Application of energy storage in systems with high penetration of intermittent renewables

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***Abstract*—Nowadays, in Uruguay, a considerable amount of energy produced by renewable resources is curtailed inducing frequent substantial reductions in the spot market prices. This paper analyses the incorporation of energy storage into the Uruguayan network, taking the different perspectives of a private investor and a central planner. From the investor point of view, we investigate the option of doing energy arbitrage in the wholesale market, taking advantage of the spot price fluctuations. From the national perspective, we develop an optimal power flow planning model to perform a cost-benefit analysis of batteries' integration in reducing thermal generation. We conclude that, from a private investor perspective, fluctuations in the spot prices are not enough to make investments in batteries profitable with current prices. On the other hand, from a national perspective, results are more promising, obtaining very high revenues in some case studies.**

***Index Terms*-- Energy Storage, Energy Arbitrage, Investment, Optimization, Renewable Energy Sources.**

I. INTRODUCTION

THE world is facing a shift in the energy sector, with increased incorporation of intermittent renewable sources, encouraging distributed rather than centralized generation [2].

Uruguay is an excellent example of how the shift from fossil fuel-based generation is possible [3]. In 2008, the Uruguayan generation mix included 1450MW of hydropower (65% of installed capacity), 700MW of thermal power (32%), 70MW of energy generated from biomass (3%) and a few MW of wind energy. However, the generation from the hydroelectric plants is heavily dependent on the rainfall. On a very rainy year, the plants can produce 10,000 GWh of energy while in a dry year around 3,500GWh. Such shortfall of energy has to be compensated by the thermal plants, and their contribution could vary from 12% to 66%.

In 2008 the production of the hydroelectric plants was not good, and the price of the oil barrel boomed leading to the exploration of new alternatives for the energy sector. The country implemented policies to favour the incorporation of non-conventional renewable energy and today clean generation provides almost 95% of the electricity consumption, and a huge excess is exported to its neighbour countries [4].

The reliable generation from hydropower plants allows Uruguay to run almost entirely with energy that does not come from fossil fuel consumption. This condition does not occur in most of the world, where generation such as coal, thermal or nuclear is necessary for a successful operation of the system.

Storage technologies are promising in future networks [5] where the need for decreasing the carbon footprint will lead to incorporating a very large amount of intermittent generation. There are no technological impediments for shifting the world into clean energy [6] [7], but it is a matter of making this shift as cost-efficient as possible. Therefore, technologies that not only make this transition possible but efficient have to be further studied. In this paper, we focus on studying the role of storage technologies in systems with massive penetration of renewable energy. For this purpose, the success of the Uruguayan energy transformation is used as a case study.

From an investor perspective, it is of interest to study the impact of energy storage in the wholesale market. Given the excess of renewable generation, the price of the energy in the spot market is most of the time $0\$/MWh$. Due to the intermittency of the energy sources, the market experiences significant fluctuations in prices. Therefore, these variations in the spot market can be exploited to maximize the revenue of an energy storage facility. On the other hand, from a national perspective, it might be of interest to reduce thermal production. Besides, the prices of the exported energy are not always representative of production costs. Consequently, studying the incorporation of storage facilities to take advantage of the flexibility they provide is of high interest.

II. BACKGROUND

Table 1 shows the generation mix in Uruguay in 2017. Even though the thermal generation capacity installed is substantial, the share of the produced energy was less than 2%, as shown in Figure 1.

In ten years, Uruguay successfully transformed its energy sector. It changed from being a country heavily dependent on oil prices, rains and importations to a country that relies on its energy resources, and it cut carbon emissions of the system from a peak of $301tCO_2/GWh$ to $14tCO_2/GWh$ in 2017 [8].

