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Multicriteria Generation and Transmission Expansion Planning in Paraguay

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Multicriteria Generation and Transmission Expansion Planning in Paraguay

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Energy and Earth Resources

The University of Texas at Austin

May 2017

Acknowledgements

First, I would like to give special thanks to Dr. Ross Baldick, Dr. David Eaton, and Dr. Suzanne Pierce for their guidance. Without them, this thesis would not have been possible. Also, thanks to PSR for let me use their software, and specially to Dr. Ricardo Cunha Perez for all his help. I would also like to thank to all the member of Dr. Baldick's research group, specially Juan Andrade and Mohammad Majidi for all the support and help brainstorming ideas. Thank you to Andres Werhle (Itaipu); I am very grateful for his advice and for the data needed for this research. Thank you to my sponsors, Fulbright/Itaipu, the Energy and Earth Resources program, the Graduate School, and the Environmental Science Institute at The University of Texas at Austin. My sincere thanks also go to the faculty, staffs, and colleagues for their help throughout the degree. Special thanks to my friends Shan Cheng and Maria de la Fuente for their emotional support. Finally, to the most important parts of my success, thank you to my family and friends; to my brother for all the feedback, to my sister for the support, and to my mom, dad, little sister, boyfriend and friends for their unconditional love. Thank you for believing in me.

Abstract

Multicriteria Generation and Transmission Expansion Planning in Paraguay

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The purpose of this research is to develop a methodology using welfare economics expanded with multi attribute decision making for portfolio selection of renewable sources in Paraguay's regulated hydroelectric market. This approach considers expansion planning of the Paraguayan Interconnected System (SIN), including generation, transmission, and 2016 Paraguay's Energy Policy. This optimization of the generation expansion problem involves a study period from 2017-2040 assuming a rate of 9.84% per year increasing demand. This study models the SIN using Stochastic Dynamic Dual Programming (SDDP), a probabilistic hydrothermal operation cost optimizer. Based on this Base Case, generation expansion is needed after 2026. Using the Optimization Expansion-Operation Module (OPTGEN-SDDP) software to solve the Expansion Case Optimization, after 2029 the transmission system cannot sustain the demand increase. By 2040, the new installed capacity needed is 26,900 MW. By 2040, there is a need for 13,571 MVA transmission expansion to connect mostly South systems to the Metro system. At 2014 prices, the generation expansion would be at a cost of $ 7.1 million per MVA of new generation capacity. A mixed-integer linear optimization formulation is implemented outside the OPTGEN-SDDP Module. The multicriteria expansion problem is analyzed using a utility function to consider socio-economical, technology and environmental criteria of energy policy interest. The result is then incorporated back to the OPTGEN-SDDP Module. Analyzing a sustainability index for each case, in all cases the Net Import index has a decreasing trend in the period of study. Furthermore, due to transmission constraints, the Reliability index cannot be improved without transmission expansion in any study case. The resultant generation portfolio in both expansion problems includes 26% solar generation, a scale in line with Paraguay's Energy Policy of diversification of the energy matrix.

Small hydro and solar generation sources are a viable alternative to build an electricity generation portfolio mix for the Paraguayan electricity market, by using both a welfare economics optimization and an extended welfare economics optimization with a multi attribute decision making approach. Transmission constraints are still a major issue for the full exploitation of these resources.

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Chapter 1

Introduction

1.1 Background

Electricity generation, transmission, and expansion are central to the economic and social development of a fast-growing country such as Paraguay, not least due to reasons such as its high share of energy exports, 99 % of its electricity coming from hydropower, and a young demographic (DGEEC, 2016). While increases in electricity supply and demand are important for economic growth, they challenge existing generation and transmission systems, causing blackouts and economic losses. To meet these challenges, utilities companies around the world have adopted different approaches, ranging from direct government subsidies, regulated monopolies and competitive wholesale markets. For example, nonprofit utilities were created to satisfy the electricity needs, to promote economic development, and the well-being of people from a region (FERC, 2015). Other criteria such as self-sufficiency, efficiency, minimum cost, and socio-environmental responsibility, have been added to policies aimed to satisfy basic electricity needs of the general population over time (FERC, 2015). The Paraguayan government officially added these criteria to its electricity and energy policies in 2016 (Decree 6092, 2016), and expressed its special interest in the relationship between electricity generation and consumption and the sustainable development of Paraguay. Therefore, to contribute to this understanding, this work analyzes the Paraguayan energy market by considering criteria that are directly linked to contemporary energy policy in the country, such as diversification and socio-environmental responsibility accompanying sustainable development.

The rate at which electricity demand is increasing in Paraguay is highly likely to exceed both its generation and transmission capacities in the next two decades (Sachs, 2013). Thus, the purpose of this research is to develop a methodology which applies expanded welfare economics for portfolio selection of renewable sources to a highly regulated hydroelectric market using the case example of Paraguay. The approach developed in this thesis considers expansion planning of hydroelectric systems, including both generation and transmission (Forsund, 2015). The energy plan of the Paraguayan National Administration of Electricity (ANDE) for the period 2014-2023 establishes the expansion works needed in the electricity system to meet this growth. In the case of electricity generation, the master plan maintains hydropower's dominance with large hydropower plants and small hydro installations, without energy efficiency policies and complementary renewable sources (ANDE, 2016b). To promote a sustainable growth of the energy system and to provide options, this thesis suggests a dynamic model for Paraguayan hydro-generation that can be built, maintained and continuously improved. This thesis models the Paraguayan system following the approach used by the Brazilian research group Power Systems Research (PSR) in Rio de Janeiro, Brazil. PSR developed a stochastic dual dynamic programing cost model that simultaneously optimizes reservoirs and hydropower generators, including interconnections (Campodónico, 2002). The model allows the evaluation of scenarios to find an adequate portfolio of electricity energy sources.

The model proposed in this work provides a holistic analysis of multiple policy and environmental scenarios for hydroelectric power and generation. As 99% of the energy currently produced in Paraguay comes from renewable sources (hydropower) the model proposed in this work may also be useful for informing evidence-based policies for sustainable development strategies which are much needed in Paraguay.

1.2 OBJECTIVE

The objective of this thesis is to propose a generation and transmission expansion planning methodology guided by Paraguay's energy policy points such as:

1. Ensuring energy security through self-sufficiency, efficiency, minimum costs, and socio-environmental responsibility accompanying a productive development;
2. Promoting the generation of economic value from domestic hydroelectric power within the context of a productive regional integration;
3. Contributing to development, and diversification of domestic sources;
4. Harnessing energy policy with social and environmental responsibility for the sustainable use of the hydropower potential of river basins; and
5. Mitigating the hydrological risks of the Parana river basin.

1.3 HYPOTHESIS

Using a welfare economics optimization expanded with a multi attribute decision making approach, small hydro and solar generation sources are a viable alternative to build a successful electricity generation portfolio mix for the Paraguayan Electricity market.

1.4 METHODOLOGY

The methodology of this work is to:

1. Understand the framework of Paraguay's energy sector, with focus on the electricity sector.
2. Build-in the model of Paraguayan hydroelectric system on a robust software to evaluate dispatch conditions.
3. Optimize the generation and its interconnection expansion planning under minimum expansion cost conditions.

4. Explore transmission expansion considerations for the Paraguayan electricity system.
5. Add a decision-making tool to consider social economic criteria based on location, technology used, and environmental considerations.
6. Optimize the generation expansion planning under a multi attribute decision making approach.
7. Report results and give recommendations for future work.

1.5 Summary

This thesis has six chapters. Chapter 2 gives a background of Paraguay's energy sector, energy policy, energy matrix, and electricity sector. Chapter 3 describes the Base Case generation dispatched model for the interconnection system using a Stochastic Dual Dynamic Programing cost model. In Chapter 4, the base case, described in Chapter 3, is used as the operational model to optimize the generation expansion planning under minimum expansion cost conditions. This extended case, the "Expansion Case" explores interconnection expansion. In Chapter 5, social aspects are explained and expanded inside the optimization model using a linear optimization methodology. The results of this "Multicriteria Optimization case" are compared to the results in Chapter 3 and Chapter 4, using sustainability indicators such as net import index, reliability, and diversification of energy sources. Chapter 6 concludes and summarizes the main policy recommendations and makes suggestions for future work.

Chapter 2

Paraguay Energy Sector

2.1 INTRODUCTION

Paraguay is a landlocked country divided in two regions by the Paraguay River: an Oriental (Southeast) and an Occidental (Northwest) region (also known as the Chaco). Each system has distinct geographical and climate features. Paraguay's total area is 406,752 km², making it slightly smaller than California (CIA, 2017). It is administratively divided in 17 districts and the capital Asunción. It is located at latitudes 23 S, and longitudes 58W and borders Brazil, Argentina and Bolivia. The rivers Paraguay, Parana and Pilcomayo border with Argentina. With Brazil, Paraguay is delimited by the rivers Apa, Parana, and Paraguay. Paraguay has improved its fiscal and monetary status through political and institutional reforms and steady growth in its gross domestic product (GDP) since 2012. Paraguay's GDP was $27.623 billion in 2015, with a predicted GDP growth of 2.979% per year (World Bank, 2017). The leading sectors contributing to Paraguay's GDP are services (62.5%), agriculture (19.9%), and industry (17.6%). The industrial sector includes sugar, cement, textiles, beverages, wood products, steel, base metal, and electric power (CIA, 2017). The American investor service Moody's graded Paraguay's government bond rating at Ba1 and stable (Moody's, 2016). Paraguay's energy sector differs from some typical emerging economies because of high hydropower capacity per capita and relatively low electricity consumption.

This chapter discusses Paraguay's energy sector, including its new energy policy (Section 2.2), the energy matrix, and energy resources. The electricity sector is described in Section (2.3), along with the sector's demand, generation, transmission, prices, issues and stakeholder. A final section of this chapter suggests a sustainability index to compare different policy strategies in the energy sector.

2.2 Paraguay Energy Policy

The present energy policy was approved on October 10, 2016 by Decree 6,092 with the top five objectives listed in Table 2.1.

Top objective-National Energy Sector	
1	Ensure energy security with criteria of self-sufficiency, efficiency, minimum cost, with socioenvironmental responsibility, that accompanies the productive development throughout the country.
2	Provide access to quality energy to the entire population with attention to consumer rights.
3	Use domestic energy sources hydropower, bio-energy and other alternative sources. Encourage the production of hydrocarbons, as strategic resources to reduce external dependence and increase the generation of greater added domestic value.
4	Consolidate Paraguay's position as the hub of regional energy integration based on the sustainable use of its natural resources and its strategic geographical location.
5	Educate the population in the understanding of the importance of energy and its sustainable use as a factor of integral development.

Table 2.1: Energy Policy Top Objectives. Source: Modification from Politica Energetica de la Republica del Paraguay (Decree 6092, 2016)

These objectives provide a strategic policy direction for the energy matrix and the electricity sector which are explained in the following sections. This thesis seeks to develop methods to help achieve the sub-objectives listed in Table 2.2.

Sub-objectives-National Energy Sector	
1	Meet the energy needs among the population and of all productive sectors, with criteria of quality, environmental responsibility and efficiency; constituting as a factor of economic growth, industrial development and social progress, within the framework of regional integration.
2	Promote the generation of value from domestic hydroelectric power within the context of regional productive integration.
3	Contribute to energy security, development and diversification of domestic sources.
4	Harness with social and environmental responsibility, hydropower potential of river basins.
5	Mitigate the hydrological risks of the Paraná river basin.

Table 2.2: Energy Policy Sub-Objectives. Source: Modification from Politica Energetica de la Republica del Paraguay (Decree 6092, 2016)

As most of Paraguay's electricity is renewable (99%), it could be used as a cornerstone of sustainable development model (See sub-objectives 1 and 2 in Table 2.2). Sub-objective 3, energy security and diversification, is explored as the hypothesis of this thesis. The model proposed in this thesis can analyze Paraguay's electric generation in the context of policy and environmental scenarios. To support social and environmental responsibility, and mitigation of hydrological risks as listed in sub-objectives 4 and 5, this methodology aims to achieve an holistic analysis of hydroelectric power used in Paraguay.

2.2.1 Energy Matrix

In 2016 electricity supply meet 18% of final energy demand and the unsustainable burning of biomass amounted to approximately 44%. Sixty percent of the biomass is directly used as an energy source, and the remaining 40% is used for producing charcoal and alcohol. About 19% of Paraguay's energy is imported oil and gas. Approximately 39% of energy is derived from crude oil derivate such as kerosene, jet fuel, diesel, fuel oil, and non-energetic products such as lubricant oil (VMME, 2016a) (see Figure 2.1). Subsections 2.2.1a and 2.2.1b below provide some details of oil, gas, and biomass as capital primary sources of energy.

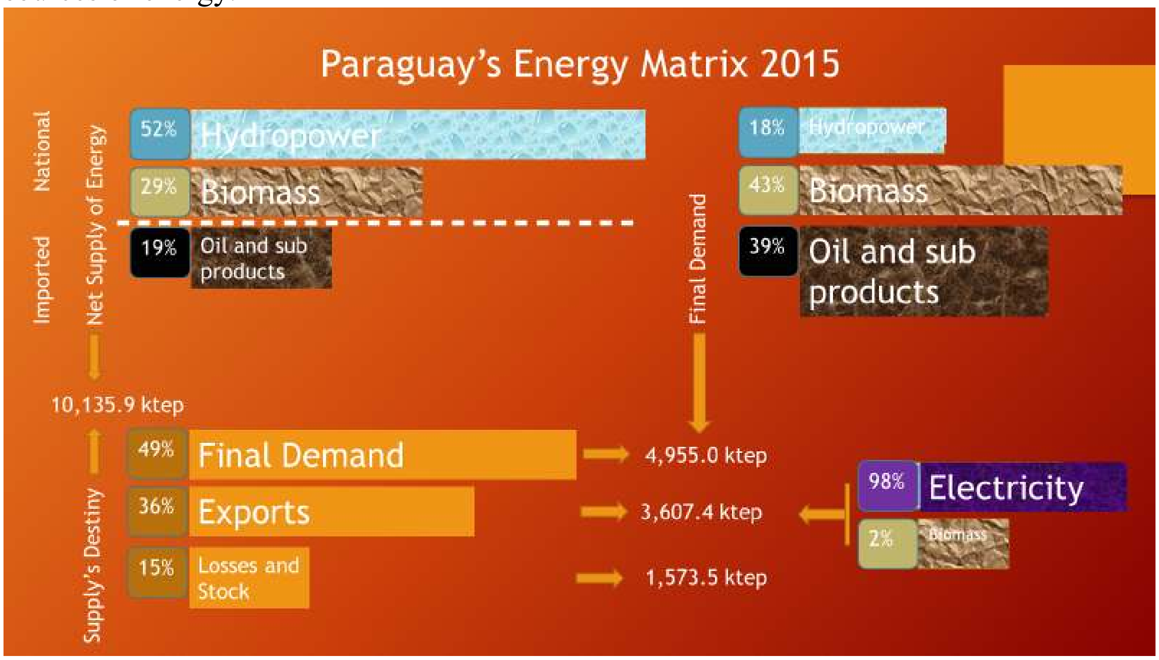

Figure 2.1: Paraguayan Energy Matrix. Source: Modification from Balance Energetico Nacional 2015, (VMME, 2016a) by Maria J Martinez at the University of Texas at Austin

2.2.1a Oil and Gas

Oil exploration in Paraguay began in 1944 in the Chaco region. Due to a vast region of sedimentary basins (95% of its territory), Paraguay has a favorable hydrocarbon potential. However, this potential has not yet been exploited because of a lack of continuity in exploration. Furthermore, this situation is exacerbated by the geological complexity of the country, insufficient technical information, and by the absence of significant private investments, as needed in this field (Wiens, 1995). The lack of such private investments is because according to the National Constitution, all hydrocarbons sources belong to the Paraguayan Republic.

Some natural gas extraction led by a private firm is occurring in the northwest of the country (VMME, 2016a). During the boom of unconventional gas, Paraguay's potential had been identified but not followed up by exploration. In South America, the Montecristo Group estimates the technically recoverable resources of shale gas as 1,225 trillion cubic feet (Verdu, 2012). Figure 2.2. illustrates the shale gas potential in Argentina and in Chaco-Parana basin (Paraguay).

