Imperial College London

Department of Electrical and Electronic Engineering

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

Author:
Lucas Narbondo

Supervisor:
Prof. Goran Strbac

Co-Supervisor:
Dr. Paola Falugi

A thesis submitted for the degree of

MSc Future Power Networks

September 2, 2019

Abstract

Worldwide interest in reducing global emissions because of environmental concerns have increased the development of renewable generation and storage technologies in order to address the intermittent nature of such resources.

An excellent example of how the shift from carbon-based generation is possible was done by Uruguay, wherein ten years, they accomplished 95% of generation coming from renewable sources. However, nowadays a considerable amount of energy is curtailed and consequently reducing the spot market price incredibly. This project will aim to study the incorporation of energy storage technologies, specifically Lithium-ion based batteries into the Uruguayan network.

We will analyse two perspectives, the first one from an investor perspective doing energy arbitrage in the wholesale market, taking advantage of the spot prices fluctuation. We will then introduce revenue coming from providing an Enhanced Frequency Response service. The second perspective will be done from a government perspective, where an optimal power flow algorithm was developed to study if the incorporation of batteries reduces the thermal production enough to make them feasible.

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 government perspective, results are more promising, obtaining very high revenues in some study cases. Thus, we conclude that more specific future works should be done to analyse with more detail the incorporation of batteries storage technologies.

Acknowledgements

First and foremost, I want to thank both my supervisor and my co-supervisor for taking me as their student, and for the freedom they gave me to take this project into a very interesting direction for me, which is my home country. Special thanks to Paola, for taking so much of her time for valuable feedback and suggestions.

I will also want to thank my family for the support they gave me through this year, and also all the friends and colleagues I have met this year at Imperial that also provided me with valuable discussions.

And more special thanks to my life partner, Cintia, who, once again, moved her whole life to a different country just for the sake of being with me. And for being by my side with emotional support, in my ups and downs, and making life easier far away from home.

Finally, thanks to the Chevening Programme and the British Foreign and Commonwealth Office, whose funding made this master's possible.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The world is facing a shift in the energy sector, with increased incorporation of intermittent renewable sources, encouraging distributed rather than centralized generation [1]. Consequently, the costs of solar panels [2], batteries [3] and wind turbines [4] have been falling for the past few years. Furthermore, global warming and increasing pollution due to fossil fuel consumption are a critical problem causing the death of nine million people per year [5]. There is plenty of natural resources to harness, given that the entire human civilization can be powered for a whole year with just one hour of solar energy [6]. Therefore, it is possible to achieve a clean energy future, much needed in order to address the massive problems we are facing nowadays.

In Figure 1.1 the evolution of wind and solar energy is plotted and how the price has plummeted, because of their widespread adoption and a worldwide interest in reducing global emissions. In fact, Bloomberg estimates that renewable sources will represent almost three-quarters of the investment in new power generation by 2040. [7]. However, there are some challenges present in a system with large penetration of intermittent generation given that it is not possible to manipulate the natural resources. Among these challenges, the constant balancing between demand and generation when fast variable sources are present require considerable advances in flexible technologies such as smart grid and energy storage.

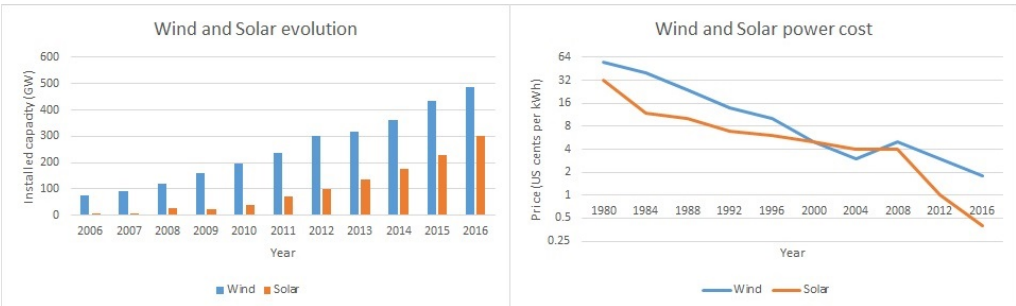

Figure 1.1: Wind and Solar Energy evolution[1]

Figure 1.2 shows a typical demand curve, and also the wind and solar generation profile, where we can observe that the peak in the evening cannot be supplied by non-conventional renewable energy, specifically because of solar that is only available during the day. Therefore, new industries looking to solve this issue are in huge rise, such as energy storage or electric vehicles (see Figure 1.3). In the future, we are looking for a demand curve as even as possible, in order to not oversize generation just for supplying peak demand.

[1] http://gwec.net/; www.solarpowereurope.org; https://www.youtube.com/watch?v=fwSkQa1tNmE

For this, vehicle to grid interaction is going to play an important role, where operators can exchange energy with EVs as desired, and fortunately, storage technologies that facilitates this are being developed extremely fast (Figure 1.4 compares the development with solar panels).

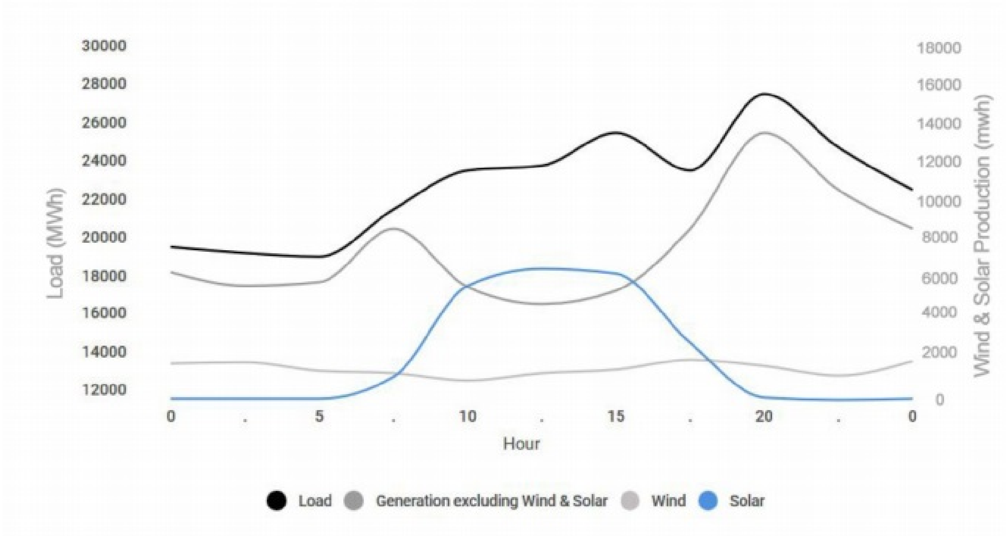

Figure 1.2: Typical Electric demand in the US[2]

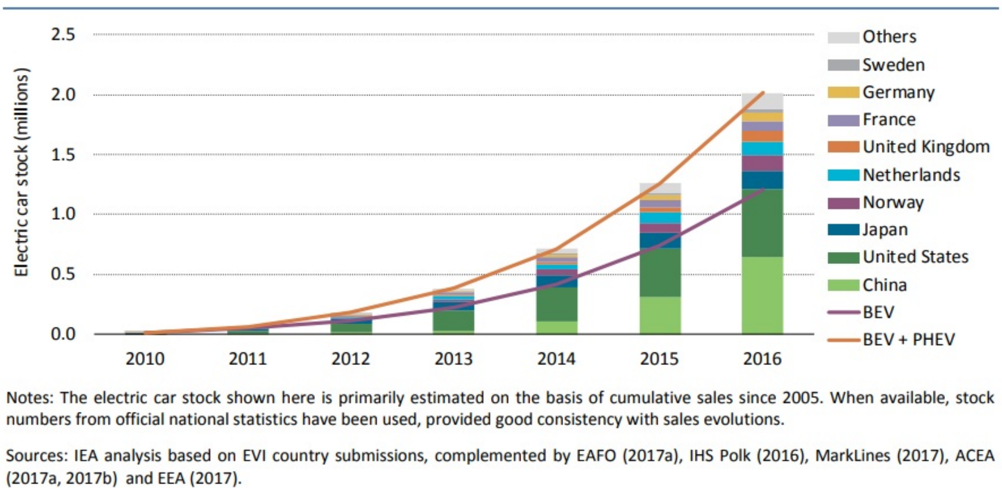

Figure 1.3: Evolution of Electric Vehicles

It has become clear that the future scene of energy will be with domination of renewable resources. According to a co-authorised Stanford and University of California-Davis study, a world where energy is 100% supplied by renewable sources (mainly hydro, wind and solar) is possible by 2050, and the only barriers are political and social, not technological [8] [9]. However, as predicted over 20 years ago, the key to an infrastructure where intermittent generation has a large penetration is storage [10].

Today, we can find several examples of places that run successfully with a large amount of renewable energy, such as Iceland, Norway, Denmark or some places in Germany. Another excellent example of how the shift from carbon-based generation is possible was

[2]https://www.seia.org/research-resources/solar-market-insight-report-2017-q2

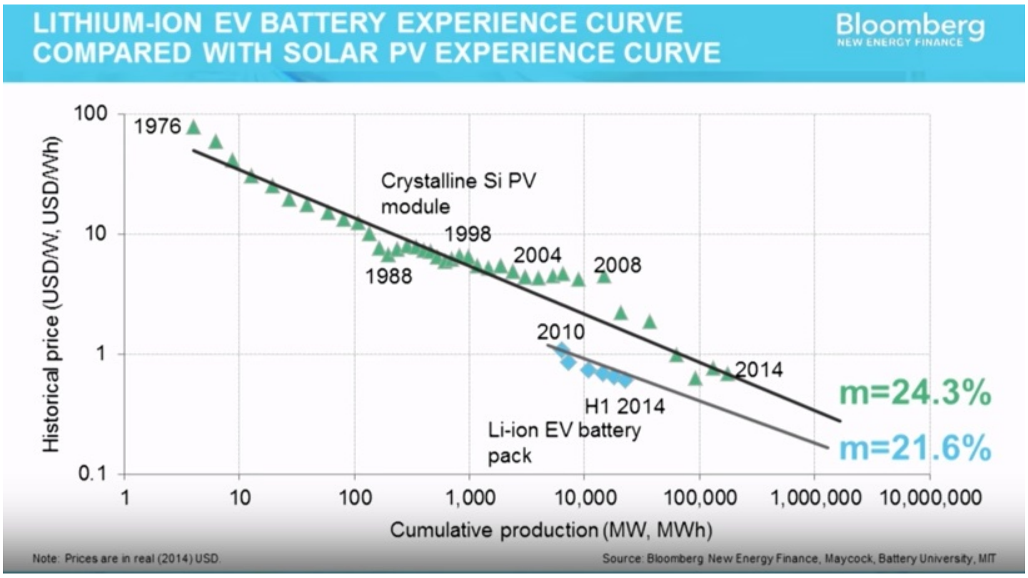

Figure 1.4: Evolution of Batteries prices compared to solar panels

done by Uruguay [11]. Ten years ago, Uruguayan generation was composed by 1450MW of hydropower (65% of installed capacity), 700MW of Thermal Power (32%) and 70MW of energy generated from biomass (3%). As can be observed in Figure 1.5 the generation from the hydroelectric power plants is heavily dependant on the rainfall. On a very rainy year, the plants are able to produce 10,000 GWh of energy while in a dry year is around 3,500GWh. This means that the shortfall of energy had to be supplied by the thermal plants which could vary from 12% to as much as 66%.

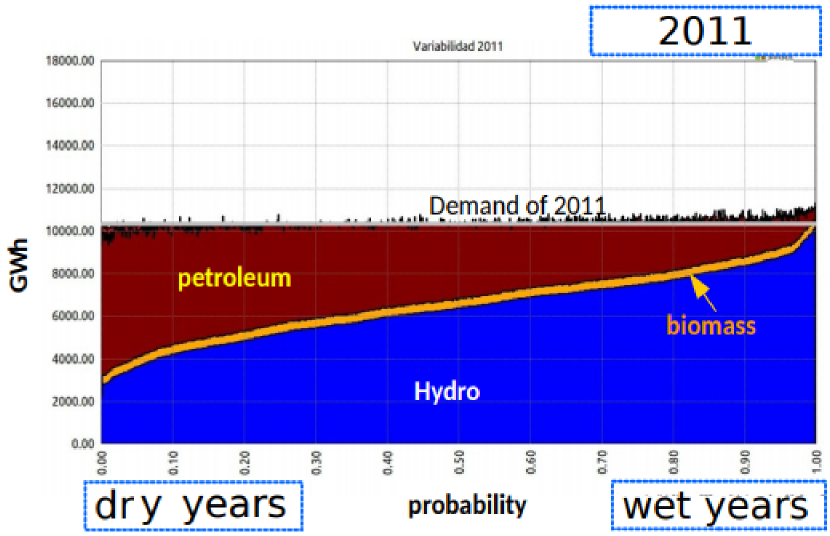

Figure 1.5: Probability of annual Hydro Generation in 2011 [12]

In 2008 the production of the hydroelectric plants was not good, and the price of the oil barrel was booming. Given that Uruguay is not an oil producer country, these two variabilities (hydro production and oil prices) imply a huge risk for the Uruguayan energy market. This lead to exploring new alternatives for the energy sector. The country implemented policies to favor the incorporation of non-conventional renewable energy and today clean generation provides almost 95% of the electricity consumption and a huge excess of energy that is exported to its neighbour countries [13]. Figure 1.6 remarks the current generation by sources, where it can be observed the increase in wind production and given the fact that these graphs are the results of stochastic realizations, with this increase of intermittent generation comes a significant increase in the error represented by the spikes. Nevertheless, it can be seen how the risk associated with petroleum derived generation is drastically reduced.

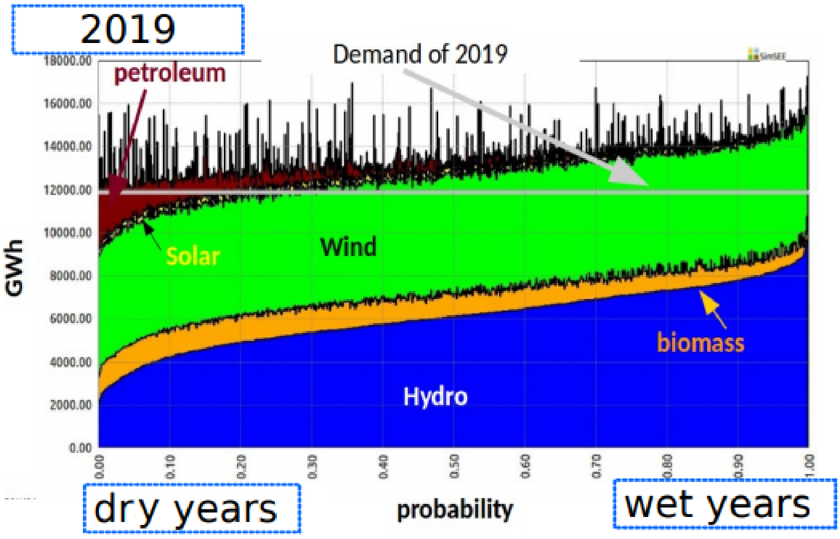

Figure 1.6: Probability of annual Hydro Generation in 2019 [14]

However, Uruguay, as well as other countries mentioned, have something in common that makes it possible to run almost entirely with energy that do not come from fossil fuel consumption. They have a very good resource of reliable generation, such as hydropower. This isn't the case in most of the world, where generation such as coal, thermal or nuclear is necessary for a successful operation of the grid. Storage technologies are promising in future networks where the need for decreasing the carbon footprint will lead to incorporating a very large amount of intermittent generation. As already mention, there are no technological impediments for shifting the world into clean energy. But it is a matter of making this shift as cost-efficient as possible. There is no point in building renewable generation if this has to be curtailed for the operation of the grid. Therefore, technologies that not only make this transition possible but efficient have to be further studied. The grid of the future will rely on smart operation rather than preventive operation, where flexibility in operation will be crucial. Demand response will have a huge role in dealing with the intermittency of resources, as well as storage technologies. In this project, we will focus on studying the role of storage technologies in systems with large penetration of renewable energy. For this purpose, the success of the Uruguayan energy transformation will be considered.

To begin with, we will consider solving the optimization problem of storage sitting. A model will be developed which will optimize the costs of a given network by allocating a portfolio of storage technologies. We will validate this model using real-world information of the Uruguayan network using a simplified model of its transmission system. We will aim to answer questions regarding the advantages of including storage technologies in a network with a high penetration of renewable energy, such as the Uruguayan. 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, there is a lot of time when the spot market is valued at $0\$/MWh$, and because of the sources intermittency, this market experiences spikes in prices. Therefore, this imbalances in the spot market can be exploited to maximize the revenue of an energy storage facility. On the other hand, from the government perspective, it is of interest to reduce the thermal production, plus the price that the energy is exported to its neighbours its not always optimal. Then, it will be of interest to study if the incorporation of storage facilities will make it possible to take advantage of the flexibility they provide.

The objective of this project is to develop optimization tools for the allocation of energy storage in systems with large penetration of solar and wind generation. This also involves the development of storage business models to maximize the revenue opportunities for storage technologies when it could provide multiple services, including frequency regulation, energy arbitrage, etc. For this purpose, this project develops a simplified model of energy storage expansion planning. There are a lot of promising opportunities for the Uruguayan energy sector to invest in energy storage technologies.

Chapter 2

Background

2.1 Literature Review

Environmental issues are of concern to every scientist nowadays, which fortunately is encouraging plenty of research in ways to mitigate the damage done so far. Therefore, the way of decarbonizing the power sector has been of huge interest. By now, it has become clear that the way the future networks operate is with very large penetration of renewable sources, with a large share of wind and solar, two resources which are intermittent by nature. Given their stochastic nature, storage technologies have been the focus of several studies to reduce the uncertainty this generation brings to the planning and operation of power grids and to improve flexibility.

When renewable generation started to become noticed, many questioned its viability and studies aimed to answer such a question. Turner in [10] presented the question: 'Should governments focus on renewable generation or CO_2 sequestration technologies?'. This introduced the persistent belief that investing in renewable resources does not generate enough energy in their lifetime to pay back the investment. He discredits this myth in his paper, and today we can say with certainty this past belief was completely baseless when almost half of the coal-powered plants run at a loss, and by 2030 wind and solar will be cheaper than 96% of existing coal [15]. Finally, he concludes with the need for storage technologies to handle the problem of intermittency.

The uncertainty in wind forecasting presents an additional requirement for balancing demand and generation. When operating a network with a large share of intermittent generation, the amount of required reserve is a function of the time scale. From a few seconds to minutes the most important factor is the potential loss in conventional plants rather than the fluctuations of renewable power. However, for forecasting over long periods of time (from several minutes to hours) reserve requirements are of extreme importance. When estimating for long-term time scales, meteorology methods (e.g forecasting weather) are preferred while statistical techniques are used for short-term (e.g probability of wind variations in the next few minutes). Nevertheless, all of these methods present uncertainty and reserve is needed to address the mismatches with the estimated generation.

The options of reserve include standing and spinning reserve, and the composition will depend on technical and economic considerations. Spinning reserve includes plants running part loaded, and inflexibility in conventional generation is also the source of another problem when considering renewable generation. When increasing wind generation the long-term need of reserve can increase up to 50% of the installed wind capacity [16]. This increases the need for reserve, and if provided with part-loaded plants the curtailment of wind can be considerable. In [16] it is found that this flexibility is key when calculating the value of storage technologies because, by providing it, spinning reserve of conventional generators can be reduced, therefore reducing the need for curtailment. Furthermore, running part-loaded plants increase CO_2 emissions because their efficiency decreases if not operating at rated conditions. Then, reducing the spinning reserve will also reduce emissions. Then, this study gave an insight into the importance of providing flexibility in conventional generation. It is concluded that the value of storage is also defined by the grid flexibility.