Source	**Power Installed (MW)**	**Share (%)**
Hydropower	1538	36
Thermal	627.2	15
Wind	1437	34
Biomass	413,3	10
Solar PV	228,5	5
Total	4244	100

Table 1: Generation mix in Uruguay by 2017 [9]

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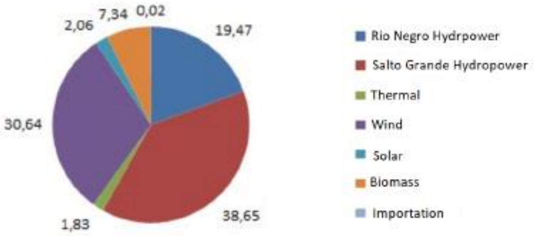

Figure 1: Energy generation by source in 2017 [9]

Uruguay attracted large investment in the wind and solar sector by offering take or pay contracts. Therefore, the dispatch of energy in Uruguay generally prioritizes wind and solar generators. Similarly, the dispatch of energy production by biomass, which is mainly obtained by two large cellulose plants, has high priority.

The Administrator of the Electric Market (ADME) calculates the spot price of the wholesale market, which is heavily dependent on the wind and hydro resource. Since most of the wind and the hydro generators have zero production cost, the spot price is zero, if both resources are high. As an example, we can observe the average spot price for 2017 in Figure 2. One can appreciate that 2017, which was characterized by rains throughout the whole year, had its spot price mostly at zero.

Furthermore, Figure 3 shows that the spot price is subject to significant variations on an hourly basis due to the intermittency of wind. These variations look promising from an investor perspective since the energy can be bought in the wholesale market when the price is at 0 USD/MWh and stored until the spot price reaches a profitable value.

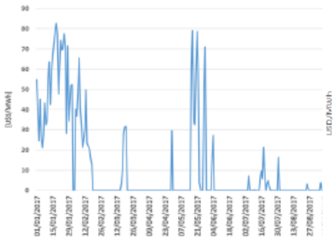

Figure 2: Daily spot price average 2017

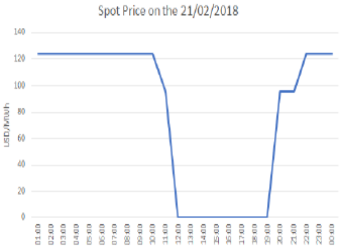

Figure 3: Spot price on the 21st of February 2018

III. METHODS

A. Private investor perspective

The optimization problem to solve is to maximize the annuitized revenue, as following [10]:

$$\max_{\Omega} \sum_{t\epsilon T} E_{sell}\ (r_d(t), t) - E_{buy}\,(r_c(t)\,, t)\ - (AIC(C)$$
$$+ MC(C) + TF \times R_c)$$

The annuitized investment cost (AIC) and maintenance cost (MC) are defined as:

$$AIC = \frac{IC}{A_{\tau,r}}, \qquad where\ A_{\tau,r} = \frac{1 - \frac{1}{(1+r)^{\tau}}}{r}$$
$$MC = 5\% \times AIC$$

where IC is the investment cost (in USD/MWh),
τ is the storage lifespan (15 years),
r is the annual interest rate (5%).

The set of decision variables is as follows

$$\Omega := \{r_c(t), r_d(t), s(t), C\}$$

where $r_c(t)$ is the charge rate, $r_d(t)$ the discharge rate, $s(t)$ the storage level and C the battery capacity. The set:

$$\mathcal{T} := \{1, \dots, T\}\ with\ index\ t$$

is the time, over a year, with hourly steps.

Finally, TF is the fee for using the network, which is a fixed value that depends on the power. The Uruguayan Ministry sets the value of TF, that currently is $\$U105/kW\ per\ Month$ and R_c is the maximum charge rate of the battery. It is worth noticing that TF does not depend on the decision variables, making it a constant for the optimization problem and therefore, not influencing the result.

The storage level $s(t), \forall\, t \geq\ 2$ is:

$$s(t) = s(t-1) + (\eta_c\, r_c(t) - r_d(t)/\eta_d)\,\Delta\, t$$
$$0 \leq\ r_c(t) \leq R_c$$
$$0 \leq\ r_d(t) \leq R_d$$
$$0 \leq\ s(t) \leq C$$

where R_c is equal to R_d and $\Delta\, t$ is the hourly time step. It is worth noticing that for the purpose of doing a sensitivity analysis, these values were kept independent of the capacity, which is unusual for lithium-ion batteries.