Figure 2.2: Shale Gas Basins in Paraguay. Source: Shale Gas Assessment South America (ARI, 2013)

2.2.1b Biomass

Biomass is an important primary source of energy in Paraguay. It includes firewood and waste from agricultural and forestry production such as coconut cob, cotton shell, shell tung, bagasse, and others. Sugar cane products such as fuel alcohol and alcohol for gasoline mixtures are also available (VMME, 2016a). However, solid biomass used in Paraguay cannot be considered sustainable. The provision of firewood is mostly an informal business, where the supply of solid biomass from sustainable production (9.5 million tons) is not enough to cover the demand (15.4 million tons) (Rios, et al., 2016).

2.3 ELECTRICITY SECTOR

2.3.1 Introduction

Paraguay's electricity transmission system is called Sistema Interconectado Nacional (S.I.N.). ANDE (Electricity's National Administration) administers a system fed by three primary hydroelectric plants: the ITAIPU dam, the ACARAY dam, and the YACYRETA dam. The ITAIPU dam on the Parana River is a binational dam that Paraguay shares with Brazil. Of the 14,000 MW of installed capacity, Paraguay's owns half of it. The ACARAY dam (200MW), located in the Acaray river, is wholly owned by the Paraguayan ANDE. YACYRETA is owned and operated jointly with Argentina. The installed hydroelectric capacity for Paraguay is 1,600 MW (ANDE, 2015c). The ANDE also owns oil thermal power plants of 25.86 MW installed capacity (ANDE, 2015c). Thus, ITAIPU and YACYRETA are binational partnerships, while ACARAY is wholly owned by Paraguay. Other small auxiliary generators, run by diesel, are commonly privately own in Paraguay due to the unreliable distribution system. In the non-hydro renewable side, remote areas and ranches use privately owned solar panel and wind mills as a source of electricity. ANDE does not own any non-hydro renewable power plant (VMME, 2015). ANDE also oversees transmission and distribution.

The following subsections describe the details of the electricity energy sources in Paraguay including its hydroelectrical potential in the Paraguay-Parana basin as well as the solar and wind energy sources. This text also discusses energy demand, electricity transmission (with emphasis in the ITAIPU-ACARAY dispatch), energy issues that can deteriorate Paraguay's substantial development and the state of the electricity prices. The main stakeholders in the electric sector include the ANDE, Ministry of Public Constructions and Communications (MOPC), the Vice Ministry of Mines and Energy (VMME), binational hydropower entities, finance sector, regulatory agencies, large consumers, academia, NGOs, and providers.

2.3.2 Electricity Energy Sources and Potential

2.3.2a Paraguay- Parana Basin

There are two large basins in Paraguay inflowing to the Rio de la Plata Basin, namely the Paraguay basin and the Parana basin. The Paraguay river is navigable for most of its length and is important for communication and national integration. In the same way, the Paraguay River has a great environmental implication for the region due to its origin in the Brazilian state of Matto Grosso, where it feeds the Pantanal Wetland. Its inflow rivers come from the Paraguay Oriental Region; they are the rivers Apa, Aquidaban, Ypane, Jejui, and Tebicuary (ITAIPU, 2013). For ANDE's generation and transmission master plan 2014-2023, the rivers Ypane and Jejui are candidates for small hydro generation sites, as well as the Paraguay River (ANDE, 2014b).

The Parana river is of great importance for Paraguay, especially due to its hydropower generation. In the Parana basin, the inflow to consider for its hydropower potential are the rivers Acaray, Yguazu, and Carapa (ITAIPU, 2013). The Parana basin inflow is 326.4 km^3 per year which is more than four times the Paraguay basin inflow of 73.27 km^3 per year (UNESCO, et al., 1992).

2.3.2b Solar and Wind Resources in Paraguay's Framework

The solar resource is 4.74 kWh/m^2 per day, for the entire Paraguayan territory, with peak at 6.20 kWh/m^2 per day during summer, with high geographic variation as seen in Appendix A.1 (VMME, 2013a). The wind resource gives an average wind velocity of 2.5 m/s in the country, also with high geographic, seasonal and daily variation as seen in Appendix A.2 (VMME, 2013b). The maximum wind velocity can be found in the farthest northern part of the Occidental Region, with velocities around 5.5 to 5.9 m/s at 10 meters high.

Jahn (2002) explores different energy sources such as solar, wind, and small hydro for decentralized rural electrification in Paraguay. His approach cross-references the renewable resource with communities' demographic and socioeconomic characteristics (see Figure 2.3). For example, in Asuncion and the metropolitan areas around it, solar systems have the most promising potential for electricity generation. This solar, small hydro, solar wind hybrid can help to develop businesses for rural electrification to reduce Paraguay's CO_2 emissions.

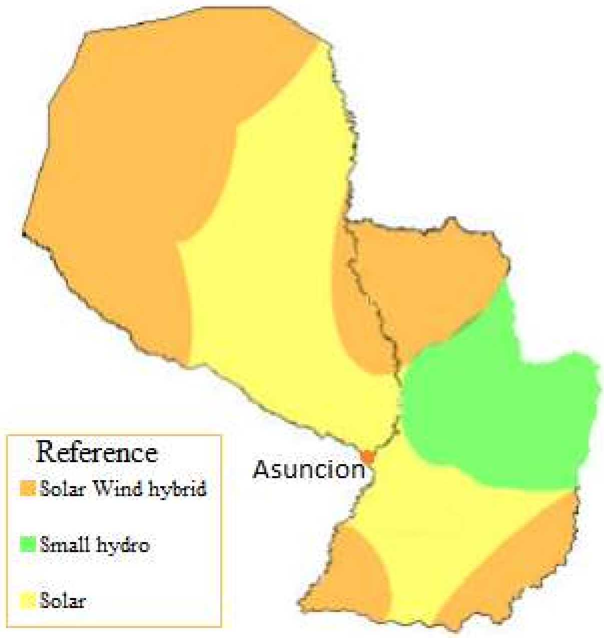

Figure 2.3: Recommended Renewable Configuration per Region. Source: Modified by Energia Renovable para la Electrificacion Rural Descentralizada, (Jahns, 2002)

However, ANDE does not take advantage of wind and solar sources. It has concentrated on strengthening the national power system in the last two decades with transmission and distribution expansion works. This had been ANDE's policy since 1993, and thanks to that policy it has reached 99.33% of households with grid connection in 2014 (ANDE, 2014a). Taking in account this approach to electrification, it is expected that any new renewable source might be integrated in ANDE power system in the future.

2.3.3 Demand

. In Chapter 3, the SIN's demand is considered an input for the model, so it should be carefully understood to make the appropriate assumptions. In 2014, the total energy demand for the SIN was 13,571,220 MWh, which represents an increase of 7.2% from the previous year. Of this total, 91.8% was bought by the ANDE from the Binational Dams, ITAIPU and YACYRETA. The other 8.2% belongs to its own generation. ANDE sells this energy for national demand, but around 0.9% (119,843 MWh) are exported to Argentina.

Paraguay's electricity coverage reached 99.47% of all households in 2014 (ANDE, 2014a), with a peak demand of 2,619 MW in that year, increasing 8.0% since 2013. This maximum demand had been increasing at annual rate of 7.8%. (See Figure 2.4).

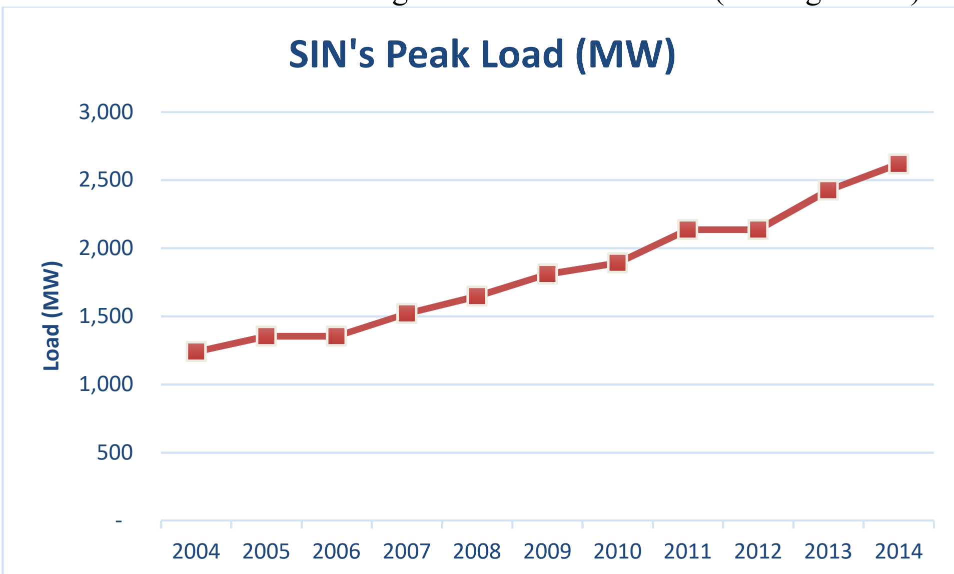

Figure 2.4: SIN's Peak Load. Source: Created by Maria J Martinez at the University of Texas at Austin with Data from Memoria Annual 2014 (ANDE, 2014a)

Paraguayan SIN's capacity factor is the ratio between the "real energy output" over a period to its "installed system capacity", assuming the peak load is constant during the entire year. In 2014, the capacity factor was 58.61% (ANDE, 2014a). The summer daily peak demand occurs around 9:00 to 10:00 PM as seen in Figure 2.5, with another peak around 2:00 PM in the afternoon. ANDE describes this as a demand with high residential component. Residential use makes a 42.3% of the total demand, whereas industrial use 22.6% and commercial uses 18.6%.

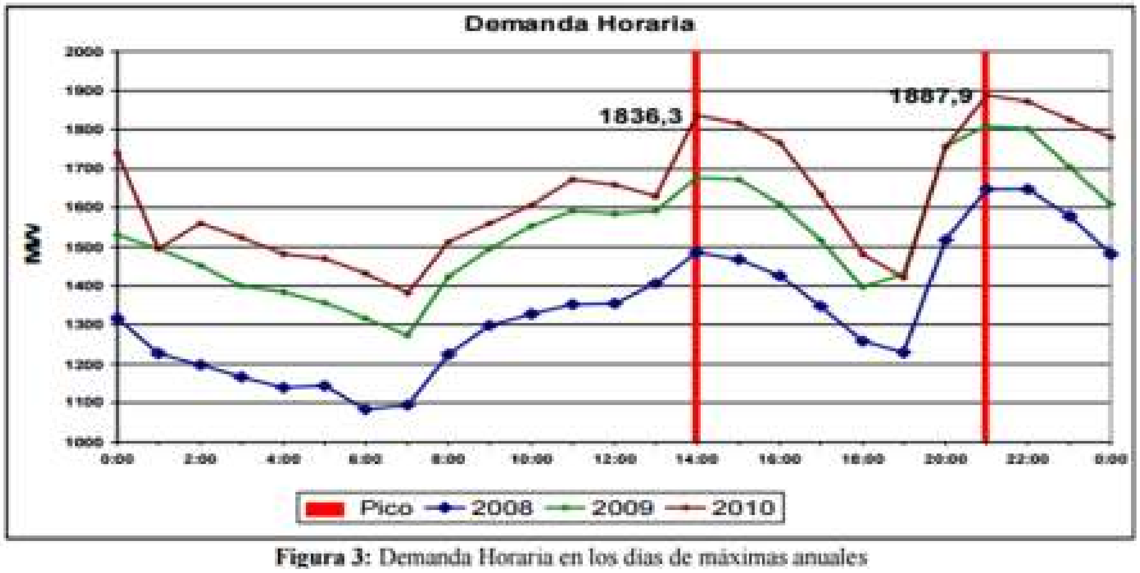

Figure 2.5: Daily Demand on the Summer Peak Source: Analisis del Comportamiento del SIN Paraguay (Nunez, et al., 2010)

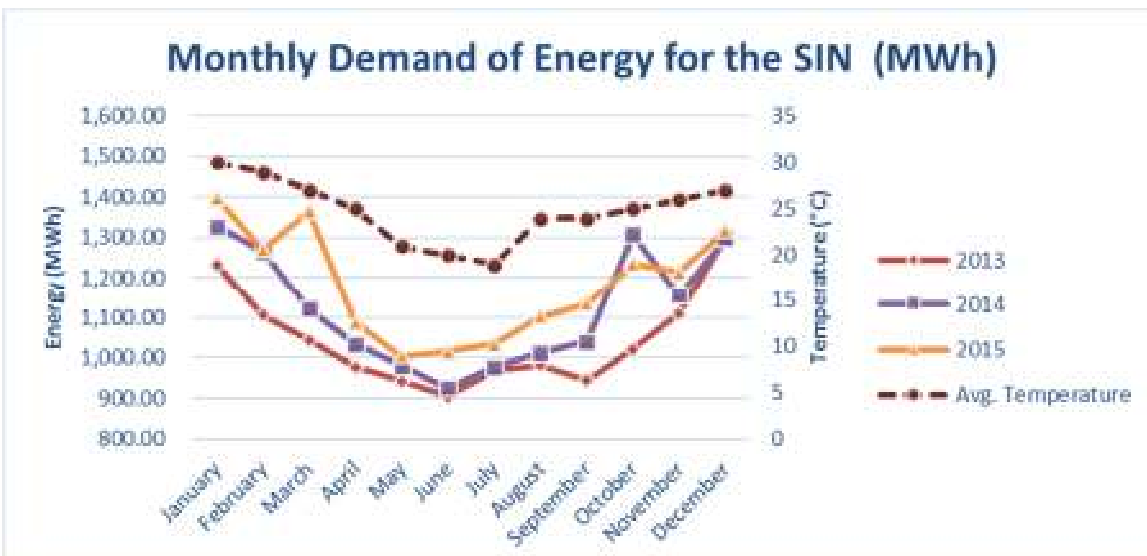

Figure 2.6: Monthly Demand of Energy for the SIN. Source: Created by Maria J Martinez at the University of Texas at Austin with Data from Energia en Graficos (VMME, 2016b)

Figure 2.6 illustrates monthly demand behavior and average temperatures. The data suggest that the monthly demand follows the behavior of the temperature and seasons. In the summer there are higher demands due to air conditioning, and in winter there are lower demands due to mild temperatures.

As a final characterization of the demand, the SIN is divided in six regional systems, as show in Table 2.3. The Metropolitan system, that includes the capital and its metropolitan area, uses 56.2% of the system total (ANDE, 2014a). The West and North System have the highest annual rate increases, with 15.3% and 10% respectively.

Demand of Electrical Energy for SIN systems					
System	2013		2014		Variation
	MWh	%	MWh	%	%
Metro	6,551,184	56.1	7,091,167	56.2	8.2
Central	1,155,248	9.9	1,233,889	9.8	6.8
South	1,035,169	8.9	1,101,091	8.7	6.4
North	515,770	4.4	567,092	4.5	10.0
East	2,264,760	19.4	2,451,375	19.4	8.2
West	153,049	1.3	176,401	1.4	15.3
System Total in 23 kV	**11,675,180**	**100.0**	**12,621,015**	**100.0**	**8.1**
ANDE's consumption G&T	8,633		8,739		1.2
Losses	840,272		820,548		-2.3
Total System	**12,524,085**		**13,450,302**		**7.4**

Table 2.3: Demand of Electricity for SIN Systems. Source: Memoria Annual 2014 (ANDE, 2014a)

Other characteristic of the SIN is its high reserve margin. Reserve margin is the percentage difference between the amount of capacity to generate electricity at a time, and the maximum amount of electricity needed (NERC, 2009). Following ERCOT calculations for an estimation, the margin reserve is 236%. For the Paraguayan system, the minimum margin reserve allowed is 20%. Some estimations suggest this minimum reserve will be reached in 2025 (Sachs, 2013) ,but these estimations vary according to the demand increase rate used.

