Chapter 3

Background

3.1 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 one of huge interest. By now, it has become clear that the way the future networks will operate is with very large penetration of renewable sources, with a large share of wind and solar, two intermittent resources by nature. Given its stochastic nature, storage technologies have been the focus of several studies for a long time now as a way to reduce the uncertainty this generation brings to the planning and operation of power grids and to improve its flexibility.

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

The uncertainty in wind forecasting presents an additional requirement for balancing demand and generation. If operating a network with a large share of intermittent generation, the amount of reserve required is a function of the time scale. For small time scale (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 (several minutes to hours) reserve requirements are of extreme importance. When forecasting for long-term time scales, meteorology methods are preferred while statistical techniques are used for short-term. 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 because by providing more storage, spinning reserve can be reduced, therefore reducing the need for curtailment. Furthermore, running part-loaded plant increase CO_2 emissions because its 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. Besides the wind capacity installed and the amount of storage to consider, 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 centre 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 US\$150 billion [17]. Several literatures have identified the potential applications of energy storage, where an exhaustive and extremely comprehensive guide can be found in [18]. Table 3.1 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 prevent 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, sages and outages

Table 3.1: Energy Storage Applications [19]

Perrin *et al.* [20] focused their paper in studying the market opportunities for storage providing ancillary services, with the focus of comparing the performance of lead-acid batteries with other storage technologies, where it is concluded that lead-acid batteries are expected to have an important share of the electricity market in the nearby 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 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 centres their study in 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 which is very useful for the introduction to the siting and sizing problem of storage is the one presented by Wogrim and Gayme in [23]. The paper aims to co-optimize the location where to install storage and then the amount of 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 introduce their own methods for optimizing the above problem. For example, according to [24] the maximum storage to achieve more than 80% of 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, the sizing is defined. Finally, the third stage models the complete system operation to quantify the benefits of storage.

Most of these studies use test networks, usually from IEEE conventions. However, some studies use real-world locations where it is of interest to assess the feasibility of storage, such as [27]. As a difference 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 scenarios of technologies 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 them extremely difficult to include them in a mathematical model. 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 $US\$675$ millions by 2014 and predicting a market of more than $US\$15$ billions 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 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 study case i.e assumptions and the employed scenarios, so one has to approach the investment problem with extreme care.

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.

Also, studies already 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 for our planet decarbonization path.

3.2 Uruguay and its electric sector

Uruguay is a small country located in South America between Argentina and Brasil (see Figure 3.1 and 3.2 [1]). It has a population of 3.4 million approximately and its area is about $176,215km^2$.

Figure 3.1: Location of Uruguay

Figure 3.2: Map of Uruguay

Its annual electricity demand in 2017 was of 11,200GWh, with a future demand growth expected of 2%. 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 electric market are:

- UTE is the state owned power company in charge of transmission distribution 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 3.3 and 3.4.

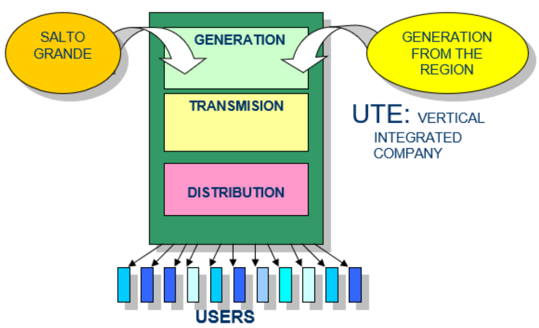

Figure 3.3: Energy sector pre-1997

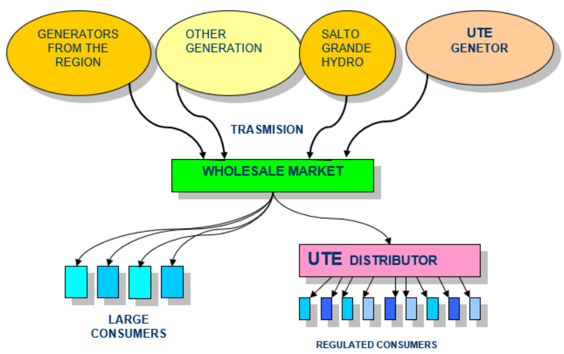

Figure 3.4: Energy sector post-1997

[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 of wind and solar energy. In Table 3.2 it is detailed the generation mix in Uruguay by 2017 [37] while in Figure 3.5 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 3.2: Characteristic parameters of the system

