-ion electrochemical batteries could be one of the most promising options for stationary applications to be implemented in the next decade, considering the projected price reduction in the next three decades [12]. Within the family of LIB, batteries with lithium-iron phosphate cathode ($Li\ Fe\ P\ O_4$) stand out today as their useful life has been considerably improved. However, other technologies in this same lithium family excel in terms of energy density, such as those derived from Nickel Cobalt Aluminum Oxide ($Li\ Ni\ Co\ Al\ O_2$) or Lithium Nickel Manganese Cobalt Oxide ($Li\ Ni\ Mn\ Co\ O_2$) that are prevalent in portable applications.

Currently, energy storage applications with lithium-ion technologies can offer compact solutions. For example, with the use of 40-foot containers, they can reach from 6 to 9 MWh and the same power capacity at a load ratio of 1C, an aspect that relates the download speed with its maximum capacity [27].

### *2.4. Chemical storage system*

Chemical storage is conceived as a secondary type of energy storage through an energy vector obtained from the conversion of a primary source of energy or another energy vector, whose storage is unfeasible on a large scale and for long periods, which happens for vectors in the form of mechanical work, heat energy, or electrical energy [28]. In the latter case, the electrical energy to be stored is used to produce a chemical compound, liquid or gaseous, with a high energy density. This process is commonly known as P2G and, in terms of storage, it is associated with the Production or Charging phase [7]. The most used chemical vectors are liquid fuels, such as diesel or gasoline; or gaseous, such as methane or hydrogen ($H_2$) [29]. When it is necessary to recover the electrical energy consumed in the P2G process, the stored chemical vector is converted back into electricity using an end-use technology, in a reverse process to the previous one, G2P associated with the Regeneration or Discharge phase. The global process, P2P, is shown schematically in Fig. 5.

Of the chemical compounds used as energy carriers, the green or blue $H_2$, commonly known by its origin (obtained from renewable and non-renewable sources with carbon capture, respectively) stands out for its versatility, high density of gravimetric energy, low level of contamination in its processes, and synergy with electricity [30]. However, an overall performance of the P2P or round trip process should also be noted, between 30 and 40%, lower than other energy storage options [31]. Its high energy density, low discharge rate, and low environmental impact could offset this disadvantage.

A differentiating feature of $H_2$SS is its coupling or integration with renewable generation sources, forming an energy supply system in cyclical operation. Thus, $H_2$ is obtained by the process of electrolysis of water; in the final stage of the chain, electricity and water are generated again, in FC or turbines, such that theoretically it constitutes a self-sustainable energy system [29]. The analysis of the $H_2$ production routes, attending mainly to the environmental dimension has been considered in the literature. Thus, Acar and Dincer [32] evaluate various $H_2$ production methods using technical, economic, and environmental criteria. Their results point to electrolysis as the process with the best average performance, with a second place in the environmental dimension. Also, Ozbilen et al. [33] compare the environmental impact of selected $H_2$ production methods, obtaining that electrolysis, coupled with wind generation, is the process with the lowest Global Warming Potential value, 0.855 kg $CO_2$-eq per kg of $H_2$ produced. The sustainability of different $H_2$ production methods has also been analyzed using hesitant fuzzy AHP [34]. Regarding the use of hydropower as a primary source of energy, Ren et al. [2] and Pilavachi et al. [35] suggest that the hydropower-electrolysis system is the most appropriate for the production of $H_2$, considering economic and environmental aspects. For example, in most of the cases (9 out of 15), the first in ranking $H_2$ production process is considered to be the hydropower–electrolysis system (H–EL) and the worst (9 out of 15) is coal gasification [35]. On the other hand, Bamisile et al. [36] study the environmental impact of the production of electrolytic $H_2$ taking advantage of the STE in a hydropower plant in the south east of China with 750 MW of power, obtaining a reduction of 0.127% of the country's $CO_2$ emissions. This work justifies the selection of electrolysis, as a process, and STE as the primary source of energy. Fig. 6 presents a general diagram for the case of the $H_2$SS as a storage medium.

Another differentiating element of the $H_2$SS is its capacity for continuous operation while the $H_2$ and oxidizing agent (air or oxygen) are supplied to the end-use technology used, FC or turbines, which does not happen in battery-type electrochemical storage systems [37]. A comparison of the technical characteristics of the storage systems

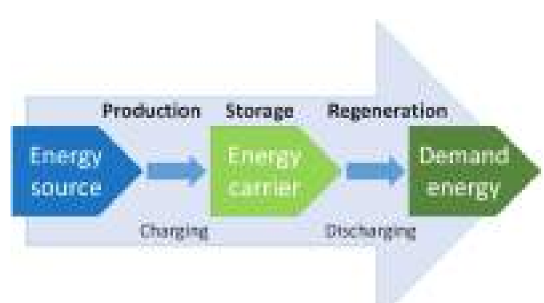


**Fig. 5.** General energy storage scheme. Adapted from Ref. [7].

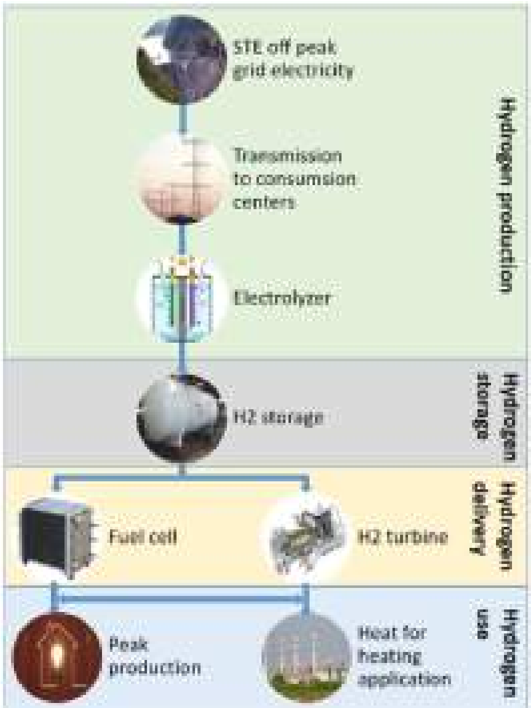


**Fig. 6.** Use of STE through $H_2$ option. Adapted from Ref. [7].

considered in this study is shown in Table 1 [38], where it is observed that the storage efficiency from $H_2$ is the lowest of the technologies compared. Detailed economic studies are necessary to compensate for the costs associated with the loss of energy.

## 3. Methods

This section describes the design and sizing aspects for both a $H_2SS$ and for the two electrochemical ESS (LIB and VRFB) selected. Likewise, an explanation of the AHP used as a method for the MCDA is included as well as the criteria considered for the comparative analysis of the storage alternatives. The AHP method proposed in this paper seeks to meet the need of developing decision making tools for determining the storage technology and operating conditions of ESS for power grid applications [39].

### 3.1. Chemical storage

In this case the design procedure is based on the formulation of an input/output type model of the global $H_2SS$ and of each of the stages that comprise it (Fig. 7), related to the energy conversion processes that take place in the $H_2$ electrolytic system, consisting of: a) the electrolyzer and auxiliary systems; b) the $H_2$ gaseous storage system, in tanks or cylinders; and, c) the system for its conversion or final use, which includes the FC and the treatment of inlet and outlet gases.