2.3.4 Transmission

Due to the difficulties in synchronizing ITAIPU and YACYRETA, the SIN worked in 2016 with two 220 kV subsystems (ANDE, 2016b). Subsystem 1's generation source is ITAIPU, and it is operated in parallel with the Brazilian system. Normally, the subsystem includes the systems East, Central, North, West, part of the South system and most of the Metropolitan system. Subsystem 2, where the principal generation source is YACYRETA, is operated in parallel with the South Argentinian system. YACYRETA feeds the South system and part of the Metropolitan system.

To feed the Metropolitan area, a single circuit 500 kV transmission line from ITAIPU is in use. Another single circuit 500 kV transmission line from ITAIPU and another double circuit 500 kV transmission line from YACYRETA, to bring electricity to the Metropolitan area are projected by 2023. To take in account the demand growth and improve the reliability of the SIN, modifications of the ANDE's Master Plan of Generation and Transmission for short and medium term for the period 2014-2023 are been implemented. ANDE's Master Plan is a synthesis of the research evaluating how the SIN can meet the demand growth. This study assumes several ANDE's Master Plan elements:

- The interchange of energy with another country is out the scope of the study.
- Permanent regimen analysis: planning the projected supply for total demand in normal conditions of operation of the system (Full Grid). That is, without violations of the voltage criteria and load in the transmission lines and transformation equipment.
- The emergency conditions are also evaluated, with the criteria N-1 or simple contingency, where only one element of the system is removed at a time.

According to ANDE's plan for the term 2014-2023, there will be a total of 236 projects divided among generation, substation, transmission lines and reactive compensation projects (ANDE, 2014b) . Appendix B represents the transmission lines in both short and long term incorporated in this thesis. A very important component of ANDE's transmission system is the ITAIPU-ACARAY dispatch which is described in the following paragraphs.

2.3.4a ITAIPU-ACARAY Dispatch

Paraguay generation dispatch for the Subsystem 1 works has two aspects to consider. First, there is the physical minute to minute dispatch. ACARAY is used synchronized with ITAIPU to adjust energy production to meet demand in the exchange ITAIPU-ANDE. In other words, ITAIPU supplies the base load, and ACARAY is a peak power plant (Encina, 2016). On the other hand, this is not what happens in economic terms. Of the energy supplied by ITAIPU, there is a power purchase agreement (PPA) to the ANDE that includes 7% of ITAIPU's firm energy, at a cost around $44/MWh in 2016 (Encina, 2016). The same proportion is used to dispatch the non-firm energy. As stipulated in the ITAIPU Treaty, the non-firm energy has a lower cost than the firm energy, and this cost generates monetary resources (approximately $5/MWh in 2016) to pay for additional royalties, extra supervision, and administration costs (Encina, 2016).

2.3.5 Issues

Paraguay's energy sector differs from other countries in the region because is a large hydropower producer, with total electricity demand in the country below the supply capacity. However, there are many problems with Paraguay's electricity supply, such as regular outages and high system losses. The losses in 2014 reach 3,398,164 MWh, around 25.3% of the net energy to the national market. Losses in transmission are around 6.1%;

losses in distribution are around 25.3%. Around half of the distribution losses are due to non-technical distribution losses. These losses include illegal interconnection to the grid, consumption meter tampering, errors in records, and nonpayment by customers (ANDE, 2014a). In 2014 interruptions in the metropolitan area were around the order of 19.4 interruptions for an average of 17.04 hours per kVA (ANDE, 2014a) These are due to not only storms and heavy rain, but also to the distribution system that transmits substantial loads above its design limits, especially during summer peaks (Sachs, 2013).

2.3.6 Electricity Prices

The cost of generation for the ANDE averages 26.47 $/MWh (See Table 2.4.) (Encina, 2016). The highest cost of generation is from thermal generators (1,620$/MWh) , while the cheapest is the ACARAY dam of ANDE, two orders less expensive than ITAIPU and YACYRETA at 17 $/MWh. When making proposals for a new electricity rate, the marginal cost of generation is 41.83 $/MWh, and the marginal cost of transmission 5.98 $/kW-month (Grupos Mercados Energeticos Consultores, 2015). In Paraguay's case, the transmission costs are mostly capital investment to build new transmission. This investment is made by the ANDE, but it is not reflected in the electricity rate before Paraguay's Executive Power approval. They also estimated the unserved energy cost in a range of 2.94 USD/kWh a 4.09 USD/kWh.

Electricity Generation Cost	
	2016
Generation	$/MWh
ITAIPU	44.80
YACYRETA	44.00
ACARAY	17.00
Thermal	1,620.00

Table 2.4: Electricity Generation Cost. Source: Analisis de la Situacion Actual del Sistema Electrico Paraguayo y propuestas de mejora (Encina, 2016)

Due to the stability of the major variables of the cost structure, that is dollar-guaranies (Paraguayan currency or PYG for short) exchange rate and power purchase agreements with the binational dams, Paraguay's electricity rate structure has not been readjusted in the last 10 years. As seen in Figure 2.7, the average rate varies yearly, around 1%. The rate in 2014 was in average 314 PYG/kWh. (ANDE, 2014a). A new rate study proposes an increment of 38%, to 412.47 PYG/kWh, and a new rate tier structure to improve energy efficiency (Grupos Mercados Energeticos Consultores, 2015).

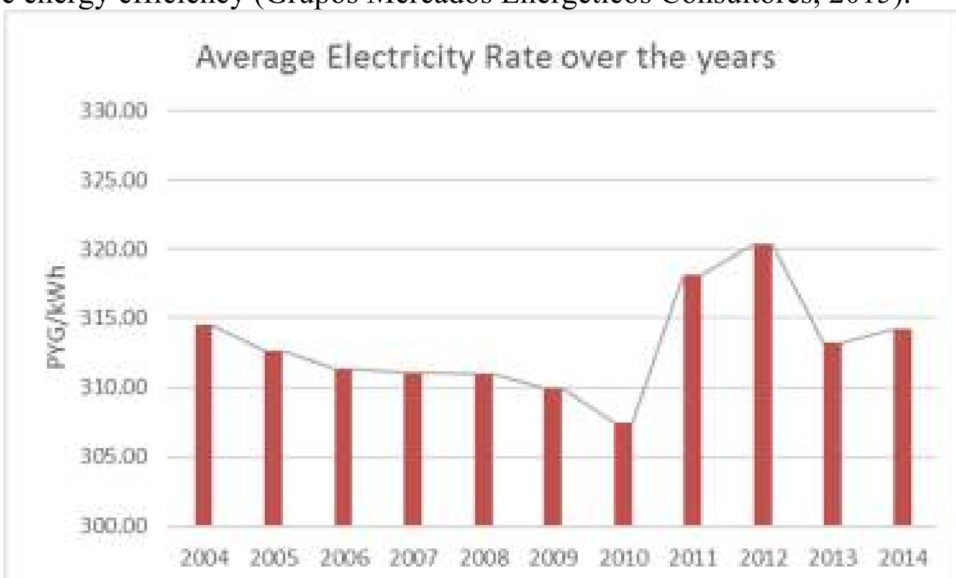

Figure 2.7: Average Electricity Rate Over the Years. Source: Created by Maria J Martinez at the University of Texas at Austin with Data from Memoria Annual 2014 (ANDE, 2014a)

2.3.7 Stakeholders of the Electricity Sector

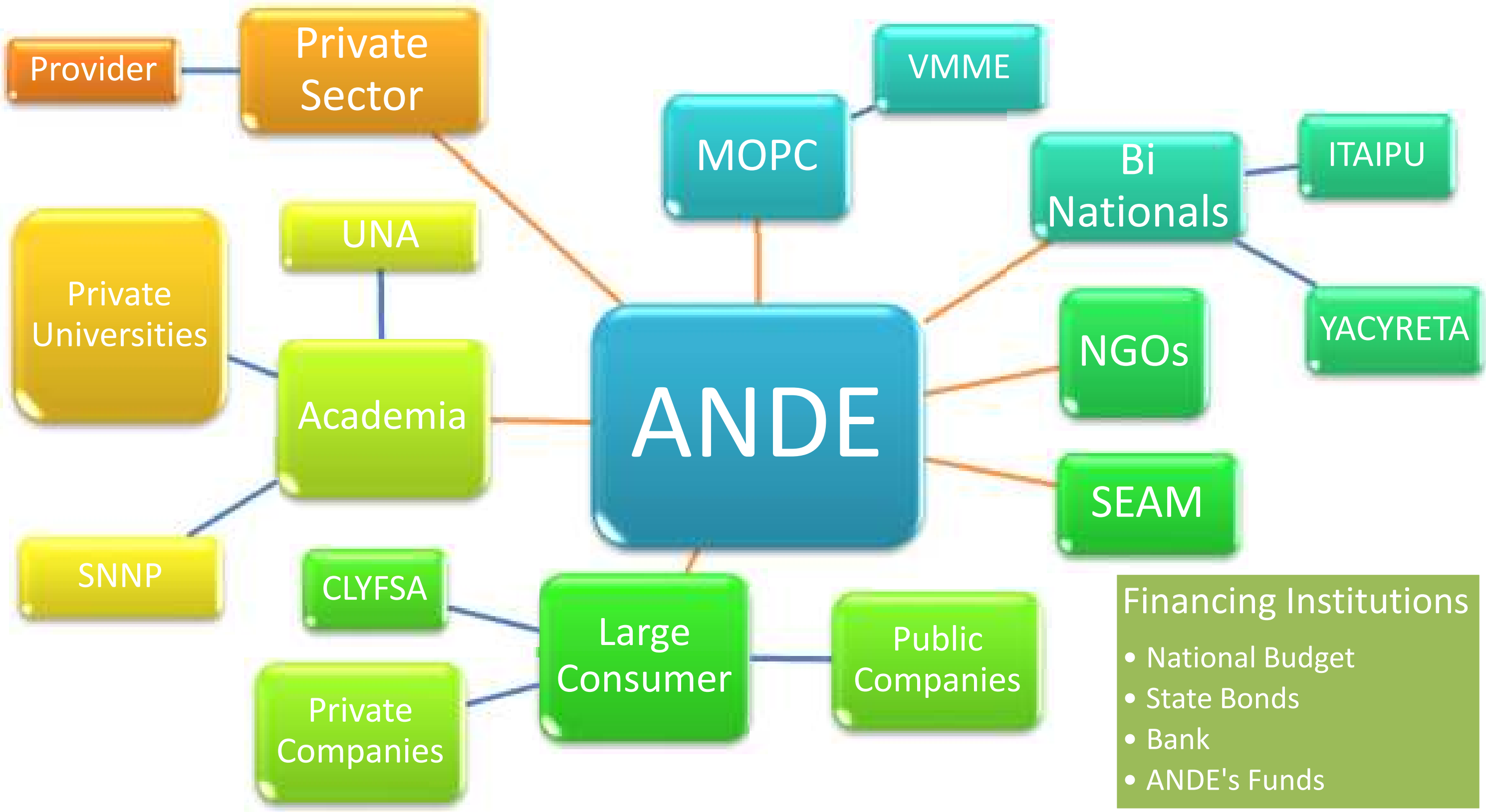

Figure 2.8: Stakeholders of the Electricity Sector. Source: Created by Maria J Martinez at the University of Texas at Austin

The institutional structure of the electricity sector includes the Vice Ministry of Mines and Energy (VMME) and the National Administration of Electricity (ANDE) which are part of the Ministry of Public Projects and Communications (MOPC). Figure 2.8 illustrates the main stakeholders and the relationship between them. The principal stakeholder to oversee the electricity sector is ANDE. Other important actors are the binational hydropower plants, which are not only important for the generation of electricity, but are also investors in the electricity sector. The royalties gained from electricity generation in the binational power plants, their costs, the energy distribution and financing are continuously part of extensive negotiations between Paraguay, Brazil and Argentina and a constant political topic in all Paraguay's presidential elections since 1990. Other stakeholders include large consumers in the public and private sector, academia and specially created regulatory agencies such as councils and secretaries. In the following section, the different stakeholders' backgrounds are expanded following Jahn's 2002 observations and the law associated to the different stakeholders.

2.3.7a National Administration of Electricity (ANDE)

The Law 966/1964 created the *National Administration of Electricity* (ANDE), as an autonomous, decentralized public administration institution, of unlimited duration, with legal personality and own property. It communicates with the Executive Power of the government through the MOPC, specifically through the VMME, but without limiting its administrative powers and functions provided by ANDE's organic law. The Ministerio de Hacienda (Ministry of Finances) appoints a trustee to audit ANDE's finances. The same ANDE oversees the technical auditing of the SIN, as it regulates everything pertinent to the electricity sector, from generation to transformation, transmission, distribution and/or supplies. Due to this, the coordination with the VMME is very limited. ANDE's primary objective is to meet the country's electricity needs adequately, promote its economic development and the well-being of the population, through the preferential use of the nation's natural resources. ANDE coordinates and guides the country's electric development and promotes energy consumption.

2.3.7b Ministerio de Obras Publicas y Comunicaciones (MOPC)

MOPC is the agency in charge of elaborating, proposing, and executing the policies and dispositions of the executive branch regarding infrastructure and basic services for Paraguay's integration and economic development. MOPC facilitates infrastructure construction establishing norms useful in the production, commercialization, and consumption of goods and services in the country. Energy and mines are part of the goods and services responsibilities that correspond to this ministerial portfolio. By decree 393/2008, the MOPC controls the technical elements of the ITAIPU and YACYRETA and other treaties created with the same purpose. The Ministry of International Relationships manages the bilateral relationships, exterior policy for energy treaties, and administration topics related to the binational entities.

2.3.7c Vice Ministry of Mines and Energy (VMME)

Within the MOPC, the VMME was created to establish and guide the policy on the use and management of mineral and energy natural resources. The VMME studies the technical, economic, financial, and legal aspects of energy resources to promote the industrial exploitation of the resources available throughout the country and supervise the proper use of the resources corresponding to its functions. Within the VMME, the Direction of Energy Resources is in command to study, identify and propose the energy alternatives to current and potential consumption needs throughout the country. Furthermore, it considers all other conventional or unconventional national and international energy developmental issues. The VMME proposes policies and regulations that are of interest to nationwide development, orienting on the best use of what already exists in the energy sector.

2.3.7d Bi-National Hydropower

The two bi-national hydropower entities ITAIPU and YACYRETA are key electricity sector stakeholders. ITAIPU was created through the Treaty of ITAIPU, which was signed between the Republic of Paraguay and the Federative Republic of Brazil on April 23, 1973. The objective of the treaty is the hydroelectric utilization of the water resources of the Paraná river. It belongs to both two countries, and includes the Salto de Guaíra of the Foz do Iguaçu river. ITAIPU was developed by ELETROBRÁS and ANDE in representation of Brazil and Paraguay, with equal participation in capital. The constructions started in 1978 with the re-routing of the Parana river. In 1984, the first turbine-generator unit started working (Itaipu, 2016).

The construction of the YACYRETA dam was part of the agreement on the "Improvement of the navigability of the Alto Parana River" signed on 1926 by Argentina and Paraguay. The contracting parties were looking for how to improve the river's navigability at the height of the Yacyreta island and the attenuation of the destructive effects of extraordinary floods. YACYRETA, like ITAIPU, was constituted with equal participation in the legal, financing capacity, and administrative responsibility from both countries. Even though the YACYRETA treaty was signed first, the actual dam construction started on 1983. By 1994 the first turbine-generator unit began operation, 10 years after ITAIPU's start operation date (Yacyreta, 2016).

2.3.7e Financing

The financing of the public electrical sector of Paraguay is accomplished through the National Budget. Other financing sources for the expansion include the Interamerican Development Bank (IDB), International Bank for Reconstruction and Development (IBRD), Japan International Cooperation Agency (JICA), Development Bank of Latino America (CAF), OPEC Funds for International Development, European Investment Bank, and Itaipu and Yacyreta dam royalties. Finally, four state bonds had been issued since 2013 at a rate of 5% to invest on infrastructure projects, including SIN expansions (Ultima Hora, 2017).

