ENERGY STORAGE AS A SYSTEM RESOURCE

Balancing Investor vs Consumers Benefit

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ABSTRACT

The origins of the electric industry can be traced back to the invention of the battery. However, Energy Storage Systems (ESS) have never been considered as a part of the electricity supply chain. Even though there has been an increase of government mandated storage investments in power grids, market driven investments are still lacking sustainable business models. Now, with the possibility that cost reductions of the technology make it viable for widespread utilization, multiple efforts have been devoted by the academia and industry to design its incorporation into electricity markets. A large majority of the proposals have been devoted to develop mechanisms for their incorporation in ancillary services markets or for arbitrage, considering storage as another market player, both still with little success in providing sustainable benefits to energy consumers and investors alike. In this paper, we demonstrate that Large Scale Energy Storage excels when incorporated as a service provider in electricity markets. Our proposal considers ESS as a grid resource, available to the ISO to achieve the optimal mix of resources in the day ahead dispatch. We demonstrate that in the Colombian system, a large ESS used in this manner may achieve high benefit-cost ratios. The results also indicate that current market designs need to evolve in order to take better advantage of energy storage and renewable energy resources.

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1 INTRODUCTION

The origins of the electric industry can be traced back to the invention of the battery [1]. The device has been in use ever since for a multiplicity of low power applications in our daily life. However, it has never been considered as a part of the electricity market supply chain. In fact, none of the modern energy market designs include energy storage as a grid resource and very few consider their participation as a generation resource in ancillary services. The consensus on power system architecture still defines the electric energy supply chain as Generation, Transmission, Distribution and Retail; and operates with the axiom that *electricity is a commodity that has to be produced at the exact time it is demanded by a customer* [2]. This has been the driver for the design of energy markets and their rules for transactions [3]. In fact, it has created several intrinsic inefficiencies at planning and operation for ensuring proper reliability and quality of supply at all times, due to the need to ensure reserves are in place for handling uncertainties on the balance of the power system [4]. Up to now, the same consensus has hold that the only resources able to handle those uncertainties are the generators and markets have designed ancillary markets around them.

Improvements in costs and energy density of storage technologies have opened the door to their widespread incorporation into the electricity supply chain [5, 6]. There are different technologies able to provide energy storage like pumped hydro, flow batteries, lead-acid and lithium-ion, among others. However, since around the beginning of this decade grid scale energy storage with lithium-ion batteries has been gaining traction into the mainstream due in major part to the ubiquity of mobile consumer products and electric vehicles [7]. Battery prices have been dropping as the production learning process has been accelerating [5, 6, 8], and the trend of cost reductions is expected to continue in the future [9, 10]. It is currently normal to have Li-ion battery facilities in the tens to hundreds of megawatts [11].

Large scale implementation of electric energy storage eliminates the historical paradigm of requiring a precise and permanent balance of generation and load. It allows to withdraw electric energy from the network when there is excess and accumulate it to deliver it later when the need arises. This capacity, enhanced with the advances in supervision, control and communications, opens an universe of possibilities for new services for the power system based on energy storage through new market and business models. Since the goal of the market is to find the optimal mix of resources to maximize overall welfare [12, 3, 13], different market incorporation mechanisms need to be designed and tested in order to find the best alternatives with the greatest benefit to society. In this paper we explore different services that ESS can provide to the power system and conclude that ESS excel when incorporated as a power system resource, maximizing consumer welfare by optimizing the overall cost of operation.

The most studied applications in the literature, which have also the most potential to bring benefits to consumers are time-shift, ancillary and congestion services. This work will analyze how a combination of these services can generate improved consumer welfare in the Colombian power system. In particular, we intent to draw a contrast between considering ESS as a merchant resource in the current electricity marketplaces, and considering it as a system resource as part of the grid, similar to transmission and distribution assets. ESS as a merchant participant obtains its revenues through price arbitrage, by purchasing energy in periods of low prices, which generally occurs during times of low demand, and then selling it during periods of high prices. The benefit of the investor lies in the margin between the purchase and sale prices. Otherwise, ESS as a system resource can be incorporated into the market optimization as a tool for providing elasticity to the demand, still minimizing the cost of generation. Both approaches were simulated considering 5 years worth of Colombian economic dispatch data from 2014 to 2018, thus obtaining the maximum possible earnings by an ESS merchant participant, buying in low prices and selling when prices are high every day, assuming a perfect knowledge or the future, and also obtaining the total consumers' benefit during the 5 years period by incorporating ESS as a grid resource. For the ancillary services benefit calculation, a comparison will be made between what has been paid to generators in the market versus the cost of an ESS able to perform the same service. For congestion management services, given that they are more localized, it is more difficult to identify a concrete example and thus some generalized examples will be performed, but applying the methodology of minimal cost investment for grid services used in the Colombian transmission planning process.

2 ENERGY STORAGE TECHNOLOGY AND APPLICATIONS

Until recently, the only viable storage alternative at system scale was the use of pumped-storage hydro resources. This technology has been around for decades, providing niche services in selected regions in the world. It requires sites with very particular geography that permits the siting of the upper and lower reservoirs and has constructing challenges and environmental impacts similar to a large hydro generator. There are not foreseeable technological developments that will change this situation or have the potential to reduce its investment costs.

Large-scale storage of electricity using batteries has recently boomed thanks to the development of Lithium-ion technology due to its high demand for batteries in laptops, cell phones and electric cars. This has generated an important path of cost reduction, prohibitive until recently, which allows it now to be considered as a viable alternative for electricity systems [5, 6].

Lithium-ion batteries are based on electrochemical processes where storage is achieved by reversible chemical reactions producing or absorbing electrical energy. Each time a cycle of charge and discharge occurs, it permanently affects a small percentage of the chemical mixture and therefore, these devices have a limited shelf life, related to the number of cycles of operation before being permanently damaged. In the case of Li-ion, these values are usually within 3500 to 5000 cycles (cycle is referred to a total charge and discharge operation)[14]. Assuming that a battery is used to store energy in the early morning and discharge it during peak hours on business days, it performs around 250 annual cycles, which corresponds to a useful life of 15 to 20 years. The technological development of this type of batteries is focused on increasing energy density (amount of energy that can be stored per unit of volume or weight), reducing costs and minimizing operational risks. Currently the costs for a complete solution are around USD$600 per kWh with 1 hour of storage, or USD$380 per kWh with 4 hours of duration, according to a 2018 analysis performed by NREL [15], and shown in figure 1.

In a different publication, NREL also identified an expected reduction in Li-ion technology prices for the next 10 years as shown in figure 2 [9].

The modularity of energy storage solutions using batteries allow for the supply of power system services by large scale concentrated facilities or by distributed installations operating as a single resource. In the latter case, appropriate use of redundant communications and cloud services are able to guarantee coordinated and reliable operation through centralized commands.

The efficiency of an energy storage system, measured as the ratio of output energy over input energy, is in a range of around 85% to 90% [16, 17, 14]. The major part of the losses in the charge and discharge processes obey to the AC-DC-AC conversion systems and the temperature conditioning systems for the batteries. For this reason, energy storage can not be regarded as an asset that adds energy to the power system, like a generator, but as an asset which provide services to the system and consumes a part of the energy flowing through it, making it similar to a transmission line or a FACTS device.

To connect the energy storage resources, being Li-ion or other electrochemical technologies, to the power system, DC to AC power conditioning devices are required. By controlling the behavior of the interconnection equipment, the charge, discharge and the characteristics of the energy delivered

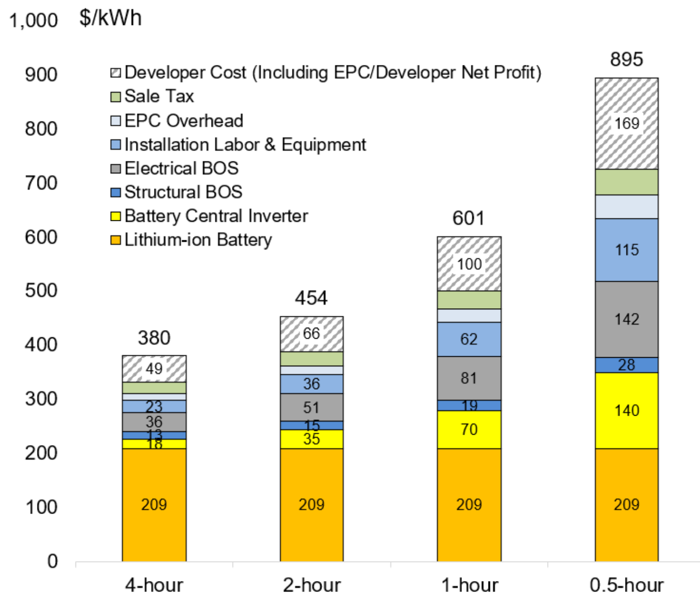


Figure 1: Current costs for Li-ion energy storage systems

to the system can be controlled. In this way, the amount of energy delivered can rapidly vary as well as the voltage at which this delivery is made. This feature allows batteries to behave sometimes as a generator and sometimes as a load, creating the potential to provide various services to the market. A widely referenced report from 2010 by Sandia National Laboratories [18] describes 17 different applications of energy storage in power systems, than can also be grouped into 5 categories, shown in figure 3.