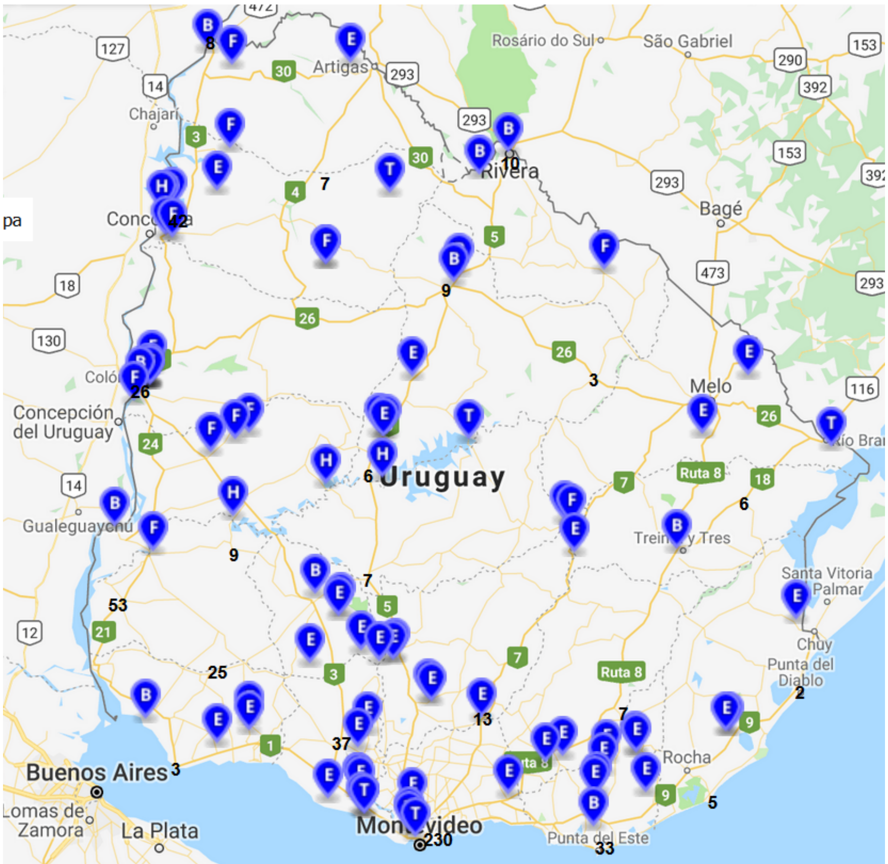

Figure 3.5: Geographic location of Generation Sources [38]
E: Eolic(Wind); F: Photovoltaics; H: Hydro; T: Thermal; B: Biomass;

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 3.6.

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.

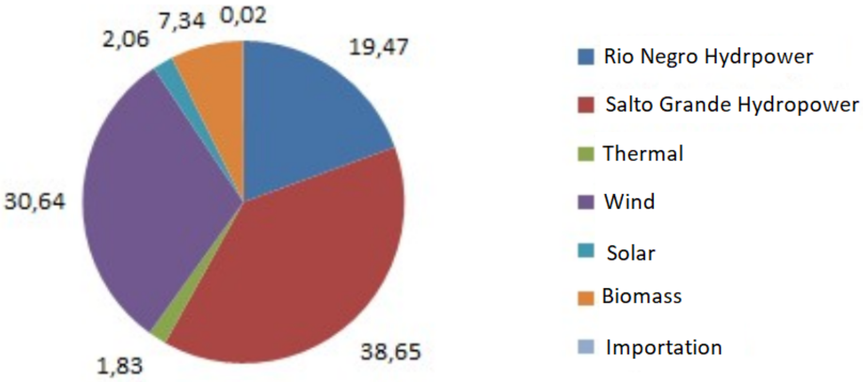

Figure 3.6: Energy generation by source in 2017 [37]

In Figure 3.7 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.