B. Enhanced Frequency Response (EFR)

When including EFR into the problem, the objective function is modified by adding the following term:

$$EFR_{Pay} \times\ P_{EFR} \times\ h$$

where EFR_{Pay} is the payment the facility receives for being available to provide the EFR service, the decision variable P_{EFR} is the amount of power the facility should provide for the EFR service, and h denotes the number of hours in a year the service is made available. Here we assume $h = 8395\, h$ to leave a margin for maintenance.

According to the UK National Grid's last tender [11], the average value of the availability price was £$9/MW$ per hour.

Furthermore, the bounds on energy are modified as follows

$$E_{EFR} \leq\ s(t) \leq\ C - E_{EFR}$$

where E_{EFR} is the amount of energy the battery needs in order to provide the service. Note that E_{EFR} appears in the left and right hand side of the above inequality, in order to inject or absorb power if needed. The time the service must be provided is at least 15 mins. Then:

$$E_{EFR} = \frac{15}{60} \times P_{EFR}$$

Finally, the maximum power the battery can provide for the EFR is limited by the maximum discharge rate:

$$1MW \leq\ P_{EFR} \leq\ R_c$$

C. National perspective

To analyse the feasibility of installing an energy storage facility, we formulated a minimization problem considering the power flow equations and the 500kV transmission network.

For this analysis, we introduce new variables. Let $\mathcal{N} := \{1, \dots, N\}$ denote the set of different bus nodes. The set Ω of optimization variables is as follow

$$\Omega : \{p^n(t), r_c^n(t), r_d^n\,(t), s^n(t), k^n, \delta^n(t), G_{curt}^n(t) \colon n\ in\ \mathcal{N}\}$$

where $p^n(t)$ denotes the production of thermal units, k^n the storage allocation, $\delta^n(t)$ the voltage angle and the index n indicates that the decision variable refers to the bus node n.

G_{curt}^n represents the curtailed generation that could be used to charge the batteries.

The formulated optimization problem minimizes the production costs (Γ) plus the battery investment:

$$\min_{\Omega} \sum_{t\epsilon T} \left\{ \sum_{n\epsilon N} \Gamma^n(t)p^n(t) + \sum_{n\epsilon N} \left(AIC(C^n) + MC(C^n)\right) \right\}$$

We have included in the problem generation limits and ramp ratings for the thermal units as follows

$$P_{min}^n \leq p^n(t) \leq P_{max}^n$$

$$-RR^n\Delta t \leq p^n(t) - p^n(t-1) \leq RR^n\Delta t$$

where the first represents lower and upper limits and the latter the ramp rates (RR^n) of thermal generation, considered as $24MW/min$ for all thermal generators.

At every time instant and every node, power flow balance conditions have to be imposed as follows

$$D^n(t) + \sum_{m\epsilon\,\Theta_n} B^{nm}\left(\delta^n(t) - \delta^m(t)\right) + r_c^n(t)$$

$$= G^n(t) + p^n(t) + r_d^n(t)$$

where Θ_n describes the set of all nodes connected to n. Then, B^{nm} represents the line susceptance between n and m.

The variable $G^n(t) = G_{curt}^n(t) + h_{gen}^n(t) + w_{gen}^n(t)$ represents non-thermal generation. The curtailed power $G_{curt}^n(t)$ includes as decision variables, the curtailed wind $w_{curt}^n(t)$ and hydro h_{curt}^n generation.

We study two cases: i) a dry week in which there is no water released, and ii) a wet week in which the released water could have been used to charge the batteries. Therefore, the upper bound of the decision variable $h_{curt}^n(t)$ is determined by the maximum possible generation of the dam minus the current generation at time t as follows

$$0 \leq h_{curt}^n(t) \leq h_{max}^n - h_{gen}^n(t)$$

Furthermore, we assume that all the decision variables regarding curtailment G_{curt}^n are only greater than zero if and only if the thermal production is zero. Therefore, we don't consider generation curtailment due to restriction in transmission lines.