2.3.7f Regulatory Agencies

The National Committee of Energy Efficiency, created in 2011, is another regulatory agency, created even before the Paraguay's Energy Policy. It has representation from all the organizations mentioned in this section plus the Ministry of Industry and Commerce (MIC), the Ministry of Education and Culture (MEC), the National Council of Science and Technology (CONACYT), the National Institute of Technology, Normalization, and Metrology(INTN), the Paraguayan Oil company (PETROPAR), academia and the private sector. It was created with the objective of elaborating and executing the National Plan for the efficient use of energy.

2.3.7g Large Consumers

The stakeholders in the consumer sector include national and public companies. Large consumers include the National Cement Industry, Aceros Paraguay(Steel), and other national industries. Also, as large consumers, two distributors without legal holding exists: CLYFSA and the Mennonites cooperative industries of the central occidental region.

The case of CLYFSA is quite interesting as it is a private electricity distributor which is not common in Paraguay. It was created in 1953 as a distributor and generator of energy for the city of Villarica in the Department of Guaira (CLYFSA, 2017) .But since January of 1973, the company works only as a distributor with a feeder of 66 KV from the ANDE. Because this voltage is inside the high-voltage rate from the ANDE, CLYFSA is considered a large consumer for the ANDE, with a contract of electricity delivery. CLYFSA reports to have more than 14,000 clients and a substation of 30 MVA of capacity. They receive the energy from the ANDE at large consumer's rate, and it sells it at ANDE's residential rates.

2.3.7h Academia, NGOs and Providers

Paraguay's stakeholders in the electricity sector also include NGOs, academia and providers. First, the NGOs working on Paraguay are focused on alternative energies such as solar, sustainable development. Furthermore, other environmental NGOs are located in the country (Jhan, 2002). The private sector includes companies that supply equipment such as Rieder/Siemens, CIE, and other companies that offer their services to public companies within tenders. The relationship between these companies and the government accelerated the expansion of the electricity in the 90's under the Self-Help System (ANDE, 2014a)

In academia, there are the National Service of Professional Promotions (SNPP), the National University system and private universities. These institutions offer professional formation on topics inside the energy sector. Also, they are home of energy research groups as the GISE, and the Energy Laboratory of the Engineering School of the National University of Asuncion.

2.4 SUSTAINABILITY FACTORS

To compare the different cases and policies to be adopted in this thesis, and in the future, it is proposed to use the approach of the "2015 Energy Sustainable Index" from the World Energy Council (WEC, 2013). Figure 2.9 illustrates a diagram of the Index structure. The total country performance includes its so-called energy performance and contextual performance. As energy reliability is an issue in Paraguay, the estimation of indicators such as "Distribution Losses as a Percentage of Generation" and "Affordable and quality of electricity relative to access" seem useful as proxies to compare policies and scenarios that recognize these as areas to emphasize. Diversity of electricity generation and the net import index (Total production of energy divided by total demand) are the indices analyzed in this thesis. In 2013, the net import index was 1.2, and the non-diversity of electricity generation (100% hydropower) helps to the exceptional environmental performance for electricity generation free of carbon dioxide (WEC, 2013).

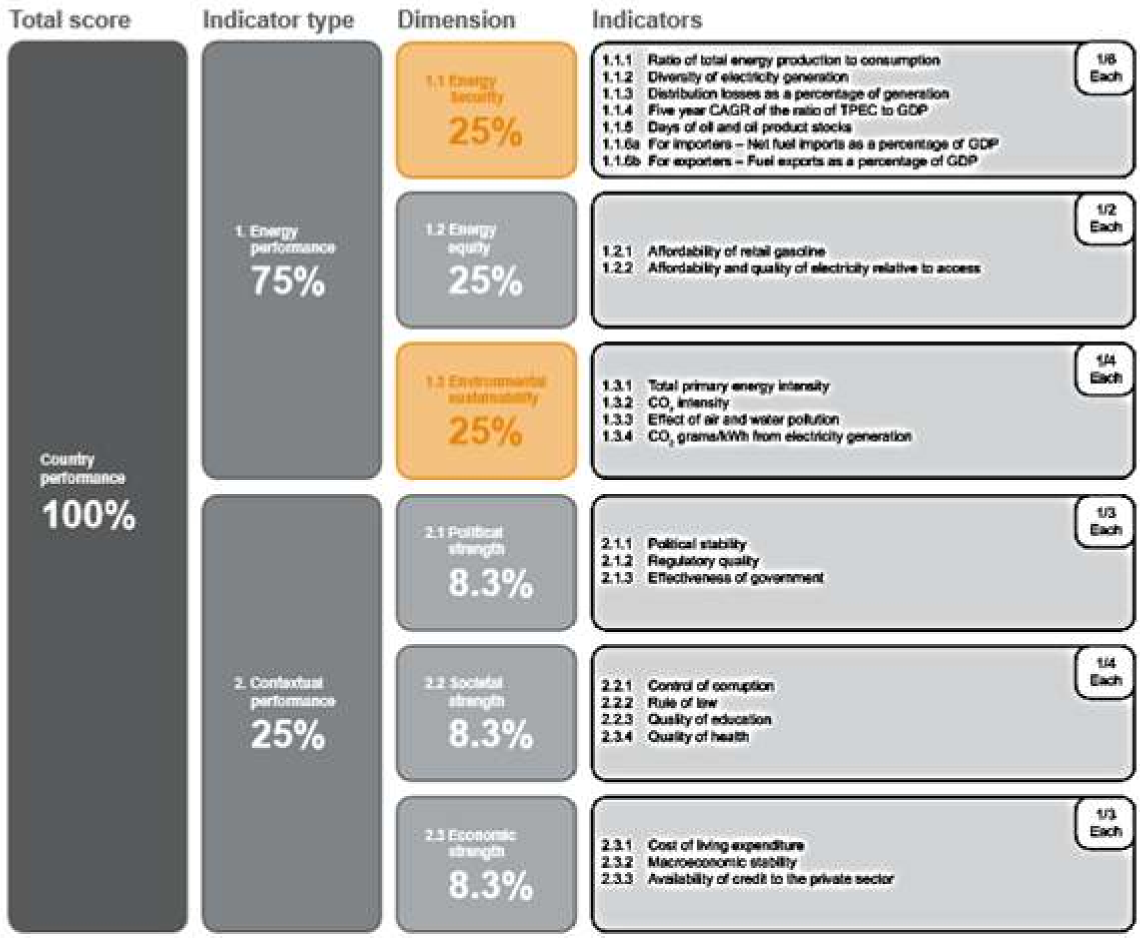

Figure 2.9: Structure of the Index. Source: 2013 Energy Sustainability Index (WEC, 2013)

2.5 Conclusion

This chapter provided a background of Paraguay's energy sector, energy policy, energy matrix and the main actors in the electricity sector. Paraguay's electricity supply issues include regular blackouts, high system losses, and the fact that electricity supply meets only 18% of final energy demand, as the burning of biomass and fossil fuels supply the rest. This imbalance is unfavorable to the country's energy security, the environment and the population's quality of life. Since October 2016 Paraguay's new energy policy promotes energy transition through more hydropower use to reduce the energy sector's biomass and oil dependency. As proposed in this thesis, goals of energy security and diversification of energy sources cannot be achieved without a tool to measure and model different scenarios for policy and decision-making. The energy power modeling enterprise requires a deep understanding of resources, stakeholders, and the electricity sector characteristics, as explored and expanded in this and the following chapters. Furthermore, an index of sustainability is proposed to evaluate the different expansion policies. With this information, the results for a model can be interpreted and evaluated inside a holistic framework that includes more than economic factors alone.

Chapter 3

Base Case: Operation Model

3.1 Introduction

The model requires data and assumptions to represent the long-term behavior of Paraguay's Interconnected System (SIN): the regional systems, demand, plants, fuel cost and interconnections. Due to lack of some data, this section develops data assumptions and model simplifications to allow this study to represent the SIN. The concept of this Base Case is to be expandable, to add supplemental considerations in future study iterations. The study period is from 2017 to 2040. The following sections describe model assumptions (Section 3.2), and results (Section 3.3).

3.2 Model and Assumptions

The SIN's operation cost is a key factor to determine the minimum cost of an expansion investment schedule. Paraguay currently generates 99% of its electricity from hydropower; thus as a result operation costs can be calculated by considering hydrologic variability. This thesis uses Stochastic Dynamic Dual Programming (SDDP) from the PSR Consulting Firm as the software to optimize dispatch of Paraguay's hydropower generators based on operation costs. The model inside SDDP considers operation restrictions including demand for each hydrologic scenario, as well as restrictions on the dam's water balance and run of the river plants, maximum and minimum capacities of generation, capacity of storage in the dams and the limits of the interconnections among regions. The program requires historic hourly electricity demand and forecasts, as well as historical inflows. Figure 3.1 illustrates the flowchart of the input data and results of the SDDP model.

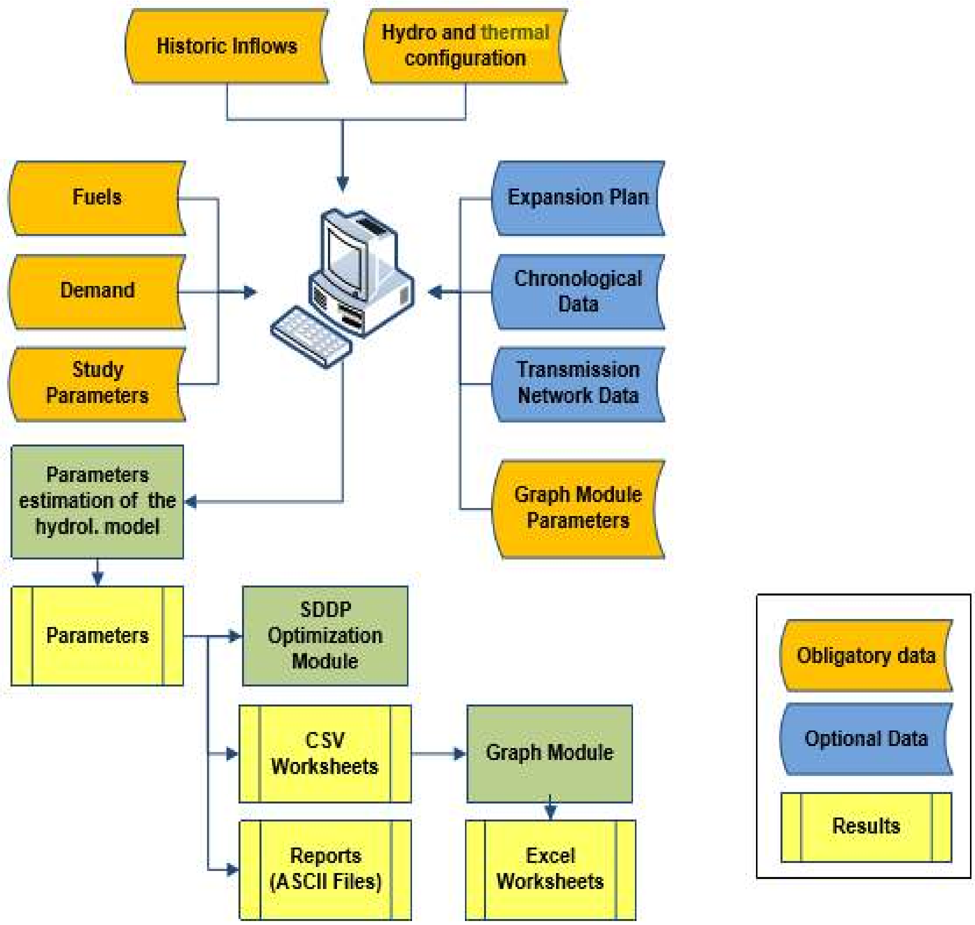

Figure 3.1: SDDP Data Flowchart. Source: SDDP User Manual, (PSR, 2015)

The objective is to minimize operation cost (OPC), as defined by SIN's hydropower immediate costs(FIC), future costs(FFC), and other costs (OC).

Objective Function: Min(OPC)=Min(FIC+FFC+OC) … (3.1)

Where FIC is given by the thermal cost and the penalization for violations of operation constraints, such as water balance, unserved load, and operation limits. FFC is dependent of the hydro inflow in each step. Other cost includes transmission cost and gas natural systems costs among others. The complete breakdown of these functions is part of SDDP methodology (PSR, 2011).

3.2.1 Transmission Network Data: Systems and Interconnections

The systems are an expansion of Paraguay's six regional systems that represent SIN's different demand and interconnection: East, North, West, Central, South and Metropolitan (Figure 3.2). Two other smaller systems are added to the SDDP, a non-interconnected system (Bahia Negra), and another poorly connected system (Fuerte Olimpo). Each of these two systems have a diesel generator of 0.55 MW that can respond to increasing demand (ANDE, 2016b).

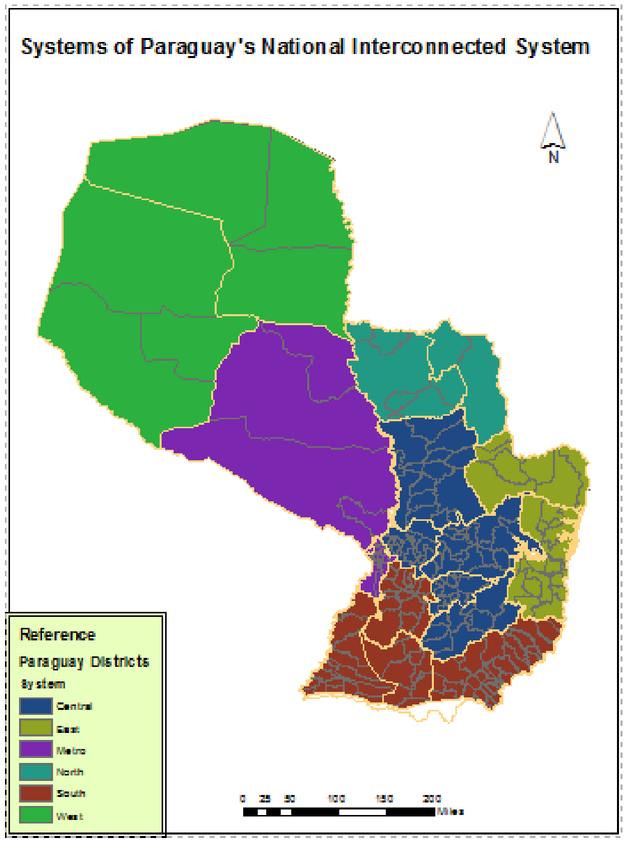

Figure 3.2: Systems of the Paraguayan SIN 2016. Source: Modified by Maria J Martinez at the University of Texas at Austin from Plan Maestro de Generacion y Transmision 2014-2023 (ANDE, 2014b)

There are two ways to represent transmission system restrictions, either with an interconnection model or a linearized power flow model. For a preliminary analysis, an interconnection model is used to model transmission interconnections (PSR, 2015). For a first iteration of the analysis, this model represents the limits for the exchange of energy among neighbor systems. It allows an estimate of the minimum value of the operation cost of the system (PSR, 2011). Table 3.1 lists ANDE's Master Plan Modifications of Interconnections.

Name	System From	System To	Date	Capacity MW
South-Metro 3	South	Metro	8/2/2022	2,000
South-Central	South	Central	28/2/2022	2,000
Central-Metro 5	Central	Metro	30/11/2019	2,000
East-Central 5	East	Central	30/11/2019	2,000
Metro-North	Metro	North	31/12/2019	350
North-West	North	West	31/12/2018	350
North-West 3	North	West	2/2/2021	350

Table 3.1: Interconnection Modification. Source: Plan Maestro de Generacion y Transmision 2014-2023 (ANDE, 2014b)

The objective is to minimize the total cost of transport (Equation 3.2), that is the sum of the cost of transfer energy to the system and from the system (PSR, 2011). The interconnection optimization uses as constraints the equation for demand-supply balance for each system and the limit for the interchange. In the demand-supply balance, the supply (energy generated per the plants in the system plus the energy that enters the systems minus the energy that leaves the system) should be equal to the total load demand of the system (Equation 3.3). Equation 3.4 represents the limit for the interchange, that is the energy transference in the interconnection should be less than the maximum capacity of the interconnection. Table 3.2 lists the nomenclature of the model.