With the increased interest in energy storage, the potential market application for these technologies has also become the subject of some studies.
Problems with the integration of renewable generation include, among others:

- Interface issues (power quality) such as flickers, harmonics or transients in wind.
- Operation and planning issues from intermittency, forecasting and balancing.

where storage could provide solutions for some of these issues. As a reference, it has been identified that in the US, power quality related problem costs customers approximately 150 billion USD [17]. Several studies have identified potential applications of energy storage, and an exhaustive and extremely comprehensive guide can be found in [18]. Table 2.1 provides an overview of the potential market of energy storage in the different levels of the electric network.

Category	Application	Definition
Generation	Rapid Reserve	Energy holded in reserve in order to prevent interruptions in case of a failure event
	Area Control	Ability for utilities to control transfer of power among themselves
	Frequency Response	Ability to inject power in case of deviations from rated frequency
	Commodity Storage	Storing cheap energy from off-peak times in order to dispatch them later
Transmission	System Stability	Ability to keep the stability of the network
	Voltage Regulation	Maintain the voltage from all buses between rated levels
	Transmission facility deferral	Postpone installation of new transmission equipment
	Distribution facility deferral	Postpone installation of new distribution equipment
Customer Service	Customer Energy management	Managing customer consumption, dispatching energy stored during low cost times
	Renewable energy management	Store excess of renewable generation to dispatch when necessary
	Power quality and reliability	Prevent voltage spikes, surges and outages

Table 2.1: Energy Storage Applications [19]

Perrin *et al.* [20] focused their paper on market opportunities for storage providing ancillary services, comparing the performance of lead-acid batteries with other storage technologies. It is concluded that lead-acid batteries are expected to have an important share of the electricity market in the near future. On the other hand, in [21] it is concluded that there is not a single storage technology that can be considered the best. This conclusion comes after exhaustive research regarding batteries, pump hydro and fuel cell technologies and the area of application of each technology for renewable integration. The selection of the storage technology will depend on the performance and the source of fuel.

Modelling each potential application of energy storage is a very extensive problem and is usually done separately to achieve significant results. If a particular application is of interest, one can find studies in each respective area. As an example, in [22] the authors focus their study on frequency control in interconnected areas, where it is necessary to model the two area interconnection with high-frequency fluctuations. Their findings include that it is possible to completely suppress these fluctuations if the proper capacity is installed.

When assessing the advantages of energy storage the question most asked in the literature is: how much storage is necessary? So far, we have defined all the possible advantages of increasing the flexibility of the network by introducing energy storage, but this question remains unanswered. Most papers, discussing the advantages of energy storage, present methods which aim to optimize the amount of storage to install in a given network.
An interesting study looking at the siting and sizing problem of storage is presented by Wogrim and Gayme in [23]. The paper aims to co-optimize the storage location and capacity for four different technologies. For this, an optimal power flow (OPF) approach is used, but as this is a non-convex problem, it is studied as a DC approximation. This is the approach that will be used in this project.

We can find many papers in the literature which present their own methods for optimizing the above problem. For example, according to [24] the maximum storage to achieve more than 80% of renewable generation penetration in California is 22% of the average daily demand.
Meanwhile, other papers focus on studying the optimal ratio of wind and solar generation [25], concluding that up to 50% of the demand can be satisfied by renewable generation without storage, provided that the right share of wind and solar is installed. Furthermore, it also studies the role of storage in such a network, finding that up to 80% of the demand can be supplied with renewable generation if small but highly efficient storage devices are used.

One interesting approach for solving the aforementioned optimization problem was the one implemented in [26] by Pandžić *et al.* The problem is separated as a three-stage procedure. The first stage aims to identify locations where the storage is optimal. The second stage, with such locations identified, determines the sizing. Finally, the third stage model analyse the complete system operation to quantify the benefits of storage.

Most of these studies use test networks, usually from IEEE conventions. However, some studies, such as [27], use real-world locations where it is of interest to assess the feasibility of storage. Differently from papers that do not model a real-world network, geographical location has to be considered for these cases. One can assume any kind of storage in a test network, but for example, pump storage is only available if the location allows a reservoir to be built. In this study, as this kind of storage is available, the optimization of storage sizing is done focusing on pump hydro in a small island with large penetration of renewable energy. It is of importance to model the stochastic nature of the resources and the load, so a fuzzy clustering technique is developed for this purpose. The optimization is done considering the dynamic security assessment (DSA) criteria that the system will be able to regulate frequency. The result concluded that it is possible a larger penetration of renewable if including pump hydro storage, improving the DSA and the economic dispatch. Finally, as the DSA is of primary importance on that particular network (result obtained from a sensitivity analysis), they propose to include a complementary technology to help provide with frequency regulation and reserve.

It is worth mentioning the ideal operating conditions considered by most of the studies. The most important characteristics include:

1. Storage Size
2. Rate of charge and discharge limit
3. Efficiency
4. Self Discharge
5. Depth of Discharge
6. Temperature Dependency
7. State of Health

Items 1 to 3 are going to be considered when developing the model for this project while the others will not because of their complexity. In [28] it is presented an extremely complex mathematical model for modelling non-ideal energy storage devices where they affirm that storage imperfections have significant consequences in the power system performance. Even though this study is very comprehensive when modelling the imperfections, temperature dependency and state of health were not modelled because they are non-linear and application dependant which make their inclusion in a mathematical model extremely difficult. However, the authors describe the importance of considering these imperfections in future works.

The final problem we are going to address for the purpose of this project is one of investment planning. Investments in energy storage have grown considerably in the past years, reaching 675 millions USD by 2014 and predicting a market of more than 15 billions USD by 2024 [29], arising several studies focusing on optimizing the investment to maximize revenue.

In the literature, one can find papers focusing on this problem from an investor perspective, whose aim is to maximize profits by doing energy arbitrage as done in [30] without considering ancillary services. In this case, the approach used in the algorithm for addressing the extent and the non-convexity of the problem is the Bender's decomposition and perfect and imperfect competition is modelled. Future scenarios using real-world data were generated for the uncertainty of the problem. Their results depend on the case study i.e employed scenarios and assumptions, so one needs to have extreme care when approaching the investment problem.

We can also find papers [31] which aim to answer more general questions regarding investment planning, such as: how does the flexibility affects investment? How does investing in storage affect renewable growth and prices? Who should do the investment planning? Here, two models were used, with the first being designed for centralized investment, and the second for decentralized investment. The study shows that storage is beneficial for operation and that decentralized planning can cause congestion so regulations are necessary.

Studies mentioned before which worked on the siting and sizing problem also includes investment planning into their research, such is the case of [23] where investment optimization was added in a later stage. For this, Monte Carlo simulations are used to address the stochastic nature of the parameters solving the model with different random scenarios while also incorporating life cycle parameters in the model. Results show that storage allocations are mainly a consequence of the network properties while investment depends on factors such as technology. The case study did not take into account factors such as wind and load uncertainty, crucial in real-world planning. Computational efforts could be very high if modelling this but still, authors recommend considering it for future works.

Climate change has grown to become one of the greatest threats to humanity. Our efforts must be put into the energy sector, not only power wise but also into transport and heating. Fortunately, scientists across the globe have identified the problem and research is being developed to tackle it. There are studies [9] that suggest a world powered with wind, solar and water is possible by 2030, and such infrastructure only needs approximately 0.50% more land for footprint and spacing with the energy cost being similar to that today. In their second part of the study, they conclude that complete decarbonization is possible and the barriers are mainly social and political [32]. For this, technologies such as electric vehicles and energy storage are crucial and we should focus future research in such topics.

To sum up, most of the works mentioned in this chapters plus plenty of others [33] [34] [35] suggest that storage will add value to future power networks and will help the integration of renewable energy, while also investing in these technologies could incur in savings. Still, the technology isn't completely developed and due to high investment costs, savings may not always be sufficient as they are dependent on several factors dominated by uncertainty, such as fuel prices, interest rates or wind production [36]. Nonetheless, even though these technologies nowadays are heavily dependent on their high investment cost and might not be profitable enough under certain circumstances, with the continuous development of storage technologies it is a matter of time before they become mainstream for power system operation if we continue through the very much needed decarbonization path for our planet.

2.2 Uruguay and its electric sector

Uruguay is a small country located in South America between Argentina and Brasil (see Figure 2.1 and 2.2 [1]). It has a population of 3.4 million approximately and its area is about $176,215 km^2$.

Figure 2.1: Location of Uruguay

Figure 2.2: Map of Uruguay

Its annual electricity demand in 2017 was of 11,200GWh, with a future demand growth expected of 2% yearly. It is interconnected with Argentina by two lines of 500kV with a capacity of 2000MW and with Brasil by two power converters totalling 570MW.

The main actors in the Uruguay electricity market are:

- UTE is the state owned power company in charge of transmission and distribution networks and acting as the sole utility.
- Ministry of Industry, Energy and Minery in charge of defining the policy in terms of electric energy and also fix tariffs to regulated consumers
- ADME (Administrator of the Electric Market) Operator of the system and comercial administration of the electric market
- URSEA State regulator company

In 1997 a regulatory framework was approved which changed the vertical integration of the monopoly company UTE, which can be visualized in Figure 2.3 and 2.4.

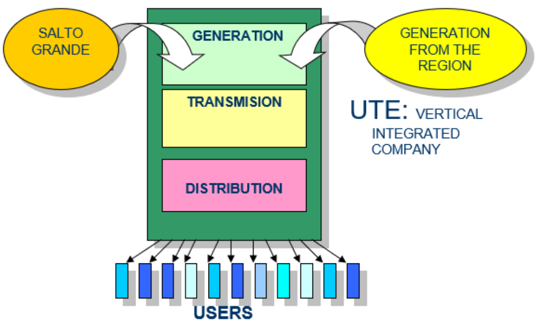

Figure 2.3: Energy sector pre-1997

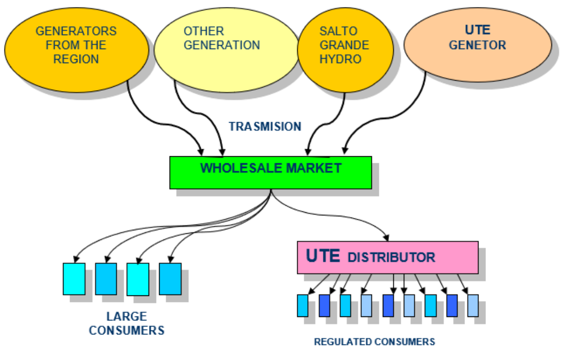

Figure 2.4: Energy sector post-1997

[1] https://en.wikipedia.org/wiki/Uruguay

Uruguay electric sector has gone through radical changes in the past 10 years. In 2008, Uruguay generation was composed 65% of hydropower, 32% of thermal power and 3% of biomass. An increase in oil barrel prices led to search of new alternatives for the energy sector, implementing policies encouraging the investment in wind and solar energy. In Table 2.2 it is detailed the generation mix in Uruguay by 2017 [37] while in Figure 2.5 all the generation units are presented in the Uruguayan map.

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 2.2: Characteristic parameters of the system

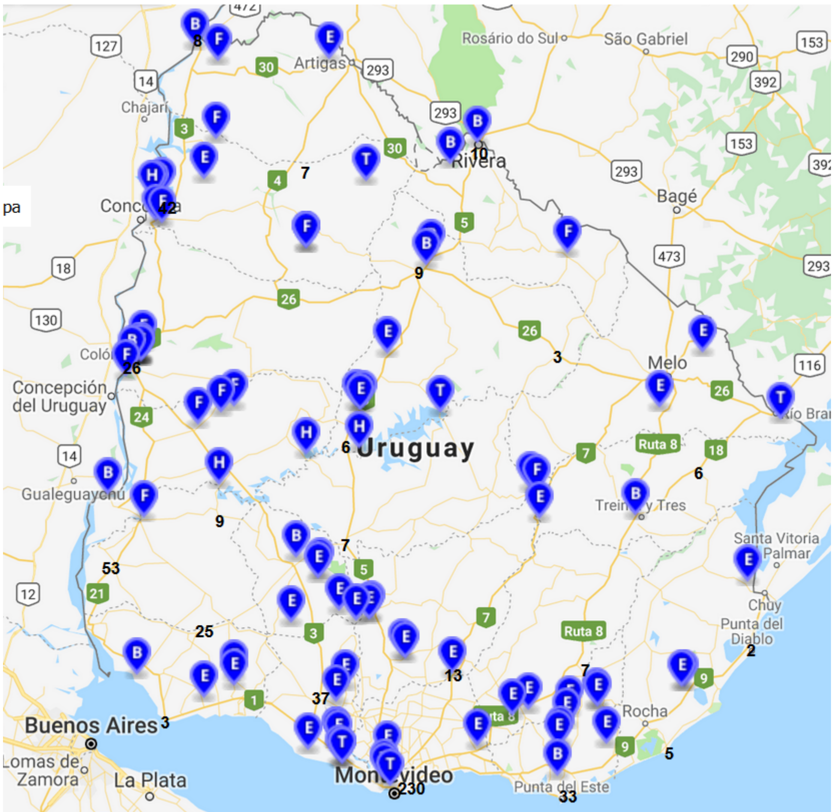

Figure 2.5: Geographic location of Generation Sources [38]
E: Eolic(Wind); F: Photovoltaics; H: Hydro; T: Thermal; B: Biomass;

Even though it has a considerable amount of thermal generation installed, the share of this energy was less than 2% for 2017. One can appreciate the energy consumed by source in Figure 2.6.

So in ten years, Uruguay achieved great success in transforming its energy sector, from being a country heavily dependant on oil prices, rains and importations to a country that only relies in its own resources which have proven to be more than enough, and cutting carbon emissions almost to zero. Figure 2.7 shows the evolution of the installed wind capacity, where it can be observed the increase from 2013 onwards.

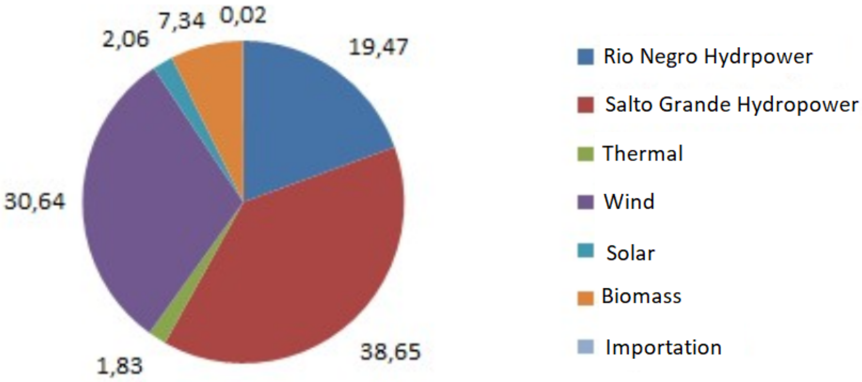

Figure 2.6: Energy generation by source in 2017 [37]

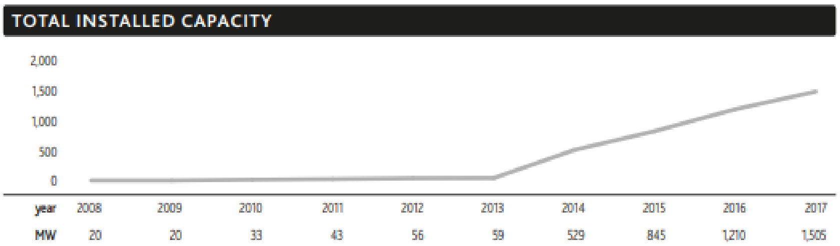

Figure 2.7: Evolution of the total installed wind Capacity [39]

In Figure 2.8 the maximum, minimum and average demand as well as the installed wind and solar generation is plotted. This way is put into perspective how much wind and solar the country has installed and even though it seems a lot it is the result of a refined investment planning. Furthermore, a lot of the surplus of energy is currently being exported to Argentina and Brasil.

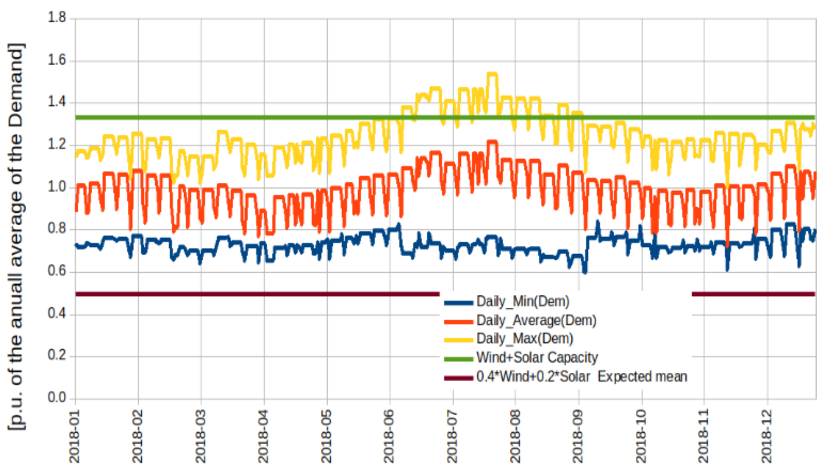

Figure 2.8: Wind and solar installed capacity compared with demand [14]

The economic dispatch in Uruguay is done by the DNC (National Loads Dispatch) in charge of ADME. It mainly depends on the variable cost of the thermal units and the value of the water in centrals which have pumped storage (this is the cost of opportunity of having water stored).

The way Uruguay attracted so many investment in the wind and solar sector is because they offered take or pay contracts. UTE buy wind energy to several private generators and if this needs to be curtailed because of DNC's operation conditions, UTE pays for the energy curtailed the same price. Therefore, the dispatch of energy in Uruguay will always prioritize wind and solar generators. There are a few wind farms, operated by a private company in Uruguay that sells energy in the wholesale market. This account for approximately 65MW of generation. Similarly, biomass production, which is mainly done by two cellulose plants, is always dispatched to the network.

The spot price of the wholesale market is calculated by ADME which is heavily dependant on the wind and hydro resource. Given the fact that most of the wind production is paid using take or pay contracts and the hydro energy has zero production cost, if both resources are high then the spot price is zero. Therefore, it is possible to characterize the spot price discerning whether it is a rainy or a dry month. As an example we can observe the average spot price for 2015 and 2017 in Figures 2.9 and 2.10 respectively. One can appreciate that during the dry months in 2015 the spot price was very high, while 2017 which was characterized by rains throughout the whole year had its price spot mostly at zero.

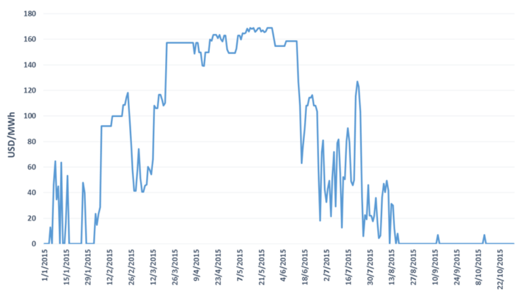

Figure 2.9: Daily spot price average 2015

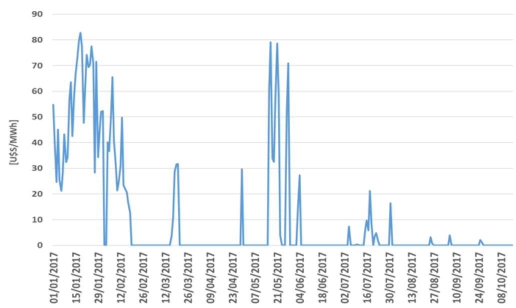

Figure 2.10: Daily spot price average 2017

Furthermore, in Figure 2.11 it can be observed the spot price can have significant variations on a hourly basis. This is because of the intermittency of wind. This variations looks promising from an investor perspective where the energy can be bought in the wholesale market when the price is at $0USD/MWh$ and stored until the spot price reaches a profitable value. These variations is what this project will try to exploit.