We also introduce transmission lines limits, such that:

$$-TC_{max}^{nm} \leq B^{nm}(\delta^n(t) - \delta^m(t)) \leq TC_{max}^{nm}$$

Finally, boundaries of the voltage angles and the slack bus are as follows

$$-\pi \leq \delta^n(t) \leq \pi$$

$$\delta^{n=1}(t) = 0$$

IV. RESULTS

A. Spot price Data

We begin our study by analysing the values of the spot price. Figure 4 and Figure 5 show the heatmap of the hourly spot price across 2013 and 2018, respectively. The decrease in the spot prices is linked to the hugely increased wind capacity from 59MW to 1529MW.

Figure 4: Spot Prices 2013 [4].

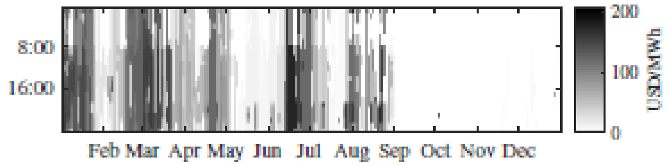

Figure 5: Spot Prices 2018 [4].

High spot prices are not sufficient to make batteries economically appealing for electric owners. Batteries present the potential of achieving an economic profit exploiting frequent significant variations in the spot market price.

Note that 2013 was the year with the highest value of spot prices but also the year with more days when the price difference was zero. The most promising year for doing arbitrage seems to be 2018. Still, for around half of the year, there is no difference in the daily price, as a consequence of it being zero from September onward.

A priori, doing arbitrage looks promising, but the analysis on the spot price indicates that the price variations might not be sufficiently significant and frequent to achieve an economic profit.

B. Private investor perspective

Figure 6 shows the optimal capacity to be installed as a function of the battery capital costs for different annual spot price realizations while fixing the battery charge/discharge rate. On the other hand, Figure 7 shows the optimal capacity as a function of the charge/discharge rate while fixing the capital cost, both without considering EFR service.

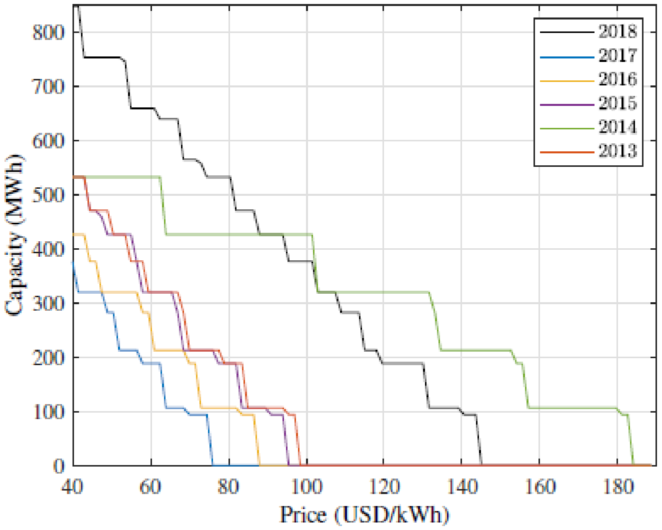

Figure 6: Battery Capacity as a function of the cost - Rc: 100MW

In Figure 6 it is essential to note that 2018 and 2014 are the best years for doing arbitrage. Instead, in 2017, the energy arbitrage would be profitable only for a capital battery cost lower than $80USD/MWh$ due to the lowest spot prices and infrequent price variations. Overall the numerical results show that the battery capital cost should be much lower than the current prices to make it profitable for the private sector.

Figure 7 shows a linear dependence between the battery capacity and its charge/discharge rate. Note that doubling the rate entails doubling the optimal capacity. Furthermore, we can observe that the battery cost has a substantial influence on its optimal sizing as highlighted by the results for 2017 when the batteries are not profitable whatever their rate is for a capital cost of 80 USD/kWh or higher.