From the list in figure 3 it can clearly be observed that energy storage applications extend beyond one category in the supply chain. For example, electric supply applications can be used in every step of the chain (G, T or D), while those about grid system are exclusively related to transmission and distribution for enhancing capacity at particular points in the grid. The special characteristic of energy storage is that all of these applications can be performed by the same storage asset connected to the grid, by simply selecting the appropriate operational parameters in their control system.

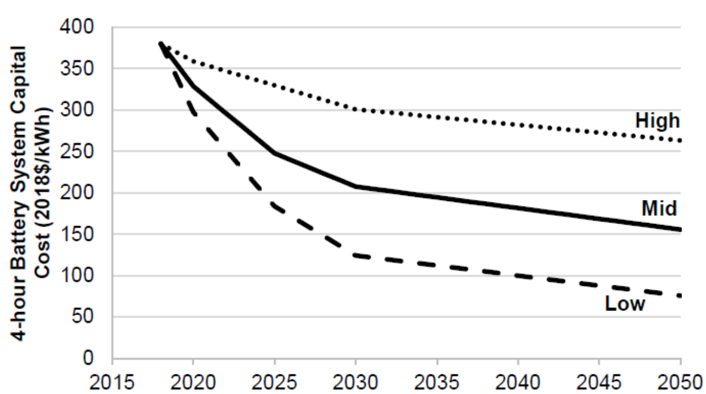


Figure 2: Costs projections for Li-ion energy storage systems

Category 1 — Electric Supply
1. Electric Energy Time-shift
2. Electric Supply Capacity
Category 2 — Ancillary Services
3. Load Following
4. Area Regulation
5. Electric Supply Reserve Capacity
6. Voltage Support
Category 3 — Grid System
7. Transmission Support
8. Transmission Congestion Relief
9. Transmission & Distribution (T&D) Upgrade Deferral
10. Substation On-site Power
Category 4 — End User/Utility Customer
11. Time-of-use (TOU) Energy Cost Management
12. Demand Charge Management
13. Electric Service Reliability
14. Electric Service Power Quality
Category 5 — Renewables Integration
15. Renewables Energy Time-shift
16. Renewables Capacity Firming
17. Wind Generation Grid Integration

Figure 3: Five categories for energy storage applications in power systems

The multipurpose characteristic of energy storage faces its greatest challenge in the capture of all the consumer benefits due to its incorporation in the electricity supply chain. In the majority of competitive markets, all the potential services of energy storage are tightly regulated, separated in different market segments and are supplied by different asset categories, such as, generation, transmission or distribution. This fact makes the provision of multiple services by energy storage an impossible feature due to regulation and devoid electricity demand of the economic and reliability benefits of its integration into the grid.

3 THE PRODUCT AND SERVICES OF THE ELECTRIC POWER SYSTEM

Energy storage has the potential to transform the power sector, therefore, it is convenient to differentiate the nature of the activities that make up the electricity market in order to help establish its potential for change regarding its design, its marketplaces, its temporal dynamics, and the appropriate participants for each market. We are giving special consideration on how Energy Storage relates to the product and services definitions of this section.

3.1 Electric Energy as the sole product on the marketplace

At the heart of the electricity market, the only product that is required by customers in order to fulfill their needs and perform work is electric energy. As we are going to explain ahead, other concepts like balancing, transportation and reliability should be considered as services. They are necessary to deliver energy to customers and ensure system stability and reliability but are not the product itself. Without electric energy there are no other products. In fact, there is no need of a system itself. It has no sense to buy frequency regulation, voltage control or balancing by themselves if there is no bulk electric energy, but we can think of buying only energy without any doubt. In fact, it is electric energy the object of bilateral contracts, without any consideration of other variables other than quantity and price. This does not mean that services are unnecessary, but they are not the product of the electric system. It is telling that the product that forms the base of the electricity market and is traded between producers and consumers is electric energy, measured in kWh or MWh.

As a matter of fact, the only resource in the supply chain able to deliver this product is the generator. It is the only one able to transform a primary energy source, being it heat, water flow, wind or photons, to electric energy. Putting it in another way, generation is the only resource able to introduce new electric energy into the grid.

Energy Storage Systems do not match this concept, given that, first, they do not supply new energy into the grid. Actually they need to be charged with electric energy from the grid before they can inject it back to it. And second, due to their conversion cycle of electric-chemical-electric energy with efficiencies close to 85%-90%, a battery has losses that makes it a net energy sink. Therefore, its electric energy balance is always negative, requiring more energy at the input than what it can deliver back to the system. Energy Storage Systems are similar to other equipment of the grid, like capacitors, SVCs, STATCOMs or FACTS. These devices serve the grid, ensuring the security and quality parameters for delivering energy, but consuming some energy in the process.

3.2 Electric Power System Services

The geographical spread of the grid, the variability and inherent uncertainty of the demand and some energy sources, hamper the accomplishment of the main goal of the integrated power system, which is to get the product (electric energy) from the generation to the consumer in a secure, reliable and economic manner. As such, several supporting power system services, in addition to the main product, should be provided by all available resources fit to provide reliability, quality, availability and flexibility [19]. In this aspect, generation is not alone. Transmission and distribution assets, energy storage and active demand resources can now effectively supply several or even all of these services. The combination of the energy product and its services comprises both the wholesale and retail electricity markets. The mechanisms by which these markets operate and transact are directly related to the nature of the energy product and its services. The main services required to fulfill the goal of a secure, reliable and economic electric energy supply are electricity transport, balancing, reliability and quality.

ELECTRICITY TRANSPORT Electric energy is seldom produced in the same site where it is required. Hence, electricity transport is required to connect supply and demand. In an interconnected power system, electricity transport enables the load to gain access to cheaper and more reliable energy sources. High voltage transmission and lower voltage distribution are the two main expressions of this service. Even though they are treated differently by regulation, their business fundamentals are quite similar.

Because of its technical characteristics, electricity transport has historically been treated as a natural monopoly, therefore receiving regulated payments. Today, in almost every market, there are rules that introduce competition for grid expansion, but the mechanism for its remuneration is directly related to the amount of investment and generally it does not change over the lifetime of the project. The most used mechanism for this competition is through dutch auctions called upon by power system planners or operators. Investment in energy transport provides increasing capacity for energy transactions between geographically separated producers and demand, allowing the free flow of energy from efficient energy resources, avoiding grid congestion. The resulting increase in social welfare provides the economic resources for markets to compensate transmission and distribution investors through established regulated or agreed upon payments.

Energy storage could provide transport services due to the fact that, as transmission lines move energy in space, it do move energy in time. Energy storage helps avoid temporal congestion and allows the grid to be used at times when it has remaining capacity. Therefore, enhancing the transmission and distribution planning with energy storage could unlock more efficient investment plans, maximizing consumer welfare.

BALANCE The dynamic characteristics of electric load and the networked physics of electricity impede a viable outside control of the amount of energy that can be served to a particular load, unless it is controlled by the load itself. There always needs to be an available source of electric energy whenever a customer connects more consuming loads at their facilities. Failure to have this, produce changes in system frequency that can result in loss of quality for the loads and even disconnection of synchronous generators, giving way for blackouts if the imbalance is large enough. For that reason, power system designers and planners introduced a time based, incremental set of control strategies for managing the imbalances, such as, primary and secondary frequency regulation, demand following and even spinning and cold reserves [4]. Even inertia can be considered as a very fast balancing response from the spinning masses of synchronous generators.

Historically, it has been considered that generators are the only resource able to provide the balancing service required to maintain frequency stability. The traditional economic construct to procure this service is trough payments to the generators as compensation for reserving part of its generation capacity for providing the balancing service. In practice, the market asks a generator to trade the selling of the energy product with providing a service with an uncertain generation profile. For this to work, the generator expects to earn more revenue in providing the service than selling its product. Payments for this service have been based on a two-part charge: one related to the cost of capital for the availability of generation capacity, and the other related to the opportunity cost of the energy product not sold, but being reserved for maintaining balance.

Today, energy storage resources can be utilized to provide balance to the system, and in some cases with better performance than most generators, given its fast response to inject or absorb electric energy from the grid [20]. The increasing incorporation of renewable generation to the system and the inherent variability of this generation has created a resulting need for more balancing services both in response time and in the amount of energy required. This enhanced balancing service is commonly called Power System Flexibility. The main resources expected to provide flexibility are storage, demand response and speedy thermal gas units.

RELIABILITY Electric power systems cover extended areas, are highly interconnected, and work under the customer expectation of total availability 24 hours a day, 7 days a week. These characteristics makes it the quintessential complex system. In order to achieve those very strict requirements, the power system needs to be designed and operated with special care of the amount of infrastructure required and operational practices that guarantee its compliance. In fact, the widely assumed n-1 rule originates from the need for the system to still operate properly even with the loss of one element of the grid. Ranging from adequacy and security [21], short and long term, global and localized, the reliability service takes a large amount of attention in the design of electricity markets.

In the long term, for the system as a global entity, the concept of reliability resides in matching demand needs with generation capacity three or more years into the future. Long term reliability is achieved by auctions where the market buys availability from the generators to supply the expected energy consumption. In most markets this translates into payments for generation capacity, but in a few, like in Colombia, are based on payments for ensuring energy supply in the future. Energy storage systems are effective for providing capacity services, however, for long term energy supply they are not a viable option given the requirements of storing large amounts of energy for extended periods of time of several months to a year.