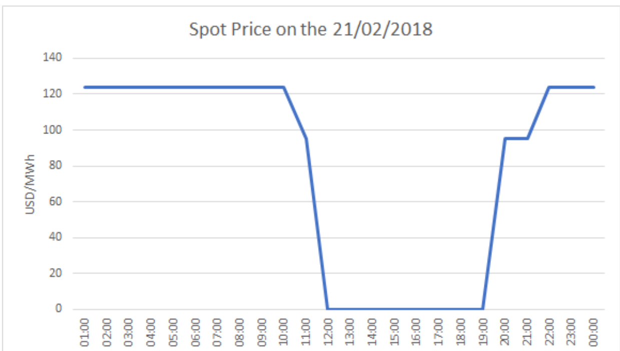

Figure 2.11: Spot price on the 21st of February 2018

Finally, the transmission network is presented in Appendix A. For the purposes of this project, the network will be modeled only in 500kV, in order to reduce the number of buses to make the optimization problem computationally possible.

Chapter 3

Methods

As already mentioned before, the main objective of this project is to study the feasibility of energy storage in the Uruguayan network, specifically Lithium-ion batteries. For this purpose, we will focus the analysis from two different scopes:

- Private investor perspective: whose aim is to maximize revenues by doing energy arbitrage in the spot market
- Government perspective: whose aim is to minimize production costs by reducing thermal generation

The data, which includes hourly spot prices, and 10 minutes intervals of generation, demand and exportation, is freely available from ADME [13]. The software used for solving the optimization was Gurobi©, and Matlab for building the equations.

3.1 Mathematical Model

3.1.1 Private investor perspective

For the first scenario, we will address the problem from a private investor's perspective. For this we will use hourly data of the spot market prices over a year, and simulate several years, up until 2013. We should note that it is not worth to use previous years, as wind generation had not been installed yet, and the spot prices are not representative of the current reality.

The reason we simulate over so many years, is because Uruguayan network has a very high penetration of hydro generation, as already mentioned before, and the rainfalls regime highly influences the prediction of the spot price. Therefore, it's necessary to simulate different scenarios to appreciate the impact of the rainfall.

Another important consideration is that the inclusion of an energy storage facility does not modify the spot prices. The wholesale market of Uruguay has some peculiarities in comparison to other markets of the same kind. As of today, there are not many participants, except for a few IPP (Independent Power Producers), as it is a relatively new market.

Therefore the prices are calculated by ADME as following:
A software (SimSEE [40]) is ran in an infinite loop which deals with the calculation of the optimal operation of the electric system and among others also calculates the spot price. It runs thousands of simulations considering many stochastic variables such as demand, wind forecast, weather events in the Atlantic, oil prices, etc. The spot price is calculated taking into account the following factors:

1. Wind, solar and hydro predicted output
2. Marginal cost of conventional generation
3. Value of water (will it be better to save water in the reservoir for future scenarios?)

So, from a private perspective, if a battery storage facility is to be installed, this wouldn't change the points above. It will buy and sell energy at the given spot price. However, regulations on batteries are still relatively new and of course it would be wise to consider them from an operator point of view (same as the value of water is considered), but as of today, and looking at it from a private point of view, that wouldn't be the case. So considering the battery as a consumer when they buy, and a generator when they sell, right now it will not impact in the spot price. The few IPPs that sell energy at the spot price are not considered in the simulations.

In a second stage of this problem, we will include a revenue for providing an Enhanced Frequency Response (EFR) service. The approach for this method is the proposed by the National Grid in their 2015 EFR tender [41], where 201MW of EFR was accepted. The EFR providers are required to deliver a minimum of 1MW of response, responding within one second to frequency deviations. For this service, the providers are paid in terms of the amount of power they provide and the amount of hours the service is available. It's worth noticing that National Grid considers a service performance measure, which derives into an availability factor and penalties for the providers, which will be ignored for the purpose of this project. For simplicity, it is assumed that the service can be provided once a day.

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

$$\max_{\Omega} \sum_{t \in \mathcal{T}} E_{sell}\left(r_d(t), t\right) - E_{buy}\left(r_c(t), t\right) - \left(AIC(C) + MC(C) + TF \times R_c\right) \tag{3.1}$$

where E_{sell} is the energy sold at the spot price,
E_{buy} is the energy bought at the spot price.

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

$$AIC = \frac{IC}{A_{\tau,r}}, \text{ where } A_{\tau,r} = \frac{1 - \frac{1}{(1+r)^{\tau}}}{r} \tag{3.2}$$

$$MC = 5\% \times AIC \tag{3.3}$$

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

The optimization set:

$$\Omega := \{r_c(t), r_d(t), s(t), C\} \tag{3.4}$$

is the charge rate, discharge rate, storage level and battery capacity respectively, and the set:

$$\mathcal{T} := \{1, \ldots, T\} \text{ with index } t \tag{3.5}$$

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

Finally, TF is the fee for using the transmission network, which is a fixed value that depends on the maximum power of the battery. This is set by the ministry of energy and the current value is around $3USD/kW.Month$. In this case, it will depend on the maximum charge/discharge rate of the battery (R_c). 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 constraints of this optimization problem are described next.
The storage level $s(t)\,\forall t \geq 2$ is:

$$s(t) = s(t-1) + (\eta_c r_c(t) - r_d(t)/\eta_d)\,\Delta t \tag{3.6}$$

This is, the storage level at the next step is equal to the charge minus the discharge considering the efficiency of the technology, in this case 94%.

Furthermore, the problem is bounded by the following equations:

$$0 \leq r_c(t) \leq R_c \tag{3.7}$$

$$0 \leq r_d(t) \leq R_d \tag{3.8}$$

$$0 \leq s(t) \leq C \tag{3.9}$$

where R_c and R_d and the charge and discharge rate of the battery which will be considered to be equal. It is worth noticing that for the purpose of doing a sensitivity analysis with the rate, these values where kept independent of the capacity, which is unusual for lithium-ion batteries.

3.1.2 Enhanced Frequency Response

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

$$EFR_{Pay} \times P_{EFR} \times h \tag{3.10}$$

where EFR_{Pay} is the payment the facility will receive for being available to provide the EFR service. According to the National Grid last tender [41], the average value of the availability price was $12USD/MW.h$.

P_{EFR} is another decision variable which is the amount of power the facility will provide for the EFR service.

h is the amount of hours a year the service will be provided. It was assumed 23 hours a day in order to leave a margin for maintenance.

A priori, one might think the most reasonable value for P_{EFR} is R_c, but if the value P_{EFR} is reduced there is more freedom to perform energy arbitrage. So, it is important to set P_{EFR} as a decision variable and confirm expectations with the results.

Furthermore, the bounded equations are modified as following:

$$E_{EFR} \leq s(t) \leq C - E_{EFR} \tag{3.11}$$

Where E_{EFR} is the amount of energy the battery needs in order to provide the service. Note that it is in both sides of the inequation, in order to inject or absorb power if needed. The time the service has to be provided is at least 15 minutes. Then:

$$E_{EFR} = 15/60 * P_{EFR} \tag{3.12}$$

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

$$1MW \leq P_{EFR} \leq R_c \tag{3.13}$$

3.1.3 Government Perspective

The second scope of the project will be to analyse the feasibility of installing an energy storage facility in order to reduce production costs from thermal generators. For this purpose, we will solve the optimal power flow problem, which aims to minimize the production costs, plus the battery investment. Given the limited amount of time and resources, it was not possible to develop a detailed model of the network. The approach used in the project is to only model the 500kV transmission network. Using the knowledge of the real network presented in Appendix A, the network was approximated by a seven bus system as shown in Figure 3.1.

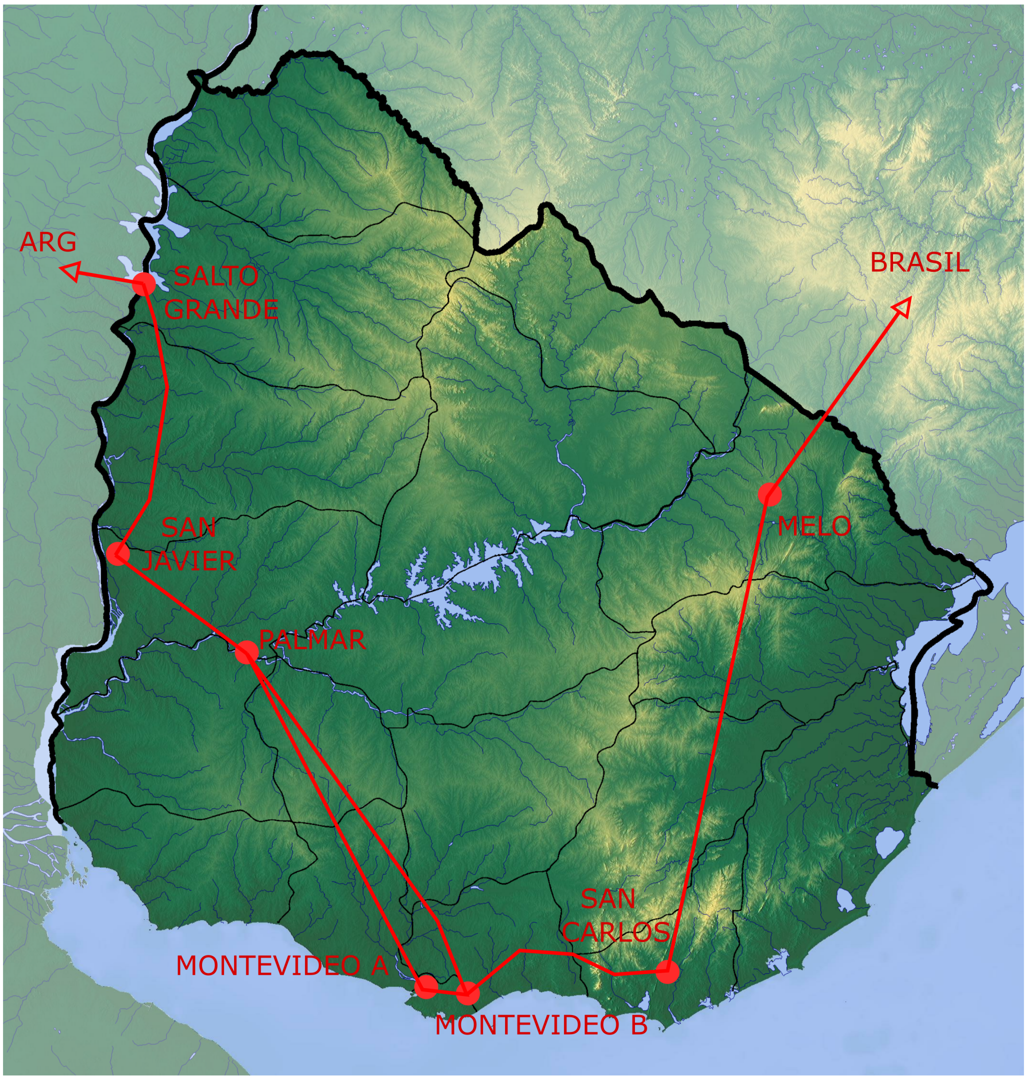

Figure 3.1: Approximate model of the Uruguayan 500kV network

The generation, demand and exportation were accordingly distributed by geographic proximity to the respective buses, as detailed in the next chapter.

Furthermore, from an investment planning perspective, the optimal case would be to use the SimSEE software in order to consider all the stochastic variables present in such problems. Again, given the time restrictions it was not possible to simulate the reality of the hydro dispatch done by ADME, so we will assume all the generation, except thermal generation, as known input for our problem. Then, the objective of the developed algorithm is to minimize the production of thermal generators which will be considered as a decision variable. Afterwards, we will compare this result with the real output of thermal units. The optimization algorithm works with one hour time steps, while the data is available as ten-minutes intervals, therefore, the average is calculated for each hour.

For this analysis we introduce some new variables. First, the set of different nodes $\mathcal{N} := \{1, \ldots, N\}$. Furthermore, the optimization set Ω is now:

$$\Omega := \{p^n(t), r_c^n(t), r_d^n(t), s^n(t), k^n, \delta^n(t), G_{curt}^n(t) : n \in \mathcal{N}\} \tag{3.14}$$

Where every variable now identifies a different node in the network, as well as the inclusion of $p^n(t)$, production of thermal units; k^n, storage allocation and $\delta^n(t)$ voltage angle at node n. G_{curt}^n represents generation that was previously curtailed and now will be used to charge the batteries. It includes the hydro curtailed h_{curt}^n and the wind curtailed w_{curt}^n.

The optimization problem is now a minimization of the production costs (Γ) plus the battery investment. This is:

$$\min_{\Omega} \sum_{t \in \mathcal{T}} \left\{ \sum_{n \in \mathcal{N}} \Gamma^n(t) p^n(t) + \sum_{n \in \mathcal{N}} (AIC(C^n) + MC(C^n)) \right\} \tag{3.15}$$

Besides equations 3.6, 3.7, 3.8 and 3.9 we include the following into the constrains of the problem:

$$P_{\min}^n \leq p^n(t) \leq P_{\max}^n \tag{3.16}$$

$$-RR^n.\Delta t \leq p^n(t) - p^n(t-1) \leq RR^n.\Delta t \tag{3.17}$$

Where the first represents lower and upper limits and the latter the ramp rates of thermal generation.

At every time instant and every node, power flow equations has to be verified. This is, total demand plus charge of batteries and inflows must be equal to discharge of batteries, outflows, plus total generation. We consider the total demand as load plus exportation to Argentina and Brasil, and total generation as hydro, wind, solar, biomass and thermal.

$$D^n(t) + \sum_{m \in \Theta_n} B^{nm} \left(\delta^n(t) - \delta^m(t)\right) + r_c^n(t) = G^n(t) + p^n(t) + r_d^n(t) \tag{3.18}$$

Where we denote the set Θ_n as the nodes m connected to bus n. Then B^{nm} represents the line susceptance between node n and m.

Inside the variable representing the non-thermal generation $G^n(t)$, we have the decision variables G_{curt}^n, which can be separated into the wind curtailed and the hydro curtailed both in Salto Grande and in Rio Negro. For this variables we have to make certain assumptions, as the generation data is given in a 10 minutes basis and the information of the wind curtailed is given per month and the hydro curtailed is given per week.

As detailed in the Results section, we have information of the average water release per week for the dams. We will study two cases, a dry scenario where there is no water released in the dams and a wet scenario with water released that could have been used to charge the batteries. Therefore, the decision variable h_{curt}^n will be bound by the maximum possible generation of the dam minus the current generation at time t:

$$0 \leq h^n_{curt} \leq h^n_{max} - h^n_{gen} \tag{3.19}$$

Furthermore, we assume that all the decision variables regarding curtailment G^n_{curt} are only greater than zero if and only if the thermal production is zero. Therefore, we will not be considering the cases where generation was curtailed because of restriction in transmission lines.

For wind generation curtailment we obtained information from the ministry of industry and energy [42], with the total amount of energy curtailed in each month. Therefore, we assume an equal distribution through the four weeks of the month, and using the amount of hours energy was curtailed (time steps in which thermal energy production was zero), we can approximate the upper bound of the wind curtailed variable.

We also introduce transmission lines limits, such that:

$$-TC^{nm}_{\max} \leq B^{nm} \left(\delta^n(t) - \delta^m(t) \right) \leq TC^{nm}_{max} \tag{3.20}$$

Finally, the boundaries of the voltage angles and setting the slack bus:

$$-\pi \leq \delta^n(t) \leq \pi \tag{3.21}$$

$$\delta^{n=1}(t) = 0 \tag{3.22}$$

Chapter 4

Results

In this section we will present the results obtained in the different optimization problems. First, it is worth noticing that once the huge amount of wind generation was installed in the Uruguayan network, we faced years with important amount of rainfall. In Figure 4.1 we can observe the energy output of hydro turbines, where it can be identified that the past four years are considered as very wet.

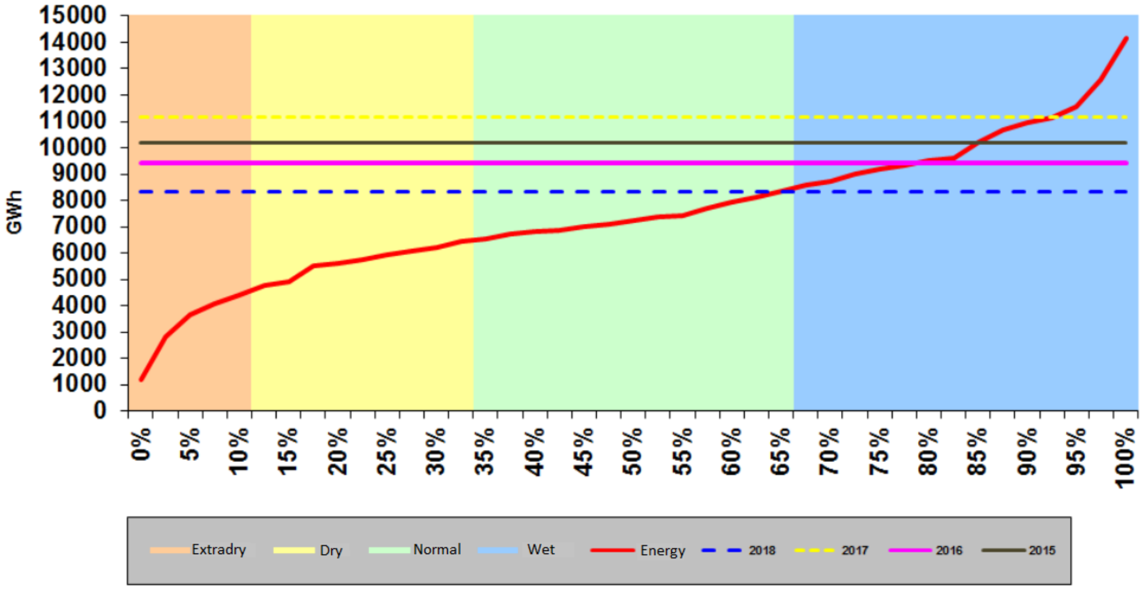

Figure 4.1: Comparison of total Hidro Energy in 2018 [13]

In fact, ADME annual reports [13] present the position each years holds in terms of wettest years. This information is available up until 2014 where out of 108 years, we can see their positions in the historic series in Table 4.1.

Year	Position as most wet year
2018	37th
2017	7th
2016	22nd
2015	16th

Table 4.1: Position as most wet years in the historic series

Even though there is no information of the exact position of 2014 and 2013, we can verify from previous reports that the hydro energy output during those years was even better than 2015. Therefore, the past years (except 2018) are considered to be in the top 20% in terms of wet years, and having such consistency in rain over so many years is considered a very rare event. This does not help the private investor study case because wet years means more hydro power, which will decrease the spot price value. Then, its important to keep in mind that the results during those years might be underestimating the real potential.

4.1 Spot Price Data

We begin our study by analysing the values of the spot price. Figures 4.2 to 4.7 show the heatmap of the hourly spot price across different years. It can be observed that prices increases during the evening, particularly noticeable in some years like 2016 or 2014. The decrease in the spot prices is clear from 2014 onward, which is linked to the hugely increased wind capacity, from 59MW to 529MW (see Figure 2.7).

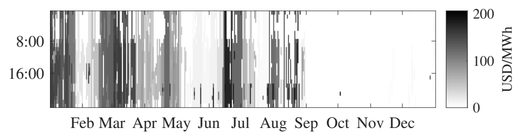

Figure 4.2: Spot Prices 2018

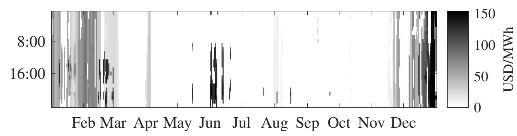

Figure 4.3: Spot Prices 2017

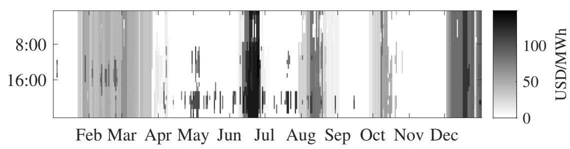

Figure 4.4: Spot Prices 2016

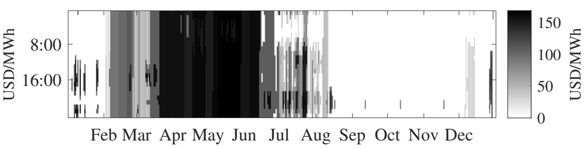

Figure 4.5: Spot Prices 2015

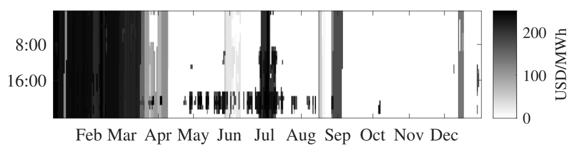

Figure 4.6: Spot Prices 2014

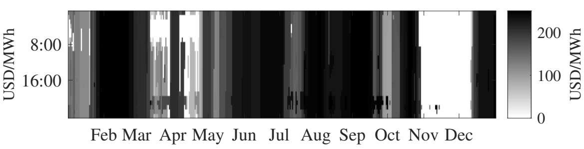

Figure 4.7: Spot Prices 2013

However, for energy arbitrage, high spot prices are not neccessarely enough, but a high difference between the maximum price and the minimum price during a day. We can observe this information in Figures 4.8 to 4.13 in the way of histograms.