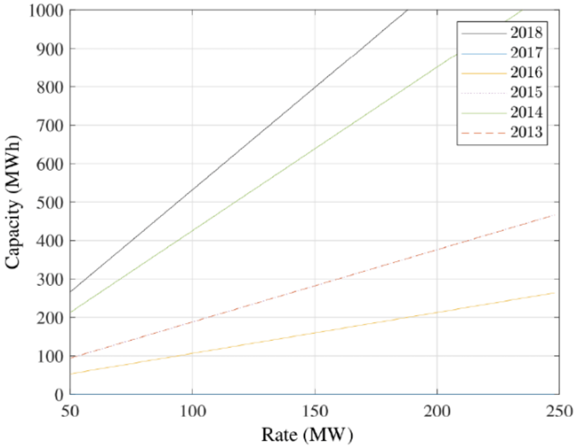

Figure 7: Capacity as a function of the rate - Cost: 80USD/kWh

When analysing the revenue, it is crucial noticing that the cost of transmission fees is exceptionally high. With the price fixed per kW as explained in section III, using an exchange value of \$U35 per USD and considering the rate to be $100MW$ the total cost of transmission fees (TCTF) would be:

$$TCTF = 100MW \times TF \times 12 = 3.6M.USD$$

This offset value of -3.6 million USD makes our objective function to be always negative, yielding no positive revenue independently of the storage size. For the sake of clarity, in the rest of this section, we neglect the effect of the transmission fee, and we resume the discussion of it in section V.

Tables 2 and 3 report the annuitized revenue (objective function result) when fixing the battery capacity and capital cost. As expected, the revenue is less than the transmission fees in every case, so it is necessary to re-consider regulations in transmission fees if it is of interest to attract investment in batteries.

Year	Price (USD/kWh)	Capacity (MWh)	Revenue (USD/year)
2018	140	94	45,948
	90	426	1,319,408
2017	140	0	0
	90	0	0
2016	140	0	0
	90	0	0
2015	140	0	0
	90	106	43,692
2014	140	213	651,170
	90	426	2,324,138
2013	140	0	0
	90	106	91,353

Table 2: Battery annuitized revenue - Rate 100MW

Rate (MW)	Capacity (MWh)	Revenue (USD/year)
150	638	1,979,111
50	213	659,703
150	0	0
50	0	0
150	0	0
50	0	0
150	160	65,537
50	53	21,845
150	638	3,486,207
50	213	1,162,069
150	160	137,029
50	53	45,676

Table 3: Battery annuitized revenue - Price 90USD/kWh

C. Enhanced Frequency Response

We can observe the effect of adding the EFR service to the investment problem in Figure 8 comparing the optimal capacity with and without EFR.

Firstly, the optimal P_{EFR} (the amount of power the facility should provide for the EFR service) is equal to the maximum charge/discharge rate R_c in every case.

Secondly, the optimal solution shows a slightly increased capacity value in every scenario. Lastly, Table 4 and 5 highlights that the inclusion of EFR services entails a substantial revenue increase, making investments in storage assets more attractive.

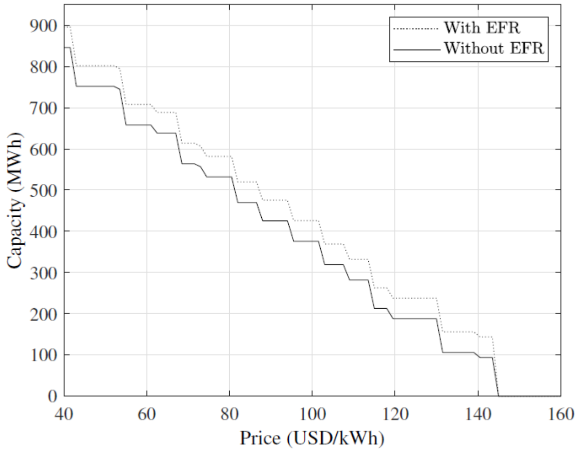

Figure 8: Optimal battery size with EFR 2018

Year	Price (USD/kWh)	Capacity (MWh)	Revenue (USD/year)
2018	140	144	5,788,040
	90	426	7,325,162
2017	140	0	0
	90	0	0
2016	140	0	0
	90	0	0
2015	140	0	0
	90	156	6,049,445
2014	140	263	6,404,025
	90	476	8,329,892
2013	140	0	0
	90	156	6,097,106