Objective Function: $\text{Min} \left(\sum_{l \in \Omega(s)} (c(l,s) \times \omega_{tk}(l,s) + c(s,l) \times \omega_{tk}(s,l)\right) \quad \ldots (3.2)$

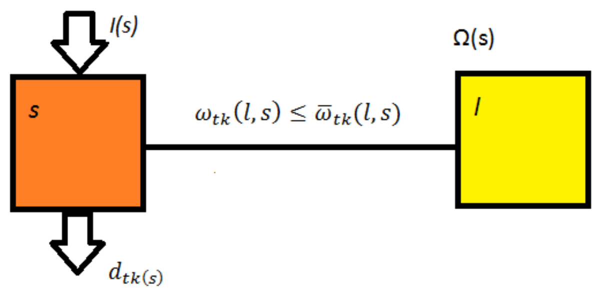

Figure 3.3: Scheme of the Interconnection Model. Source: Created by Maria J Martinez at the University of Texas at Austin

The Constraints are:

Demand Supply: $\sum_{i\in I(s)} g_{tk}(i) + \sum_{i\in \Omega(s)}\big(\omega_{tk}(l,s) - \omega_{tk}(s,l)\big) = d_{tk}(s)$ … (3.3)

Limit of transference: $\omega_{tk}(l,s) \le \bar{\omega}_{tk}(l,s)$ … (3.4)

Where:

Symbol	Description	Unit
s	system index	
S	number of systems	
c(l,s)	cost of transference of energy from system l to system s	$/MWh
c(s,l)	cost of transference of energy from system s to system l	$/MWh
$d_{tk(s)}$	demand of energy in the system s in block t step k	MWh
g_{tk}(i)	energy generation for i in block t step k	MWh
I(s)	Hydroelectric dams in the system s	
Ω(s)	Systems connected to s	
$\omega_{tk}(l,s)$	Energy from l to s in the block t step k	MWh
$\bar{\omega}_{tk}(l,s)$	Capacity of interconnection between system l and s	

Table 3.2: Nomenclature for Interconnection Model. Source: Created by Maria J Martinez at the University of Texas at Austin from SDDP Methodology Manual (PSR, 2011)

Transference cost can include operation cost and capital build cost, among others. In this iteration of the model, the transference cost was not specified due to lack of data, so the total cost of transference in any operation scenario (Equation 3.2b) is always zero. However, the constraints 3.3 and 3.4 should still be complied in every scenario.

Objective Function: Min $(\sum_{l\in\Omega(s)}(c(l,s)\times \omega_{tk}(l,s) + c(s,l)\times \omega_{tk}(s,l))$= Min $(\sum_{l\in\Omega(s)}(0\times \omega_{tk}(l,s) + 0\times \omega_{tk}(s,l)) = 0$ … (3.2 b)

3.2.2 Demand Rate Increase

To estimate the yearly load demand, a proxy for demand in each system is assumed as total demand per month distributed per the percentage of energy demand on each system. The assumption is that each system behaves during months of the year in the same way as the overall country's demand. This assertion is not likely to be true, because some systems can be more seasonal than others. There are five demand scenarios in the ANDE'S Master Plan from the 2012 ANDE's Market Study (See Table 3.3) (ANDE, 2012).

Scenario	Demand Increase Rate (%)
High economic growth 1	9.10
High economic growth 2	7.04
Medium economic	5.66
Low economic	4.03
High economic growth 1 with EII	9.84

Table 3.3: ANDE's Master Plan Scenarios. Source: Estudio de Mercado Electrico Nacional, proyecction 2013-2023 (ANDE, 2012).

Table 3.3 and Figure 3.4 show the national electrical market projection 2013-2023, based on demand increases without new electro-intensive industries (EII). With new electro-intensive industries, the demand can increase by 9.84% per year. According to the decree 7406, the installation of EII with a load of 250 MW (2.200 MWh) should have these conditions: a 220 KV connection to the grid, a 85% load factor and different rates per systems. During peak hours, factories are obliged by contract to work in a fraction of the contract load. For this last scenario, all industries work 75% during three hours of peak demand.

For transmission expansion planning, the ANDE used a high economic growth scenario with electro-intensive industries (ANDE, 2014b). The same scenario is chosen in this base case. This case includes a demand increase for all systems of 9.84% per year except for Bahia Negra, which has a rate increase of 7% each year (Navarro, 2012).

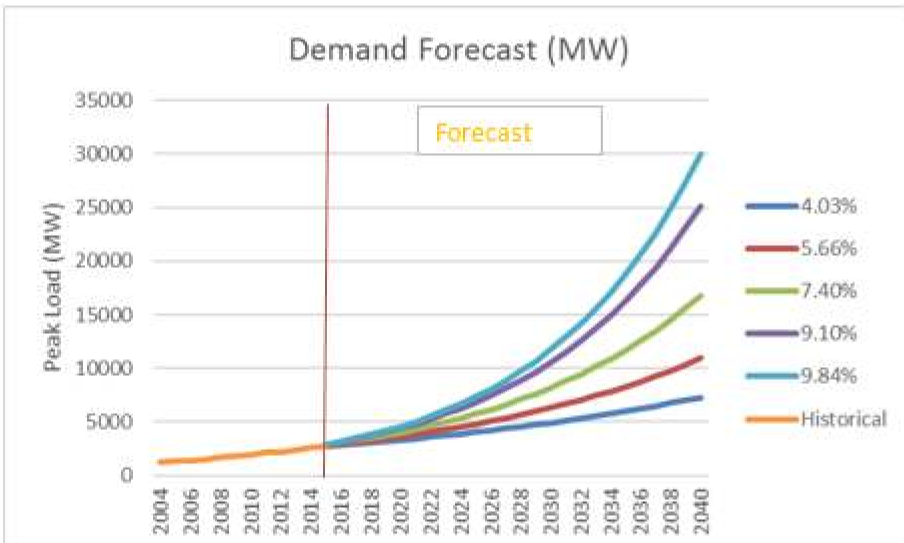

Figure 3.4: Demand Forecast. Source: Created by Maria J Martinez at the University of Texas at Austin with Data from Estudio de Mercado Electrico Nacional, proyecction 2013-2023 (ANDE, 2012)

3.2.2a On-Peak and Off-Peak Demand

To be able to model both on-peak and off-peak loads, it is worthwhile to establish at least two blocks in SDDP associated with a duration in hours and load in GWh (PSR, 2015). As mentioned in Section 2.3, in the demand characterization there is monthly energy demands and peak loads during two periods of the day during the summer. For Block 2 during the Summer, September to March, the electricity demand assumes the peak load is reached for 10% of the hours of the month (Equation 3.5). Then from to 2:00 pm to 3:30 pm and from 9:00 pm to 10:00 pm:

$$d_{2k(s)} = 0.1 * \mathrm{d(t)} * \text{peak load (MW)} \qquad \ldots (3.5)$$

For Block 2 during the Winter, April-August, the electricity demand is 10% of the total electricity demand in the month during the hours from to 2:00 pm to 3:30 pm and from 9:00 pm to 10:00 pm (Equation 3.6).

$$d_{2k(s)} = 0.1 * \text{Total Demand in the month} \qquad \ldots (3.6)$$

For Block 1 the demand in the other hours during the year is the difference between the total demand in the month and the demand in the Block 2 (Equation 3.7).

$$d_{1k(s)} = \text{Total Demand in the month} - d_{2k(s)} \qquad \ldots (3.7)$$

Where

d(t): number of hour in the month.

$d_{tk(s)}$: demand of energy in the system s in block t step k (MWh)

Block 1 was constructed to represent the off-peak load and Block 2 the peak load, which does not mean that the load (in MW) is larger in Block 2 for all the months in the year. Due to the two Block 2 model seasonal considerations, during months January to March, peak load occurs in Block 1. As Figure 3.5 illustrates, from April to August both Block 1 and Block 2 have the same load per block. From September to December, the peak load is in Block 2.

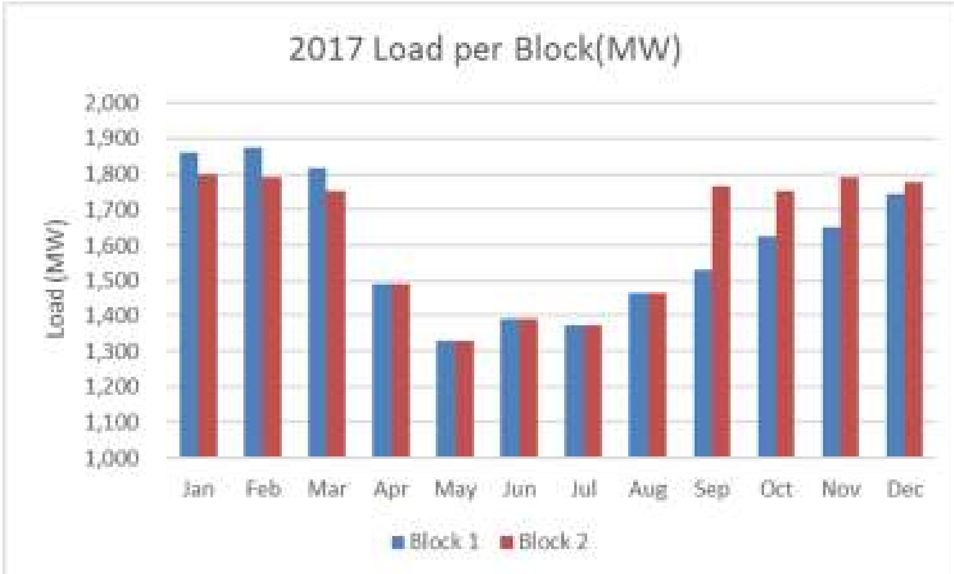

Figure 3.5: 2017 Estimation of Load per Block. Source: Created by Maria J Martinez at the University of Texas at Austin

3.2.3 Water Balance

The water balance of the plants includes both hydrology inflow data and hydraulic (technical) data from the plant. To assume mass balance, three other constraints had to be added to the dispatch cost optimization (PSR, 2011). The first constraint is the balance in consecutive steps as seen in the equation 3.8: "storage" in the end of the step t (start of the step t+1) is equal to "final storage" less the "total outflow" (spill, turbining, irrigation) plus the "inflow" volume (lateral flow plus the outflow of other dams upstream). The second and third constrains are about storage availability and turbining capacity for the plant. The storage in the reservoir at the end of step t should be less than the maximum storage available (Equations 3.9). "Turbining capacity" constraint refers to the turbining of the plant, and it should be less than its maximum turbining capacity (Equations 3.10).

Water balance: $v_{t+1}(i) = v_t(i) - u_t(i) - s_t(i) + a_t(i) - r_t(i) + \delta r_t(i) + \sum_{m \in U(i)}[u_t(m) + s_t(m)]$ … (3.8)

Storage availability: $v_t(i) \leq \bar{v}(i)$ for i= 1,…,I … (3.9)

Turbining capacity: $u_t(i) \leq \bar{u}(i)$ for i= 1,…,I ...(3.10)

For i=1,…,I
Where:

Symbol	Description	Unit
i	index hydroelectric plants	
I	number of plants	
$v_{t+1}(i)$	storage in plant i at the end of step t	m^3
$v_t(i)$	storage in plant i at the beginning of step t	m^3
$a_t(i)$	lateral inflow to the plant i in the step t	m^3
$r_t(i)$	irrigation in the plant i in the step t	m^3
$\delta r_t(i)$	violation of the irrigation of the plant i in the step t	m^3
$u_t(m)$	turbining volume in the step t	m^3
$s_t(m)$	spill volume in the step t	m^3
$m \in U(i)$	amount of the plants immediately upstream of plant i	
$\bar{v}(i)$	Storage in the plant i	m^3

Table 3.4: Nomenclature for Water Balance. Source: Created by Maria J Martinez at the University of Texas at Austin from SDDP Methodology Manual (PSR, 2011)

The gauging stations are representation pointers for inflow database inside SDDP. As a guide, Figure 3.6 illustrates the spatial location of the gauging stations. There are some historical hydrological data from 1995 to 2009 for each dam, from by PSR, (VMME, 2016b) and (Yacyreta, 2016). With these data, stochastic inflow parameters for the rest of the study period can be estimated by SDDP. The method used by SDDP to measure the quality of the statistical fitting is the residual variance change criteria (PSR, 2015).

Figure 3.6: Gauging Stations Outline. Source: Created by Maria J Martinez at the University of Texas at Austin

The SDDP model includes the hydropower plants capacity, maximum turbine outflow, and mean production coefficients (Table 3.5). This data mostly comes from PSR database, YACYRETA 2016, VMME 2016 and ITAIPU 2016.

Name	System	Total Inst Cap (MW)	Max inflow (m3/s)	Mean prod. coeff (MW/ m3/s)	FOR %	COR (%)	O&M cost ($/Mwh)	Min Sto (Hm3)	Max Sto (Hm3)	Controlable Spillage
ITAIPU	East	6,300	11,826	1.11	1.19	6.69	38.02	-	1,000	Yes
YACYRETA	South	1,750	1,500	1.17	-	-	44.00	-	100	Yes
ACARAY	East	200	80	2.50	-	-	17.00	-	10	Yes

Table 3.5: Hydropower Plants Data. Source: Created by Maria J Martinez at the University of Texas at Austin with Data from PSR Consultation work (PSR, 2016), Generacion Yacyreta (Yacyreta, 2016), Energia en Graficos (VMME, 2016b)

3.2.4 Thermal Plants

ANDE has four diesel-fueled thermal generation plants. These thermal plants enhance supply reliability in communities such as Fuerte Olimpo, Pedro J. Caballero and

Salto del Guaira. The last two areas were connected to the SIN by insufficient transmission lines for years, before the upgrading of the lines between 2015 and 2016 (ANDE, 2015a).

Bahia Negra is an island system not connected to the SIN, and its electricity is produced by two diesel-fueled generators of 0.5 MW. This installation is planned to be complemented with renewables; solar energy is the most favorable in the area (ABC, 2016). The total thermal plant capacity installation is 25.86 MW, less than 0.31% of the total installed capacity in the country. These data are in the model, but are not explicitly analyzed in the results section.

3.2.5 Renewable Sources

In the Base Case, there are no alternative renewable sources such as wind, solar or small hydro. These alternative energy sources can be added in the SDDP model for consideration during the Expansion Optimization Case, as will be explained in chapters 4 and 5. To represent a renewable source, data in configuration and modification of the plants are needed in each scenario. Table 3.6 lists configuration data, as the installed capacity and number of units, and modifications in the plants (if there are going to be built, retired, or improved during the study period). Table B.2 in Appendix B lists generation scenarios. Renewable sources are not considered directly in SDDP's dispatch module, as renewable generation is tracked as reduction from the system load before the dispatch optimization is run (PSR, 2015). Table 3.6 below shows a list of renewable sources candidate plants.

Renewable Sources			
Name	Type	Number of Units	Installed Capacity MW
Acaray III	Hydro	1	300
Ypane I	Small Hydro	1	7
Ypane II	Small Hydro	1	8
Ypane III	Small Hydro	1	12
Jejui	Small Hydro	1	9
Carapa	Small Hydro	1	10
Carapa II	Small Hydro	1	30
Pirapo	Small Hydro	1	4
Rio Paraguay I	Hydro	24	72
Rio Paraguay II	Hydro	24	96
Brazo Ana Cua	Hydro	5	273
Corpus Christi	Hydro	20	2,875
Itacora Itati	Hydro	32	1,600
Bahia negra Solar	Solar	1	1
Ypane I Solar	Solar	1	18
Ypane II Solar	Solar	1	16
Jejui Solar	Solar	1	25
Carapa Solar	Solar	1	25
Carapa II Solar	Solar	1	75
Pirapo Solar	Solar	1	10
Rio Paraguay I Solar	Solar	1	136
Rio Paraguay II Solar	Solar	1	160
Brazo Ana Cua Solar	Solar	1	610
Corpus Christi Solar	Solar	1	7,004
Itacora Itati Solar	Solar	1	4,215
Rio Paraguay I SH	Small Hydro	1	30
Rio Paraguay II SH	Small Hydro	1	30
Brazo Ana Cua SH	Small Hydro	1	30
Corpus Christi SH	Small Hydro	1	30
Itacora Itati SH	Small Hydro	1	30

Table 3.6: Renewable Sources Candidate Plants. Source: Created by Maria J Martinez at the University of Texas at Austin with Data from Plan Maestro de Generacion y Transmision 2014-2023 (ANDE, 2014b)

3.2.6 Renewable Scenarios

To represent the seasonal changes in energy production for the alternative renewable sources, the generation scenarios are specified as a factor per unit (p.u.) of its installed capacity. This thesis includes different set of considerations to build each scenario, such as the installed capacity size of each type of renewable source.