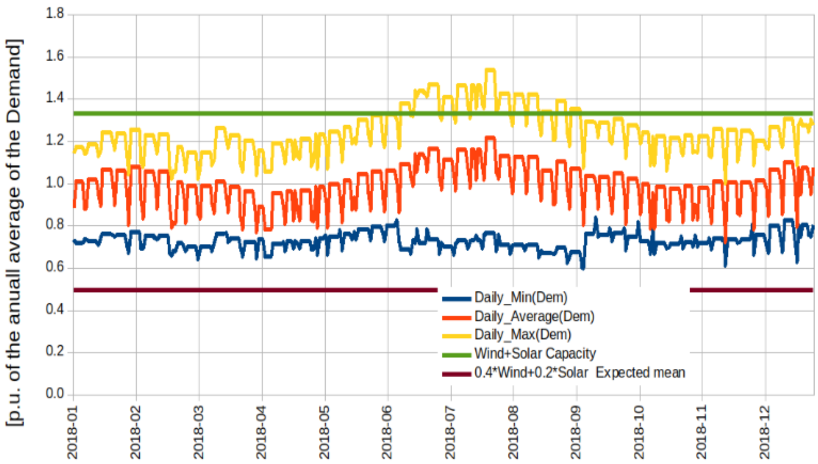

Figure 3.7: Wind and solar installed capacity compared with demand [14]

The economic dispatch in Uruguay is done by the DNC (Nationa 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 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 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.

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 3.8 and 3.9 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.

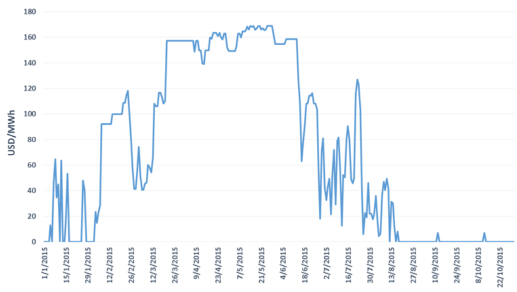

Figure 3.8: Daily spot price average 2015

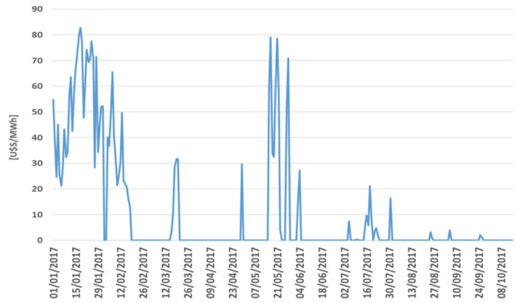

Figure 3.9: Daily spot price average 2017

Furthermore, in Figure 3.10 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 $0\,USD/MWh$ and stored until the spot price reaches a profitable value. These variations is what this project will try to exploit.

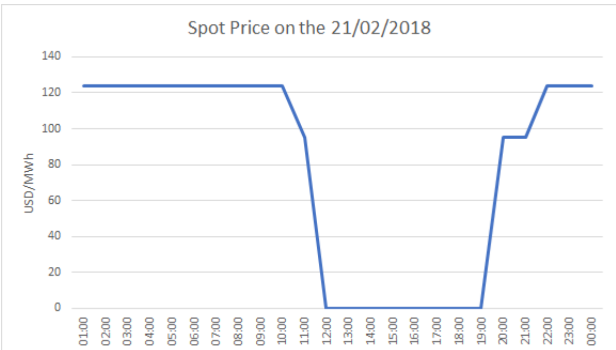

Figure 3.10: Spot price on the 21st of February 2018

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.