Table 4: Battery annuitized revenue - Rate 100MW

Rate (MW)	Capacity (MWh)	Revenue (USD/year)
150	688	11,215,351
50	263	3,434,972
150	0	0
50	0	0
150	0	0
50	0	0
150	210	9,301,777
50	103	2,797,114
150	688	12,722,447
50	263	3,937,337
150	210	9,373,268
50	103	2,820,094

Table 5: Battery annuitized revenue Price - 90USD/kWh

D. National perspective

Information on generation and curtailment was only available simultaneously for 2017. To make the problem computationally tractable, we describe the system operation using typical weeks. In particular, we consider two dry and wet cases, which are representative of scenarios that could happen any week at any year.

The information on wind curtailment is illustrated in Figure 9 for 2017.

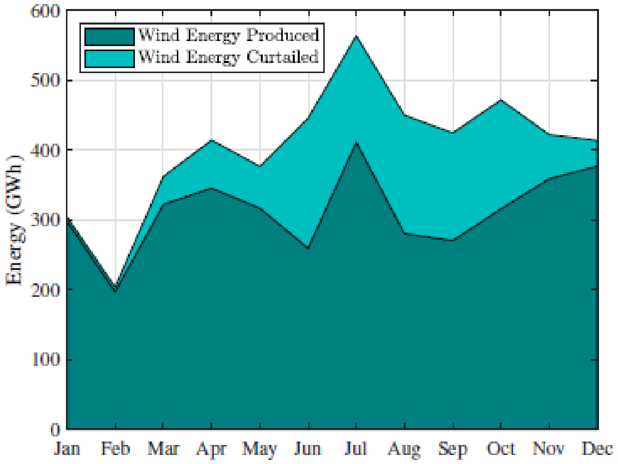

Figure 9: Wind energy curtailed throughout 2017 [8]

As observed, the wind curtailment represented an important amount of energy in 2017. It accounted for 8.9% of the total demand, which was 10784 GWh. Therefore, it looks promising to study the feasibility of installing an energy storage facility to use all the curtailed generation.

In Figure 10, we can see the average weekly water harnessed from the Salto Grande dam, and the amount of water released through the dam because of natural constrains in the reservoir. This water could have been used to store energy if the power of the turbines was less than the rated.

Using the information on the Salto Grande and Rio Negro dams, we can identify weeks representative of the dry and wet seasons. For example, both January and February of 2017 have almost zero water released from any dam, so we consider these months as dry. Contrarily, in June and October, the released water was abundant, so these months are representatives of the wet season.

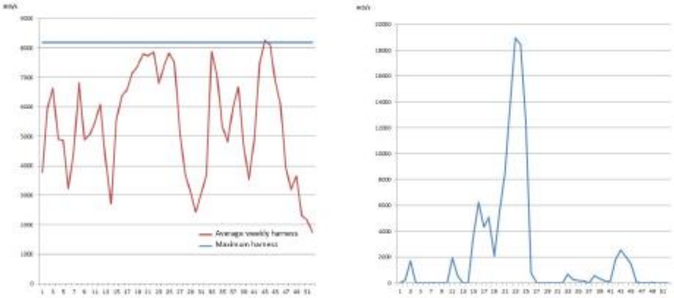

Figure 10: Salto Grande average weekly water harness (red) and release (blue) in 2017 [9]

First Wet Scenario

For the first scenario and an annualized battery investment cost of $200 USD/kWh$, the optimal capacity to install is of $487.3 MWh$.