Localized reliability services aim to maintain system stability and to control overloads in the grid. The most evident example is congestion management in transmission lines. The solution methods for such congestion are: fixed generation scheduling, independent of its cost, in the short term; and grid expansion in the long term. Energy storage systems are a cost-effective alternative for short term reliability services due to its ability to inject power in precise locations, charging when there is no congestion in the transmission grid. In fact, the characteristic of its control equipment allow for a faster response than generators to events in the network, and without restrictions about minimum up-time, ramps, or technical minimums.

QUALITY In addition to an stable frequency and voltage, every consumer require some minimal quality characteristics from energy, such as: waveform, harmonics content, voltage dips and swell, among others [19]. Generally, this service is treated as the less relevant, mainly due to the fact that there are several simple and economic mechanisms to comply with the minimal requirements. Energy storage can also contribute to the systems quality service given its ability to condition the output voltage using its inverter.

4 ENERGY STORAGE IN WHOLESALE ELECTRICITY MARKETS

4.1 Literature review

Energy storage integration in electricity markets has been a major focus of research in the past decade. In the current state of the industry, there is a rush to identify proper economic mechanisms to incorporate energy storage into power system markets and operations in order to reap its many expected benefits in reliability and cost efficiency. Literature has established that Energy Storage produces consumer welfare benefits measured in reduced overall cost of service and increased reliability in the power system. Sioshansi et al. [22] analyzed arbitrage (time-shift) opportunities for storage with the conclusion that consumer welfare is increased when storage is able to reduce prices on-peak, even when it increases them off-peak. Additional societal benefits can be obtained by optimizing the need of grid assets, emissions reduction and effective renewables integration [18]. Strbac et al. [23] list more benefits in helping the transition to a low carbon electricity supply in reducing the need for investment and reducing system operation and balancing costs. In [24], Sioshansi also found that there is a direct link between market structure and the ability of ESS to impact social welfare, where in perfectly competitive generation cases, ESS does not generate welfare losses; but in markets with strategic generating firms, a merchant ESS owned by generators can reduce social welfare. In that paper, he stresses the need for long term incentives for storage investment in order to achieve consistent social welfare benefits over time. In the same line, Virasjoki et al. [25] established that ESS can increase consumer welfare depending on market competition and asset ownership. They found that a welfare-maximizer owner under perfect competition invests the most in storage, as it uses storage to mitigate economic inefficiencies, and consumer welfare is considerably higher than that of the investor in any case of market organization. However, they found that there is also a risk of increased market power when merchant investors participate. In energy-only markets, energy storage can produce arbitrage and capacity value to the consumers in similar fashion as peak generators, as also stated by McConnell et al.in [26]. Luburic et al. [27] compared ESS operation under a vertically integrated market and a deregulated market. Their paper concluded that ESS produce social welfare benefits under vertically integrated markets that do not translate into a deregulated market due to the interest of merchant investors to maintain price differences to ensure profits. Grijalva et al. reached a similar conclusion in [28], in that the benefits are found for vertically integrated markets, but it doesn't work on deregulated markets. For deregulated markets, a major benefit is that ESS mitigates uncertainty as found by Yu et al. in [29], specially when they contain large proportions of renewable sources. In fact, McPherson shows that ESS provide benefits both at low and high shares of renewable generation due to its contribution to system flexibility [30]. Merchant investors tend to under use ESS compared with welfare maximizing ESS owners [31, 25].

Several authors have also found that benefits for the consumers from the incorporation of energy storage are larger when it is able to simultaneously perform all its potential applications as stacked services. A seminal report from Sandia Laboratories [18], proposes a service synergy matrix relating energy storage services that can be aggregated and their benefits accumulated using the same asset. They concluded that there are multiple combinations able to provide increased value to the consumers, taking advantage of the multipurpose characteristic of ESS. Strabac et al. [23] describe all the potential benefits to the UK power system when permitting an ESS to provide all the combined services across all available markets overlooking the existing regulatory restrictions. Even when installed as as a distributed resource, ESS can take advantage of parallel revenue streams, as shown by Braeuer et al. [32]. On the other hand, if the multi-service characteristic is neglected, the benefit of ESS incorporation into the power system will be undervalued [22] and result in under-investment. Authors conscious about this drawback, have proposed alternative methods of compensation for the contribution to welfare not accounted for [33, 29]. The key concept is that the value of ESS to the power system cannot be deduced from an individual service standpoint. However, there is a strong limitation for ESS to provide stacked merchant services along others regarded as regulated like grid support because it crosses the boundary set by current unbundling of electricity market. From the literature, it can be derived that there are two sides in the discussion in how to incorporate ESS in electricity markets, the individualists (merchant first, social welfare second) and the systemics (value from social welfare) [30].

In contrast with the potential benefits described above, it has also been found that ESS can reduce welfare when certain market conditions exist or under specific ownership models. Multiple works have found that there is a strong contradiction between the competitive merchant participant model and social welfare. According to Sioshansi in [24], the incorporation of ESS as a merchant participant can reduce welfare whether standalone or owned by a generator, when there are strategic generating firms and the sector lacks perfect competition. A similar effect is shown by Virasjoki et al. [25] in that storage investments would not occur or be inefficient when market power is exerted, restricting the benefits of increased consumer welfare produced by storage. Contreras [34] also demonstrated that strategic bidding by an ESS increases its profits but results in an overall decrease of social (consumer) welfare. Several authors have indicated that incorporating ESS as a merchant competitive participant can also increase market power, with the consequential detriment to consumers welfare. In scenarios with high amount of market power, there is less appetite for merchant ESS investment and, in contrast, low market power can lead to more investment in it [31]. Mokhtari [35] simulated a precise market condition where there is a dominant producer and found that ESS increases the market power of such generator. The incompatibility between ESS merchant participation and consumer welfare is such that Waterson in [36], states that there is a missing money and market opportunity when considering only private incentives instead of public desirability for ESS investment. Suazo et al. [37], Yu [29] and Fernandez [38] found that profit maximizing and social welfare are contradicting objectives for optimizing ESS participation in the market.

According with the preceding discussion on the literature, a delicate balance exists between consumer welfare and investor returns for incorporating ESS efficiently into electricity markets. Further, there is no guarantee that the status quo on market designs can provide consumer welfare improvements by assuming merchant participation of ESS in electricity markets.

While there is a consensus on the potential benefits of ESS in power systems, still the mechanisms for incorporation into electricity markets are an open research topic. Recent literature proposes several different models to integrate ESS into market designs, and several countries have developed or are in the process of developing regulation to accommodate them. the most studied topics have been the incorporation as a merchant participant in day ahead markets and in ancillary markets. Most of the recent work discussed the incorporation of storage in electricity markets trying to accommodate it to fit into the established market structures, seldom considering the multi-service characteristic or the economic benefits to the consumers. Sometimes there is no analysis of the impact to the customers or social welfare at all, but only mechanisms by which they are incorporated into the Day Ahead Market.

Most authors have considered energy storage investors as merchant participants in day ahead markets. This concept is guided by a preconceived view of competition occurring only at the day ahead market. Siddiq, Sioshansi and Conejo [31] evaluated the opportunity of ESS as both a profit maximizing and a welfare maximizing agent in day ahead markets, using the price differences in a day as a revenue maker. Grijalva found opportunities in arbitrage due to swing in prices in PJM's real market data [39], using a statistical method to maximize profits. The variable nature of price differences guided several works on finding methods for considering uncertainty in the bid process, trying to maximize revenues for the investor [40, 41, 42, 43, 44]. The volatility of price differences has also raised questions on the profitability and certainty of return of investment of Energy Storage Systems as merchant participants. Dvorkin [45] proposed a convoluted mechanism to accommodate merchant revenue for grid services, even when understanding that the spatio-temporal characteristic of ESS are more suited for a regulated service. Spodniak [46] and Zakeri [47] found that the profitability of ESS as a merchant participant is questionable in the German market. Stafell [48] reached the same conclusion in UK, Bolado [49] in the Netherlands and Grijalva [39] in the US. McConnell in [26] goes further and recalls that no electricity market is fully merchant for generators, there is hedging involved in long term PPA contracts, capacity payments or other mechanisms. Hence, it does not make sense for an investor to install an ESS in a pure spot or ancillary market, since that model does not mitigate the risk associated with the large investment. He also says that the long term impact on prices affects the profitability and sustainability of ESS; concept that Sioshansi also shares in [22]. Also, as Sioshansi says, in current market designs, ESS will end up cannibalizing its own profits by flattening demand and eliminating price differences. Concept also backed by Kim [50] in their analysis on the Korean market. However, it is a fact that this reducing effectiveness is attributable to his presence. If ESS were not present, then the price differences would return. This is one more reason to argue that the current considered merchant design is not efficient enough for successful incorporation of this technology.

Other market mechanisms more oriented to ESS as a grid service, where the system operator is the responsible for the decisions have been proposed in [24, 34]. Also, a recent proposal for reverse auctions for incorporating ESS, similar to renewable energy auctions was presented by Lacker [51], given the failure of merchant mechanisms to attract investment. Several governments have established incentives for ESS incorporation without a complete definition of its market rules, as in the case of California [52], China [53] and Korea [54]. However, in all of them exists the concern that for a proper market integration, comprehensive market changes have to be made.