**Table 1**
Comparison of technical characteristics of storage systems [38].

| Technologies | LIBs | VRFB | $H_2SS$ |
|---|---|---|---|
| Power Rating (MW) | 0.1–100 | 1–100 | 0.01–1000 |
| Cycling | 2.7–27 years (1000–10,000 cycles) | 33–38 years (12,000–14,000 cycles) | 5–30 years |
| Self-Discharge (%) | 0.1–0.3 | 0.2 | 0–4 |
| Energy Density (Wh/l) | 200–400 | 20–70 | 600 |
| Efficiency (%) | 85–98 | 60–85 | 25–45 |


**Fig. 7.** Block diagram of $H_2SS$.

The characteristics of the $H_2SS$ must be:

a) The $H_2SS$ will be placed in a location close to the site of the final use of the electrical energy generated in the conversion system (FC system).
b) In the electrolytic system the first conversion takes place, from P2G.
c) The electrolyzer considered is of the alkaline type, because of its operational simplicity, technological maturity and costs, although it has a lower efficiency than the Polymer Electrolyte Membrane (PEM) electrolyzer and a possible degradation of its operation because of corrosion [40].
d) $H_2$ is stored in cylinders, in the form of compressed gas, at 200 bars, in a quantity sufficient to guarantee a safe and continuous supply of $H_2$ to the FC system, according to the scheduled daily operation. This type of storage has been chosen considering the amount to be stored, the storage cycle, costs, reliability, end use, and maturity of the storage technology [41]. The reconversion of $H_2$ to electricity (G2P) is carried out in the FC system, generating the power required to satisfy the load profile specified by the peak demand.
e) In this case, PEM-type FC have been chosen, considering the output power, their ability to operate at a variable load, and response time [42].
f) The total P2P process efficiency is determined by the relationship between the output energy of the G2P component and the input energy to the P2G component.

The block diagram of the chemical storage system considered in Fig. 7, shows the Input/Output variables of each stage and other variables of interest.

In the design of the $H_2SS$ (Fig. 7) the Bottom-Up approach is used [43], since the calculation of the input and output variables of the different components or stages of the $H_2SS$ starts from the power that must be generated in the FC system and continues with the calculation of the amount of $H_2$ stored, then the $H_2$ to be produced and, finally, the power required by the electrolysis system to obtain such production. Conceptually, it is assumed that the operation of the global process, P2P, can be represented by a macroscopic model in steady state, with the Input/Output values of $H_2$ in each of the components and global efficiency as the main variables of interest, taken into account for this work.

The formulation and application of the model is presented next:

a) Electric energy to be generated in the End Uses component.
   Its value is determined from the daily power, $P_o$, required to satisfy the load according to the peak demand in the pre-established operating time, $t_0$. It will be calculated for unit values of power (1 MW) and time (1 h) to determine the performance of the P2P process for energy $E_0$ of 1 MWh.
b) Hydrogen consumed in the FC system, $H_{FC}$, $Nm^3H_2$.

$$H_a = \frac{E_o}{\eta_{fu} \times E_E \times F_U} = 616.94\ \left[Nm^3 H_2\right] \tag{1}$$

For the selection of $\eta_{fu}$ value we propose use 0.57 taken from the average value of previous studies about PEMFC. Thus Staffell et al. [44] stablish a maximum efficiency of 0.65 for 2020 year. While Nazir et al. [45] determine a range of efficiency between 51 and 67%. Finally, the results of experimental tests carried out in the

Micro-grid Laboratory of the University of Cuenca [46] obtains the value of 54%.

c) Stored hydrogen.

In the calculation of the stored quantity, an Overdesign Factor, $F_S$, of 10% is included [47] since storage containers, composite cylinders, cannot reduce their pressure below established safety criteria.

$$H_{Storage} = 1.1 \times H_a \cong 682 \left[Nm^3 H_2\right] \tag{2}$$

It should be specified that this value is useful only to measure the storage tank, while the value of $H_2$ in this component in the model is $H_a$, considering a stable operation.

d) Electrical energy required by the $H_2$ production component.

The $H_2$ to be produced in the electrolytic system corresponds to that required by the FC system, such that $H_p = H_a$. The electrical energy to be supplied to the electrolytic system is calculated considering the efficiency of the P2G conversion, $\eta_e = 0.75$ [44], the HHV of $H_2$ and the daily production of $H_2$, $H_p$.

$$E_{Elec} = \frac{H_p \times E_E}{\eta_e} = 2,924[kWh] \tag{3}$$

The total electricity consumption in this component must include the electricity consumption of the auxiliary systems of water treatment, gas compression, measurement and control, which represents around 16% of the electricity consumption in the electrolyzer [24], such that the total consumption is:

$$E_i = 1.16 \times E_{Elec} = 3,392[kWh] \tag{4}$$

e) Total performance of the P2P system.

It is expressed as the ratio between the output and input energy of the overall system.

$$R_{Total} = \frac{E_o}{E_i} \times 100 = 29\% \tag{5}$$

This performance is lower than those indicated in several studies for the P2P or round-trip process of $H_2$SS. Thus, in Ref. [7] an average value of 30% is indicated, while in Ref. [31] a round-trip efficiency range is established between 35 and 40% and in Ref. [45] for the complete P2P cycle, an efficiency range between 34 and 44% is reported. However, it should be noted that in these calculations only take into account the efficiency in the electrolyzer and FC, without considering the auxiliary systems of water treatment, gas compression, measurement, and control which adversely affect the efficiency of the entire process. All of these topics have been included in this study.

### 3.2. Electrochemical storage

In the case of electrochemical ESS, its sizing is simpler compared to $H_2$SS. Electrochemical battery technologies allow, in most cases, a modular design; for example, adding more battery banks parallel to the DC voltage bus can increase storage capacity without modifying nominal power. Today, options with basic infrastructure and commissioned in a short time are available in the market, which positions them as widely used in the world. For LIB, companies such as Samsung [48] or Wärtsilä [49], offer turnkey solutions in 40-foot containers with storage capacities close to 9 MWh per container with an efficiency greater than 85%.

In the case of VRFB, as with LIB, the market offers pre-assembled solutions with storage capacities of 2 MWh that occupy an area close to 220 $m^2$, with a yield of 60% and a necessary volume of electrolyte from the typical energy density of this technology of 20 Wh/l [50].

### 3.3. Multi-criteria decision analysis

Multiple-Criteria Decision Analysis (MCDA) is a sub-discipline of operations research that evaluates multiple conflicting criteria in a decision-making process. It is a valuable tool applicable to solving problems that are characterized as a choice among alternatives. There are many possible ways to classify the existing MCDA methods. According to Baumann et al. [11], MCDA methods are separated into Multi-Objective Decision Making and MADM. MADM methods concentrate on problems with discrete decision spaces, where a set of decision alternatives has already been predetermined [15]. MADM can be separated into elementary methods, Classic Compensatory Methods, also called multi-attribute utility theory methods (American school), and outranking methods (OM–European school). Elementary methods include non-preference information methods without a decision maker (e.g., dominance, maximin, maximax) and multi-attribute information methods with a decision maker input as weighted sum method (WSM), also called weighted product method or value measurement model [15, 51]. WSM is one of the most frequently used MADM methods. These methods are direct and require minimum calculation efforts. On the other hand, they do not consider tradeoffs or potential inconsistencies of attributed weights to different criteria [15].