In Figure 11, generation, demand and storage level are plotted. In this case, not only the wind curtailed is used to store energy but also the hydro. Figure 12 plots a comparison of the thermal output pre and post battery.

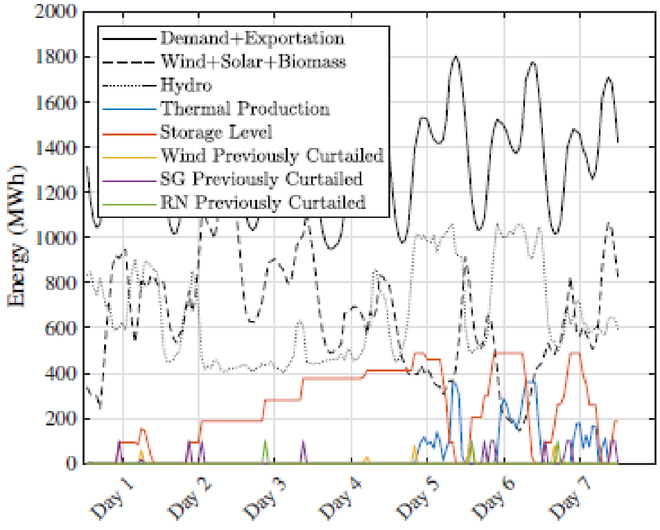

Figure 11: Generation and demand Wet-Case 1

From the ADME data regarding generation, we can approximate the amount of energy each power plant produces during this week. Then, from our results, we calculate the costs of thermal production after the installation and operation of batteries. In Table 6, this difference is reported.

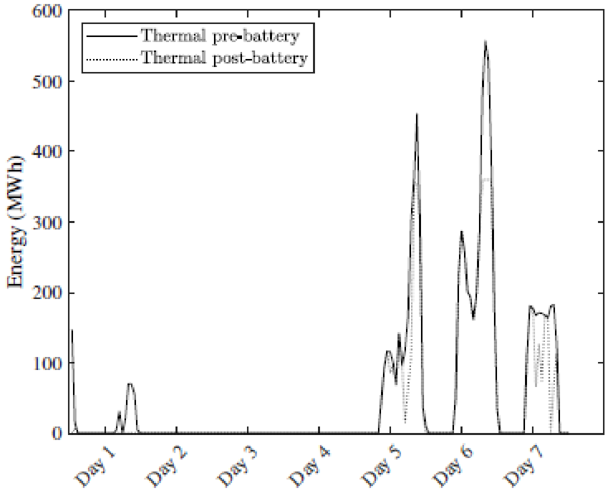

Figure 12: Thermal production pre and post battery - Wet-Case1

Central	Pre Battery (Data From ADME)		Post Battery (Data from software)	
	Generation (GWh)	Cost (USD)	Generation (GWh)	Cost (USD)
Punta Del Tigre	81.7	9,806,000	67.2	8,059,600
CTR and Battle	6.1	855,400	0	0
Total	87.8	10,661,400	67.2	8,059,600

Table 6: Thermal output and cost pre and post battery Wet-Case1

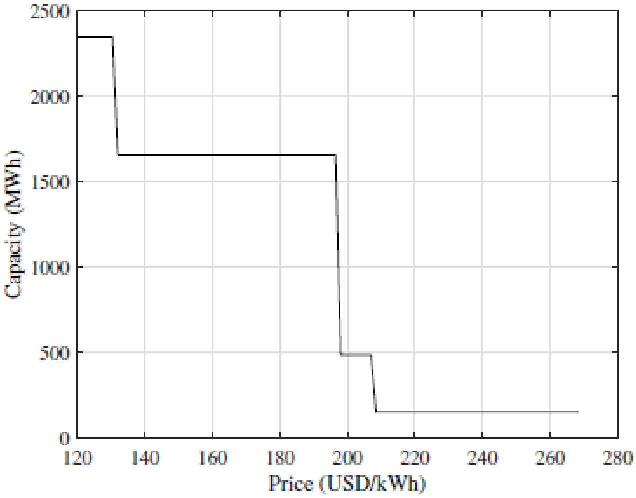

Figure 13: Optimal battery capacity - Wet-Case1

Second Wet Scenario

The second scenario yielded similar results as the first one, and for brevity, they are not reported. For further details, please refer to [1].