3.2.6a Solar

The variability of the production of solar over the year is reflected as an installed capacity factor. During Block 2, solar contributions during peak hours (2:00 pm and 9:00 pm) are represented, so the solar installation assumes full capacity during the peak hour of the afternoon. Then the capacity factor during Block 2 is 0.5 p.u. Outside the peak hours (Block 1), less than 30% of capacity factor is available (IRENA, 2015). With this consideration, it is estimated the monthly factor variation of the solar energy production as follows; The highest average radiation that reaches Paraguay is in January. This thesis assumes January as the month with the highest capacity factor, 30%. For other months is assumed the capacity factor is assumed to be 30% times the fraction of its average monthly radiation and the radiation in January (see Table B.2 in Appendix B).

3.2.6b Hydro

Small hydro includes hydropower plants with installed capacity less than 30 MW (IRENA, 2012). Estimations have been made for the rivers Carapa, Ypane and Jejui regarding the size of the plants (in MW) and energy production (in GWh) (ITAIPU, 2013), using a methodology of prospection of hydropower potential using geographical information systems (Peixoto, 2008). This approach can be used to project the production factor for each month. Table 3.7 lists the nomenclature for this approach. For a first iteration of the model, the production factors are similar during both blocks of the demand.

The simplest equation for power in the inflow is equal to a constant (the density of the water times the gravity and the efficiency) times the inflow and the difference in high between the water intake and output (see Equation 3.11).

$$P_{inflow} = \rho * g * \eta * Q_{inflow} * \Delta H \qquad \ldots (3.11)$$

The sum of the energy produce each month is equal to the total production of the plant in the year (Equation 3.12).

$$\sum_1^{12} E_i = E_T \qquad \ldots (3.12)$$

Assuming the difference between the water intake and output is a constant for this first iteration of the model, the energy produced each month is a constant times the total inflow in the month (Equation 3.13).

$$E_i = \propto * Q_{i_{inflow}} * d(t) \qquad \ldots (3.13)$$

Finally, substituting 3.13 in equation 3.12, there is equation 3.14.

$$\alpha * \sum_1^{12} Q_{i_{inflow}} * d(i) = E_T \ldots (3.14)$$

Using the median of the data for each river as $Q_{i_{inflow}}$, that is 50 percentage of the time, the inflow would be larger than the median. With that assumption, alfa can be estimated from equation 3.14.

The factor of installed capacity per month is a fraction of the energy produced each month divided by the energy the dam can produce (Equation 3.15). This estimation is enough in a first run of the model since the total capacity for this small hydro are less than 1% of the total installed capacity.

$$f_i[p.u] = \frac{E_i}{P * d(t)} = \alpha * \frac{Q_{i_{inflow}}}{P} \qquad \ldots (3.15)$$

Where:

Symbol	Description	Unit
P_{inflow}	power in the inflow	J/s
ρ	density	kg/m^3
g	gravity	$m/\,s^2$
η	plant efficiency	
ΔH	high between the water intake and output	m
i	month	
E_i	violation of the irrigation of the plant i in the step t	J
$\propto$	constant representing $\rho * g * \eta * \Delta H$	
$Q_{i_{inflow}}$	water inflow in month i	m^3/s
$d(i)$	seconds in month i	s
E_T	total annual energy	J

Table 3.7: Nomenclature for Small Hydro Renewable Scenarios. Source: Created by Maria J Martinez at the University of Texas at Austin.

Hydropower plants and other small hydropower plants are modeled as renewable sources due to their small scale and lack of hydrological data. For example, the two hydropower plants in the Paraguay River represent less than 2 % of the total installed capacity. The large hydropower plants on the Parana River can be assumed to deliver at least the contracted capacity. This assumption is reasonable, based on the ITAIPU dam behavior after the drought of 2014 in Brazil. The 2014 drought is considered the worst drought in 60 years. During that year, ITAIPU produced 87,795 GWh, while its contracted capacity is 75,135 GWh (ITAIPU, 2016). The same year, the downstream hydropower plant YACYRETA produced 20,314.7 GWh with an increase of 1% from the year before (ABC, 2015). Detailed behavior of energy production due to droughts should be studied carefully for any future project (Melo, et al., 2016). For the renewable scenarios in all the large hydropower plants, the factor of installed capacity as a first estimation is estimated to be equal to the capacity factor. If developed, these large hydropower plants should be modeled on SDDP or on similar software for an accurate optimization of its dispatch.

3.2.7 Summary

Table 3.8 lists the most important input data and assumption of Paraguay's SIN model inside SDDP as discussed within this chapter, section 2.3 and Appendix B. Sources and sections that expand beyond the assumptions in this paper are provided to guide the reader.

Base Case Data and Assumptions			
	Section	**Data**	**Assumptions**
Demand	3.2.2	Historical from 2004-2014 for 6 regional systems. (ANDE, 2012)	High economic growth 1 with Electro Intensive Industries (EII) (9.84%) (ANDE, 2012)
Fuel		Diesel Cost 45.15 $/GCAl (PSR,2016)	Constant During Study Period
Study parameters			Study Period 2017-2040 Stochastic (100 Scenarios) Unserved Energy Cost 4090 $/MWh
Historic Inflow	3.2.3	Historical from (Yacyreta ,2016) (VMME, 2016) (ITAIPU, 2013) (PSR,2016)	
Hydro and thermal configuration	3.2.3 3.2.4	Configuration from (ANDE, 2014)	
Expansion Plan	Table 3.1	Plan from (ANDE, 2014)	No new sources installations
Transmission Network Data	3.2.1 Appendix B	Configuration from (ANDE, 2014)	Interconnection Model
Renewable Sources	3.2.5 3.2.6 Appendix B	Hydropower and small hydro	The alternative for candidate plan are solar sites Renewable Scenarios

Table 3.8: Summary of Base Case Model Data and Assumptions. Source: Created by Maria J Martinez at the University of Texas at Austin

3.3 Results

In this section, the Base Case is analyzed to see the behavior of SIN considering the inputs and assumptions described above. The key assumptions are a study period from 2017 to 2040 and a demand increase rate of 9.84% per year. First, the dispatch in 2017 levels is compared to prior dispatch levels for the hydropower plants. Second, the annual deficit risk, the probability of having load unserved due to generation or transmission constraints, is analyzed in two periods; one period is from 2017 to 2023 that coincide with ANDE's Master Plan and the execution of all the transmission projects under the plan. A second period is from 2024-2040. This section describes the behavior of the SIN after the final installment of ANDE's Expansion Master Plan, the new generation and transmission needs, and the energy index behavior.

3.3.1 Dispatch in 2017

The Paraguayan electricity system includes two interconnected systems, ITAIPU and ACARAY, feeding Subsystem 1 and YACYRETA for Subsystem 2. As mentioned before, the Subsystem 1 includes the regional systems East, Central, North, West, part of the South system and most of the Metropolitan system. Subsystem 2 feeds the South system and part of the Metropolitan system. The dispatch to analyze is in the Subsystem 1, because of the two dams operating within that one system. On the other hand, YACYRETA always is serving 100% of the Subsystem 2's demand. As seen in Table 3.9, ACARAY supply 4% and ITAIPU 96% of the demand of the Subsystem 1 in 2017. In 2016, per the real dispatch data, ITAIPU supplied 91% of the demand in Subsystem 1, while ACARAY provided 9%. That means an error from the model of 54% for ACARAY, and 6% for ITAIPU. This discrepancy can be traced to ACARAY Hydraulic data for the model.

In the dispatch optimization, the reservoir constraints for ACARAY is binding (Equation 3.9). This can be seen in the output of marginal value of water, defined by the

SDDP manual as "the change in operating cost with respect to an infinitesimal change of the water availability in the hydropower plants' reservoirs at the beginning of the stage" (PSR, 2015). ACARAY marginal value of water on 2017 is around 14 k$/hm3. In future iterations of the base case the ACARAY Hydraulic data should be revised.

Year	Subsystem 1			Subsystem 2		Percentage of the Demand		
	ACARAY	ITAIPU	Total	YACYRETA	Total	ACARAY	ITAIPU	YACYRETA
	GWh	GWh	GWh	GWh	GWh	%	%	%
2013	903.11	8,809.99	9,713.09	2,357.90	2,357.90	9%	91%	100%
2014	1,104.69	10,143.37	11,248.05	1,812.87	1,812.87	10%	90%	100%
2015	1,065.32	10,617.50	11,682.83	2,607.89	2,607.89	9%	91%	100%
2016	1,178.07	11,202.52	12,380.59	2,458.98	2,458.98	10%	90%	100%
2017	**996.00**	**21,736.00**	**22,732.00**	**2,172.00**	**2,172.00**	**s4%**	**96%**	**100%**

Table 3.9: Percentage of the Demand per Subsystem. Source: Created by Maria J Martinez at the University of Texas at Austin from SDDP Output Data and Energia en Graficos (VMME, 2016b)

The consequence of having transmission constraints, where both subsystems are not interconnected, is that marginal price of generation to serve the South System is higher than the others regional systems (see Figure 3.7). The marginal cost is the cost of generating the next MWh. For the South System, the marginal cost due to YACYRETA generation is 44 $/MWh, while in the other regional system is 38 $/MWh, based on ITAIPU's generation cost.

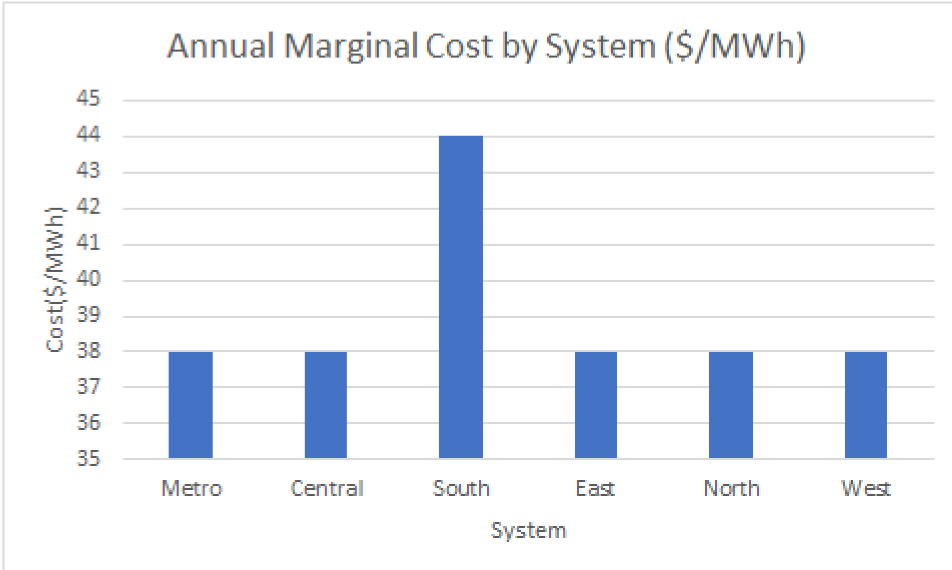

Figure 3.7: Annual Marginal Cost by System 2017 ($/MWh). Source: Created by Maria J Martinez at the University of Texas at Austin

3.3.2 Behavior During 2017-2023: ANDE's Master Plan

During the period 2017-2023, the deficit risk is low: around 0.9 % in the Subsystem 1, as seen in Figure 3.8. This deficit risk is due to transmission constraints. On the other hand, there is not risk of load unserved in Subsystem 2 in this period.

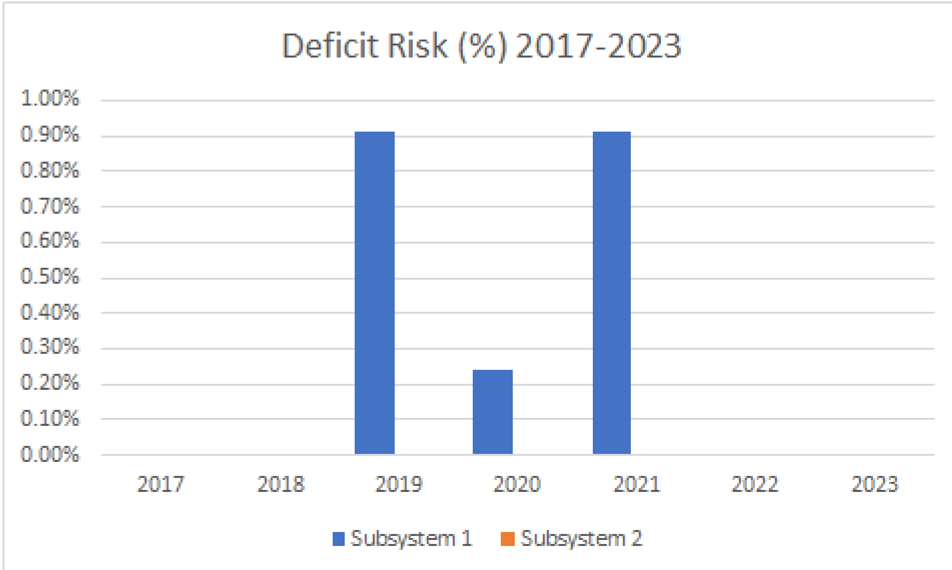

Figure 3.8: Deficit Risk 2017-2023. Source: Created by Maria J Martinez at the University of Texas at Austin

Figure 3.9 illustrates the generation per year of ITAIPU and YACYRETA does not reach the minimum generation possible. Both plants are not selling Paraguay's full capacity to the country and there are still exports to Brazil and Argentina. The deficit risk in Subsystem 1 is not due generation constraints. By analyzing the input energy to the Metropolitan system and its demand, the deficit can increase between 2019 and 2021 (Figure 3.10), as illustrated in the deficit risk percentage in Figure 3.8. As seen in Table 3.1, in 2022 a new interconnection between East System and the Metro System is built, that allows the diminution of the deficit risk in the Subsystem 1 from 1.5% to 0% in 2022 (Figure 3.10). In the period 2017-2023, transmission expansion is enough to decrease deficit risk.