As mentioned, high spot prices does not necessary mean potential for arbitrage as seen in such figures, where 2013 was the year with highest value of spot prices but also the year with more days where the price difference is zero. The most promising year for doing arbitrage seems to be 2018, year where the rainfall regime was the lowest. Still, around half of the year there is no difference in the daily price, consequence of it being zero from September onward.

A priori, buying energy at the spot market at zero cost looked interesting for arbitrage, but the analysis on the spot price indicates that it might not be as promising, given the low difference between maximum and minimum prices during the day.

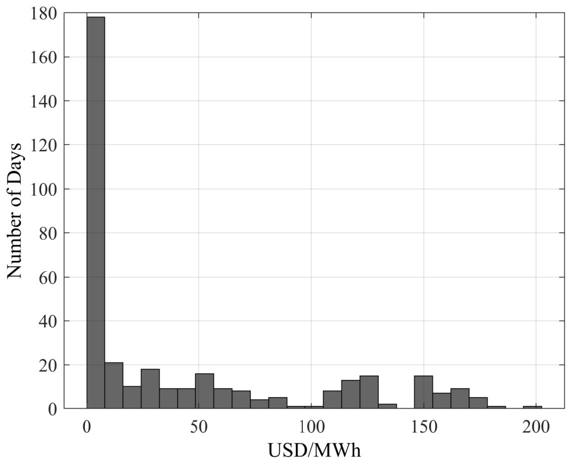

Figure 4.8: Difference between daily minimum and maximum price 2018

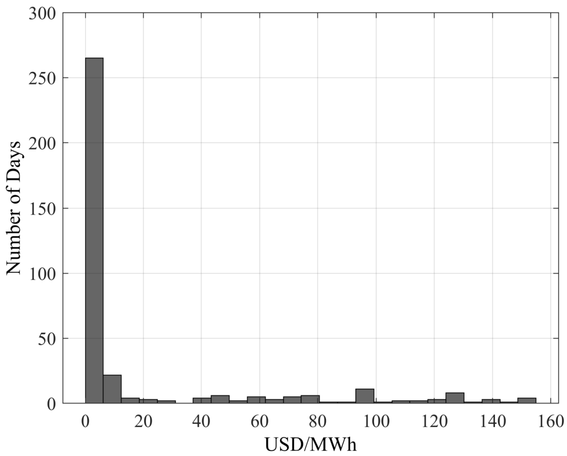

Figure 4.9: Difference between daily minimum and maximum price 2017

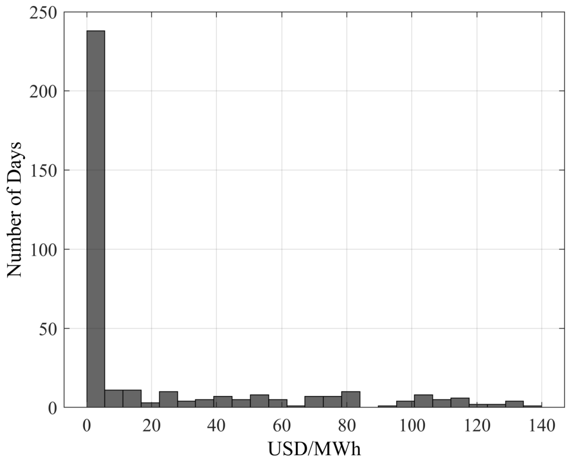

Figure 4.10: Difference between daily minimum and maximum price 2016

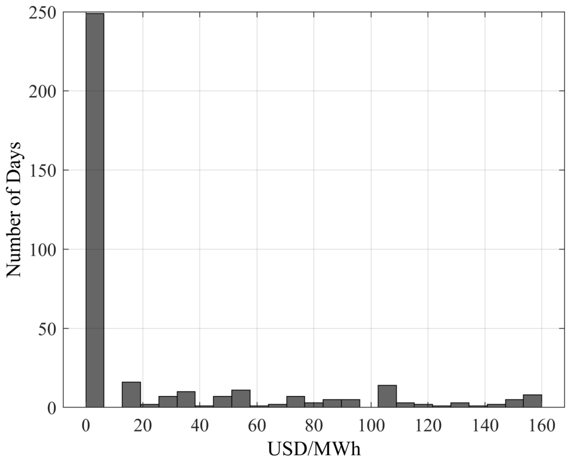

Figure 4.11: Difference between daily minimum and maximum price 2015

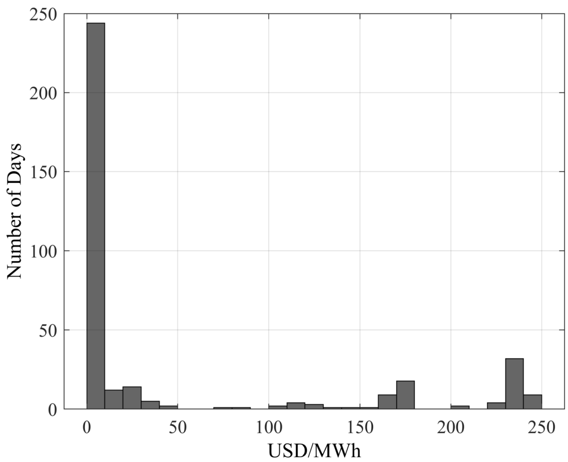

Figure 4.12: Difference between daily minimum and maximum price 2014

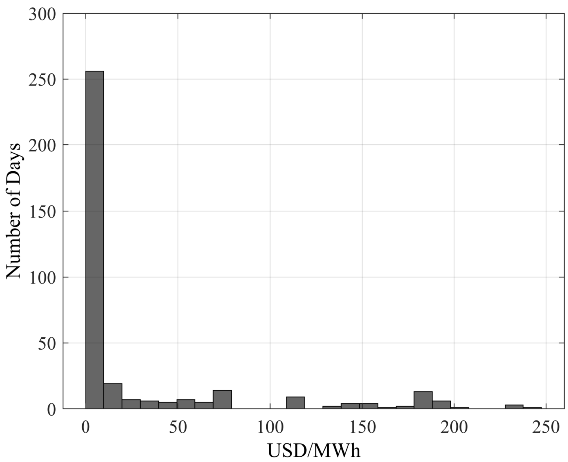

Figure 4.13: Difference between daily minimum and maximum price 2013

4.2 Private Investment

The linear programming optimization problem consists of 26,281 continious variables and 26,280 constrains equations when simulating over a whole year. It is possible to build the constrains equations just once and save them in a Matlab data file, and do a sensitivity analysis with variables that do not modify the constrains, such as the price battery and the charge/discharge rate. When all the model is built, Gurobi solves the problem in 1.60 seconds using a computer with an AMD Ryzen 7 2700U, 2.20GHz, 8GB RAM.

Figure 4.14 shows the optimal capacity to be installed as a function of the battery price for different years, while fixing the battery charge and discharge rate to $100MW$. On the other hand Figure 4.15 shows the optimal capacity as a function of the charge/discharge rate while fixing the price to $80USD/kWh$.

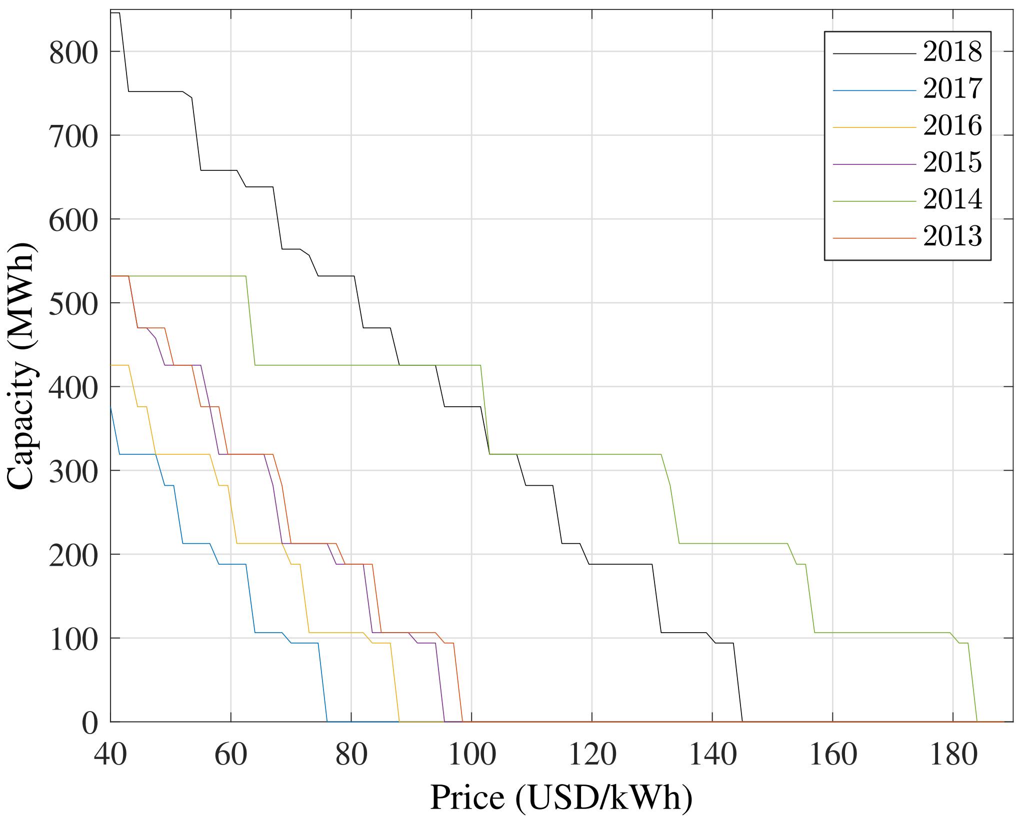

Figure 4.14: Battery Capacity as a function of the price - R_c: 100MW

In this first figure it can be appreciated how 2018 and 2014 are the best years for doing energy arbitrage, while in 2017, the year characterized by the lowest spot price and most days with a price difference of zero, it would not be feasible to install a battery storage facility for prices above 80USD/MWh. For the rest of the years an extremely low battery price is necessary to make it profitable.

In the second figure it can be observed a linearly dependence between the charge/discharge rate, where doubling the rate incurs in doubling the optimal capacity. Furthermore, we can observe that the price has the biggest influence when optimizing the battery size, given that the year that isn't profitable for a price of $80USD/kWh$ (2017) won't be profitable whatever the value of the charge/discharge rate.

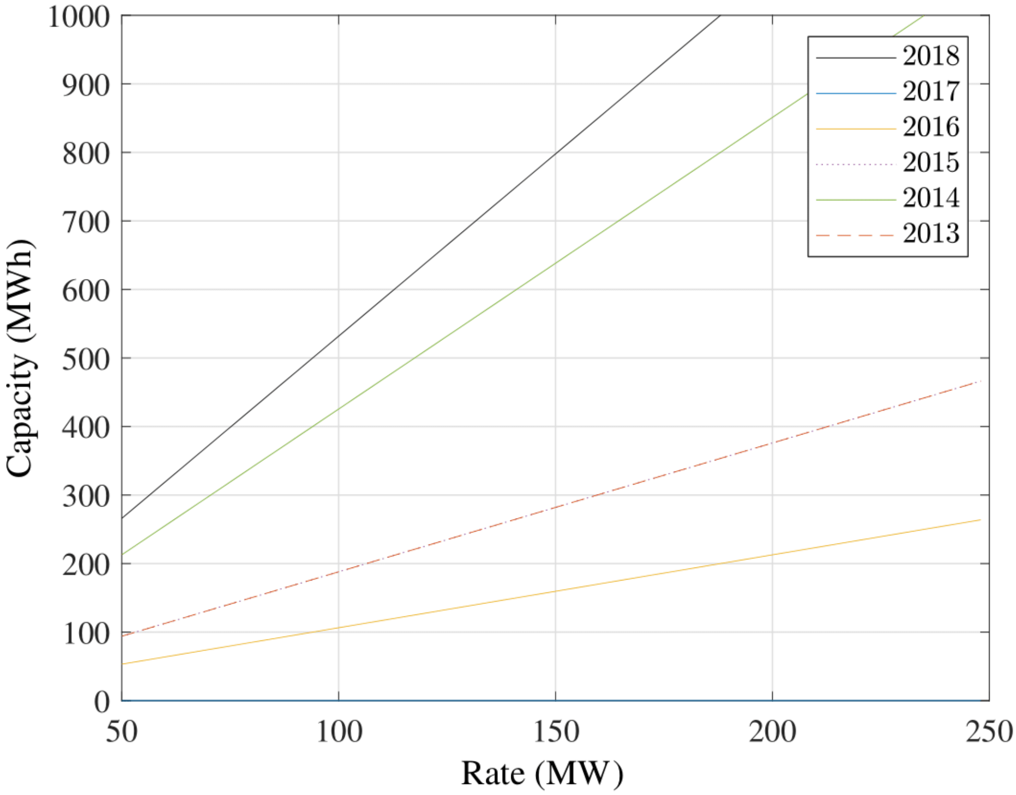

Figure 4.15: Battery Capacity as a function of the price - Price: 80USD/kWh

When analysing the revenue, the first thing to note is the cost of transmission fees. At the price fixed per kWh as explained in section 3.1.1, and considering the rate to be $R_c = 100MW$ the cost of transmission fees would be:

$$TC = 100MW * 3USD/kW.Month * 1000 * 12 = 3.6\text{million USD} \tag{4.1}$$

This offset value of -3.6 million makes our objective function to be always negative, yielding no positive revenue independently of the size. Therefore, for the sake of discussion we will not consider transmission fees and will discuss more about it in section 5.

In Tables 4.2 and 4.3 is reported the annuitized revenue (objective function result) when fixing the rate and the price respectively. 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 4.2: 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 4.3: Battery annuitized revenue Price 90USD/kWh

For a particular scenario we can plot the behaviour of the battery across the year. In Figures 4.16 and 4.17 we can observe a snapshot where we can see the behaviour of the battery, where on the first figure we can appreciate the storage level and the charge/discharge rate, while in the second figure we can observe how the battery charges while the spot price is at zero and discharges while its value is high. The particular scenario plotted is March 2018, with a charge/discharge rate of $100MW$ and a price of $120USD/MWh$. For this particular year, we can see how the battery barely operates during the months where the spot price is zero (September onward) in Figure 4.18.

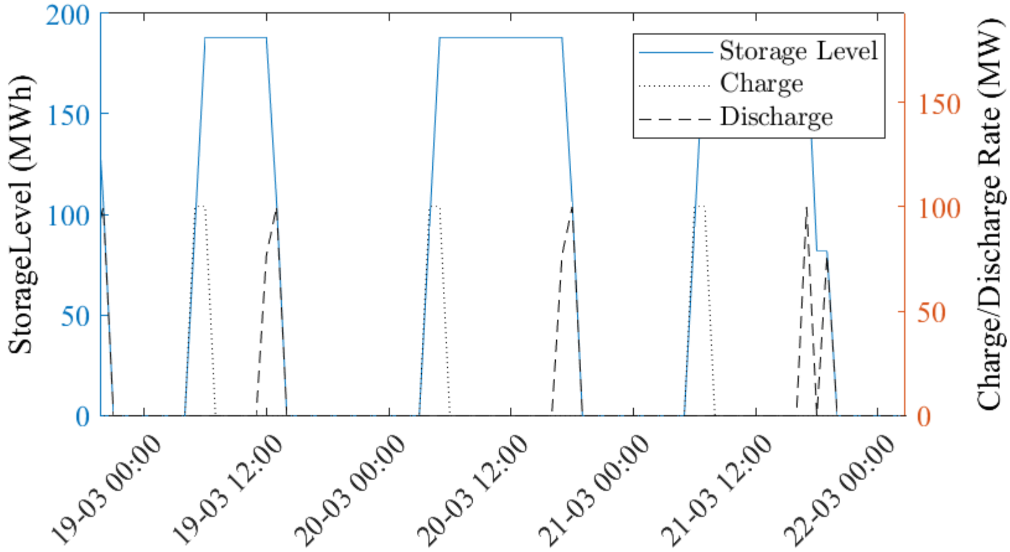

Figure 4.16: Storage Level and Charge/Discharge Rates on March 2018

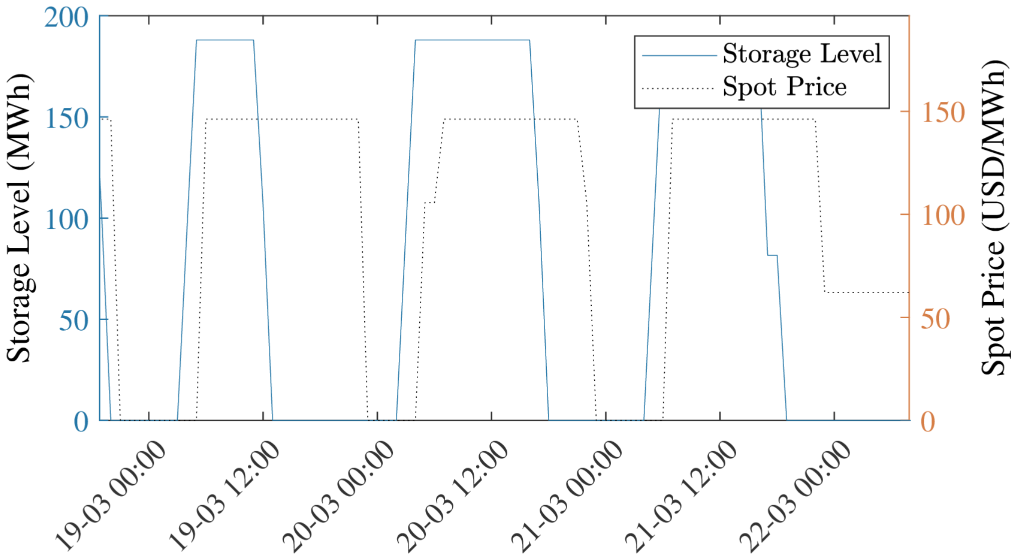

Figure 4.17: Storage Level and Spot Prices on March 2018

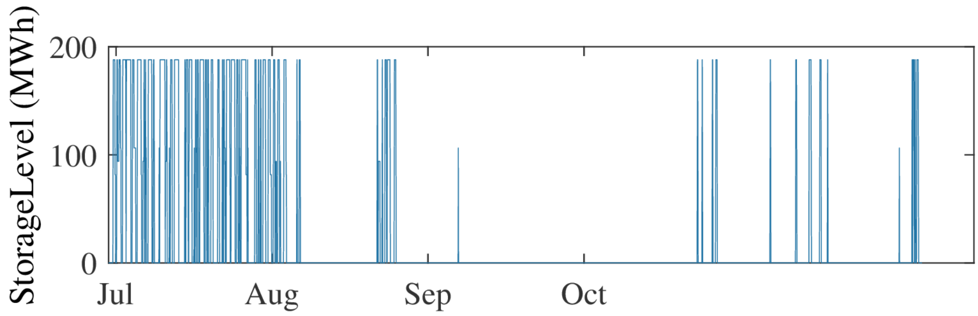

Figure 4.18: Storage level in the second semester of 2018

As observed, very low battery prices are required in order to make the installation profitable, far away from the reality of current prices. Therefore, in the next section, we will introduce an extra revenue from the battery providing the EFR service, in order to analyse if this extra benefit would incur into better prospects of private investment in batteries.