Our interest is focused in how to obtain consumer welfare benefits by designing proper market mechanisms for incorporating ESS, which provide the investor with proper rate of return according to the risk of its investment. Ongoing discussions are in place in different markets in the world, trying to balance achieving larger potential consumer benefits vs disrupting an established market design and status quo. Current market and regulatory designs prevent the achievement of the potential benefits of ESS integration and weakens its business case [23]. In addition, markets are poorly designed to accommodate all ESS services simultaneously [31], mainly due to the unbundling rules present in the majority of developed markets.

But when social welfare impacts are analyzed, it has been found that considering ESS as a merchant participant fails to produce benefits. Several authors found that for incrementing social welfare, ESS should be operated by the System operator and be able to provide several services [29, 38, 55, 31]. Again, the issue of ownership and the unbundling requirements forbid the same asset to provide services in different markets. In a seminal article from 2009 [22], Sioshansi states that social welfare and merchant revenue are at odds. This clearly creates barriers analyzed by several authors [56, 57, 58, 52] for extracting all the social welfare benefits. Recently, several authors have proposed to incorporate ESS as a system resource, but there are still questions on how to assess and appraise its benefits and to regulate it properly for obtaining the best value for the consumers and social welfare.

Latin America was one of the first to install a market driven ESS in Chile by a generator intending to improve its standing in the energy market. For Latin America, there is scarce literature [37, 59]. Recent studies have found that there is a market potential of around 8,000 MW just in Colombia, Brazil and Mexico [60]. However, regulators in the region are still performing evaluation and research projects, but have yet to design comprehensive market mechanisms to incorporate ESS. Several trade organizations are working on advising regulators on how to regulate ESS [61]. Colombia took the first step in the region with enacting of rule CREG 098/19, which enables ESS to provide transmission services to manage congestion, but there is still no consensus in the country on the pertinence of fully incorporating ESS for other services into the market [62].

4.2 Arbitrage in the Day Ahead and Real Time Markets

Energy arbitrage refers to the process of buying energy in low priced periods, which usually happens during low demand hours; and its selling during high priced hours, at peak load time. The investor revenue results from the margin between sale and purchase energy prices. As pointed above, a large body of literature is centered in identify mechanisms to incorporate energy storage using this approximation. However, when calculating investment returns, they found that arbitrage margins are not enough to even pay for storage investment. Even further, the uncertainty associated with the volatility of market prices increases the risk of obtaining a positive rate of return. For this reason, just a few of energy storage systems in the world participate in spot markets performing arbitrage, and when doing so, they earn a minimal revenue in addition to its main source of income for providing another service.

To illustrate this situation, we used information from the Colombian electricity market to test the potential of an energy storage system to generate revenue in a 5 years period, from January 2014 to December 2018, taking advantage of the already solved economic dispatches by the system operator [63]. For each day we registered the maximum and minimum marginal prices, along with their corresponding demand as shown in figure 4. From them, it is straightforward to calculate the investor's revenue when charging the storage system at the lowest price moment and discharging it at the maximum priced moment. In all cases it is assumed that the charge and discharge events do not change the system marginal price, being this the most optimistic condition for the investor, since when charging prices tend to increase with the added demand for the system and in discharging prices tend to decrease given than less generation is required. The prices spreads found are the potential maximum expected revenue for the investor.

Figure 5 presents the evolution in time of the price spreads for the analysis period of 2014 to 2018. It evidences high volatility and uncertainty over the recurrence of high price spread events, reducing the expectation of reliable forecast for an investor in this market. The highest price spread, appearing in October 2015 and produced by a market shock due to the forecasting of an El Niño event, did not repeat itself in the analysis period, making it difficult to rely on cases like it to support an investment decision. Later in that year, whit the El Niño event in place, price spreads decreased, even though the overall prices in the wholesale market were an all time high.

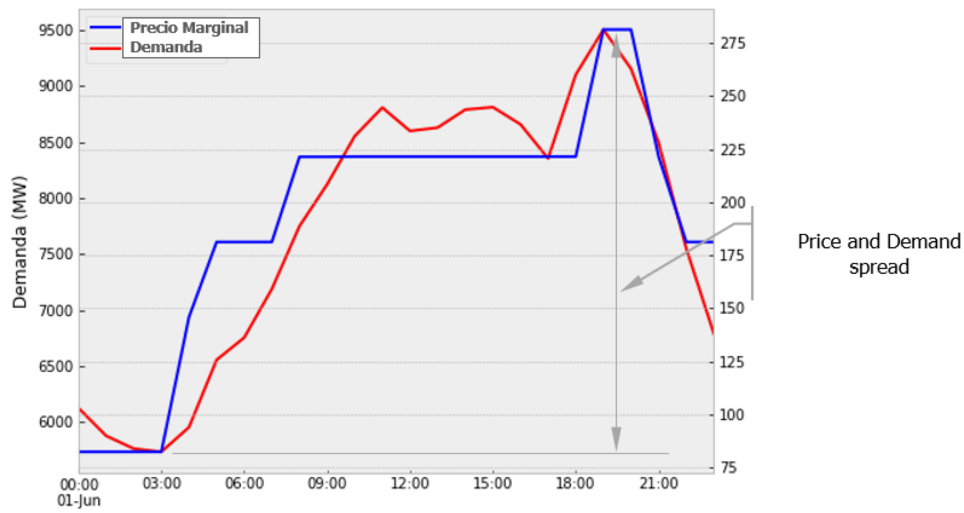


Figure 4: Price and demand spreads for a day

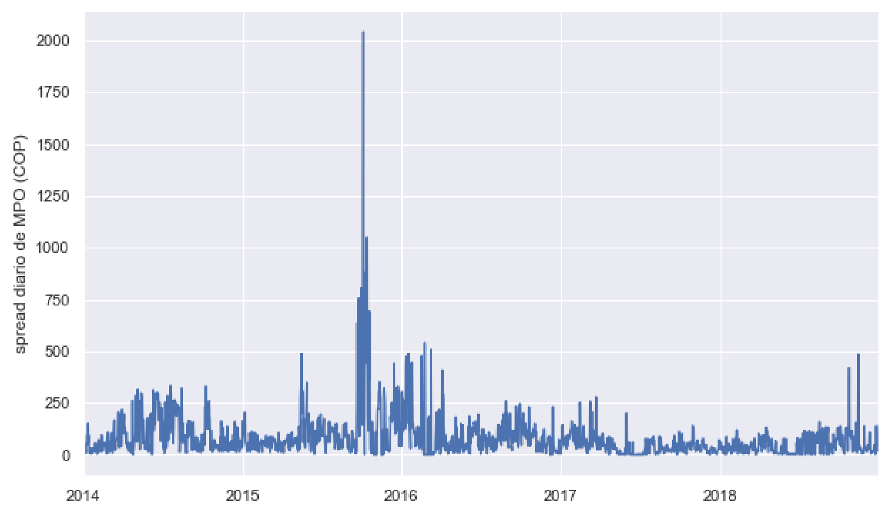


Figure 5: Evolution in time of daily price spreads in the period 2014 - 2018

Figure 6 presents the results of the statistical analysis of price spreads for the 5 years period of January 2014 to December 2018. In it, each point represents the price spread and demand spread for a particular day. The curves in front of each axis show the statistical distribution of both the price spread variable and the demand spread variable. The shadow in the chart body represents the density of points.

The results of the statistical analysis of the price spreads in the Colombian electricity market show that 75% of them are below COP 100/kWh (USD 0.026/kWh), with an average of COP 55/kWh (USD 0.014/kWh).Also, it may be concluded that the maximum capacity required from energy storage to provide energy arbitrage in Colombia is between 1300 and 1700 MW, calculated as half of the average demand spread of the analysis period.

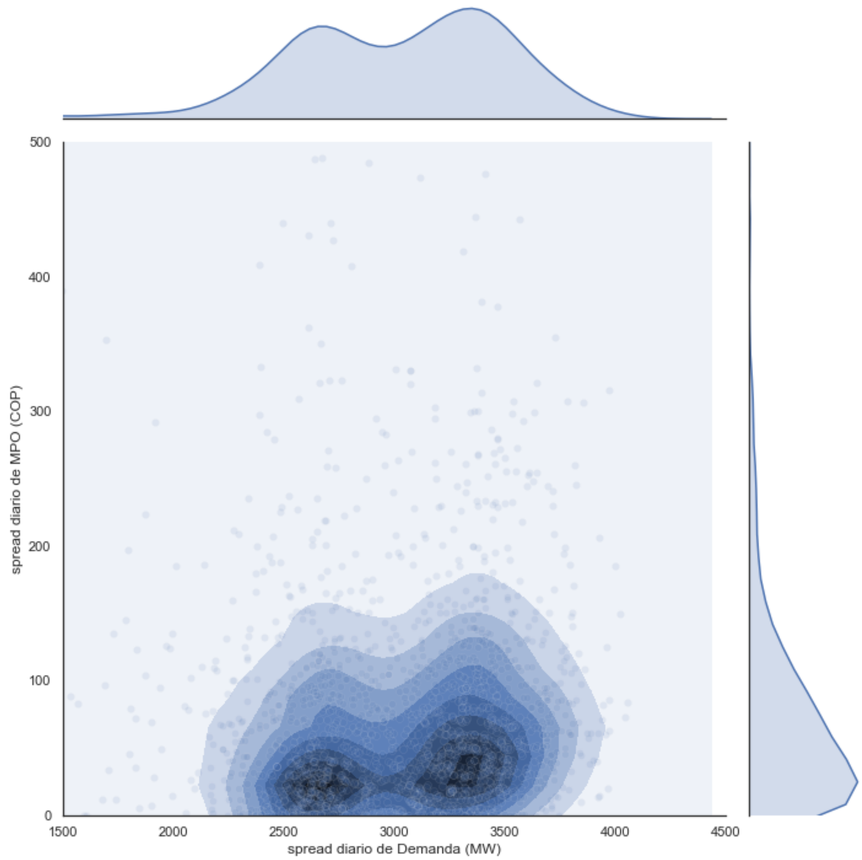


Figure 6: Daily spreads of spot prices and demand in the period 2014 - 2018

The expected revenues for a would be energy storage investor in the period January 2014 - December 2018 can be calculated using the price spread information obtained above, assuming it would have participated as a merchant resource performing arbitrage in the Colombian electricity market. Here, the price spread for each day represents the revenue per kW of energy storage capacity with one hour duration (Given that we are simulating only the price spreads of one hour at charging and one hour at discharging). In other words, if in one particular day the energy storage system charges in the lowest priced hourly period and discharges in the maximum priced hourly period, the investor would have had a revenue equal to the price difference per each kW of battery capacity. Table 1 shows the results.