When using a WSM method, a value *V* is assigned to each alternative. These scores produce a preference order for the alternatives, such that *a* is preferred to *b* ($a > b$) if and only if $V(a) > V(b)$. When using this approach, the various criteria are given weights w that represent their partial contribution to the overall score, based on how important this criterion is for the decision-maker (DM).

Equation (6) shows an additive value function (multi-attribute value function), one of the most commonly used approaches [51]:

$$V(a) = \sum_{i=1}^{m} w_i v_i(a) \tag{6}$$

Where $v_i(a)$ is a partial value function reflecting alternative *a*'s performance on criterion *i*. The partial value function must be normalized to some convenient scale (e.g., 0–10). Using equation (6), a total value score $V(a)$ is found for each alternative *a*. The alternative with the highest value score is preferred. This is a simple and user-friendly approach where the DM only needs to specify value functions and define weights for the criteria to receive useful help with his or her decision [51].

The AHP developed by Saaty [52] is a common decision-making method when dealing with multi-criteria problems. The AHP has many similarities to the multi-attribute value function approach. Consequently, their results are directly comparable [51,53].

The major characteristic of the AHP method is the use of pairwise comparisons, which are used both to compare the alternatives with respect to the various criteria and to estimate criteria weights. In the pairwise comparison, a special ratio scale (from 1 to 9) is used [52]. The results from all the comparisons are put into a matrix from which an overall ranking of the alternatives can be aggregated. The alternative with the highest overall ranking is preferred to the others [51,54].

AHP has some widely accepted concepts, such as structuring complexity in a hierarch, making pairwise comparisons, and using redundancy of judgments to improve accuracy and deal with «fuzziness» [53].

The AHP utilizes a tree structure in order to simplify complex decision-making problems resulting in simplified subproblems. AHP can be developed into four main steps [35]:

1. Creation of a tree structure, with an objective, criteria, and alternatives.
2. Evaluation of each alternative solution in relation to each criterion.
3. Calculation of the criteria weighing factor with subjective evaluation using pairwise comparisons.

4. Synthesis of the results of stages 2 and 3 in order to calculate the overall each alternative's evaluation.

Fig. 8 presents the structure for this paper's case study where there is one objective (ETS), three criteria (technical, economic, and environmental), and three ESS technological alternatives.

a. Objective

Defining the application is a key factor for the choice and design of a suitable ESS. The utility-scale application in the case study is ETS, also referred to as energy arbitrage. In this application, energy is stored during periods of low-electricity market prices and discharged during times of high prices [55].

b. Criteria

- Economic (LCC): For the economic assessment, most of the studies use LCC or LCOE as a performance indicator to compare various ESS for different applications. LCC is proposed for a systematic comparison of alternatives, considering the total expenditures (initial investment, capital, replacement, operation, energy, and disposal costs) over the entire economic lifetime of a product. International guidelines, such as IEC 60300-3-3, explain the purpose of LCC and outline the general approach [55]. The LCOE is a well-known analysis tool and is calculated by dividing the total annualized cost of storage ($) by the annual energy throughput of the system (kWh) [56].
- Environmental (CF): CF is proposed for these criteria. CF quantifies the GHG emissions of a product over its entire life cycle, in order to determine its contribution to global warming. CF follows LCA principles, an environmental management tool that considers not only direct emissions but also all upstream processes (i.e., resource extraction) and downstream processes (i.e., decommissioning) [55].
- Technological: For technological aspects, three sub-criteria can be defined: maturity (technology's track-record; global installed capacity), technological flexibility (ability to respond to fast-changing operation conditions), and technology performance (efficiency, life cycle, cost). The latter refers to technological properties [11]. The present case study analyzes only the third sub-criterion based on three parameters: efficiency, energy density, and number of cycles (calendar lifetime).

The weights ($W$) for each criterion are defined in the literature or through consultation with key stakeholders.

c. Alternatives

As shown in Fig. 8, the ESS's alternatives considered for ETS in Ecuador are: 1) $H_2$SS; 2) LIBs; and 3) VRFB. These three storage systems will be fed by STE from Paute's hydropower complex. From Equation

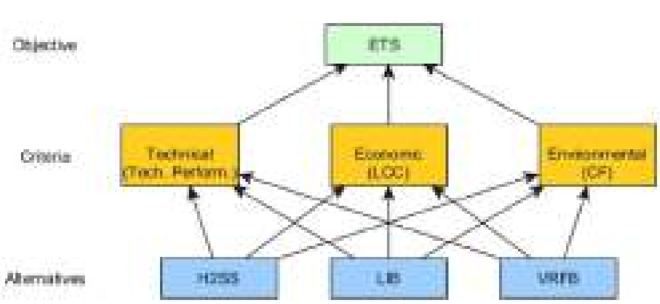


**Fig. 8.** Tree structure for the three ESS's alternatives selected for ETS. Adapted from Ref. [35].

(6), it is possible to determine a prioritization index for each alternative:

$$V_i = W_1 C_{1i} + W_2 C_{2i} + W_3 C_{3i} \tag{7}$$

For the $C_{ni}$ values, for each criterion $n$, the best of three alternatives $i$ is assigned with 10 points, and a proportion value is assigned for the other two.

As for the case study, a deeper analysis of criteria, as well as the weights assigned to them, are presented in Section 5. Next section details Ecuador's case study.

## 4. Case study

Historically, Ecuador's energy matrix has been characterized by its high dependence on oil. Proof of this is that, in 2018, it represented 87.5% of the structure of the primary energy supply, followed by hydroelectricity (5.9%), and natural gas (4.7%). Regarding the secondary energy offered, only 22.5% was electricity and the rest corresponded to oil derivatives [4] (Fig. 9).

Petroleum derivatives are consumed mainly in the transportation, industrial, and residential sectors and, to a lesser extent, in the generation of electricity [57]. Indeed, in 2018, 48.8% of energy demand came from the transport sector, while 14.5% corresponded to the industry sector, and 13.2% to the residential sector [4], as indicated in Fig. 10.

In the electricity subsector, the power generation matrix has two main sources, hydroelectricity, and to a lesser extent, conventional thermoelectric energy, based on the combustion of petroleum derivatives and natural gas. The high contribution of the first has been consolidated in the last decade [57]. This low portfolio of sources makes the Ecuadorian electricity generation matrix vulnerable because it depends on the volatility of oil prices (and its derivatives) and water seasonality. Consequently, the diversification of the primary sources used for electricity generation has been a priority in Ecuador in recent years, to reduce thermoelectric generation progressively (and its environmental impacts) and the eventual import of energy, making the Ecuadorian electricity sector more independent from external sources and environmentally sustainable.

Because of the presence of abundant water resources, during the last decade, Ecuador has built several hydroelectric plants to increase the participation of renewable energy in the electricity generation matrix. In addition, the Ecuadorian government aims to increase the currently incipient participation of NCRE (i.e., wind, solar, and biomass) in the electricity sector [57]. In the next five years, large-scale wind farms (160 MW in total) and photovoltaic solar projects (200 MW) are expected to be connected to the national electricity system, increasing the share of electricity produced by NCRE. Table 2 presents the evolution of the effective power capacity in Ecuador's power grid or National Interconnected System (SNI, for its acronym in Spanish) during the 2008–2018 period. In 2018, the total installed power in the system was 7177 MW, of which renewable installed capacity represented 70%, while non-renewable power represented 27% (1959 MW). The contribution of NCRE sources was marginal, with 183 MW in total, which represents 2.5% of the total installed [58].