First Dry Scenario

For the first dry scenario, and a battery cost of $100 USD/kWh$, the optimal capacity to install is of $101.6 MWh$.

Table 7 reports thermal production and a cost comparison for this scenario. For further details, see [1].

Central	Pre Battery (Data From ADME)		Post Battery (Data from software)	
	Generation (GWh)	Cost (USD)	Generation (GWh)	Cost (USD)
Punta Del Tigre	51.6	6,191,700	46.6	5,598,600
CTR and Battle	0	0	0	0
Total	51.6	6,191,700	46.6	5,598,600

Table 7: Thermal output and cost pre and post battery Dry-Case1

Second Dry Scenario

For the second dry scenario, and a cost of $100 USD/kWh$, the optimal result was no battery to be installed.

Discussions

From a private investor perspective, we found that transmission fees are not adequate for an energy storage facility participating in the wholesale market. Furthermore, and even without considering transmission fees, the installation of batteries for doing arbitrage is not economically attractive, as illustrated by our study, given their annuitized capital cost is still above $178 USD/kWh$ [12].

The participation of batteries to EFR services following the scheme adopted by the National grid in the UK generates a considerable increase in the revenue. However, payments for ancillary services such as frequency regulation are currently not operative in the Uruguayan electricity market.

From the central planner perspective, we analysed two scenarios of the rainfall regime.

In one of the dry scenarios, by installing 100MWh of energy storage, we obtained savings of approximately 2 million USD in a month exclusively using energy previously curtailed. Similar results have been recently achieved by a 66 million USD Tesla battery of $129 MWh$ in Australia.[13].

Moreover, when considering 'favourable' scenarios, it was extremely profitable to install batteries, even for prices as high as $280 USD/kWh$. For a fixed price of $200 USD/kWh$, the optimal result was almost $500 MWh$ for the first wet scenario and $700 MWh$ for the second, obtaining profits as high as 5 million USD a week for the best case. However, the installation of a $700 MWh$ facility will not be optimal year-wise for obvious reasons. When analysing these results, it is more realistic to assume profits of approximately $6000 USD/MWh$ a week, corresponding to the value obtained for the dry scenario. However, the previous pessimistic estimation of the profits would allow paying back the investment in around 4-5 years. This estimate looks very promising.

V. CONCLUSIONS AND FUTURE WORKS

This paper has investigated the potential integration of energy storage into the Uruguayan network, taking the perspectives of a private investor and a central planner.

Our analysis shows that an investor participating in the wholesale market does not achieve any revenue whenever transmission fees have a fixed value depending on the maximum capacity, which suggests a revision of the regulatory system.

On the other hand, from a national perspective, the incorporation of batteries seems more appealing, obtaining revenues of approximately $6000 USD/MWh$ per week in more than one scenario. The flexibility that batteries provide could be of enormous interest to take advantage of the curtailed energy.

Future work will focus on investment planning problems spanning several years and including modelling of uncertainty at the operational level to evaluate the merit of storage flexibility in hedging against the risk of asset stranding and cost inefficiency.

Furthermore, from the private investor perspective, it is significant to perform the analysis including a risk-based and probabilistic analysis regarding the rainfall regime.

Finally, the option of exporting energy is also of interest in both perspectives. In one case, the central planner can decide whether to sell electricity to its neighbours or to, instead, store such energy to reduce thermal production in the nearby future. Meanwhile, a private investor could perform arbitrage and export energy if possible.

The obtained preliminary results are promising, and they encourage to analyse further the potential benefits of flexible technologies for better use of renewable resources in the Uruguayan network.

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