Concept	Value
Average yearly revenues	USD 10876/MW-year
Yearly revenues volatility	USD 14266/MW-year
Annualized investment	USD 93250/MW-year
Revenue/Investment Ratio	0.116

Table 1: Revenue-cost relationship for arbitrage in the Colombian system

For simplicity, this analysis does not consider the effect of losses in the charging-discharging cycle, hence, it should be considered as an optimist case from that standpoint

The results presented above confirms the literature findings that arbitrage is not a viable business model for energy storage. In this case, the revenues could only cover 11.6% of the investment cost. Also, this exercise assume a perfect knowledge of the future, so that the investor is able to submit offers for charging and discharging in the periods of the day where they maximize his earnings. In real life, the limited information that a market participant has in relation to the offers of the other resources in the market and the variable operating conditions of the system, further reduces their potential profit. For this exact reason, this model of ESS participation in wholesale markets presents high risk and expected low returns, making it almost impossible to participate by reasonable investors, as reality stubbornly shows. Furthermore, the goal of maximizing the investor revenue is opposite to the goal of increasing consumer welfare given that the investor will get more revenues as long as the price differences increase, negating the potential economic benefits to the load.

In addition to the above, the participation mechanism for storage as a merchant player in the spot market presents an unpalatable risk to the investor. Even in energy only markets, generators count with hedging mechanisms in the form of long term contracts to mitigate the risks associated to volatility in the spot market. A related analysis for energy storage in the Australian market was performed by McConell [26], and concluded that without similar hedging mechanisms, it would be economically infeasible for an ESS to participate as a merchant, price taker actor in the spot market.

5 ENERGY STORAGE AS A SYSTEM RESOURCE

The application of Energy Storage as a system resource has been less studied than as a merchant participant, even though it is clearly more appropriate for delivering social welfare maximization. It is counter-intuitive that ESS can provide true measurable benefits to consumer welfare but has a clear risk of not being profitable, as discussed in section 4.1. In most of the mechanisms studied to date, ESS is considered as a merchant participant in a market dominated by generators, in which strategic behavior can deepen the market power of a small set of generation resources. As can be seen from above, most of the analyses have been done on isolated services and not in an integrated fashion. In this sense, they have not exploited the advantage of ESS capable of providing multiple services. It seems to be clear that a new alternative of market incorporation is needed, other than merchant participant, with the goal of realizing all the potential economic benefits for consumers.

The previous section concluded that arbitrage using energy storage is not a viable business model for a merchant investor in a spot market. This has resulted in the absence of this market mechanism in almost every power system in actuality, depriving consumers of potential benefits represented in more efficient prices. A different approach to consider energy storage in the economic dispatch and in ancillary markets is as a *System Resource*, available to the system operator for providing services in the power system, such as optimizing its operation cost, frequency regulation or operational reserves.

As we discussed in section 3, energy storage cannot be regarded as a generation resource because it does not inject new energy into the system, it only shifts in time energy that was already present in the grid. In fact, when it takes energy from the grid and releases it in the future, consumes part of the energy in the storage process. In terms of net electric energy it is a consumer, but the benefit for the consumers of shifting that energy in time is considerable larger than its own energy consumption. An accurate analogy can be made as while power lines move cheap energy in space, causing some energy losses in the process, energy storage systems move cheap energy in time. Therefore it makes sense to consider Energy Storage as a grid asset. An idea that has been previously hinted in the literature by authors like Dvorkin [45], however, without elaborating into the market design changes implications. Derived from this is the concern about ESS playing a role in affecting the market by changing spot prices, and therefore affecting competition for generation resources. In fact it is the same as building a line to a heavily congested zone minimizing the possibility of market power. Therefore, the solution for ESS integration into the market can be guided by the mechanisms for incorporating new transmission into the power system.

Our approach to using energy storage as a system resource to optimize the power system operation costs is that it enables the demand to increase its elasticity to prices in the short term. It creates the opportunity to reduce energy prices at peak load and has the potential to generate considerable savings given that any reduction in spot prices benefits all the consumers.

Figure 7 presents an ideal supply-demand diagram for the electricity market. It presents both the charging and discharging effects to the total demand and the potential benefits to both the investor in storage and the consumers. The benefit of a reduction in energy costs at the peak of consumption for the system as a whole does have the potential to achieve appreciable value, since these benefit the entire demand. the figure shows the comparison of the benefits for the system (areas A2 - A1) and the investor (area highlighted in green), where it is clearly observed that the benefit for the system is significantly greater than the benefit of the investor. It can be seen that the benefit for the consumers is large, even with small price spreads. Simple visual inspection reveals that the benefit achieved by the consumers as a whole is greater than the investor's benefit. Now, it is necessary to prove it preferably under close-to-real conditions. The best way to gain insight on this issue is to compare real dispatch cases with simulated incorporation of ESS into the day ahead market on the same days and hours.

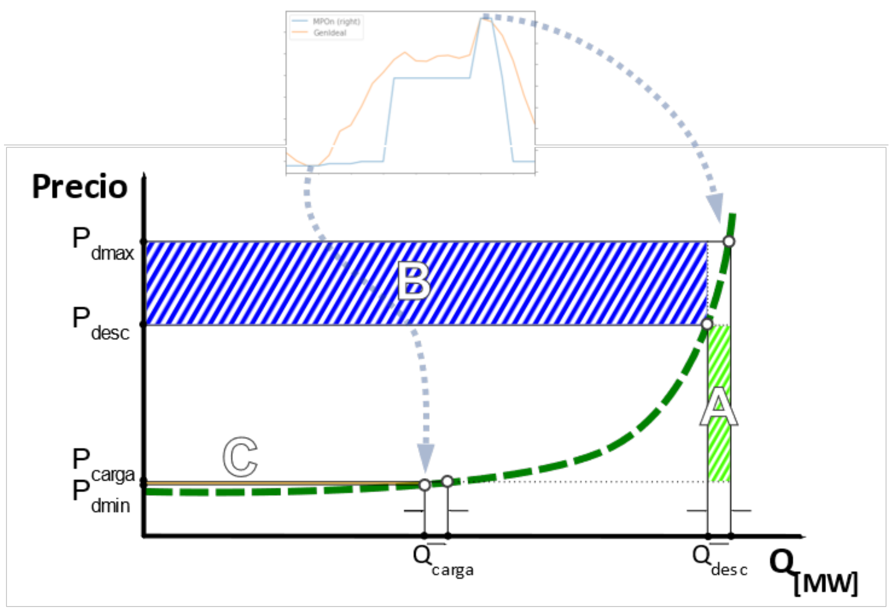


Figure 7: Welfare comparisons for energy storage application in the spot market

It is evident in theory that counting with energy storage to discharge in high demand period increments consumer welfare. To capture this benefit it is required to know beforehand the sequence of prices for the specific day and the dispatch profile of the generation. In this circumstance, the ISO is the only actor with access to complete information to effectively manage the use of these resources and able to materialize the potential economic benefits to the consumers.