Energy contribution, according to the type of plant, was: hydroelectric 20,661.59 GWh, thermal 4177.90 GWh, photovoltaic 34.77 GWh, biogas 45.52 GWh and wind 73.70 GWh [4]. In other words, hydroelectricity represented more than 83% of the total generated in 2018 (Fig. 11).

Regarding the projected growth of demand, considering the average scenario, for the period 2018–2027 a growth between 5 and 8% is estimated (Fig. 12) [58].

### 4.1. Problem to be solved

The hydroelectric plants in Ecuador, in operation and construction, are located mainly in rivers that flow into the Amazon basin; the rest are in rivers that flow into the Pacific Ocean. Table 3 shows the current and

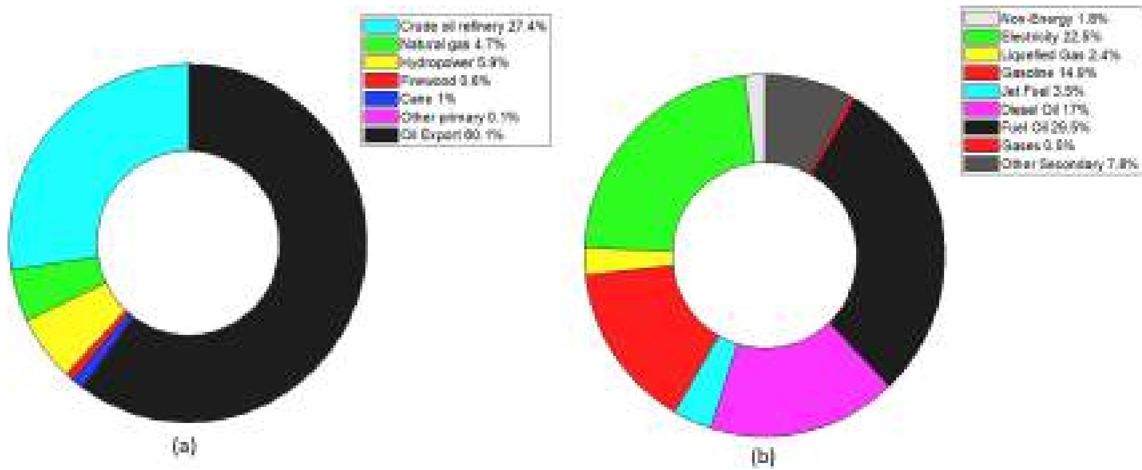


**Fig. 9.** (a) Primary energy supply, (b) Secondary energy supply in Ecuador. Adapted from ARCONEL [4].

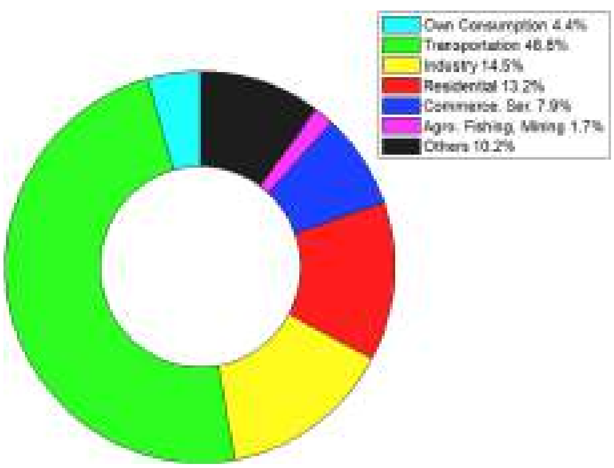


**Fig. 10.** Energy demand by sectors in Ecuador [4].

planned hydroelectric generation installed capacity both on the Amazon River slope (east of the Andes Mountain range) and in the basins with slopes towards the Pacific Ocean (west of the mountain range), with the hydroelectric capacity installed in the eastern zone equal to 88% of the country's total hydroelectric capacity. Hydroelectric plants' location on both sides of the Andes Mountain range has been an option that partially balances the seasonality of the water resource. On the east side (Amazon basin), March to September are generally characterized by abundant rains that cause large flows of water in the rivers. On the contrary, October to February are drier and the participation of hydroelectric generation is limited (it can be reduced up to a third of its nominal capacity) [59]. On the west side of the country (Pacific basin), the rainy season occurs between January to May. Fig. 13 shows the relative pattern of water entry into the main hydroelectric plants. From October to December water flow is reduced on both sides of the Ecuadorian Andes, because rain levels are also reduced. As a result, generation of hydroelectricity is limited during these months.

The seasonality of hydropower generation in the country could jeopardize electricity supply and its sustainability in the medium term, particularly during the last months of the year, as shown in Fig. 13. NCRE and some (relatively old) thermoelectric plants could help partially offset the effect of seasonal rains on hydropower generation in the future. Although Ecuador is looking for alternatives to help the generation of electricity in the coming years, especially during the dry season, the large-scale storage alternatives that could help to strengthen the EPS have not been analyzed in detail.

Indeed, in the rainy season there may be the case of water discharges from the reservoirs of hydroelectric power plants, which would give rise to excess hydroelectricity or STE, understood as the energy that could be generated by starting from turbinable water but that must be spilled due to several factors, such as: limited demand, high availability of water resources in the dams due to the rainy season or for operational reasons [61]. This excess energy could be stored in electrochemical batteries or produce $H_2$ via electrolysis (for direct combustion or transformation through FC), while improving the capacity factor and the efficiency of the hydroelectric plant.

The other important component of the Ecuadorian power system corresponds to thermoelectric generation. Despite its low contribution to the electricity generation matrix in the country, it plays an important double role in the operation of the SNI. First, it provides energy security during contingencies or dry periods in hydroelectric plants; and second, it fulfills the function of guaranteeing the quality of electrical service.

Having energy security is vital for a society's normal development. For residential users, and fundamentally commercial and industrial

**Table 2**
Evolution of effective power capacity in the SNI period 2008–2018 [58].

| Year | Biomass | Thermal | Solar | Hydraulic | Wind | Biogas | Total |
|---|---|---|---|---|---|---|---|
| 2008 | 94.50 | 1598.00 | 0.00 | 2028.00 | 0.00 | 0.00 | 3720.50 |
| 2009 | 94.50 | 1793.43 | 0.00 | 2028.61 | 0.00 | 0.00 | 3916.54 |
| 2010 | 93.40 | 1894.59 | 0.00 | 2211.54 | 0.00 | 0.00 | 4199.53 |
| 2011 | 93.40 | 1904.25 | 0.00 | 2203.52 | 0.00 | 0.00 | 4201.17 |
| 2012 | 93.40 | 2130.25 | 0.00 | 2232.62 | 0.00 | 0.00 | 4456.27 |
| 2013 | 93.40 | 2094.10 | 3.46 | 2232.62 | 16.50 | 0.00 | 4440.08 |
| 2014 | 136.40 | 2204.83 | 24.42 | 2237.28 | 16.50 | 0.00 | 4619.43 |
| 2015 | 136.40 | 2227.93 | 23.55 | 2398.03 | 16.50 | 0.00 | 4802.41 |
| 2016 | 136.40 | 2148.19 | 23.57 | 4412.78 | 16.50 | 1.76 | 6739.20 |
| 2017 | 136.40 | 1838.61 | 23.57 | 4481.01 | 16.50 | 6.50 | 6502.59 |
| 2018 | 136.40 | 1958.71 | 23.57 | 5035.14 | 16.50 | 6.50 | 7176.82 |