4.2.1 Enhanced Frequency Response

We can observe the effect of adding the EFR service to the investment problem in Figures 4.19 to 4.24, comparing, for every year, the optimal capacity with and without EFR.

First, the result of the optimization is that the decision variable P_{EFR}, optimal power of the EFR service is equal to the maximum charge/discharge of the battery R_c in every case. This was excepted, as mentioned in section 3.1.2, and now confirmed throughout simulations.

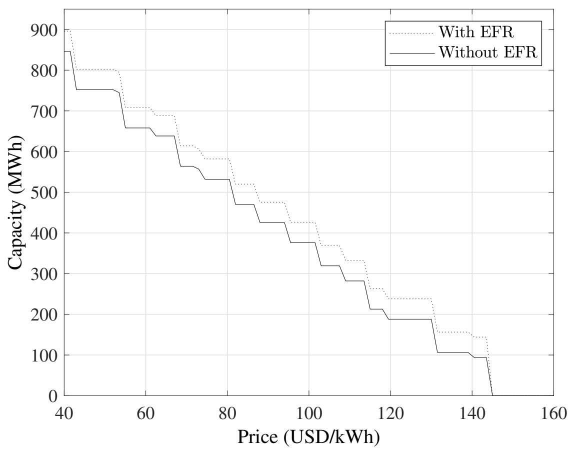

Figure 4.19: Optimal battery size with EFR 2018

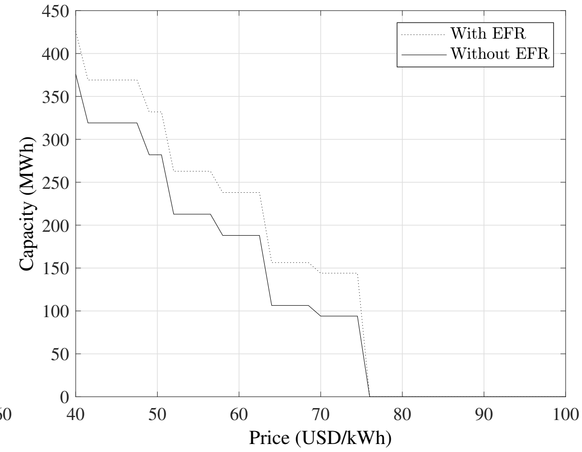

Figure 4.20: Optimal battery size with EFR 2017

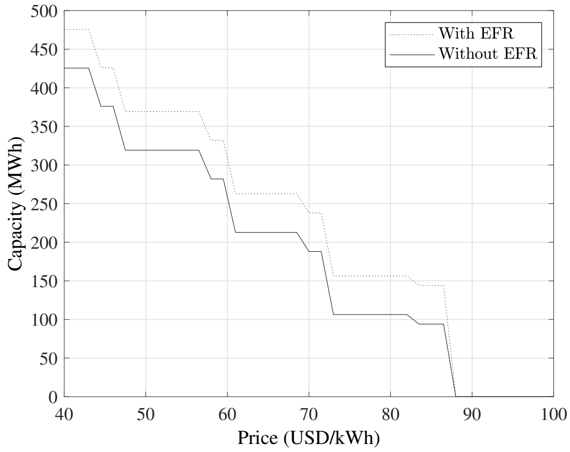

Figure 4.21: Optimal battery size with EFR 2016

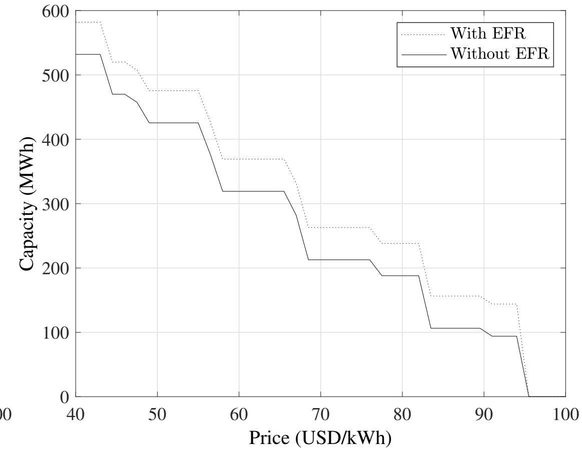

Figure 4.22: Optimal battery size with EFR 2015

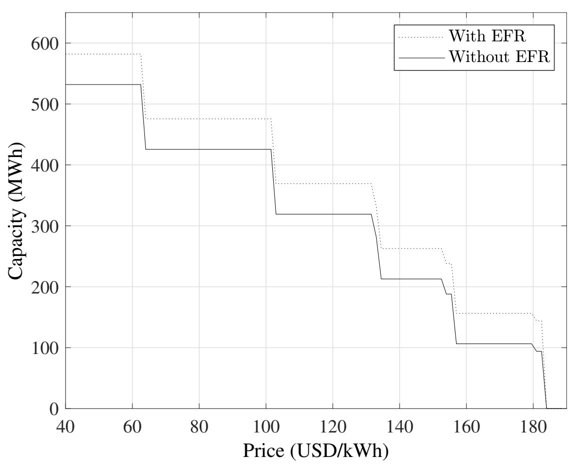

Figure 4.23: Optimal battery size with EFR 2014

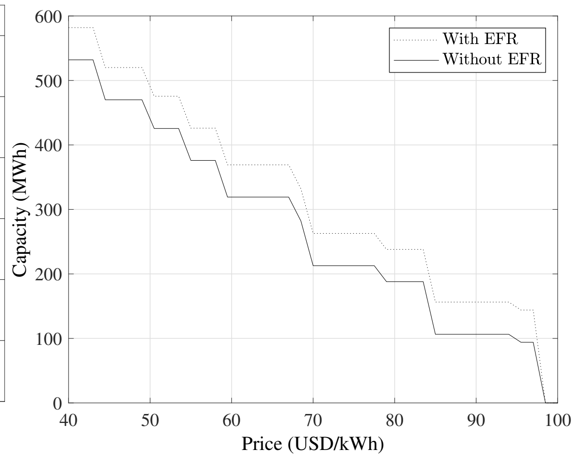

Figure 4.24: Optimal battery size with EFR 2013

In Table 4.4 and 4.5 it is reported some of the revenue results when including the EFR service.

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 4.4: Battery annuitized revenue Rate 100MW with EFR

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 4.5: Battery annuitized revenue Price 90USD/kWh with EFR

A slight increase in the amount of optimal capacity to install can be observed in every scenario. Furthermore, we can see that the revenue greatly increases making it much more attractive to invest in batteries if the EFR revenue is considered. However, we still observe the dependence with the rainfall regime, where wet years still need extremely low prices to make it profitable.

4.3 Government Perspective

In this section we have considered the perspective from the government, with the objective of minimizing production costs. First, in Table 4.6 is reported how the generation is distributed in the approximated model of the network (using information acquired from Figure 2.5).

Bus	Hydro Salto Grande (%)	Hydro Rio Negro (%)	Wind (%)	Solar (%)	Biomass (%)
Salto Grande	100	0	10	100	0
San Javier	0	0	15	0	100
Palmar	0	100	15	0	0
Montevideo A	0	0	20	0	0
Montevideo B	0	0	20	0	0
San Carlos	0	0	20	0	0
Melo	0	0	10	0	0

Table 4.6: Distribution of generation in approximate model of Uruguayan Network

Furthermore, the exportation is located in two different buses: to Argentina, in Salto Grande bus and to Brasil, in Melo bus. The capacity of the 500kV transmission lines is of $1380MW$. In every case the rate considered for the batteries was of $100MW$

Thermal units are located in Montevideo buses; In 'Montevideo A' 360MW are located representing 'Punta del Tigre' thermal central, with an operation price of $120USD/MWh$ [43]. Meanwhile, in Montevideo B, 280MW representing thermal centrals 'CTR' and 'Batlle' are located, with an operation price of $140USD/MWh$ [43]. The hourly ramp rate RR of the thermal generators is of $24MW$

The power flow equations add many constrains to the optimization problem. Therefore, because of computational effort it is impossible to simulate over the whole year, and we will have to use a period of one week. To analyse the government perspective, much more information was needed, including the 10-minutes data of generation, demand and exportation, plus information regarding curtailment.

Unfortunately, the generation information was only available for 2018 and 2017, while information regarding curtailment, specifically wind, was only available for 2017 and 2016. Therefore, it was only possible to simulate over information from 2017. However, given that we are not simulating over the whole year but for a week, we will be considering several cases, which includes very dry scenarios and very wet scenarios, which are representative of scenarios that could happen any week at any year. Figure 4.25 shows the total thermal energy during this year.

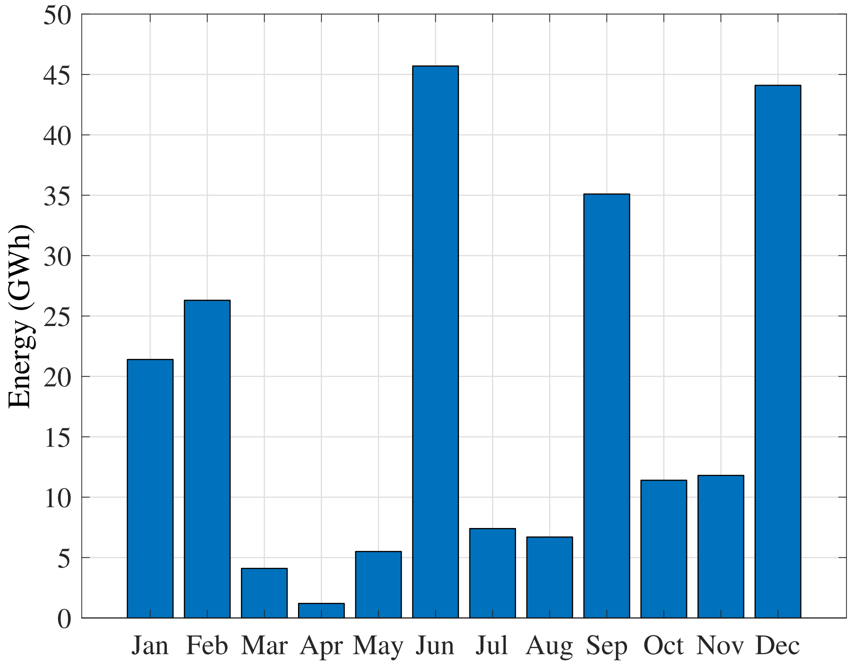

Figure 4.25: Thermal production throughout 2017

4.3.1 Wind Curtailment

First, we will introduce the information regarding the curtailment of wind done in 2017. Table 4.7 shows the energy curtailment in each month while we can observe this information illustrated in Figure 4.26.

Month	Wind Produced (GWh)	Wind Curtailed (GWh)	% of curtailment
January	298.4	5.9	1.95
February	197.3	6.5	3.21
March	322.3	40.0	11.05
April	345.5	68.6	16.57
May	316.9	59.8	15.87
June	259.7	186.1	41.74
July	411.3	152.2	27.00
August	280.5	169.4	37.65
September	270.4	154.0	36.29
October	315.9	155.9	33.05
November	358.9	63.1	14.96
December	377.1	36.5	9.69
Total	3,754.4	1,098.3	22.63

Table 4.7: Wind energy curtailed throughout 2017

As observed, the wind curtailment represents an important amount of energy in 2017. In fact, it accounts for 8.9% of the total demand in 2017 of $12400GWh$. Therefore, it looks promising to study the feasibility of installing an energy storage facility to make use of all of this curtailed generation.

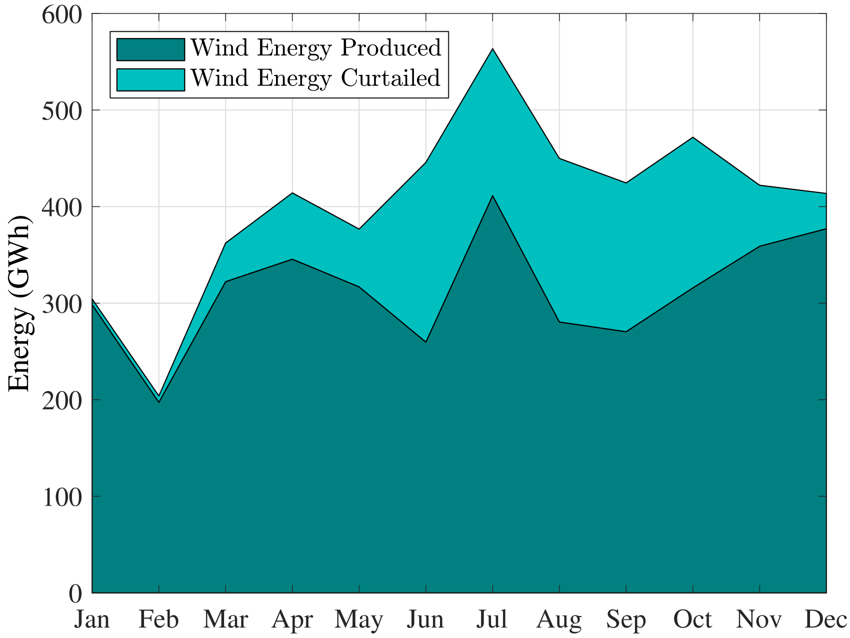

Figure 4.26: Wind energy curtailed throughout 2017

4.3.2 Hydro Curtailment

To analyse the Hydro Curtailment, we use ADME annual report of Salto Grande and Rio Negro dams operation [37].

In Figures 4.27 and 4.28 we can see the average weekly water harnessed from 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 for energy if the power of the turbines was less than the rated. The same information is plotted in the next figures for Bonete and Palmar dam in Rio Negro.

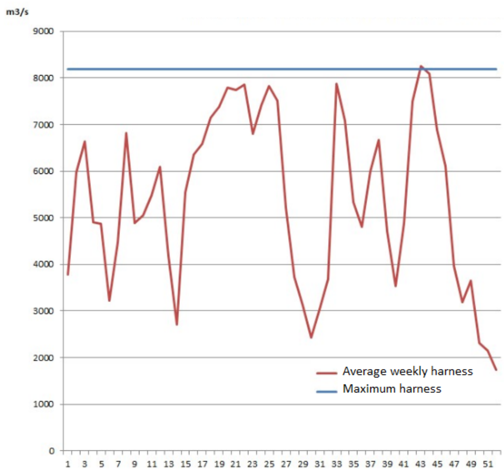

Figure 4.27: Salto Grande average water weekly harness 2017

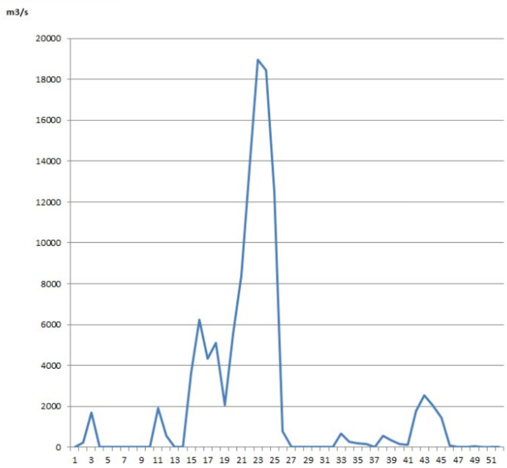

Figure 4.28: Salto Grande average water weekly release 2017

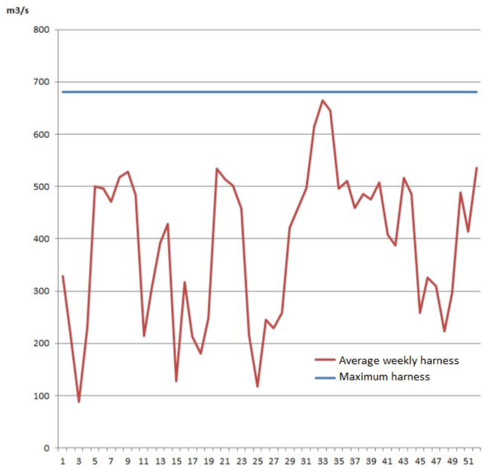

Figure 4.29: Bonete average water weekly harness 2017

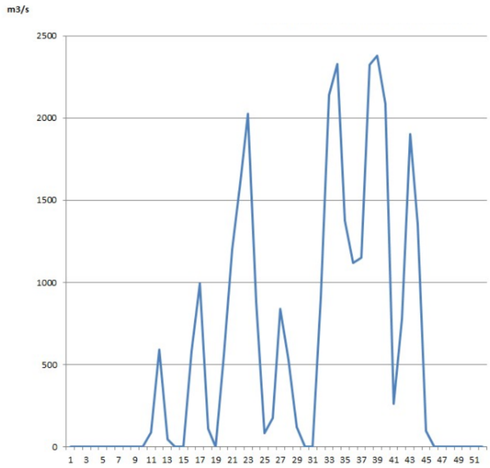

Figure 4.30: Bonete average water weekly release 2017

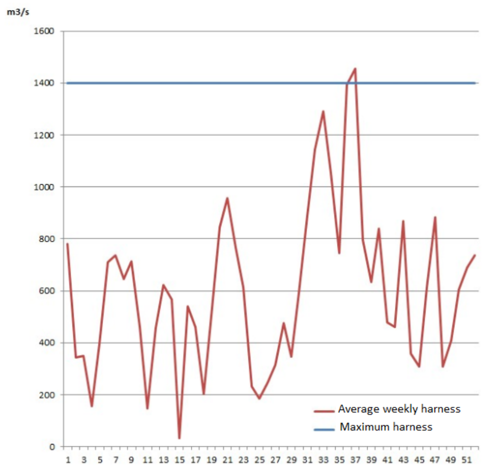

Figure 4.31: Palmar average water weekly harness 2017

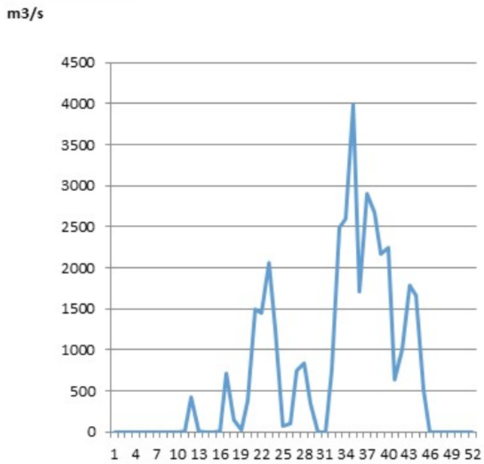

Figure 4.32: Palmar average water weekly release 2017

With this information, we will identify weeks that can be representative as dry and wet. For example, both January and February have almost zero water release from any dam, so we will consider these months as dry, while June and October have a considerable amount of water being released from the dams, therefore considering these as wet. In the next section the scenarios considered will be detailed.

4.3.3 Dry Scenario

For each scenario, dry and wet, we will consider two different cases. The first case considered as dry will be the fourth week of January, where, as seen in the Figures before, the water released was zero. The second case will be the second week of February, again with zero water released from any dam.

Figures 4.33 and 4.34 show the thermal generation from ADME data for the first case and a histogram of said information (in a 10 minute basis). Meanwhile, in figures 4.35 and 4.36 the same information is plotted for the second case.