5.1 Economic dispatch co-optimization model

In order to achieve the potential benefit for the consumers, we propose a co-optimization mechanism for the economic dispatch, where the aggregated energy storage capacity is considered as a system resource. As such, it is available to the ISO for charging and discharging according to the generation cost minimization problem for an entire day. This approach considers energy storage as a net demand modifier, changing the profile of the demand curve, providing it with more elasticity, respecting storage power and energy limits. Here, energy storage is not considered as a resource belonging to the offer side of the optimization, but as grid resource that enables the shifting of energy between operation periods. Mathematically, it is part of the constraints associated with demand in the optimization model. The equations below present the simplified optimization model proposed:

$$\min_{G_{i,t},B_t} \sum_{t=1}^{24}\sum_{i=1}^{n} p_{i,t}G_{i,t}$$

subject to:

$$\begin{aligned}
\sum_i G_{i,t} &= D_t + B_t && ,t = 1\cdots 24\\
S_t &= S_{t-1} + B_t && ,t = 1\cdots 24\\
|B_t| &\leqslant B_{max} && ,t = 1\cdots 24\\
S_t &\leqslant S_{max} && ,t = 1\cdots 24\\
G_{i,t} &\leqslant G_{max,i} && ,t = 1\cdots 24, i = 1\cdots n\\
G_{i,t}, B_t, S_t &\geqslant 0 && ,t = 1\cdots 24, i = 1\cdots n\\
S_0, S_{24} &= 0
\end{aligned}$$

A more realistic implementation of the ESS will include charge and discharge efficiencies making the modelling a little more complex, as shown below:

$$\min_{G_{i,t},B_t^c,B_t^d} \sum_{t=1}^{24}\sum_{i=1}^{n} p_{i,t}G_{i,t}$$

subject to:

$$\begin{aligned}
\sum_i G_{i,t} &= D_t + B_t^c - B_t^d && ,t = 1\cdots 24\\
S_t &= S_{t-1} + B_t^c\cdot\eta^c - B_t^d/\eta^d && ,t = 1\cdots 24\\
B_t^c\cdot B_t^d &= 0 && ,t = 1\cdots 24\\
B_t^c, B_t^d &\leqslant B_{max} && ,t = 1\cdots 24\\
S_t &\leqslant S_{max} && ,t = 1\cdots 24\\
G_{i,t} &\leqslant G_{max,i} && ,t = 1\cdots 24, i = 1\cdots n\\
G_{i,t}, B_t^c, B_t^d, S_t &\geqslant 0 && ,t = 1\cdots 24, i = 1\cdots n\\
S_0, S_{24} &= 0
\end{aligned}$$

Here, B_t^c and B_t^d are respectively the charging and discharging values of the ESS for each hour, and S_t is the state of charge of the ESS. η^c and η^d are respectively the charging and discharging efficiencies. $G_{i,t}$ is the hourly generation of each plant and D_t is the consumer demand each hour.

The goal of this analysis is to find how the demand benefits from the use of the co-optimization strategy presented above, using the Colombian power system to test it. In this particular case we had the advantage of counting with previously solved economic dispatches by the Colombian power system operator for the same 5 years analysis period than the preceding section: January 2014 to December 2018. Because of this, the co-optimization problem can be simplified, accepting a minor precision loss in the result, but gaining in favor of obtaining close-to-real results related with historical operation. Therefore, the problem was divided in two stages, where the first one correspond to the economic dispatch of generation plants without the presence of energy storage, which was previously solved by the system operator for every day in the analysis period. The second stage uses the results of marginal prices and generators dispatch as inputs, plus the original generator offers and availability statuses.

The second stage problem is a minimization of the system operation cost by optimizing energy storage charge and discharge quantities around the generation dispatch solution found previously by the system operator. This approach, though simple, enables us to perform an approximate comparison between the operational cost of both solutions with and without the presence of energy storage. It does not takes into account other factors like technical characteristics of generator units which could produce wider price spreads, therefore, we estimate that our results are conservative. Formally, the second stage problem formulation is presented below:

$$\min_{B_t^c, B_t^d} \sum_{t=1}^{24} P_t^m \cdot (D_t + B_t^c - B_t^d)$$

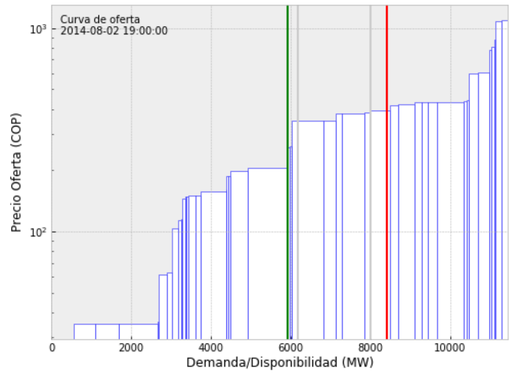
subject to:

$$\begin{aligned} S_t &= S_{t-1} + B_t^c \cdot \eta^c - B_t^d/\eta^d & ,t = 1 \cdots 24 \\ B_t^c \cdot B_t^d &= 0 & ,t = 1 \cdots 24 \\ B_t^c, B_t^d &\leqslant B_{max} & ,t = 1 \cdots 24 \\ S_t &\leqslant S_{max} & ,t = 1 \cdots 24 \\ B_t^c, B_t^d, S_t &\geqslant 0 & ,t = 1 \cdots 24 \\ S_0, S_{24} &= 0 & \end{aligned}$$

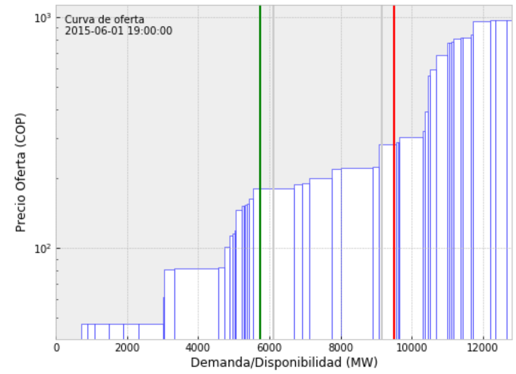
with:

$$P_t^m = f(D_t + B_t^c - B_t^d) \quad ,t = 1 \cdots 24$$

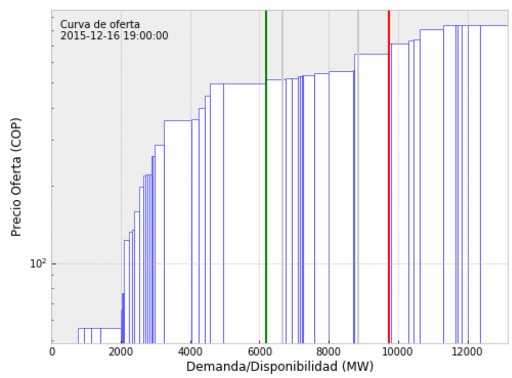
In this stage, the variable P_t^m refers to the marginal price of the solution of the previously solved economic dispatch by the Colombian system operator. In particular, it is obtained from the Maximum Offer Price (MPO due to its Spanish spelling) resulting from the ideal dispatch solution. The function $f(D_t + B_t^c - B_t^d)$ for obtaining the marginal price due to the change of net demand produced by the optimization of energy storage charge and discharge cycles, is a table built from the resulting data of the economic dispatch published by the system operator which relates the daily offer prices of generators, versus their accumulated availability. This function is represented graphically as a step-wise supply curve as shown in figure 8 for 4 different days in the analysis horizon. The charts use a logarithmic price axis in order to show better the price differences. Also, in each chart the green line corresponds to the minimum demand of the day and the red line corresponds to the maximum demand of the day. The staged form of the supply curve and the constraint for the exclusive charging or discharging operation of the ESS, makes this optimization problem as non-linear and ill conditioned. Hence, we utilized an evolutionary strategy optimization method for solving the second stage problem, using the original solution of the economic dispatch as a starting point.



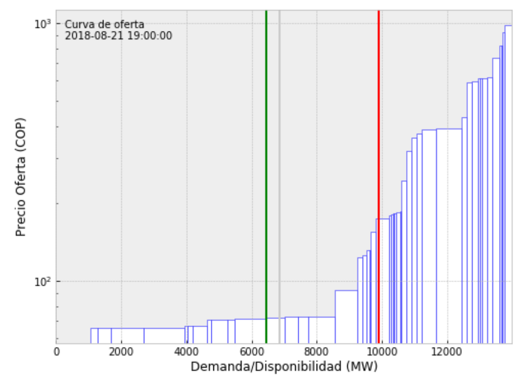
(a) Offer August 2,2014



(b) Offer June 1,2015



(c) Offer December 16,2015



(d) Offer August 21,2018

Figure 8: Real supply curves for the Colombian electricity market

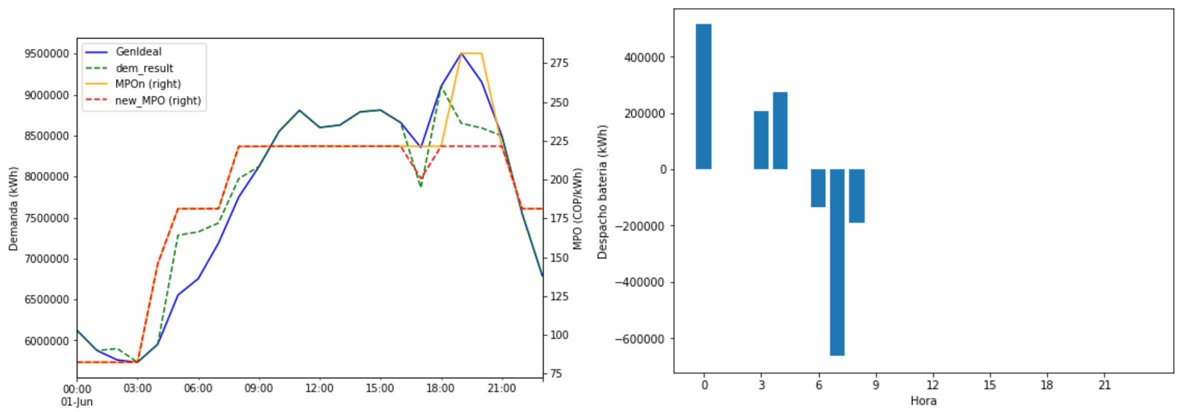
5.2 Application in real economic dispatch cases

We simulated three different sizes of energy storage systems, applying the two stage optimization formulation as shown above for every day in the analysis horizon of January 2014 to December 2018, For each day we registered the system operation cost with and without energy storage and calculated the daily savings in system cost which represent the increase in consumer welfare. Table 2 show the three different sizes of energy storage simulated.