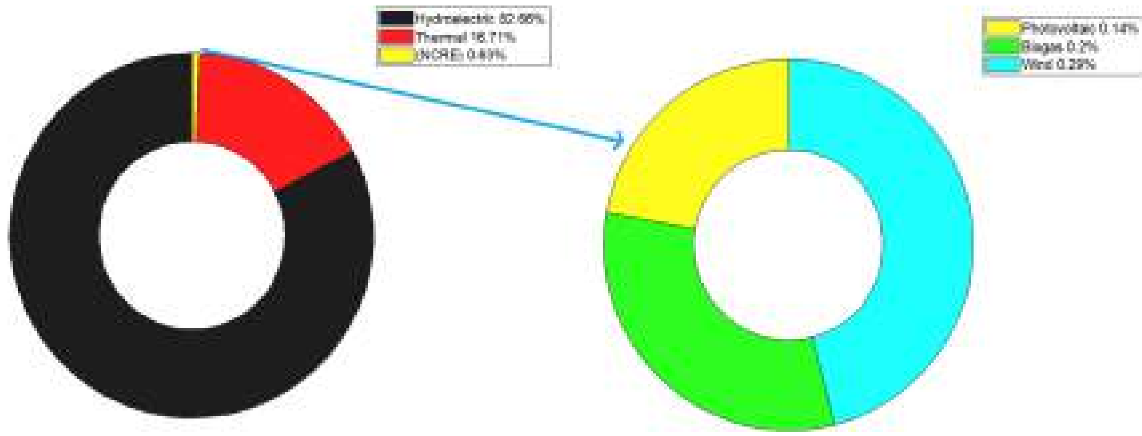


**Fig. 11.** Contribution of power plants - SNI. Adapted from Ref. [58].

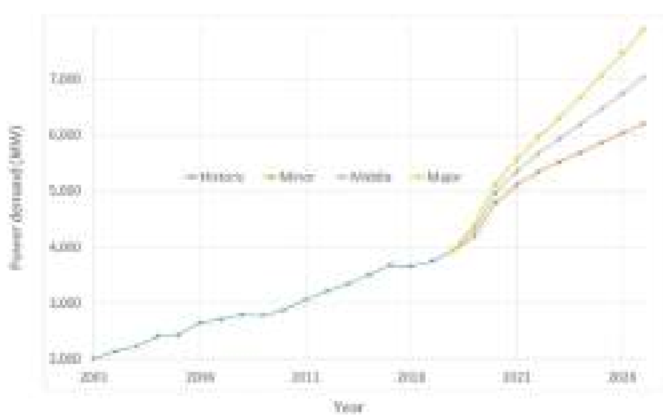


**Fig. 12.** Projection of power demand (MW) in Ecuador in generation terminals [58].

**Table 3**
Current (as of November 2019) and potential hydropower capacity on rivers of both sides of the Ecuadorian Andes [58].

| | Pacific Ocean basin | Amazon River basin |
|---|---|---|
| Current hydropower capacity (MW) | 590 | 4409 |
| Potential hydropower capacity (MW) | 2600 | 5200 |

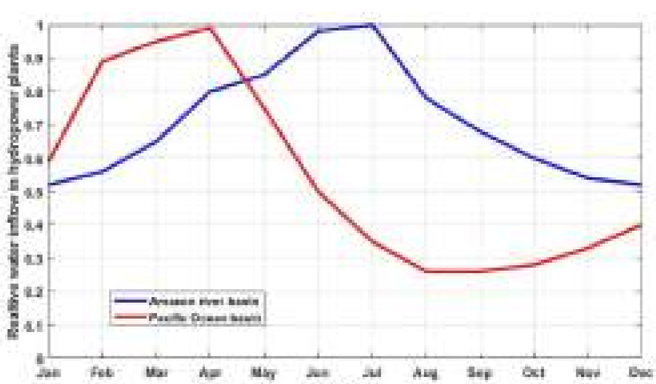


**Fig. 13.** Monthly water flow variation in hydropower plants located in the Amazonian River and the Pacific Ocean basins in Ecuador. The lines show mean values from 1964 to 2016. Adapted from Ref. [60].

users, it is essential to have the certainty that electrical energy is available when needed. It will allow for production planning and growth projection without worrying about energy limitations. Thus, in recent years, particularly in 2010 (after the low-water energy rationing of 2009–2010), the generation park has increased, and there are thermal power plants that guarantee energy during severe droughts.

The second very important use of thermal power plants is associated with guaranteeing the quality of service, overcoming operational limitations of various kinds. In particular, it refers to Forced Generation that is required in certain areas or regions of the country. To explain these operational requirements, thermal power plants are generally geographically located next to the main consumption centers, since, unlike renewable energy plants, a thermal power plant does not require specific conditions for its location. By being conveniently located near consumption centers, losses due to energy transport or unavailability due to transmission failures are greatly reduced.

It is common that as demand increases in consumption centers, limitations to transport energy arise and voltage drops from distant hydroelectric generation plants increase. In the first case, it is possible that some transmission line, transformer, or other structural element of the electrical system becomes saturated and limits the capacity to satisfy certain demand from the generator with the cheapest dispatch, which is supplied by local power generation (generally thermal which is more expensive). In the second case, the voltage profile in long transmission lines gradually decreases because of their losses. Although generation plants work at maximum voltage values allowed in the regulations, when electricity reaches distant consumption centers, their voltage levels are lower than the minimum established in the regulation. Having local generation with adequate voltage levels reduces line losses and guarantees regulatory compliance. This is the current case of Ecuador, with its main hydroelectric plants in the Amazon, east of the Andean Mountain range, but several of its important centers of consumption are cities on the far west coast.

Thus, due to either of the two operating limitations, there is Forced Generation, which is the need to operate thermal power plants close to consumption centers and to be flexible in terms of their minimum number of hours of operation, since normally these operating limitations occur during peak hours of electricity consumption (from 6:00 p.m. to 10:00 p.m.). The average generation cost of these plants is much higher than the generation average at the national level, as explained below.

On the other hand, in the early hours of the morning (from 11:00 p.m. to 6:00 a.m.), the demand decreases and many times not all the energy available is generated in the hydroelectric plants because the demand is covered. Consequently, the volumes discharged from the dams (STE) increase in those hours, or in the following days, since the dams operate at levels very close to the discharge level. Thus, under these conditions, faced with a small increase in the flow of the rivers that feed the reservoirs of the hydropower plants, in a few hours there will be discharge of significant volumes of water. However, if there is a higher demand during the early morning hours, hydroelectric power plants can produce more electricity (at a lower cost than thermal power plants), which would optimize the use of this renewable resource, increasing, at the same time, the plant factor of said plants.