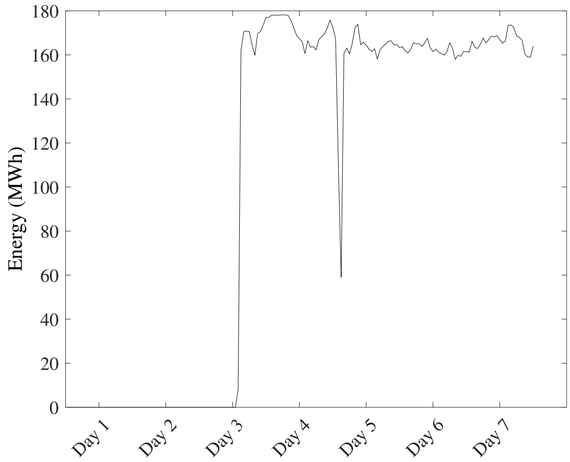

Figure 4.33: Thermal Generation
Dry-Case 1

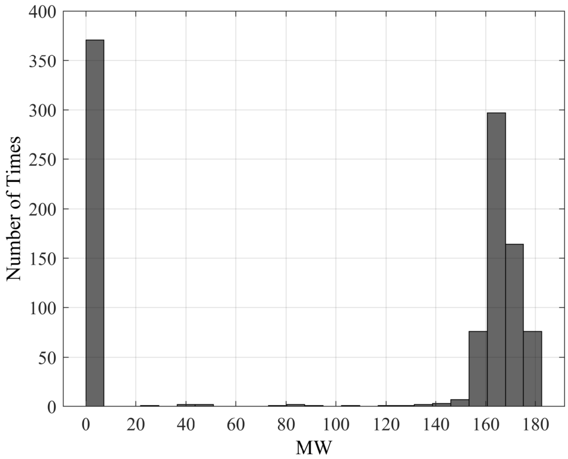

Figure 4.34: Thermal Histogram
Dry-Case 1

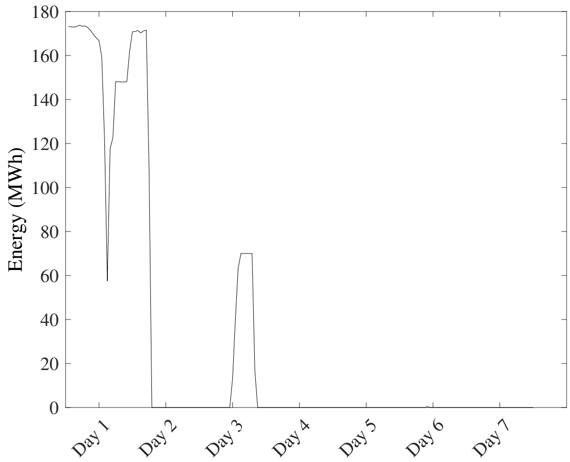

Figure 4.35: Thermal Generation
Dry-Case 2

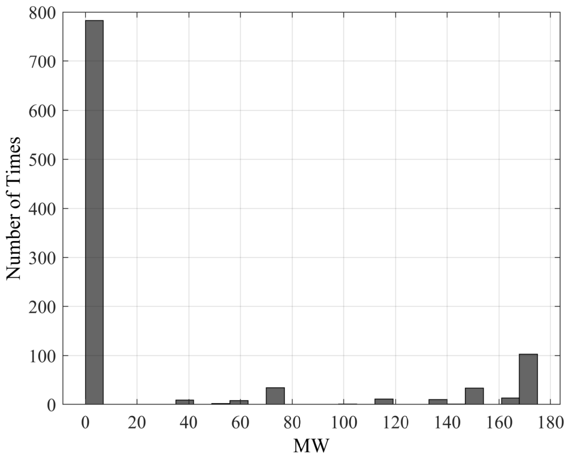

Figure 4.36: Thermal Histogram
Dry-Case 2

From the histograms, we can calculate the upper bounds for the wind curtailment, using the information of Table 4.7. The results are:

$$W_{curt}^{max} = 24MW \text{for Case 1} \tag{4.2}$$
$$W_{curt}^{max} = 13MW \text{for Case 2} \tag{4.3}$$

Meanwhile, the hydro curtailment are set as zero for these cases

The optimization problem consists of 7,399 variables and 10,752 constrains equations for a week of simulation. Then, building the constrains equations for a whole year takes an incredible amount of time and it is not possible with the given resources and time.

First Case - Dry Scenario

For the first case, for a value of $100USD/kWh$, **the optimal return of the software was no battery to be installed.**

In Figure 4.37 generation and demand are plotted, while in Figure 4.38 the thermal output returned by the software is plotted. For this case it should be equal to the thermal production from ADME data, which we can observe is almost the same. There are some differences because ADME data comes from the SCADA which has some error, while our values come from a power flow analysis. Finally, Figure 4.39 shows the amount of storage to install, while varying the price of such technology.

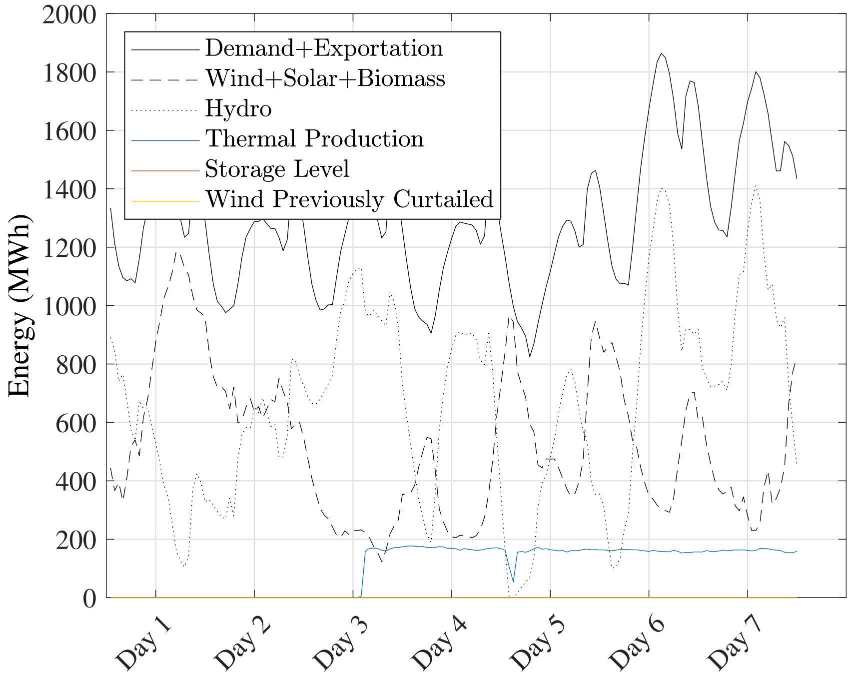

Figure 4.37: Generation and demand Dry-Case 1

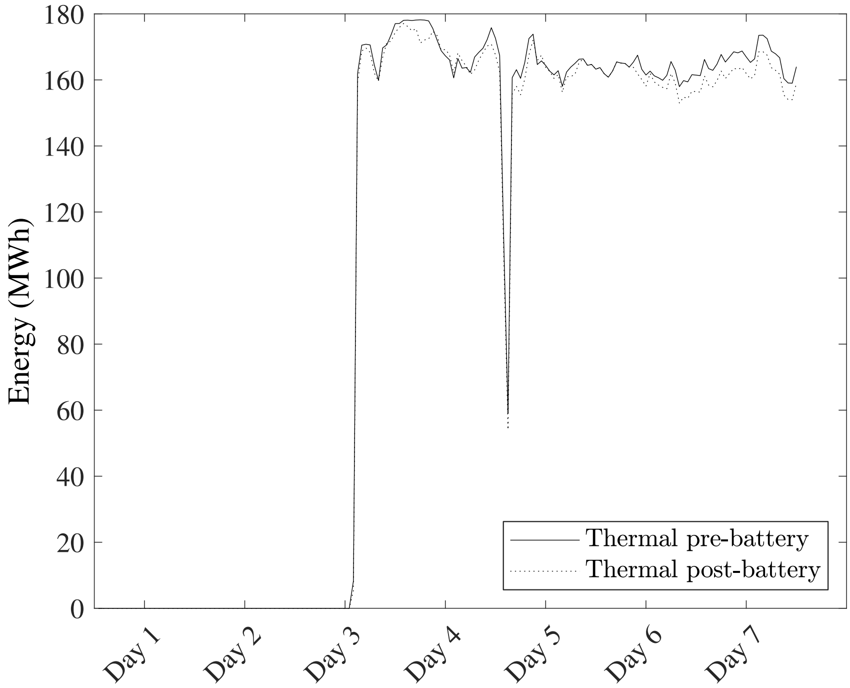

Figure 4.38: Thermal production from software and ADME data

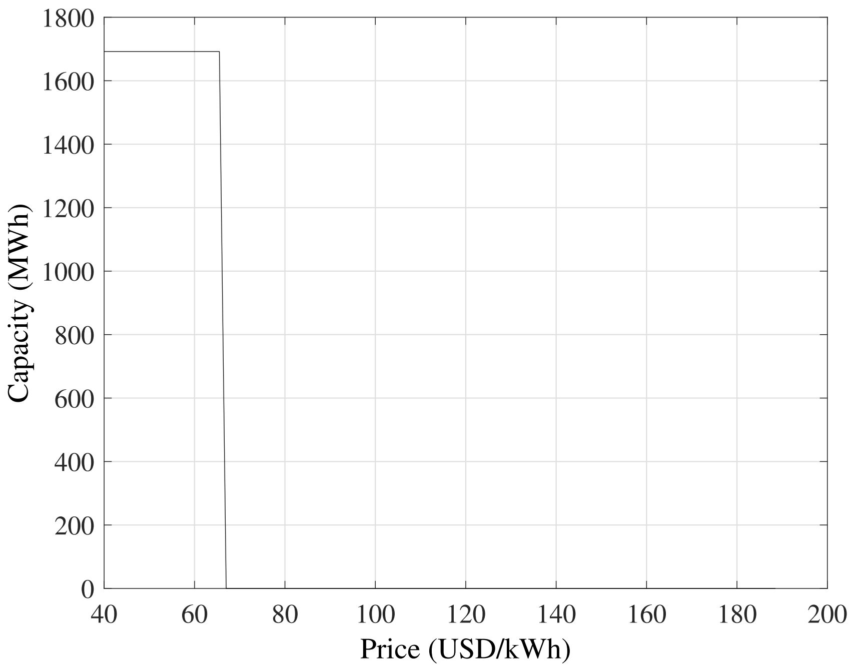

Figure 4.39: Optimal battery capacity to install Dry-Case1

We can observe a break point for which is profitable to install battery, but with an extremely low price.

Second Case - Dry Scenario

For the second case, for a value of $100USD/kWh$, the optimal return of the software is reported in Table 4.8.

Bus	Amount of Storage (MWh)
Salto Grande	8.46
San Javier	0
Palmar	20.19
Montevideo A	28.20
Montevideo B	28.20
San Carlos	12.34
Melo	4.23

Table 4.8: Optimal distribution of Storage Dry-Case2

In Figure 4.40 generation, demand and storage level are plotted. We can appreciate how the wind curtailment energy is used to store energy for a later release. Figure 4.41 plots a comparison of the thermal output pre and post battery. Furthermore, Figure 4.42 shows the storage level with the charging rate, where negative values represents discharge.

From ADME data regarding generation, we can approximate the amount of energy each central will produce during this week, and from our software we can calculate how it will be different. In Table 4.9 this difference is reported.

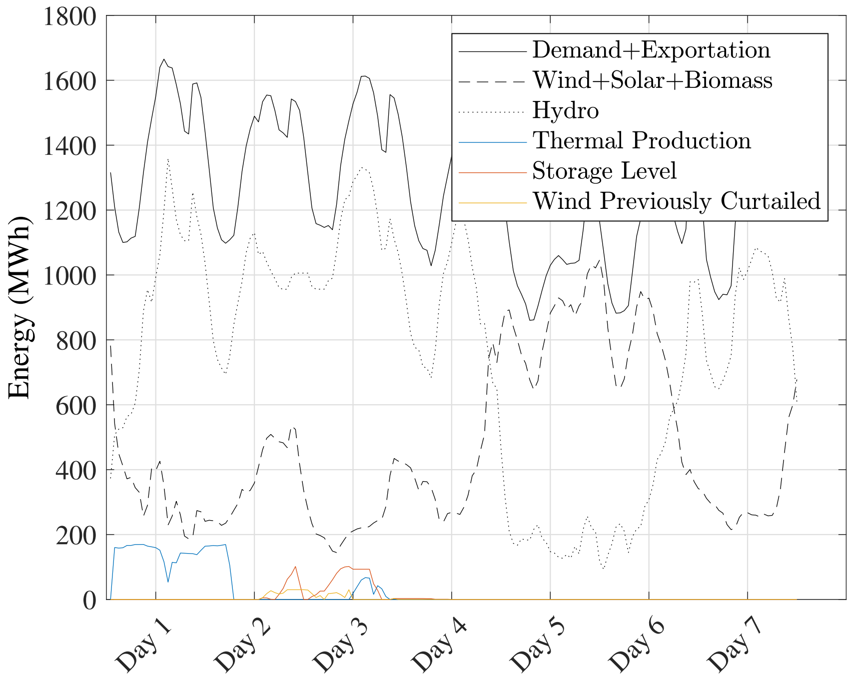

Figure 4.40: Generation and demand Dry-Case 2

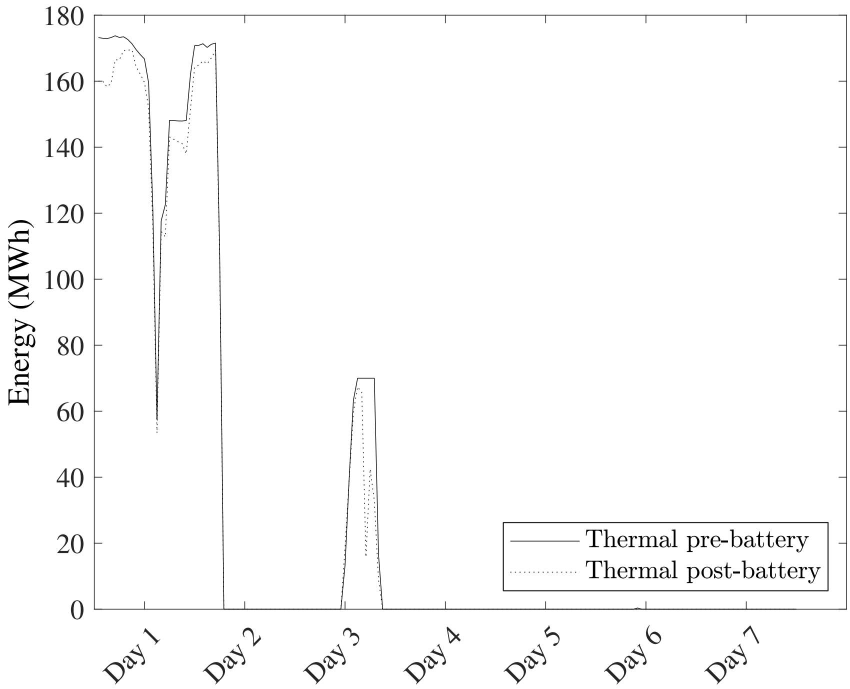

Figure 4.41: Thermal production pre and post battery Dry-Case2

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 4.9: Thermal output and cost pre and post battery Dry-Case2

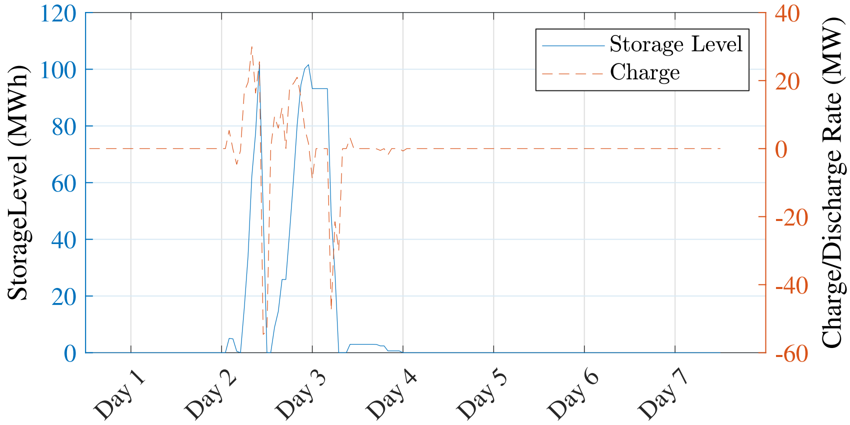

Figure 4.42: Charge and discharge rate Dry-Case2

Finally, Figure 4.43 shows the amount of storage to install, while varying the price of such technology.

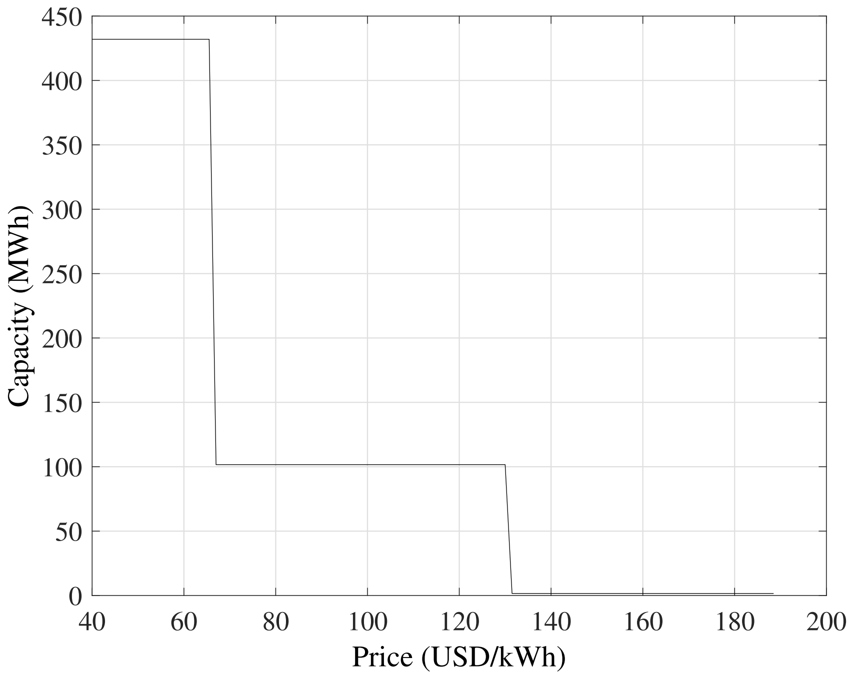

Figure 4.43: Optimal battery capacity to install Dry-Case1

4.3.4 Wet Scenario

The first case considered as wet will be the last week of June (week 24), where, as seen in the Figures before, the water released was very considerable. The second case will be the last week of October (week 44), again with plenty of water released from all dams.

Figure 4.44 and 4.45 show the thermal generation from data for the first case and a histogram of such information (in a 10 minute basis). Meanwhile, in figures 4.46 and 4.47 the same information is plotted for the second case.