Case	Power Capacity	Energy Capacity
1	45 MW	45 MWh
2	300 MW	600 MWh
3	1000 MW	2000 MWh

Table 2: Power and Energy Capacity of ESS simulated

The results for particular days show evidence of the benefits of reducing system prices in peak hours as shown in figure 9, for the case of an ESS sized 1000MW/2000MWh from the simulated day June 1, 2015. In it can be clearly observed the charge behavior at low demand hours without resulting in price increase (Hours 0 to 9), and the discharge at peak time with a 21% reduction in marginal price at that time. Therefore resulting in savings of COP 1306 millions (USD 353000), corresponding to a 3.5% of savings in operational cost for the day. This clearly shows the benefit of using energy storage as a tool for increasing short term demand elasticity, providing a net increase in consumer welfare.



(a) Demand and marginal price, with and without ESS

(b) ESS operation profile

Figure 9: Economic dispatch co-optimization result for June 1, 2015

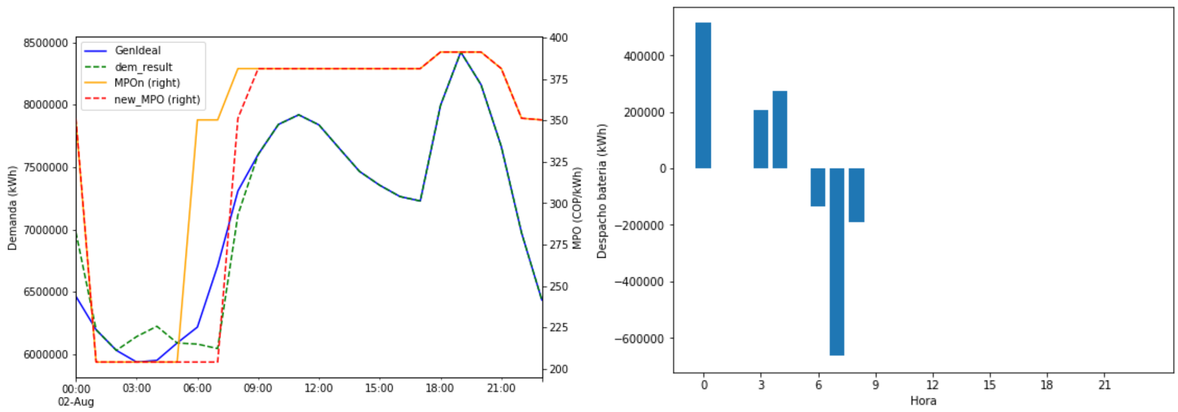
In some days, optimal operation using energy storage does not imply necessarily its discharge at peak demand hours. Figure 10 shows the result of the two stage optimization for August 2, 2014, where the evolutionary strategy algorithm found that the best operational profile for the ESS was to charge in the early hours of the day and discharge it at mid morning, when prices took a steep increase. It is interesting to note that the system's marginal price difference at the peak is relatively small. For that day, the simulation found savings of COP 2012 millions (USD 544000), corresponding to 3.4% savings in operational cost.

Figure 11 presents the savings resulting from the two stage optimization simulation for all the days in the analysis period, corresponding to the ESS sized at 1000MW/2000MWh. The resulting savings time series has a maximum around October 2015 when an El Niño event was predicted and the system expected a decrease in energy inflows for the hydro plants.

Figure 12 presents the statistical distribution of savings for the same period and the same size of ESS. It is clearly noted that the majority of daily savings are small, less than COP 2000 millions (USD 540000), or less than 5% savings in daily operational cost. However, the recurrent savings accumulated for a yearly period represent quantities capable of providing relevant increase to consumer welfare.

The simulation results for the three cases of different storage sizes are presented in table 3

Table 4 show the benefit/cost ratios for the three different sizes of ESS simulated, considering the results in savings and the overall cost of capital and operation. For calculating the cost of each solution, we used the cost of investment for Li-ion batteries as shown in figure 1, a yearly AOM of 2% of Capex, and a discount rate of 11.5% in a 15 year horizon. The results show that in all cases the savings cover all the capital and operations costs, with an attractive result for the 45MW storage facility of 2.3 times.



(a) Demand and marginal price, with and without ESS

(b) ESS operation profile

Figure 10: Economic dispatch co-optimization result for August 2, 2014

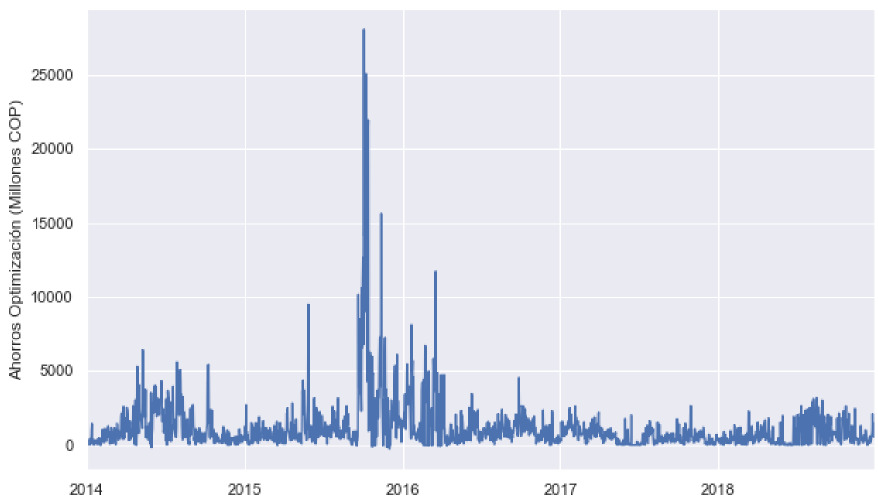


Figure 11: Savings time series from the economic dispatch optimization

Case	ESS size	Yearly average savings [MM USD]
1	45MW/45MWh	9.67
2	300MW/600MWh	69.38
3	1000MW/2000MWh	150.55

Table 3: Power and Energy Capacity of ESS simulated

The results presented in this section unequivocally evidence that using energy storage as a tool for the consumers for increasing their aggregated short-term elasticity brings savings several times larger than its costs, even for large ESS sizes. This, compounded with the ability of energy storage to provide multiple services to the power system, opens the door to large scale incorporation of the technology in the Colombian power system, providing cost efficiency and improved reliability for the consumers.

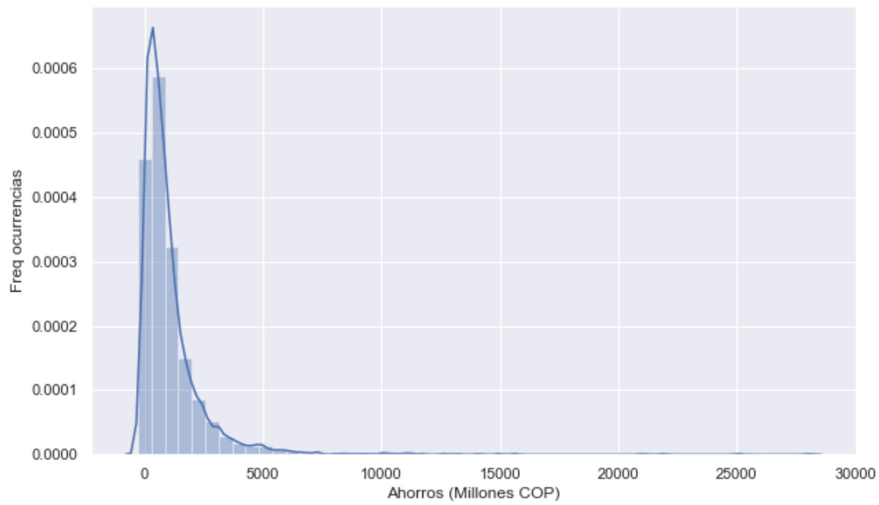


Figure 12: Savings histogram from the economic dispatch optimization

Case	ESS size	Solution cost [MM USD]	NPV savings [MM USD]	Benefit/cost ratio
1	45MW/45MWh	29.4	67.7	2.305
2	300MW/600MWh	296	485	1.641
3	1000MW/2000MWh	974	1053	1.081

Table 4: Benefit/cost ratios for simulated ESS solutions in the Colombian power system

It can be concluded that the incorporation of grid scale energy storage as a system resource, able to provide several services, without regard of the kind of remuneration of the investor is a viable solution which brings large benefits to the consumers.

5.3 ESS for Ancillary Services

Generation - Load balance and supply quality services in the power system are usually aggregated into the concept of Ancillary Services. The most common services are secondary frequency regulation (also known as AGC, Automatic Generation Control), demand following, spinning and cold reserves as stand-by for last-minute needs and Volt/VAr regulation [4, 64]. All of these services can be provided by energy storage devices by continuously controlling their charging and discharging regimes, with the advantage that they can also provide other services associated with the network. In fact, in several cases it has been shown that the provision of ancillary services with batteries can be more effective and economical than with the traditional generation mechanisms (as in the case of frequency regulation in PJM) [20].

Historically, frequency regulation services have been delegated to generators given the fact, absent other capable technologies, that some of them are able to rapidly change their output to balance generation and demand. Now, the wide availability of energy storage, enables their utilization for this services in a potential better form. The speed of response and the ability to precisely modulate power injection and retrieval from the grid makes energy storage a more efficient resource to regulate frequency.