From an economic point of view, the variation in the demand for electrical energy during the 24 h of the day, together with the limitation of its storage, causes a wide variation in the price of electricity depending on the time at which it is produced. Each generator or generation plant has its own production price per kWh of energy, depending on many factors: technology used, cost of its inputs, operation and maintenance costs, investment and amortization cost, profitability, among others. The problem of economic dispatch of generation plants has been widely studied [62] and, as a result, a short-term hourly production planning is obtained for the different generation plants, each one with its own production cost. The energy management policy allows the plants with the most economical dispatch to have priority and work throughout the day at their maximum available capacity, and as demand increases, it incorporates the following cheaper generators into production, always respecting their operating restrictions, including environmental ones.

However, when comparing the variable cost of production (costs directly related to energy production, such as fuels, lubricants, maintenance, etc.) of the plants that are incorporated to supply the peak of electricity demand (6:00 p.m. to 10:00 p.m.), with the variable cost of production of the hydropower plants that continue to work in the early morning, ratios of 50 to 1 can be obtained in the Ecuadorian EPS. This is because even the most expensive plants (economically and environmentally) operating with diesel for forced generation can work during peak demand hours.

From the analysis of the dispatches made for the national electricity system, it can be seen that every day, during peak demand hours, thermal power plants operate in coastal areas due to power flow restrictions (saturation of network elements) and voltage compensation from the point of view of demand. It is observed that at least 15 MW of power during peak hours (from 6:00 p.m. to 10:00 p.m.) is constantly dispatched. This is the reason why, in this study, the proposed ESS will have a nominal capacity of 60 MWh, corresponding to 15 MW of power during 4 h.

This specific analysis for the Ecuadorian case can be extended to countries or regions with a similar context, particularly to those with an important hydroelectric contribution.

### 4.2. Solution proposed: STE storage

As shown on Table 2, the hydropower installed in Ecuador doubled in the last 10 years. Several of these plants have reservoirs that allow their production to be regulated to the country's medium and long-term energy needs and also to adapt to variations in daily demand. However, other plants do not have a reservoir and do not have the capacity to store energy (they are known as run-of-the-river hydroelectric plants), and only take advantage of the flow that the river has at a certain time. In other words, if it cannot produce immediately because of any operational restriction, the energy potential of the flow is not used. The importance of this description in the Ecuadorian context lies in the fact that the largest plant in the country (Coca Codo Sinclair, with a capacity of 1500 MW) has this characteristic. Given this background, it is important to highlight that 57% of hydroelectric energy in Ecuador comes from run-of-the- river power plants [63], and they are given priority in energy dispatch over another similar power plant that has a reservoir.

Because of these two factors (the increase in installed hydropower and the preference in the daily dispatch of run-of-the-river plants over the plants with reservoirs), the Paute Integral Hydropower Complex and other plants with reservoirs have been displaced in the daily energy dispatch, to where there is STE every month, energy that could be used if demand increases in the early morning, which is when more energy is wasted. The opportunity cost of this energy is minimal, since, by not taking advantage of it immediately, that energy is poured. This is how Ecuador has become an electricity exporting country to its neighboring countries of Colombia and Peru, even in the dry months of the Amazon basin [4].

Under the aforementioned, Table 4 presents the STE that could have been used in the "off-peak" hours, calculated for the average of the years 2017–2019 (measured in MWh/day), for the three generation plants of the Paute Integral Hydroelectric Complex [64].

Knowing that there is STE in "off-peak" hours of electricity consumption, energy that is economical and friendly to the environment, and that during peak consumption hours thermal energy (expensive and polluting energy) is required near the points of consumption, the proposal is to combine these two realities through an effective ESS; this would specifically be undertaken during the early mornings (from 11:00 p.m. to 06:00 a.m.) to store energy in a location close to high consumption points that require Forced Generation during peak hours, energy that comes from the hydropower plants of the Paute Complex. For our case, it should store enough to deliver 15 MW for 4 h, 60 MWh per day, value that is fully met in any case (Table 4). When the hour of maximum consumption arrives, instead of producing energy with a conventional thermal power plant that operates with oil, energy is taken from the ESS and delivered to the EPS in better technical and economic conditions. Once the power and capacity of the ESS have been delimited, it is possible to find, from Figs. 3 and 4, that for this case study, the operating power would be in the range of tens of megawatts in periods of hours, which is limited for the applications of: integration of renewable sources, T&D investment deferral, and especially energy arbitrage.

In relation to the economic aspect, a favorable opportunity exists that justifies the viability of ETS or energy arbitrage. The variable cost of production of the Ecuador's hydroelectric plants is barely 0.2 cents USD/kWh of energy, whereas these costs for thermal power plants in the Manabí coast area are 5 cents USD/kWh (Manta 2 plant) and up to 10 cents USD/kWh (Miraflores plant) [65]. In other words, the energy coming from water sources during the early morning hours would be stored in an ESS, to displace 15 MW of (thermal) energy 50 times more expensive during peak hours.

Considering a nominal power of 15 MW and energy storage capacity of 60 MWh (15 MW for 4 h), for chemical storage, it would require approximately 204 MWh/day to meet the need, since the total efficiency of the P2P system is 29%, as shown in Subsection 3.1. In the case of LIB and VRFB, yields of 85% and 60%, respectively, have been considered. Therefore, the daily energy values to be fed from the hydroelectric plants would be 70.6 MWh and 100 MWh, in that order. The energy required for the three storage alternatives are well below the total STE values indicated in Table 4.

**Table 4**
STE of the Paute River plants (Mazar, Molino, and Sopladora). Daily-Monthly average obtained from the last 3 years of operation, expressed in MWh/day.

| Average (2017–2019) | | | | |
|---|---|---|---|---|
| Month | Mazar | Molino | Sopladora | Total |
| Jan | 0 | 0 | 416 | 416 |
| Feb | 195 | 283 | 2555 | 3033 |
| Mar | 269 | 1185 | 819 | 2274 |
| Apr | 361 | 1921 | 1013 | 3295 |
| May | 921 | 2582 | 1516 | 5019 |
| Jun | 1018 | 4115 | 2788 | 7921 |
| Jul | 1084 | 4867 | 3168 | 9118 |
| Aug | 830 | 2594 | 3223 | 6647 |
| Sep | 283 | 475 | 1992 | 2750 |
| Oct | 332 | 636 | 481 | 1449 |
| Nov | 90 | 101 | 788 | 980 |
| Dec | 79 | 381 | 1098 | 1559 |

Table 5 shows the capacity to meet the ESS' demand with respect to the daily-monthly average STE in the Paute complex, appreciating that the demand is widely covered for any of the three storage alternatives throughout the year. For example, for any day in January (the worst scenario) the available STE represents 416 MWh, which can supply more than double what is required by a $H_2$SS, almost 6 times what a LIB would require and more than 4 times for a VRFB system.

This result motivates future studies to analyze the possibility of allocating the $H_2$ obtained from the surplus of the generable power to chemical, petrochemical, or other types of industries. Also, the method developed in this paper would allow the analysis of energy arbitration case in other countries or regions that have reservoir hydroelectric plants with representative volumes of STE in their operation. That is the case of the Itaipu hydropower plant, between Brazil and Paraguay [66], in Nepal [67], and in Brazil, combined with other renewable energies [68].