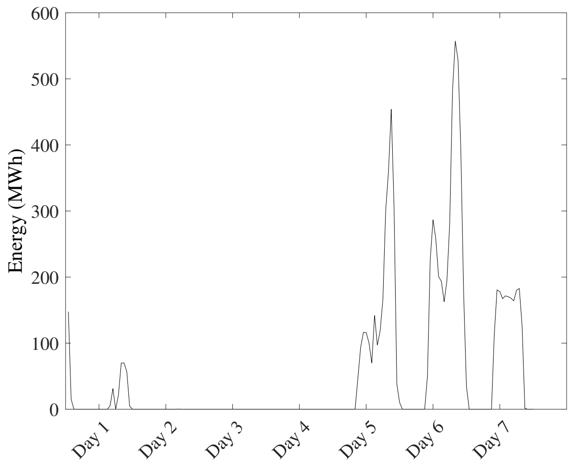

Figure 4.44: Thermal Generation
Wet-Case 1

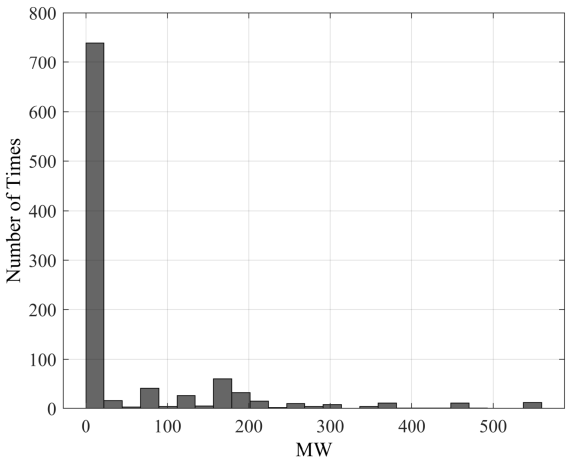

Figure 4.45: Thermal Histogram
Wet-Case 1

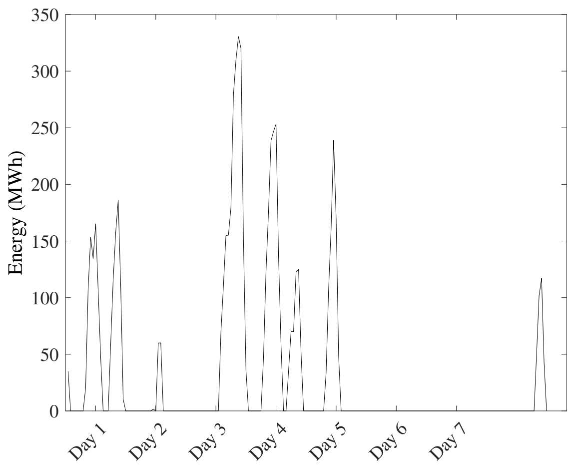

Figure 4.46: Thermal Generation
Wet-Case 2

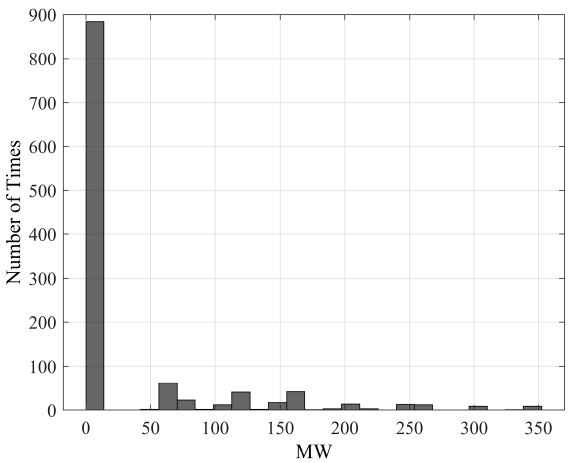

Figure 4.47: Thermal Histogram
Wet-Case 2

Again, we calculate the upper bounds for the wind curtailment, using the information of Table 4.7. The results are:

$$W_{curt}^{max} = 400MW \text{for Case 1} \tag{4.4}$$
$$W_{curt}^{max} = 280MW \text{for Case 2} \tag{4.5}$$

Now, the hydro curtailment will not be zero, and will be limited by the difference between the maximum rated power and the production.

First Case - Wet Scenario

For the first case, for a value of $200USD/kWh$, the optimal return of the software is reported in Table 4.10.

Bus	Amount of Storage (MWh)
Salto Grande	309.79
San Javier	0
Palmar	94.00
Montevideo A	83.51
Montevideo B	0
San Carlos	0
Melo	0

Table 4.10: Optimal distribution of Storage Wet-Case1

In Figure 4.48 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 4.49 plots a comparison of the thermal output pre and post battery, while Figure 4.50 shows the storage level with the charging rate.

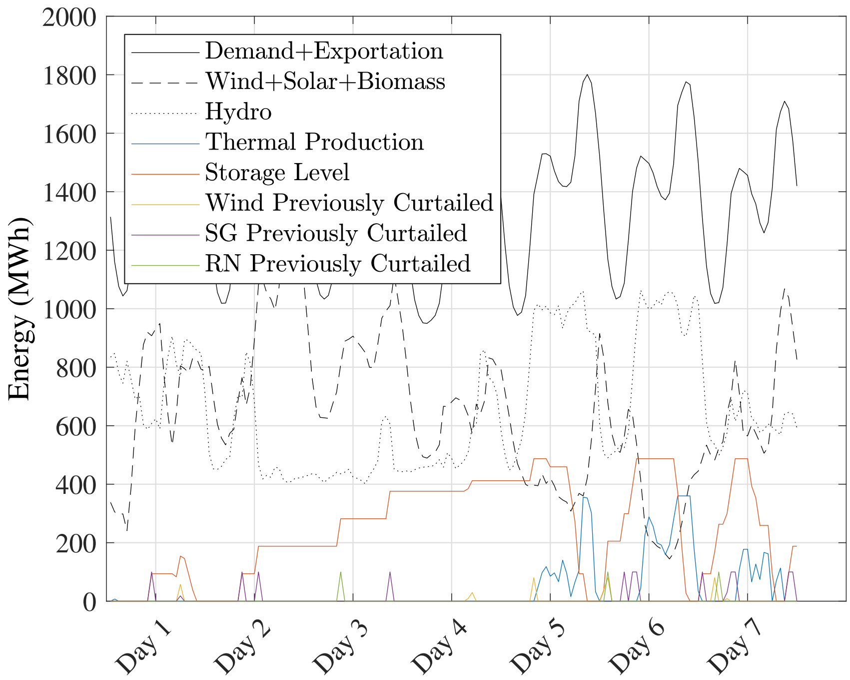

Figure 4.48: Generation and demand Wet-Case 1

In Table 4.11 thermal production and costs are reported for this scenario before and after the installation of the batteries. Finally, Figure 4.51 shows the amount of storage to install, while varying the price of such technology.

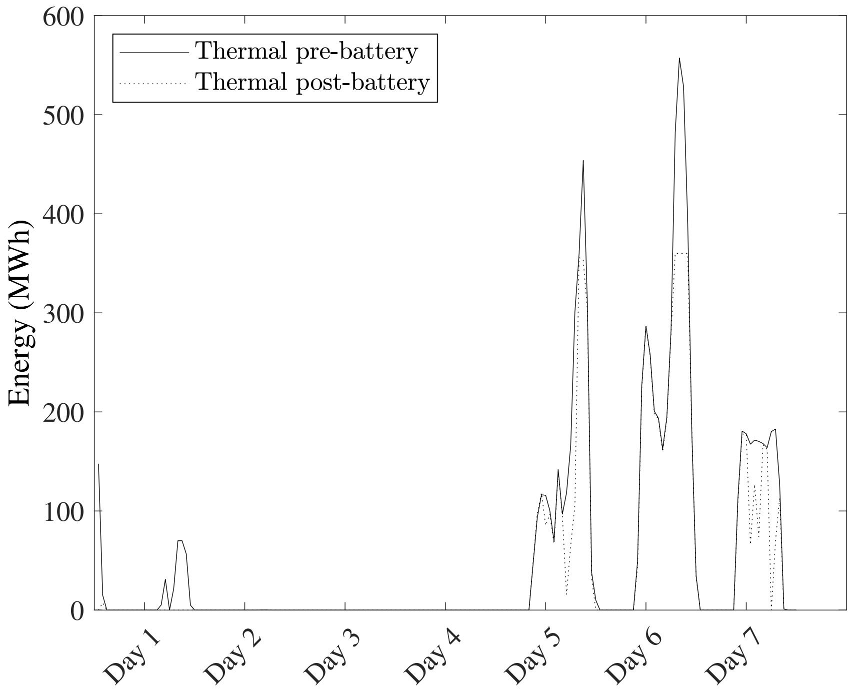

Figure 4.49: Thermal production pre and post battery Wet-Case1

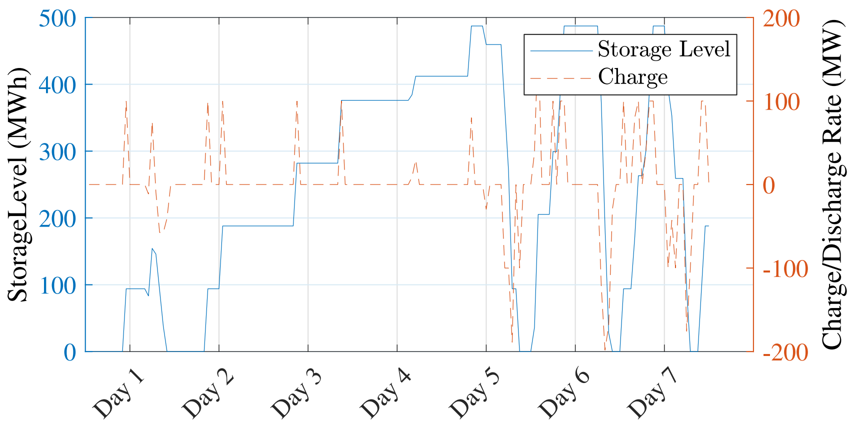

Figure 4.50: Charge and discharge rate Wet-Case1

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 4.11: Thermal output and cost pre and post battery Wet-Case1

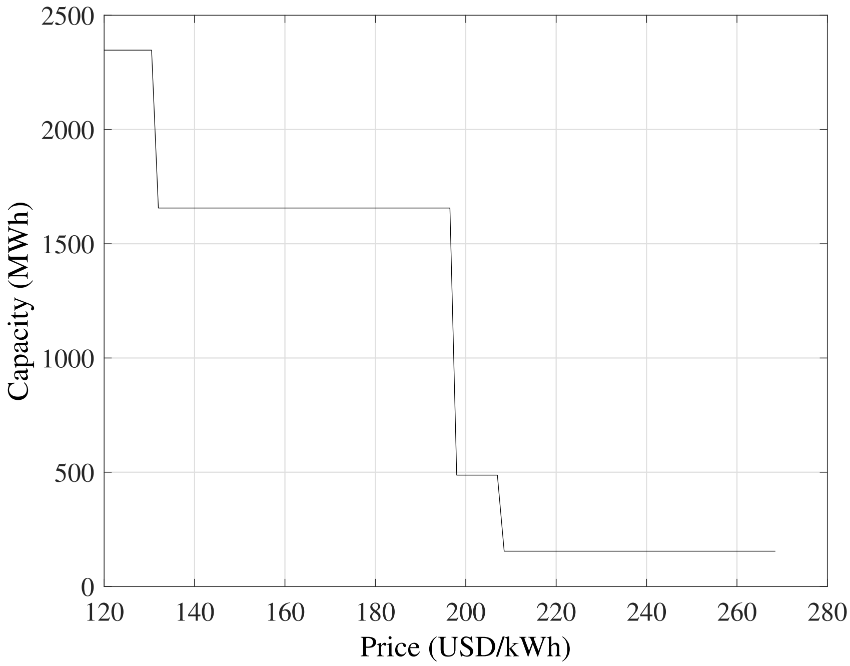

Figure 4.51: Optimal battery capacity to install Wet-Case1

Second Case - Wet Scenario

For the second case, for a value of $200 USD/kWh$, the optimal return of the software is reported in Table 4.12.

Bus	Amount of Storage (MWh)
Salto Grande	192.91
San Javier	0
Palmar	157.92
Montevideo A	105.28
Montevideo B	157.18
San Carlos	52.64
Melo	29.16

Table 4.12: Optimal distribution of Storage Wet-Case2

In Figure 4.52 generation, demand and storage level are plotted. Again, the wind and hydro curtailed is used to store energy for a later release. Figure 4.53 plots a comparison of the thermal output pre and post battery. Furthermore, Figure 4.54 shows the storage level and the charge/discharge rate.

The amount of energy each central will produce during this case, both before and after battery, is reported in Table 4.13. Finally, Figure 4.55 shows the amount of storage to install, while varying the price of such technology.

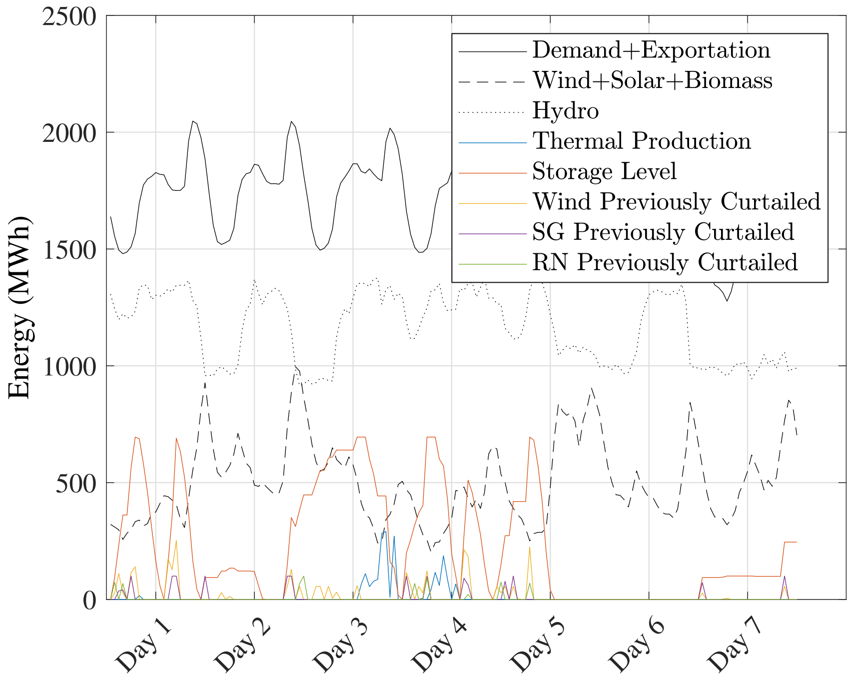

Figure 4.52: Generation and demand Wet-Case 2

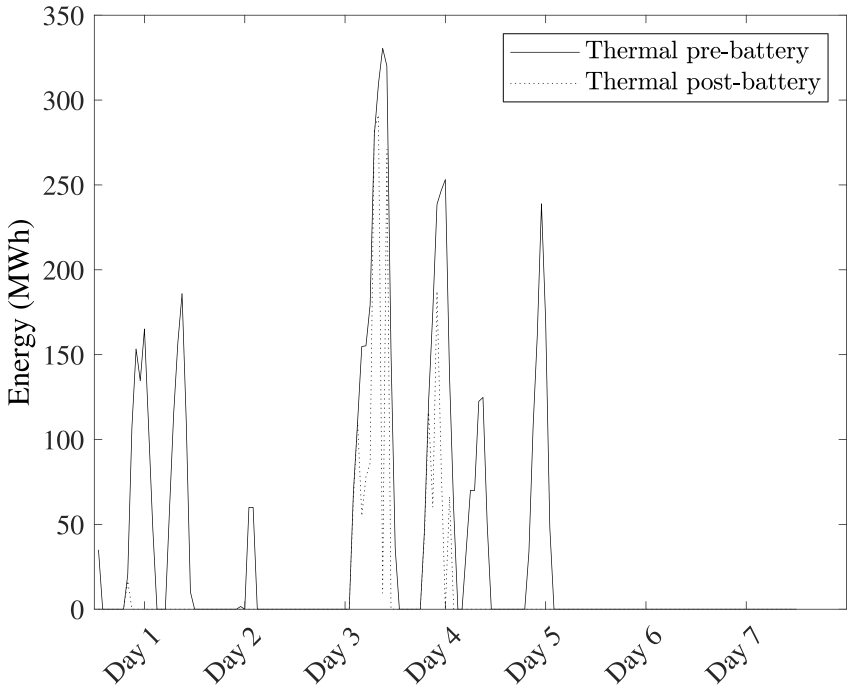

Figure 4.53: Thermal production pre and post battery Wet-Case2

Central	Pre Battery (Data From ADME) Generation (GWh)	Pre Battery (Data From ADME) Cost (USD)	Post Battery (Data from software) Generation (GWh)	Post Battery (Data from software) Cost (USD)
Punta Del Tigre	61.37	7,365,000	18.24	2,188,300
CTR and Battle	0	0	0	0
Total	61.37	7,365,000	18.24	2,188,300

Table 4.13: Thermal output and cost pre and post battery Wet-Case2

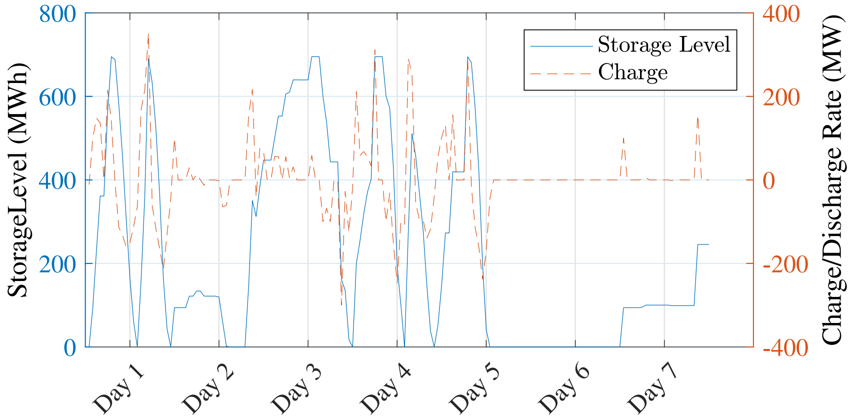

Figure 4.54: Charge and discharge rate Wet-Case2

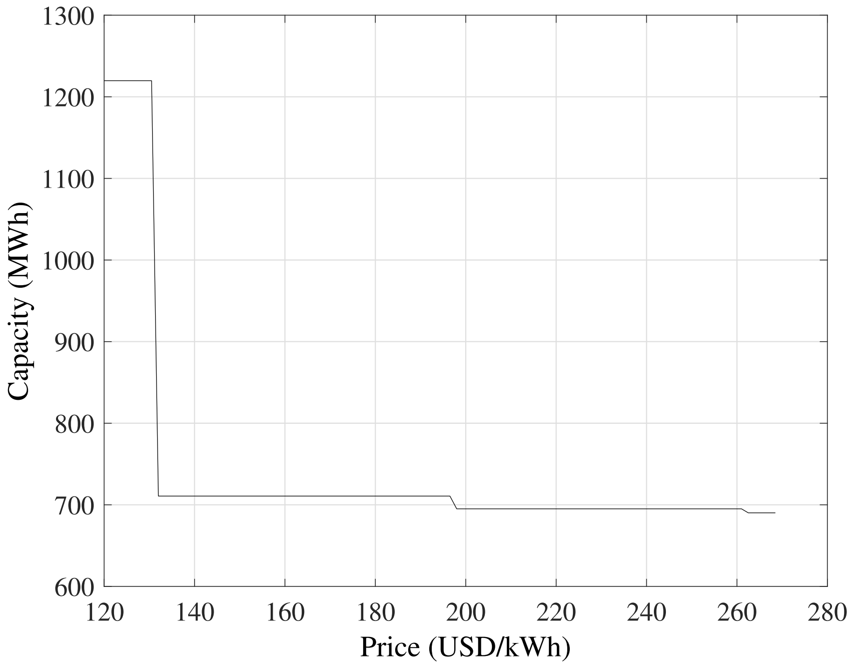

Figure 4.55: Optimal battery capacity to install Wet-Case1

Chapter 5

Conclusion

We have successfully studied the incorporation of energy storage into a system with a large penetration of renewable energy: the Uruguayan electrical network. The problem was approached from two different perspectives, obtaining interesting results in both of them.

When analysing the private investor perspective doing arbitrage in the spot market, the first conclusion is that better regulations are needed if it's of interest to incentivise the incorporation of batteries operating in the wholesale market. One of our first results showed no revenue at all if we consider the current transmission fees as a fixed value depending on the maximum capacity.

The current regulations in transmission fees do not consider the possibility of a battery storage facility and were thought mostly for wind farms generators that need some firm power from the grid to feed their ancillary services 24/7. Furthermore, this power is usually in the kW order, much less than the farm's capacity, so, even though it is a price to consider for them, it will not impact on the CAPEX of the whole project. For an energy storage facility, where the transmission fees would be considered in terms of the plant's capacity, this is an extremely high cost, and to even analyse investing into batteries, regulation in transmission fees have to be reconsidered.