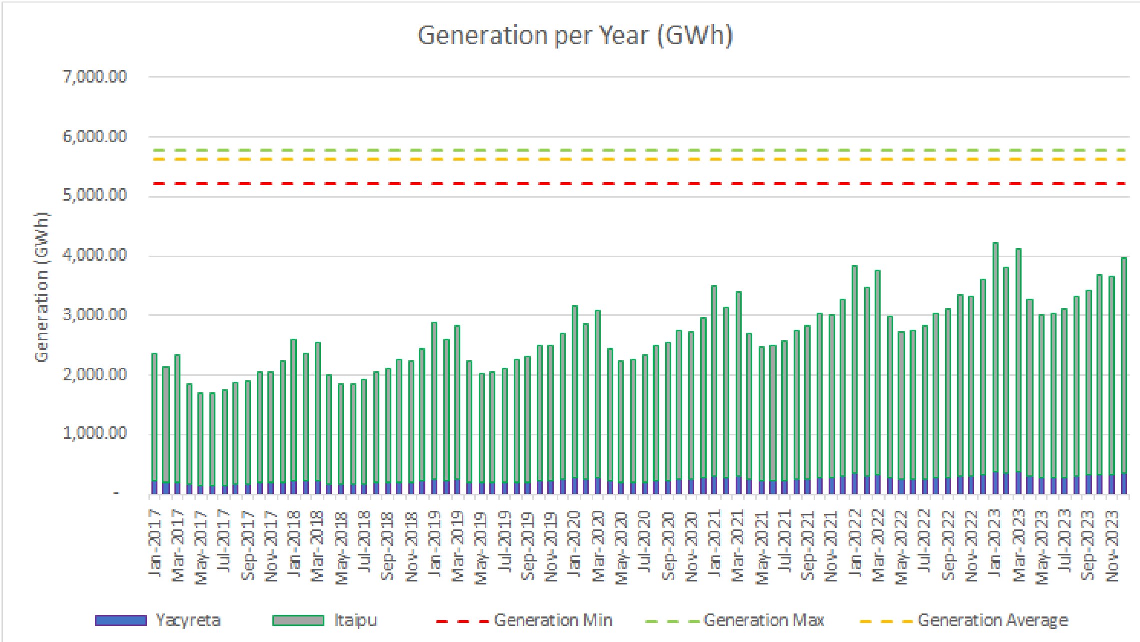

Figure 3.9: Generation 2017-2023 Base case. Source: Created by Maria J Martinez at the University of Texas at Austin

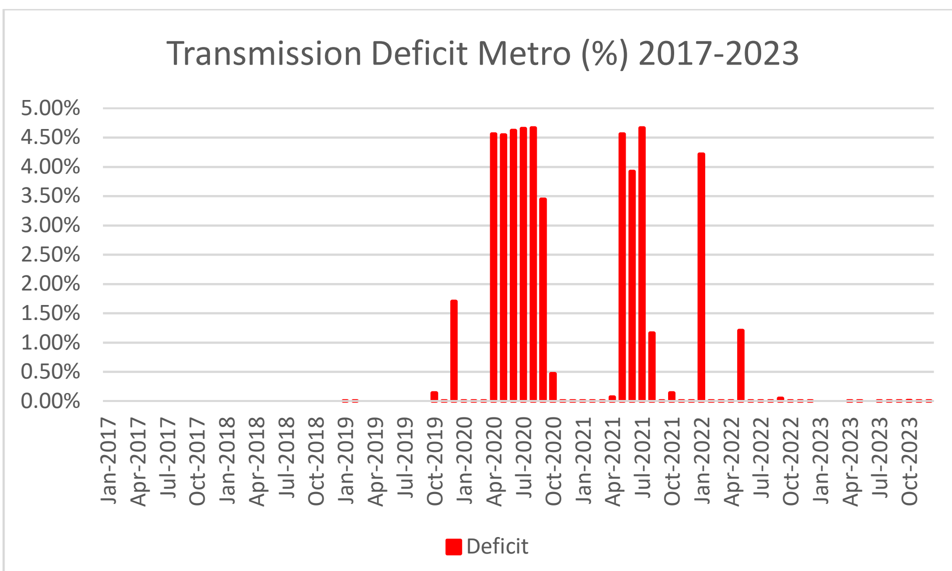

Figure 3.10: Transmission Deficit for Metropolitan System 2017-2023. Source: Created by Maria J Martinez at the University of Texas at Austin

3.3.3 Period 2024- 2040: Generation Expansion

The SDDP model gives various indicators pointing out that expansion is needed for Paraguay's SIN such as deficit risk percentage, generation and demand on the systems, marginal cost of generation and transmission, value of water, among others. For example, due increasing demand after 2023, the deficit risk starts to increase in 2026, reaching 100% in 2029 for most of the systems (See Figure 3.11). More details on these deficits are discussed in chapter 4.

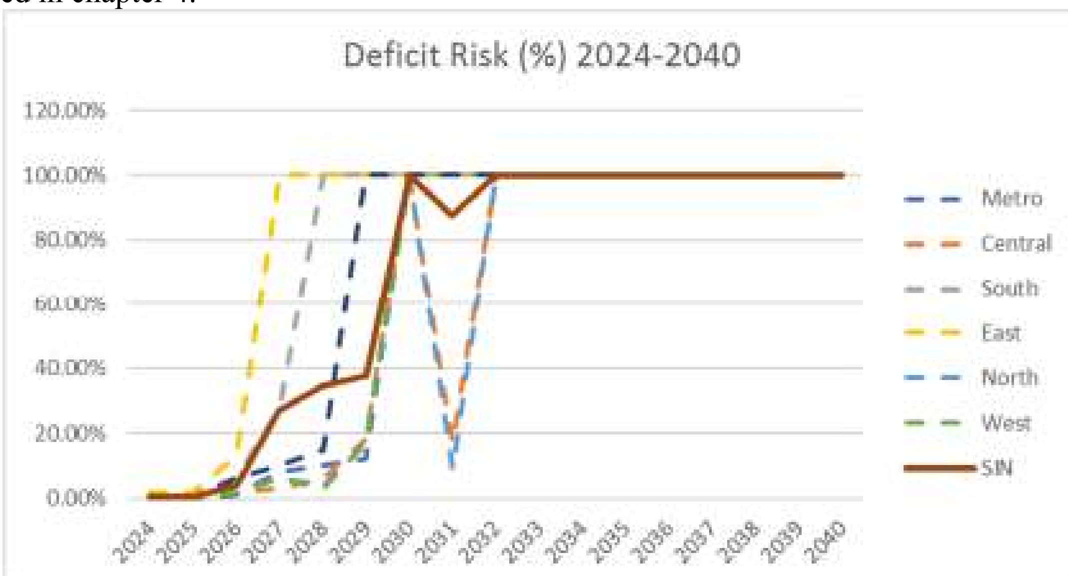

Figure 3.11: Deficit Risk for all Systems from 2024 to 2040. Source: Created by Maria J Martinez at the University of Texas at Austin

Figure 3.12 shows the electricity demand for 2025 to 2026. The demand can be larger than the minimum of the "Maximum Generation" band for the months of January, February and December, which represents a deficit risk on the system. Generation might not be enough to serve the demand in this period.

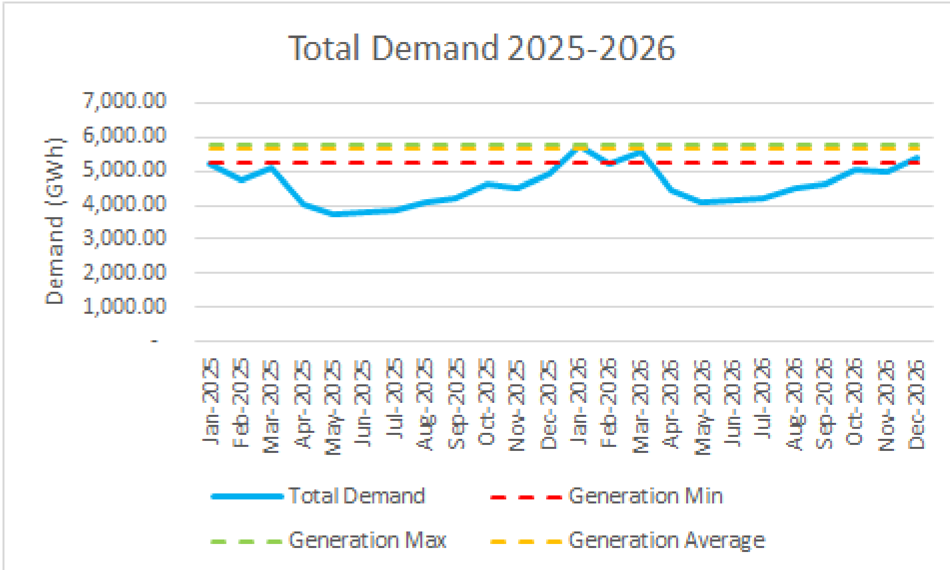

Figure 3.12: Total Demand 2025-2026. Source: Created by Maria J Martinez at the University of Texas at Austin

In conclusion, even in a simplified model such as the Base Case, there are indicators, such as the deficit risk, pointing out that expansion in generation and transmission is needed after 2023 for the given 9.84% demand increase rate per year. Using a spreadsheet approach to the problem, it can be estimated for the mean demand rate increase (5.6%) and evident that the generation deficit starts to increase around the year 2030 (See Table in Appendix B.3).

3.3.4 Sustainability Indices

Some useful energy indices from this Base Case are: Net Energy Imports and Energy Reliability index, the last one estimated by the deficit risk of the system (See Figure 3.11). Because the deficit risk is increasing after 2026, the Reliability Index would tend to decrease (WEC, 2013). To estimate the behavior of the Net Energy Imports index over the study period, the biomass and oil consumption can be kept in the same level as 2015. With this consideration, Paraguay can be considered a Net Exporter of electricity only until 2024 at best (See Figure 3.13). According to the data considered, in March of 2018, for first time, the Net Import index is below 1. In addition, by 2025 ITAIPU and YACYRETA have a capacity factor reaching 100% for Paraguay in certain months (Figure 3.12). They reach their full installed capacity for the entire year by 2026. That is, by 2026, Paraguay does not exported electricity to Argentina or Brazil because it needs the full hydropower output to meet its demand.

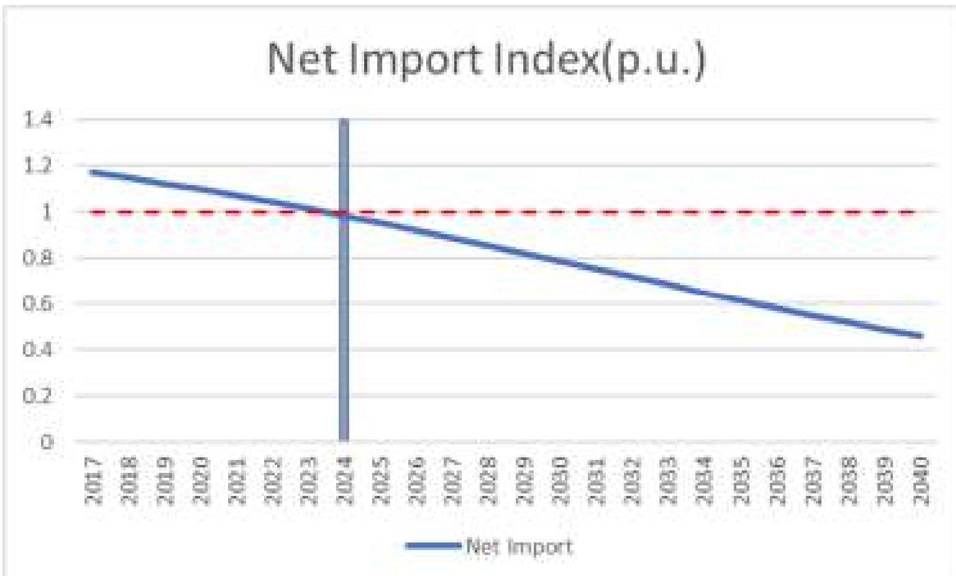

Figure 3.13: Net Import Index. Source: Created by Maria J Martinez at the University of Texas at Austin

3.4 CONCLUSION

This chapter introduced the logic and data behind the Interconnect System (SIN) model for Paraguay. With this Base Case, the worst-case scenario for the SIN was developed, with an increase in demand at a rate of 9.84% per year. This case reflects high economic development and deep electrical industries penetration. This case is not likely to happen because the actual mean annual demand increase is lower than 9.84%. The high demand scenario has the advantage of including not only a worst demand scenario but also a scenario where electricity represents a high portion of Paraguay's energy matrix. Based on this Base Case, expansion would be needed to meet demand during the study period. This will be considered in the following chapter.

The energy indices proposed in Chapter 2 were examined accordingly to this Base Case. The indices of Energy Reliability and Net Import have a decreasing tendency over the study period 2017-2040. Furthermore, Paraguay stops being a Net exporter of energy by 2024, and by 2026, Paraguay does not export electricity to Argentina or Brazil.

Chapter 4

Generation and Transmission Expansion

4.1 INTRODUCTION

According to the analysis presented in the previous chapter, to meet rising demand generation expansion would be needed in Paraguay after 2026. This chapter evaluates generation expansion, using a multi-area generation and interconnection expansion planning computational model called OPTGEN. The data needed for this analysis includes expansion cost, investment decision constraints and operational constraints. This chapter explains the model, data (Section 4.2), and results (Section 4.3) of the expansion optimization model are explained, as well as an analysis of transmission expansion considerations.

4.2 MODEL AND ASSUMPTIONS

The Paraguayan electric system can be approximated using spreadsheet calculations, although there are others software for optimizing generation planning, such as Plexos and Aurora. OPTGEN allows an analysis that iterates between the operation and the planning optimization models. The communication between the two is what makes it different from the others. SDDP is a stochastic program constructed for modeling hydropower dispatch, and OPTGEN is a traditional optimization software used for generation and interconnection expansion. Figure 4.1 illustrates a flowchart of the input data and results of OPTGEN.

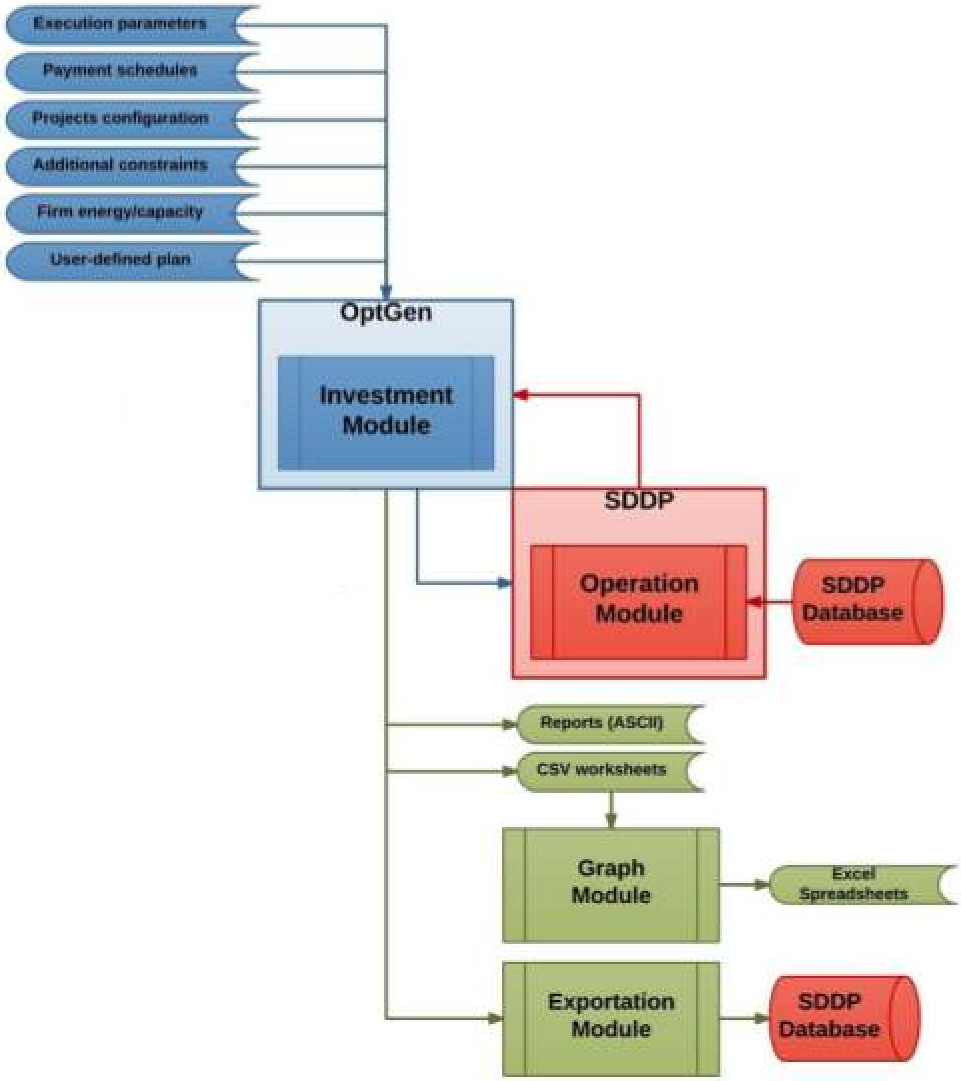

Figure 4.1: OPTGEN Data Flowchart. Source: Modification by Maria J Martinez at the University of Texas at Austin from OPTGEN Manual user (PSR, 2005)