## 5. Analysis of criteria and results

### 5. Economic analysis

As mentioned in Subsection 3.3, both LCC and LCOE are used as performance indicators for comparing ESS technologies; LCOE is calculated by dividing the total installed cost of storage (USD-annualized) by the annual energy production of the system (kWh). In DOE, US [56] the total installed costs (USD/kWh) are compared between VRFB and LIBs, with values of 554 and 411, respectively, for a 10 MW–4 h storage system, which is in the range of the solution proposed in this case study (for $H_2$SS, there is only information for 100 MW, 10-h system). This comparability gets stronger for the next few years. By 2030 installation costs for the flow batteries are expected to decrease two-thirds to between USD 108 and USD 576/kWh with the VRFB's cost not exceeding USD 360/kWh. For large-scale stationary, LIB the costs would be between USD 245/kWh and USD 620/kWh [69].

The battery LCC are calculated using the annuity method (net present value - NPV) whereas the operation period for the entire energy storage system is assumed to be 20 years [55]. Energy applications (i.e., ETS) are cheaper than power applications (frequency regulation and voltage regulation) [31]. Both LCOE and LCC differ from one scenario to the next, mainly due to different operational characteristics considered in the applications. LIBs perform better economically in all the applications than the other batteries. However, the performance of a VRFB is comparable with LIBs for energy applications [31,55].

The LCOE of thermoelectric plants (diesel and fuel oil) vary from one country to another, depending on various factors related to costs of investment, operation and maintenance. For reference, at the international level, this LCOE fluctuates between 14 and 56 USD cents/kWh [70,71]. In Ecuador, for the case study analyzed and for the year 2019, the average generation cost of the Manta 2 thermoelectric plant was 9 USD cents/kWh while that of the Miraflores thermoelectric plant was 24 USD cents/kWh [65]. These values can be compared with the LCOE of the three storage alternatives with a rated power of 15 MW, for the ETS as an application. The charging cost is reflected in electricity's leveled cost. The LCOE will change if the electricity source changes because electricity production costs differ by source. The charging cost will not be considered in our case study as the source for the three ESS alternatives is the same: hydropower. Therefore, storage levelized cost (excluding charging cost) could be a better performance indicator than electricity leveled cost for comparing the ESS [31]. Lazard's Levelized Cost of Storage (LCOS) analysis compares several storage technologies and concludes that LIBs are approximately 30% cheaper than VRFB for wholesale applications such as energy arbitrage or frequency regulation [72]. In addition, Schmidt et al. [12] conclude that LCOS of different technologies will reduce by one-third to one-half by 2030 and 2050, respectively, with LIBs likely to become most cost efficient for nearly all stationary applications from 2030 [12]. On the other hand, VRFBs are associated with higher uncertainties and should be considered rather indicative. However, VRFBs seem to perform well under economic aspects in applications with a high energy-to-power (E/P) ratio [55]. Additionally, studies, such as Mongird et al. [73], estimate that VRFBs could have a leveled cost of energy storage lower than those of the LIBs type in the medium and long term.

Based on the information above, it was determined that LIBs are the best alternative for any indicator (LCOE, LCC, and LCOS) for the present case study. From the economic perspective, this technology is currently the best one to replace Ecuadorian thermopower generation for the analyzed power grid application.

### 5.2. Environmental analysis

Along with the economic evaluation, environmental performance is an important aspect for the selection of energy storage technologies. However, there is little information on environmental performance, especially for electrochemical batteries. To measure this performance, LCA is used in order to compare several technologies based on the level of emissions of $CO_2$ eq/kWh [31]. LCA is an environmental management tool to assess the impacts and resources used throughout a product's life cycle [74]. For LCA analysis, the system boundaries include raw material production, construction, operation, and decommissioning (a cradle-to-grave analysis technique). In comparing different energy storage technologies, some studies assess the impacts from cradle-to-grave, whereas others consider cradle-to-gate without including the electricity to charge the batteries in the use phase because the GHG emissions in this phase depend on the electricity mix of each location [31]. As in the economic analysis, hydropower is the source considered to charge the three ESS alternatives therefore the present analysis adopts the cradle-to-gate scope.

In Table 6, the row corresponding to LCA presents cradle-to-gate values for LIBs and VRFB, while for the $H_2$SS alternative the values correspond to cradle-to-grave. However, the amount of $CO_2$ per kWh for $H_2$ technology is considered the lowest in the range (50.6) because the energy that comes from hydroelectricity generates fewer emissions

**Table 5**
Level of demand coved by the proposed ESS.

| Month | Required [MWh/day]<br>$H_2$SS LIBs VRFB<br>203.5 70.6100 | | | |
|---|---|---|---|---|
| | [MWh] | Coverage percentage [%] | | |
| Jan | 416 | 205% | 590% | 416% |
| Feb | 3033 | 1490% | 4292% | 3033% |
| Mar | 2274 | 1117% | 3221% | 2274% |
| Apr | 3295 | 1619% | 4668% | 3295% |
| May | 5019 | 2469% | 7110% | 5019% |
| Jun | 7921 | 3892% | 11,221% | 7921% |
| Jul | 9118 | 4481% | 12,918% | 9118% |
| Aug | 6647 | 3266% | 9417% | 6647% |
| Sep | 2750 | 1351% | 3896% | 2750% |
| Oct | 1449 | 712% | 2053% | 1449% |
| Nov | 980 | 481% | 1388% | 980% |
| Dec | 1559 | 766% | 2208% | 1559% |
| Average | 3705 | 1821% | 5249% | 3705% |

**Table 6**
Economic and environmental merits when comparing the three ESS.

| Evaluated characteristic | $H_2$SS | LIB | VRFB |
|---|---|---|---|
| LCOE USD/kWh [31] | 0.48 | 0.05–0.20 | 0.32–0.37 |
| LCC €cent/kWh [55] | N/A | 31 | 44 |
| LCAs (g $CO_2$ eq/kWh) [31] | 50.6 1620[a] | 177–810 | 40.2 |
| CF (kg $CO_2$ eq/kWh) [55] | 0.42–1 [75] | 0,45 | 0,58 |
| Economic merit | 2.60 | 10 | 6.32 |
| Environmental merit | 7.94 | 2.27 | 10 |

[a] Emissions from electricity production also included.

compared to other conventional sources. Similarly, CF includes battery, production, installation, and battery operation (electricity lost during charge/discharge of each ESS). The batteries' end-of-life handling is not considered because of insufficient data [55]. For comparative analysis, the environmental impact of battery production becomes the differentiating element as the installation of these systems represents a minimal impact while the CF of the operation, which depends on the internal efficiencies of each equipment, is already considered in the technological comparison section (Table 1).

The environmental impact of battery production is associated with the amount (the mass) of the battery that will be produced [55]. VRFB shows low CF per kg of battery produced because of their simple manufacture, whereas their low energy density reduces this advantage on a per kWh basis. On an energy capacity basis, the CF of both VRFB and LIB are quite similar [55] as shown in Table 6. Hydrogen production/storage for power applications is in the same range as well [75]. However, despite no reliable sources regarding recycling of stationary battery systems in the literature, VRFB would have additional environmental merit as the recycling of its electrolyte is assumed to be high (simple recovery) as compared to LIB [31,55].