Still, without considering transmission fees, the prospective for installing batteries for doing energy arbitrage doesn't look very good. Even though a priori the spot market looked promising, buying energy at zero cost, the reality is that Uruguay has installed so much wind energy that the spot prices are not high enough to make a profit out of sales. Costs of Lithium-ion batteries are not well defined, Bloomberg in their ninth Battery Price Survey [44] talks of $178 USD/kWh$ while Lazards in their fourth version of the Levelized cost of storage show that batteries for a wholesale market level costs around $204 - 298 USD/kWh$. From the results in Figure 4.14, we can conclude that for those prices, installing batteries today is not profitable.

The prospective improves when considering an EFR service. We observed huge increases in revenues if the remuneration of providing an EFR service is like the approach used by National Grid. However, due to Uruguay being interconnected by a very large link with Argentina, and Argentina being more than 10 times the size of Uruguay, the frequency regulation is done entirely by Argentina, so right now EFR service is not something the Uruguayan government is considering. Further in the future, with Argentina also incorporating large amounts of intermittent energy, this service could become valuable for both countries, and if batteries were to be encouraged, analysing the provision of EFR could be of huge interest.

On the other hand, from the government perspective, the incorporation of batteries seems more interesting right now. As already explained, Uruguay has installed so much renewable energy that wind curtailment levels reached as high as 22% in 2017. Furthermore, hydro reservoirs in Uruguay are such that every year at some point an important amount of water is released. Therefore, the flexibility that batteries provide for the operation could be of huge interest to take advantage of energy that is otherwise wasted.

We analysed two scenarios of the rainfall regime, that could be considered as 'bad' and 'good' for the operation of an energy storage facility, where, as expected, wet scenarios performed better than dry scenarios to operate the batteries, because of the large amount of water released across the dams. Nevertheless, from the second case of the dry scenario, we observed that by installing 100MW of energy storage we could reach savings of approximately $600kUSD$ in a week just from wind curtailment (which was considered to be around 3%, far from the year average). This means more than 2 million USD in a dry month. As a reference, Tesla recent battery in Australia of $129MWh$ cost 66millions USD [45], which, in a worst-case scenario, where a lot of dry weeks were to be repeated in the year, that revenue could still be enough to pay back for the investment of the battery in its lifetime.

Moreover, when considering the 'good' scenarios of wet weeks, it was extremely profitable to install batteries, even for prices as high as $280USD/kWh$. For a fixed price of $200USD/kWh$, the optimal result was of $500MWh$ for one case and $700MWh$ for the second case, obtaining profits as high as 5 million a week for the best case, but obviously, the installation of a $700MWh$ will not be optimal year-wise. When analysing the first case, with approximately 2.5 million profits a week with a 500MWh battery, it would be safe to assume approximately $600kUSD$ profits a week if the battery would be of $100MWh$, which coincides with the value obtained in the dry scenario. Therefore, doing very raw numbers, and assuming only half of the weeks a year which would be possible to take advantage of the batteries, that revenue would be plenty for paying back the investment in around 4-5 years, an estimate that looks very promising.

However, the year 2017 was specifically wet in terms of rainfall, so there are a lot of months the thermal production did not surpass even $10GWh$. This value in terms of costs represents around 1.2 million USD, which again if it was possible to reduce these costs with an energy storage facility (which should be possible if the month is a wet month), could be enough for paying back the investment very soon. Then, even if we face a very wet month, with very low production of thermal energy, it could be enough to provide the expected revenues. It is worth noticing the dilema around installing batteries and having wet or dry years. This is, having wet years means an excess of energy but also low production of thermal energy, while dry years works the other way around. Thus, although the results we obtained look promising, the time windows simulated are not long enough and might account to misleading results.

To sum up, installing batteries in Uruguay, from a government perspective looks very interesting. Given the fact a very large amount of wind generation was installed in Uruguay, a product of years worth of policies encouraging renewable generation, and such policies being implemented as pay or take contracts, then, it is very harmful for the government to have to curtail such energy. Consequently, the feasibility of studying energy storage technologies seems like the next step the government has to take to make the most out of the transition the energy sector has gone through. This first study presents interesting conclusions that might encourage to look further into these technologies for better use of renewable resources in the Uruguayan network.

Chapter 6

Future Works

As for today, there is not much of a point to keep on studying the investment in storage technologies from a private perspective. Results show that for current prices, there is not a single scenario in the last six years where it is profitable to invest in batteries for energy arbitrage.

In a nearby future, if the prices of batteries keep decreasing and the spot market in Uruguay remains similar, then it might be reasonable to do the analysis once again, updating current prices. Furthermore, risk-based analysis could be carried out, with a probabilistic analysis regarding the rainfall regime. Furthermore, having access to more historical data would be very useful, given that the incorporation of intermittent renewable sources of generation was done from 2014 onward.

Another thing that might be worth considering is using the arbitrage but to export energy to Argentina. In recent years, the first private company was allowed to export energy from Uruguay to Argentina [46], but the political process was not easy. So it might not be very straightforward or even possible to acquire the necessary permits, more so if we consider it means a private company buying cheap energy from a country and exporting it to others. Moreover, Argentina's recent policies are encouraging the installation of renewable generation, so in a nearby future they might not be interested in importing energy.

If Argentina keeps on its track of increasing intermittent sources of energy, then inertia of the whole interconnected system will reduce considerably, and EFR would become more attractive. As of today, from an Uruguayan perspective, it is of no interest to provide revenues from this service but in the future, it might be useful for both countries.

From the government perspective, we can find more attractive works to be continued after this project. From our results, we can agree that the incorporation of energy storage as a way to deal with the high curtailments is definitely worth looking into with more detail.

The first thing to do would be to increase the efficiency of our software, and using more powerful tools to simulate over longer periods. It would be ideal to simulate the whole year, the same way we did with the private investment perspective. This will remove the uncertainty of dealing with 'dry or wet' weeks and we can discuss a more realistic perspective of 'dry and wet' years. Secondly, another easy option to incorporate into the software would be a more realistic model of the network, for example including the 150kV transmission lines.

Thirdly, obtaining further information of curtailment and generation to do the simulations such as 2018, 2016, and soon 2019. This will provide a better perspective by analysing different years under different conditions. Then, we can analyse the information and again, with a risk-based analysis, conclude the optimal battery size to install. Another possible extension to the work would be to analyse the exportation of energy. What is the revenue from exporting energy to Argentina and Brasil, and would it be better to store such energy to reduce thermal production in the future?

Also, it will be interesting to incorporate the SimSEE software ADME uses for the optimal operation of the system into the problem. Instead of using historical data, use the real-time information and include a battery into the loop to analyse the optimal operation of such system, and its feasibility. This way, we can consider several stochastic variables which are not taken into consideration in this problem and solve the problem with a long term vision, analysing the optimal expansion of the system.

Finally, we can include storage technologies into transmission and distribution planning. These technologies have the potential of reducing and/or replacing investments in distribution and transmission. An analysis of the Uruguayan transmission and distribution network should be carried out to analyse its current status and to define if its necessary further investment. If this is the case, considering storage technologies in the planning might reduce the investment into transmission and distribution and make them more attractive.

Electric vehicles could also be of interest in such future studies, both from a private and government perspective. From the government perspective, V2G interaction could be analysed, and the potential revenue that could be provided for this service. From a private perspective, if operating a big fleet of vehicles, we could optimize the time to charge the fleet in order to be available for usage and also maximizing profits from doing arbitrage. It is clear that electric vehicles will be a huge incorporation in future grids, and Uruguay has the possibility to study a smooth an optimal incorporation of such technologies, while also making the most out of them.

Uruguay has done a very good job in changing its energy mix and reducing their carbon footprint, by installing a lot of renewable generation. However, nowadays a lot of curtailment is done and we should put more focus on improving the operation. Thus, we are very well positioned for the usage of energy storage technologies, and more resources should be put into analysing its feasibility and their impact in reducing thermal production.

Appendix A

Uruguayan transmission network

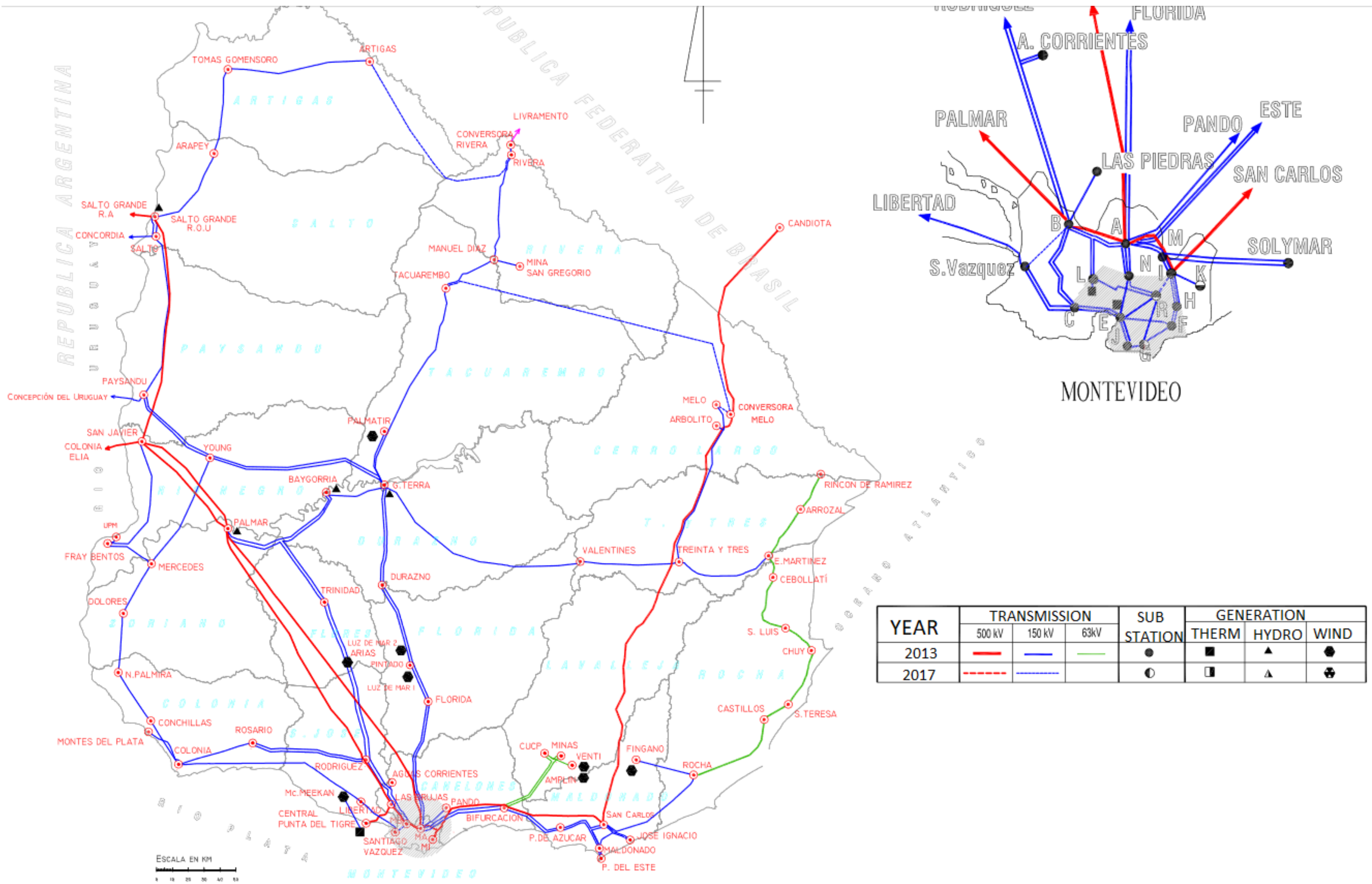

Figure A.1: Uruguayan Transmission Network [38]

Bibliography

[1] Green Technology. The shift toward a decentralized, distributed electric grid is already underway. *https://www.greentechmedia.com/articles/read/three-pathways-to-grid-edge-evolutiongs.48cmyic*, 2015.

[2] Energysage. How solar panel cost and efficiency have changed over time. *https://news.energysage.com/solar-panel-efficiency-cost-over-time/*, 2019.

[3] Bloomberg New Energy Finance. Lithium-ion battery costs and market. *https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf*, 2017.

[4] National Renewable Energy Laboratory. 2015 cost of wind energy review. *https://www.nrel.gov/docs/fy17osti/66861.pdf*, 2015.

[5] Washington Post. Pollution kills 9 million people each year, new study finds. *https://www.washingtonpost.com/news/energy-environment/wp/2017/10/19/pollution-kills-9-million-people-each-year-new-study-finds/?utm_term=.e3e44f3c6906*, 2017.

[6] Sandia National Laboratories. Solar faq. *http://www.sandia.gov/ jytsao/Solar%20FAQs.pdf*, 2006.

[7] Bloomberg New Energy Finance. New energy outlook 2017. *https://about.bnef.com/new-energy-outlook/*, 2018.

[8] Mark A. Delucchi and Mark Z. Jacobson. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy*, 39(3):1170–1190, 2011.

[9] Mark Z. Jacobson and Mark A. Delucchi. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy*, 39(3):1154–1169, 2011.

[10] J. A. Turner. A Realizable Energy Future. *Science*, 285(x):687–689, 1999.

[11] The Guardian. Uruguay makes dramatic shift to nearly 95% electricity from clean energy. *https://www.theguardian.com/environment/2015/dec/03/uruguay-makes-dramatic-shift-to-nearly-95-clean-energy*, 2015.

[12] Ruben Antonio Chaer, Eliana Cornalino, Pablo Soubes, Electricity Market Management, and Enzo Coppes. Handling the Intermittence of Wind and Solar Energy Resources , from Planning to Operation. Uruguay's success. *36th USAEE/IAEE NORTH AMERICAN CONFERENCE, At Washington DC USA*, 2018.

[13] ADME (Electric Market Administrator). Valores acumulados (cummulative values). *http://adme.com.uy/*, 2019.

[14] Ruben Chaer. Adjusting energy planning practices.examples from uruguay. *http://www.epe.gov.br/sites-pt/sala-de-imprensa/noticias/Documents/21_ Ruben_ Chaer_ Adjusting_ Planning_ Uruguay.pdf*, 2019.

[15] Carbon Tracker. 42% of global coal power plants run at a loss. *https://www.carbontracker.org/42-of-global-coal-power-plants-run-at-a-loss-finds-world-first-study/*, 2019.

[16] Mary Black and Goran Strbac. Value of storage in providing balancing services for electricity generation systems with high wind penetration. *Journal of Power Sources*, 162(2 SPEC. ISS.):949–953, 2006.

[17] SANDIA. Review of power quality applications of energy storage systems. *SANDIA report SAND98-1513*, 1998.

[18] Jim Eyer and Garth Corey. Energy storage for the electricity grid: Benefits and market potential assessment guide. *Sandia National Laboratories*, 20(10):5, 2010.

[19] SANDIA. Energy storage opportunities anal- ysis. *SANDIA report SAND2002-1314*, 2002.

[20] M. Perrin, Y. M. Saint-Drenan, F. Mattera, and P. Malbranche. Lead-acid batteries in stationary applications: Competitors and new markets for large penetration of renewable energies. *Journal of Power Sources*, 144(2):402–410, 2005.

[21] Mohammed Yekini Suberu, Mohd Wazir Mustafa, and Nouruddeen Bashir. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renewable and Sustainable Energy Reviews*, 35:499–514, 2014.

[22] Akiko Murakami and A Yokoyama. Basic study on battery capacity evaluation for load frequency control (LFC) in power system with a large penetration of wind power generation. *Transactions on Power*, pages 236–242, 2006.

[23] Sonja Wogrin and Dennice F. Gayme. Optimizing Storage Siting, Sizing, and Technology Portfolios in Transmission-Constrained Networks. *IEEE Transactions on Power Systems*, 30(6):3304–3313, 2015.

[24] A. A. Solomon, Daniel M. Kammen, and D. Callaway. The role of large-scale energy storage design and dispatch in the power grid: A study of very high grid penetration of variable renewable resources. *Applied Energy*, 134:75–89, 2014.

[25] Stefan Weitemeyer, David Kleinhans, Thomas Vogt, and Carsten Agert. Integration of Renewable Energy Sources in future power systems: The role of storage. *Renewable Energy*, 75:14–20, 2015.

[26] Hrvoje Pandzic, Yishen Wang, Ting Qiu, Yury Dvorkin, and Daniel S. Kirschen. Near-Optimal Method for Siting and Sizing of Distributed Storage in a Transmission Network. *IEEE Transactions on Power Systems*, 30(5):2288–2300, 2015.

[27] Paul D. Brown, J. A. Peças Lopes, and Manuel A. Matos. Optimization of pumped storage capacity in an isolated power system with large renewable penetration. *IEEE Transactions on Power Systems*, 23(2):523–531, 2008.

[28] Yashar Ghiassi-Farrokhfal, Srinivasan Keshav, and Catherine Rosenberg. Toward a realistic performance analysis of storage systems in smart grids. *IEEE Transactions on Smart Grid*, 6(1), 2015.

[29] Renewable Energy World. Energy storage market outlook 2015. *https://www.renewableenergyworld.com/articles/2015/02/energy-storage-market-outlook-2015.html*, 2015.

[30] Ehsan Nasrolahpour, S. Jalal Kazempour, Hamidreza Zareipour, and William D. Rosehart. Strategic sizing of energy storage facilities in electricity markets. *IEEE Transactions on Sustainable Energy*, 7(4):1462–1472, 2016.

[31] Dina Khastieva, Ilias Dimoulkas, and Mikael Amelin. Optimal investment planning of bulk energy storage systems. *Sustainability (Switzerland)*, 10(3):1–23, 2018.

[32] Mark Z. Jacobson and Mark A. Delucchi. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy*, 39(3):1154–1169, 2011.

[33] Anya Castillo and Dennice F Gayme. Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management*, 87:885–894, 2014.

[34] Danny Pudjianto, Marko Aunedi, Predrag Djapic, and Goran Strbac. Whole-systems assessment of the value of energy storage in low-carbon electricity systems. *IEEE Transactions on Smart Grid*, 5(2):1098–1109, 2013.

[35] Pavithra Harsha and Munther Dahleh. Optimal management and sizing of energy storage under dynamic pricing for the efficient integration of renewable energy. *IEEE Transactions on Power Systems*, 30(3):1164–1181, 2015.

[36] David Connolly, Henrik Lund, Brian Vad Mathiesen, Emmanuel Pican, and Martin Leahy. The technical and economic implications of integrating fluctuating renewable energy using energy storage. *Renewable energy*, 43:47–60, 2012.

[37] ADME (Electric Market Administrator). 2017 annual report. *https://www.adme.com.uy/db-docs/Docs_secciones/nid_526/InformeAnual2017.pdf*, 2017.

[38] UTE. `https://portal.ute.com.uy/`. Accessed: 2019-06-12.

[39] GWEC (Global Wind Energy Council). Global wind report - annual market update 2017. *file://icnas3.cc.ic.ac.uk/mn1218/downloads/GWECGlobalWindReport_April2018_Final.pdf*, 2017.

[40] SimSEE, ADME. `https://adme.com.uy/imasd/simsee_principal/simsee.php`. Accessed: 2019-07-30.

[41] National grid EFR. `https://www.nationalgrideso.com/balancing-services/frequency-response-services/enhanced-frequency-response-efr/`. Accessed: 2019-07-15.

[42] Ministerio de industria, energia y mineria. `https://www.miem.gub.uy/energia/series-estadisticas-de-energia-electrica`. Accessed: 2019-08-09.

[43] Introduccion a los mercados de energia electrica, fing. `https://eva.fing.edu.uy/course/view.php?id=512`. Accessed: 2019-08-05.

[44] A behind the scenes take on lithium-ion battery prices. `https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/`. Accessed: 2019-08-18.

[45] Tesla's massive powerpack battery in australia cost 66 million and already made up to 17 million. https://electrek.co/2018/09/24/tesla-powerpack-battery-australia-cost-revenue/. Accessed: 2019-08-18.

[46] Empresa privada uruguaya exporta energía eólica a la argentina. https://www.lanacion.com.ar/economia/empresa-privada-uruguaya-exporta-energia-eolica-a-la-argentina-nid2072924. Accessed: 2019-08-18.