In fact, performing ancillary services is alien to generators. In order to participate in this market, the generation unit needs to reserve some capacity to it. This implies programming its dispatch in an operation set-point that leaves room to increase and decrease its generation to respond to changes in frequency. Hence, there is an inefficiency in programming these resources given that more expensive generation have to be dispatched to cover for the reserved capacity, plus the market is required to cover the opportunity cost of this displaced capacity to the generator, with the result of a more expensive service for the consumer. In the case of frequency regulation from non merit generators (more expensive than the marginal price), they need to be programmed at their technical minimum plus the regulation margin, displacing more economical generation and making the system operation more expensive.

An added advantage for using energy storage to provide balance is that it liberates generation capacity for being used as intended, as provider for the basic product of the market: Electric Energy. ESS can inject or retrieve power from the grid to regulate frequency at all times without the need to be programmed in a specific set-point, only respecting their power and energy limits. Another advantage is that ESS has no opportunity cost other than the cost of energy when it was charged, but that amount will be zeroed when the ESS injects the energy back into the grid when required, leaving only the losses to be covered by the energy system.

ESS is fast, which means no additional reserve due to delayed response as with generators. In the following graph from [20], it can be seen that the batteries have a superior performance even than the hydraulic resources in terms of frequency regulation, achieving an adjustment of 97% with batteries versus 74.7% with hydraulic plants. Due to this feature, secondary frequency regulation in the PJM market has a rapid response category that receives additional remuneration.

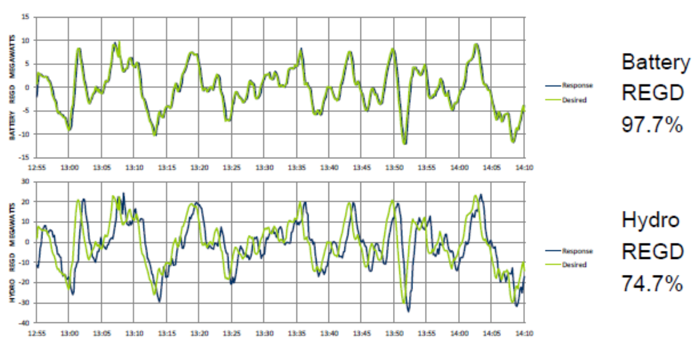


Figure 2: Example Plots Comparing Responses to RegA and RegD Signals. The plots show RegD having a faster-moving signal than RegA, and an overall mean closer to zero. (Benner, Performance, Mileage and the Mileage Ratio 2015)

Figure 13: Frequency regulation performance comparison [20]

In the Colombian electricity market, the frequency regulation service is denoted as AGC and is remunerated in two components: one corresponding to the capital cost of the generation capacity and other corresponding to the opportunity cost of the generation capacity being reserved.

$$\mathrm{AGC} = \text{Capital cost} + \text{Opportunity cost}$$
$$\mathrm{AGC} = 2 \cdot \mathrm{HO} \cdot \mathrm{DP}_{\mathrm{AGC}} + (\mathrm{G}_r + \mathrm{HO} + \mathrm{G}_p) \cdot \mathrm{P}_{\mathrm{AGC}}$$

Where HO is the capacity reserved for frequency regulation, G_p and G_r are respectively the unit's programmed and real generation, with DP_{AGC} as the unit price for available capacity and P_{AGC} as the offer price of the generating unit.

The maximum hourly capacity reserved for frequency regulation in Colombia is 400 MW at the peak [63], with an usage average of 300 MW. For the past 5 years the remuneration of frequency regulation to generators in the Colombian system is presented in table 5 according to published information from the system operator [63].

Year	Cost of service [MM USD]
2015	593.55
2016	392.82
2017	178.23
2018	187.45
2019	240.21

Table 5: Historical cost of frequency regulation service in Colombia

In an hypothetical case of replacing the entire capacity for frequency regulation in Colombia, it would require an energy storage system of 400MW/200MWh, assuming that in average half of an hour it would be charging and half or an hour it would be discharging, with a net zero energy balance at the end of each hour. Using the cost information from figure 1 and the same assumptions from section 5.2, the net present value of the ESS would be USD 195 millions, with an annualized cost of USD 28 millions. In addition to the capital cost, the analysis needs to include the energy cost of the losses due to the energy cycling in the battery. For that, we used the 300 MW of average usage of frequency regulation capacity with half an hour of charging and half an hour of discharging. Therefore on average, an ESS for the Colombian system would cycle 150 MWh of energy each hour. By assuming an full cycle efficiency of 90%, it yields losses of 15 MWh each hour, corresponding to 131400 MWh losses every year. That results in additional annual costs USD 6.57 millions, considering average spot price of USD 50/MWh in the Colombian electricity market. Hence, the total yearly cost for an infrastructure based frequency regulation service using energy storage would cost USD 34.57 million dollars a year for the Colombian power system.

According to the previous discussion, we can compare the yearly cost for the current frequency regulation service in Colombia, with the equivalent yearly cost of an energy storage infrastructure solution for the same service. In this case, taking the latest year on record, the cost of the current market based service was USD 240 millions. In contrast, the infrastructure based service using energy storage would have costed USD 34.57 millions. A cost reduction of 85%, compared with the traditional short term market business model.

The previous analysis assumed that the energy storage system could be procured through one or several dutch auctions asking for frequency regulation capacity in long term contracts. The yearly remuneration for the service is then the bid of the winner storage system, and is maintained over the term of the contract. In this case the short term spot market for frequency regulation is replaced with an auction based market for long term contracts, providing an equivalent or even better service for the consumers. In fact, this proposed mechanism can represent an improvement to the market given that it increases consumer welfare while it provides appropriate remuneration to the investor with a lower market risk.

5.4 ESS for Congestion Management

As stated in section 2, Energy Storage can be considered for providing grid services, similar in some cases to energy transport through cables, to support localized load requirements, such as security, reliability, congestion relief, and peak shaving. ESS solutions are increasingly being used as a non-wired alternative in locations where traditional network solutions are more expensive or even infeasible due to environmental or social restrictions. In Colombia, several projects have been identified by the Independent System Operator (XM) and the Energy System Planner (UPME) where

Electric Energy Storage is the technology of choice for lifting network restrictions. In the case of the northern city of Barranquilla, both UPME and XM found that a storage solution of 80 MW/ 160 MWh can provide reliability and economic benefits to the system by installing it in two substations in the zone, as a stand-by resource for n-1 outages [65]. The benefit-cost analysis resulted in ratios between 2:1 to 8:1, depending on the simulated scenarios. Additional applications in the city of Cartagena and in northern Bogota are being analyzed for similar solutions. Grid services provided by ESS minimize the risk of localized blackouts, reduce the need of out of merit generation due to congestion and defer transmission investments. The best solutions are achieved when the operation of storage resources is coordinated by the independent system operator with aggregated or direct control.

This kind of solution generally require the discharge in peak hours, at the same time as cost optimization applications, even further, when there is no need of operation for congestion, the asset could provide regulation services.

COLOMBIA IS ONE OF THE FIRST MARKETS REGULATING ESS FOR CONGESTION MANAGEMENT. The Colombian Electricity Regulator (CREG) issued order CREG 098 in august of 2019 [62] stating that Energy Storage can be used as an alternative resource to mitigate congestion in the power system, opening the door for including the technology in expansion planning, and government sponsored auctions for its installation, performed by UPME. It is expected that the first of such auctions will be called for the Barranquilla system by the beginning of 2020.

6 CONCLUSIONS AND RECOMMENDATIONS

Energy storage is a multipurpose resource that can provide various services to the electrical system that in a short time has become a viable option in the energy market. It is not framed within the traditional activities of generation, transmission or distribution, but it can be defined as an independent service with applications that until now have been associated exclusively with each of such activities. However, its incorporation goes hand in hand with advances in energy policy and regulation.

The storage of electrical energy can be used by providers of conventional activities , as well as by end users to obtain operational or commercial efficiencies. However, under the existing regulatory framework , when storage resolves operation problems such as network congestion or services such as frequency regulation, among others, it is not possible to state that it is a service of a particular activity, although You can provide services inherent to all existing ones regardless of their location on the network .The storage of electrical energy does not constitute a natural monopoly nor is it restricted to an activity of those already existing, since its existence was not anticipated when the current regulation was originally developed and is the result of technological development. In this way, there are no reasons to restrict competition in the development of these services in the energy market. Therefore, energy storage stands as a new service that can be offered to the system to solve problems concerning its operation, and therefore, that benefits all consumers.

The benefit of a reduction in energy costs at the peak of consumption for the system as a whole does have the potential to achieve appreciable value, since these benefit the entire demand. In contrast, it can be clearly demonstrated that the benefit for the system by incorporating ESS is significantly greater than the benefit of the investor as a merchant participant of the market. Indeed, it is our concern that energy systems across the world are missing the opportunity of gaining short term benefits by incorporating storage as a system resource, because they are still rooted in the traditional view that storage should be treated as a generation resource, participating as a merchant player in the market.

Regulation should have these concepts into account to provide the best benefit possible to the consumer. Storage is a provider of services into the market, and as such, it ideally doesn't affect the provision of the product of the market (i.e. energy) given that this is directly related to the contracts and spot price of power generation and not the services required to guarantee an efficient and secure power system.

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