Considering this analysis, the VRFB results the best alternative for both environmental indicators (LCA and CF) for the present case study.

Meanwhile, new players in the power grid such as electric vehicles (EV) could play an important role in energy storage systems. For this study, 60 MWh could be reached with the use of 4000 EVs connected to the grid with an available capacity of 15 kWh each, this without taking into account the potential from the second-life applications of electrochemical batteries such as LIB nowadays widely used in EVs. In environmental terms, reuse of these batteries could improve the weight of their environmental indicators by increasing the useful lifetime in addition to reducing costs due to recycling. There is no doubt that future challenges of ESS will be related to environmental aspects as these technologies become more widespread.

### 5.3. Technical analysis

As stated in Subsection 3.3, it is possible to determine a prioritization index for each ESS alternative. In addition to energy density, the most influential technical parameters affecting cost and environmental performances are round-trip efficiency, and cycle length (lifetime) [30]. For example, if efficiency is evaluated (Table 1), with values of 29% for $H_2$SS, 85% for LIBs, and 60% for VRFB, 10 points are assigned to the best (LIB) and by a simple proportion to this efficiency, 7.06 is assigned to VRFB and 3.41 to $H_2$SS. The other two parameters were evaluated accordingly for the present case study.

### 5.4. Results

By integrating Table 1(technical characteristics) and Table 6 (Economic and environmental merits), Table 7 is obtained as a result of applying the AHP, where the prioritization index between the analyzed storage technologies is determined, for the application defined (ETS) as the problem to be solved in the case study.

From the literature [15] and based on the professional judgment of the authors of this paper, using pairwise comparisons, the beginning weights proposed for each criterion are: Economic (35%), Environmental (35%), and Technical (30%); however, a sensitivity analysis is also is included with different assigned weights. Social aspects are not considered as they refer to social acceptance and regulatory frame. These sub-criteria are not easy to measure and, for Ecuador's case, they can be considered the same for every ESS's technology as there is no experience so far with any of these alternatives at the power system level.

**Table 7**
AHP's results for ETS by comparing three ESS.

| Criterion | Weight | $H_2$SS | LIBs | VRFB |
|---|---|---|---|---|
| 1.- Economic | 0.35 | 2.60 | 10.00 | 3.62 |
| 2.- Environmental | 0.35 | 7.94 | 2.27 | 10.00 |
| 3.- Technical | 0.30 | | | |
| 3.1.- Efficiency | 0.10 | 3.47 | 10.00 | 7.06 |
| 3.2.- Energy density | 0.10 | 10.00 | 5.00 | 0.75 |
| 3.3.- Life cycles | 0.10 | 8.57 | 4.29 | 10.00 |
| Total | 1.00 | 5.90 | 6.22 | 6.55 |

### 5.5. Sensitivity analysis

The sensitivity analysis is conducted based on a key aspect of any MCDA or AHP: weights variation [11]. For the evaluation of the three storage alternatives, with the use of the AHP, four cases were carried out. These cases were the base case (close to an equal weighted case), and three predominant-criteria cases for each of the criteria considered. For this, the predominant criterion was assigned a weight of 60% and the other two 20% each. Table 8 shows the results.

## 6. Conclusions

This study analyzes the challenges that EPSs face when operating with renewable technologies, which are friendlier to the environment than fossil technologies, but require complementary management strategies to improve their effectiveness and efficiency, so that they allow, as much as possible, the displacement or replacement of fossil energy use, one of the main causes of global warming. Furthermore, renewable generation infrastructure is not always fully utilized, despite the primary renewable resource being available. For its part, the T&D infrastructure is normally underutilized in "off-peak" hours, while in "peak" hours it is not always able to satisfy the demand of the main consumption centers, making it necessary to incorporate local thermoelectric energy. In Ecuador, this incorporation can be up to 50 times more expensive than the corresponding renewable generation.

With the application of ESS on a large scale, the integration of renewable generation results in benefits of energy arbitrage and postponement of investments in the T&D system, in addition to reducing losses and improving the electrical system's reliability. To these technical benefits, economic benefits are also added, because of the reduction in the overall cost of generation, and other environmental advantages are obtained by reducing GHG emissions, by substituting fossil-based generation.

In order to recommend the best ESS alternative for the case study, the AHP's tree structure was used to simplify this complex decision-making problem. The AHP method, based on pairwise comparisons, results a useful tool when selecting the alternatives with respect to the various criteria and allows to estimate the criteria weights. Therefore, the analysis developed in this paper contributes with a decision-making tool for ranking storage technologies for power grid applications.

For the analysis of ESS options, LIBs was selected for its efficiency and low cost, VRFB for its robustness, versatility, and durability, and $H_2$SS, for its clean operation and energy density. With real data from the Ecuadorian EPS dispatch, it can be seen that for the period 2017–2019 the STE of the Paute Integral hydropower complex has the capacity to feed an ESS of 60 MWh/day, from any of the three selected storage technologies, of which LIB presents greater efficiency, requiring 71

**Table 8**
AHP's results for ETS by comparing three ESS with sensitivity analysis.

| Style code | Third | *Second* | First |
|---|---|---|---|
| Scenario | $H_2$SS | LIBs | VRFB |
| 1: Base Case (equal weighted case) | 5.90 | *6.22* | **6.55** |
| 2: Economic-predominant criteria | 4.62 | **7.74** | *5.36* |
| 3: Environmental-predominant criteria | *6.76* | 4.65 | **7.91** |
| 4: Technical-predominant criteria | **6.52** | *6.31* | 6.29 |

MWh/day.

From the analysis of the base case (Table 6) the VRFB option is recommended for the application studied, energy arbitrage. From the economic perspective, LIBs can be considered the best alternative for stationary electrochemical energy storage. The LCOE of the LIB shows its competitiveness with respect to the current average generation cost of the Miraflores and Manta 2 plants. However, when comparing the LCOE values of the three alternatives selected with those of other thermoelectric plants operating in Ecuador, all of them are competitive. While LIB currently represent the most economical alternative, ESS cost projections could put VRFBs ahead in first place. However, the information available on this type of ESS is scarce, incorporating a degree of uncertainty into its economic projections. In the comparison prioritized by the technical criteria, the three alternatives have a similar performance, with the $H_2$SS slightly higher. While, by prioritizing environmental aspects, VRFB technology prevails.

Finally, as greater integration of renewable generation is achieved, whether concentrated or distributed, the incorporation of an ESS in the EPS would be more justified, by achieving better use of the installed infrastructure and greater stability and efficiency of the EPS. However, selection of the best ESS technology must be regularly evaluated, due to its continuous technological, environmental, and commercial advancement. The methodological approach and analysis procedure developed in this work is a contribution to this purpose and could be replicated in other case studies, taking into account their specificities and characteristics, especially, where there is the possibility of generating low-cost electricity from STE, as is the case in Paraguay, China and Brazil, between others.

## Credit author statementst

Fausto Posso Rivera: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. Javier Zalamea: Conceptualization, Methodology, Software, Supervision, Writing – review & editing. Juan Espinoza: Investigation, Methodology, Writing – review & editing. Luis Gerardo Gonzalez: Conceptualization, Data curation, Formal analysis, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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