Appendix A

Uruguayan transmission network

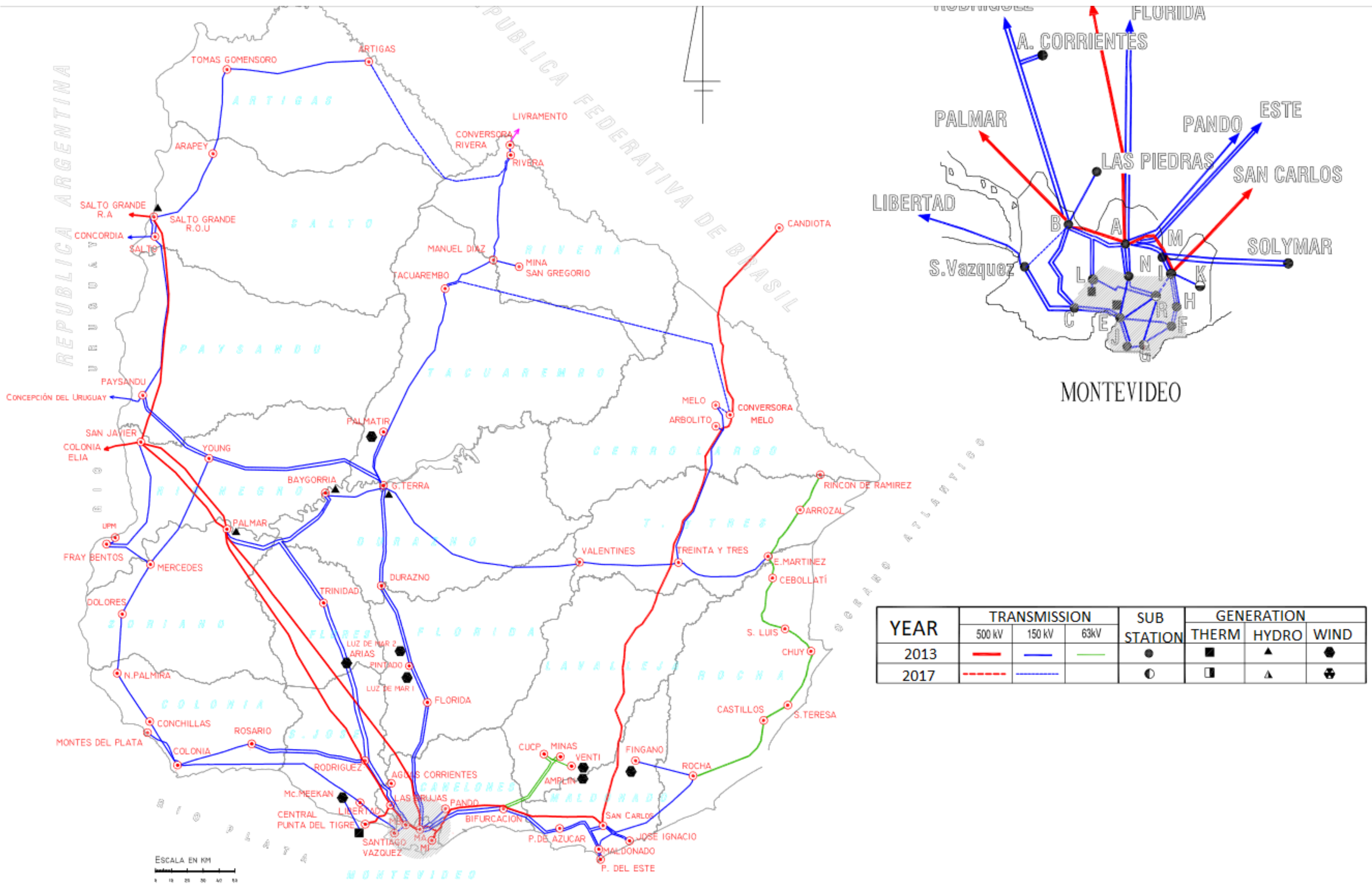

Figure A.1: Uruguayan Transmission Network [38]

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