4.2.1 Generation Expansion Problem

The generation expansion optimization is a large mixed-integer problem, where the number of variables depends on the number of candidate plants and the study period. The problem becomes more complex with the different constraints and system configurations. Figure 4.2 illustrates the problem block structure to find the least-cost investment schedule,

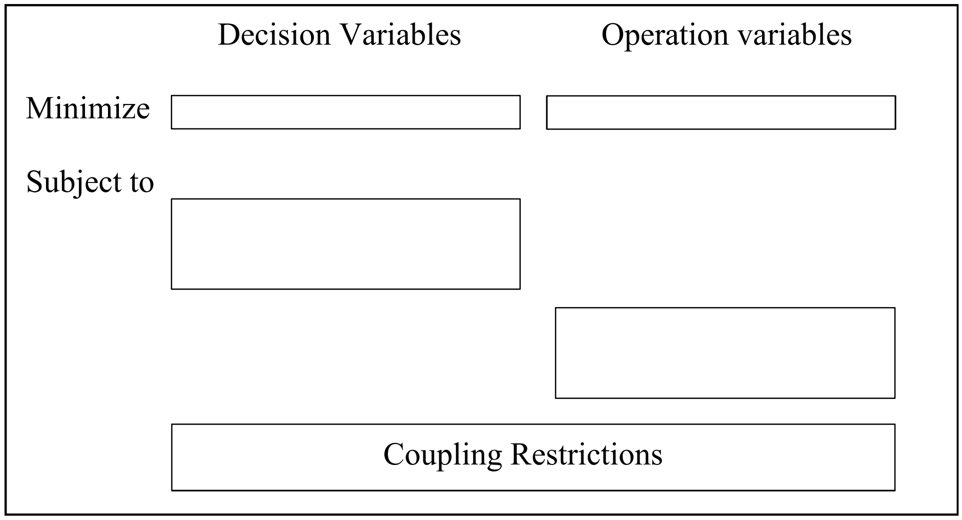

Figure 4.2: OPTGEN Block Structure. Source: OPTGEN Methodology Manual (PSR, 2009)

For the chosen plants, the investment total cost, estimated by the SDDP module, includes the sum of capital cost and expected production cost. Following the block structure, there are two general types of constraints. There are operational constraints, such as load supply, hydro balance of plants in cascade, maximum and minimum generation capacity, reservoir storage, and energy transfer. Those constraints were set in SDDP and described in the previous chapter. There are investment related constraints, such as minimum and maximum dates for project construction decisions, associated or mutually exclusive projects and precedence constraint are set, which are described in the following sections.

4.2.2 Investment Cost

4.2.2a Installation and Operation Cost

Table 4.1 lists the estimated installation cost, operation cost, and lifetime of the power plant per type (IRENA, 2015). From a planning point of view, these data are a first approximation. In future iterations, more detailed calculations can be used to refine the cost estimates of the projects in Paraguay's territory.

Cost per Plant			
Type	Investment $/KW	O&M $/KW-year	Lifetime Years
Small Hydro	3,333	83	40
Large Hydro	7,650	172	60
Solar	7,000	14	20

Table 4.1: Cost of candidate plants. Source: Created by Maria J Martinez from data by Renewable Power Generation Costs in 2014 (IRENA, 2015) and Renewable Energy Technology: Cost Analysis series (IRENA, 2012)

4.2.2b Interconnection Cost

Table 4.2 lists ANDE's interconnection cost data. The transmission expansion costs needed to connect the plants are inside interconnection costs and included substation costs, transmission, and soft costs. The transmission line size for each plant was chosen for the installed capacity of the plant. Soft costs include compensation to people, right of way, taxes, supervision, contingencies, and others (ANDE, 2015b).

Interconnection Cost			
Item	Cost	Unit	Capacity (MVA)
Substation	23,500	$/MVA	--------------------
Line 23 kV	15,000	$/km	6
Line 66 kV	70,000	$/km	40
Line 220 kV	140,000	$/km	200
Line 500 kV	387,000	$/km	2,000
Soft cost	37,128	$/MVA	---------------

Table 4.2: Interconnection Cost. Source: Created by Maria J Martinez at the University of Texas at Austin from Estudio de factibilidad del uso de energia solar y eolica para generacion de energia solar electrica en el destacamiento militar Sgto. 2 Estanislao Rodriguez en el Chaco Paraguayo (Carreras & Ramirez, 2012) and Línea de Transmisión de 500 kV Yacyretá – Ayolas - Villa Hayes (ANDE, 2015b).

4.2.2c Payment Schedule

The payment schedule is set to model how the total investment cost is distributed over time. Assuming one disbursement for projects smaller than 300 MW, and two disbursements for larger projects: one of 15% in Year 1 and another of 85% in Year 2. This pattern follows previous investment schedules presented by the ANDE (ANDE, 2014b).

4.2.3 Investment Constraints

4.2.3a Project Schedule

The first assumption in that small and large hydropower plants, can be defined by binary decision variables; the plant is constructed (1) or not (0). On the other hand, solar decision variables are continuous by recommendations of OPTGEN (PSR, 2005). The entrance schedule of the large hydropower plants is assumed to follow ITAIPU's in-service schedule of three turbines per year (ITAIPU, 2017). The small hydropower plants entrance schedules is that all turbines enter at the same time. If the plant is needed, the minimum installation entrance would be after 2023 (ANDE, 2014b) and the maximum installation would be after the period of study.

4.2.3b Project Constraints

Based on recommendations of the model developer, for the system to converge, precedence and obligatory constraints are set. These constraints represent obligatory plants, such as Acaray III (ANDE, 2014b). Ypane III is considered an obligatory plant because it is under bidding (ANDE, 2016a). There is only one precedence constraint: the upstream Corpus Christi plant should be built before the Itacora Itati power plant. Mutually exclusive constraints are set, such as large hydropower is constructed if the small hydro are not constructed.

4.2.3c Firm Energy Capacity

Figure 4.3: Paraguay's Reserve Generation margin. Source: Línea de Transmisión de 500 kV Yacyretá – Ayolas - Villa Hayes (Sachs, 2013)

As mentioned before, the reserve margin is the percentage difference between the amount of capacity to generate electricity at a time, and the maximum amount of electricity needed (NERC, 2009) (See Figure 4.3). The minimum reserve margin allowed in Paraguay is 20%. This criterion of reliability is what planners use to determinate the amount of generation that should be available over a period. To model the capacity reserve constraints in OPTGEN, the firm capacity factor is used. It is a proportion of all the SIN generation capacity in terms of load's proportion. In this expansion case that is 1.2 times the load of Paraguay's system.

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4.2.4 Summary

Table 4.3 below shows a summary of expansion optimization case model data and its assumptions.

Expansion Optimization Case Data and Assumptions			
	Section	**Data**	**Assumptions**
Execution Parameters			Study period 2017-2040 Operation planning Investment Annual Discount Factor 12% Unserved Energy Cost 4090 $/MWh
Payment Schedule	4.2.2	(ANDE, 2014b), (Itaipu, 2016)	One disbursement or two consecutively year disbursement
Project Configuration	4.2.2	(IRENA, 2015)	Cost per technology type of the Candidate Plants
Additional Constraints	4.2.3	(ANDE,2014)	Must construct Acaray III and Ypane III; Corpus Christi is constructed before Itati Itacora
Firm Energy/Capacity	4.2.3	(ANDE,2014)	Firm Capacity type: Reserve Margin 20%
User Define Plan	3.2.1	Plan from (ANDE, 2014)	Transmission Modification from SDDP Base Case
Solution Strategy		(PSR,2016)	Use six year rolling horizon Converge tolerance 2%

Table 4.3: Summary of Expansion Optimization Case Model Data and Assumptions. Source: Created by Maria J Martinez at the University of Texas at Austin

4.3 RESULTS

Using OPTGENs rolling horizon method, there are four time periods of six years each. The decision of constructing each plant is solved for each period and then fixed to analyze the next period (PSR, 2005). Under these constraints, the only periods with constructions are the periods 2017-2022 and 2023-2028. Table 4.4 illustrates the results. As obligatory plants, Acaray III and Ypane III are built during the first horizon period. During 2027 to 2028, eight small hydros, one solar project, and one large hydropower are built in the different systems for a total if new installed capacity of 3,992 MW. The system with the greatest increase of installed capacity is in the South System, with 3,556 MW, most of it due to the Corpus Christi solar (CCS) alternative. To clarify, the CCS project could represent one plant or multiple solar plants in the South system with 30% of capacity factor and able to replace the large Corpus Christi hydropower project.

Plants						
Rolling Horizon	**Date**	**Name**	**System**	**Technology**	**Decision %**	**Capacity (MW)**
1	12/2019	Ypane III	North	Small Hydro	100	12
	01/2022	Acaray III	East	Hydro	100	300
2	01/2026	Brazo Ana Cua	South	Hydro	100	273
	01/2027	Rio Paraguay I SH	Metro	Small Hydro	100	30
	01/2027	Pirapo	South	Small Hydro	100	4
	01/2027	CCS	South	Solar	4	271
	01/2027	Corpus SH	South	Small Hydro	100	30
	01/2027	Itacora SH	South	Small Hydro	100	30
	01/2027	Carapa I	East	Small Hydro	100	10
	01/2027	Carapa II	East	Small Hydro	100	30
	01/2027	Ypane I	North	Small Hydro	100	7
	01/2027	Ypane II	North	Small Hydro	100	8
	01/2027	Jejui	Central	Small Hydro	100	9
	01/2027	Rio Paraguay II SH	North	Small	100	30
	01/2028	CCS	South	Solar	42	2,949
Total						**3,992**

Table 4.4: Schedule for New Installed Capacity. Expansion Case. Source: Created by Maria J Martinez at the University of Texas at Austin

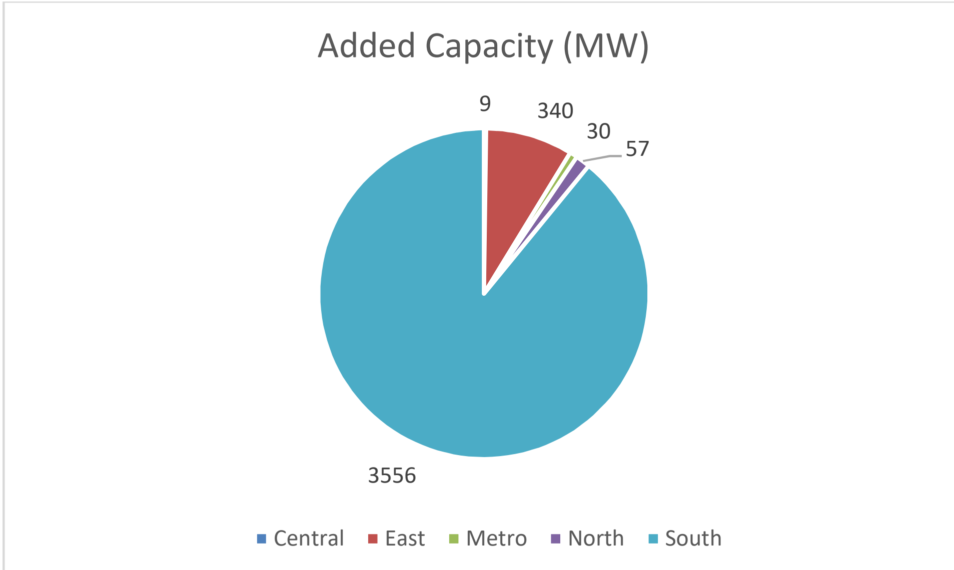

Figure 4.4: Added Capacity per System. Expansion Case. Source: Created by Maria J Martinez at the University of Texas at Austin

Even though the candidate plants represent a total of 17,591 MW of installed capacity, they are not built due to transmission constraints. The first system with high deficit risk is the East System, like the Base Case in 2027, but with different percentage. In the base case, the deficit risk goes from 13% to 100% energy deficit in a year. On the other hand, for the expansion case, the increase is from 2% to 95% energy deficit in a year, reaching 100% deficit two year later, in 2029 (see Figure 4.4).

In Figure 4.5 there is a comparison between the Base Case's deficit risk and the Expansion Case's deficit risk for the entire SIN. In the latter case, in 2031, it reaches 100% of risk. In the Base Case, the 100% risk is reached in 2030, to drop again to 86% in 2031. This drop for the base case in 2031 is because 2031 is the first year when the original 8,250 MW of installed capacity does not meet any month maximum load. There is low deficit risk in the Central (7%) and North system (2%) due to Ypane III.

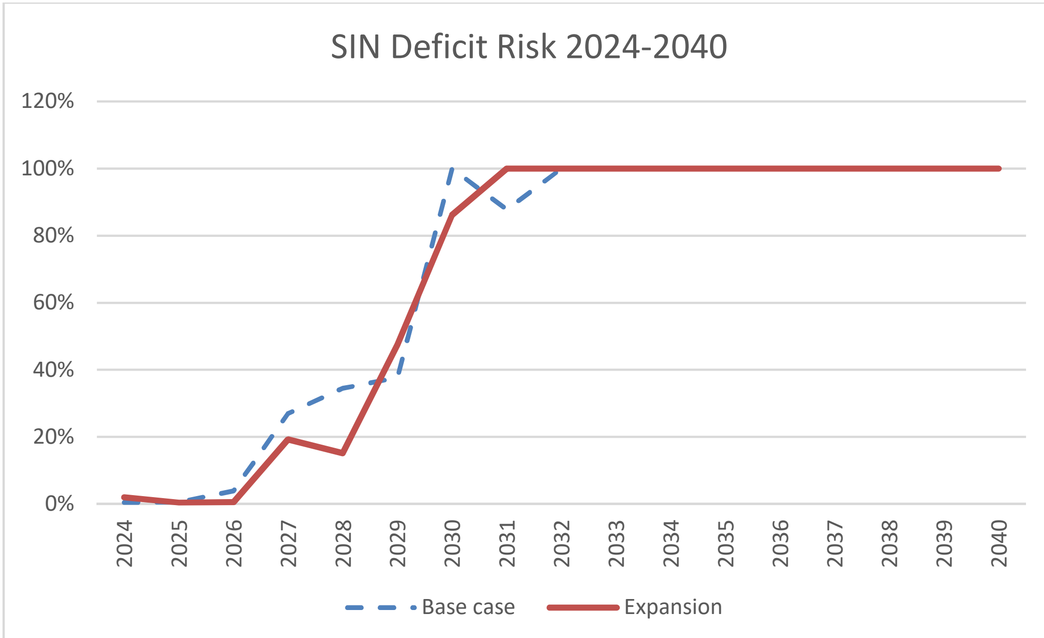

Figure 4.5: Deficit Risk 2024-2040 for the SIN Expansion. Source: Created by Maria J Martinez at the University of Texas at Austin

Figure 4.6 illustrates that the candidate plants are insufficient to reduce the deficit risk as the reserve margin criterion is reached in 2029. Thus, due to transmission constraints, the 20% of reserve margin consideration cannot be met either in 2027 or 2029. Due to this criterion of reliability, transmission expansion is needed after the year 2029 to be able to deliver the generated energy to the load's centers from the chosen and candidate plants.

Figure 4.6: Reserve Margin 2023-2030. Expansion Case. Source: Created by Maria J Martinez at the University of Texas at Austin

4.3.1 Transmission Expansion Considerations

Due to the limitations of the existing transmission system, and the cost that involves transmission expansions, this section will focus on the analysis for the case of Paraguay in the period 2017-2040. This analysis assumes to add new capacity to feed 1.2 times the demand of 26,900 MW in 2040. With a 20% of reserve margin that is 24,000 MW of new installed capacity by 2040. Also, it considers the original candidate plants (17,591 MW), plus any other not yet defined sources (6,421 MW).

Appendix C.1 describes a simplified spreadsheet dispatch model, taking into account cost and availability. Most capacity is installed in the South System (80%) and Metro System (16%) as seen in Figure 4.7. A simplified transportation model (Appendix C.2) can be used to estimate the interconnection capacity needed by 2040. The assumptions in the transportation model set the possible paths among systems minimizing the cost of transport of the energy to serve a demand. Table 4.4. lists the results for this approximation.

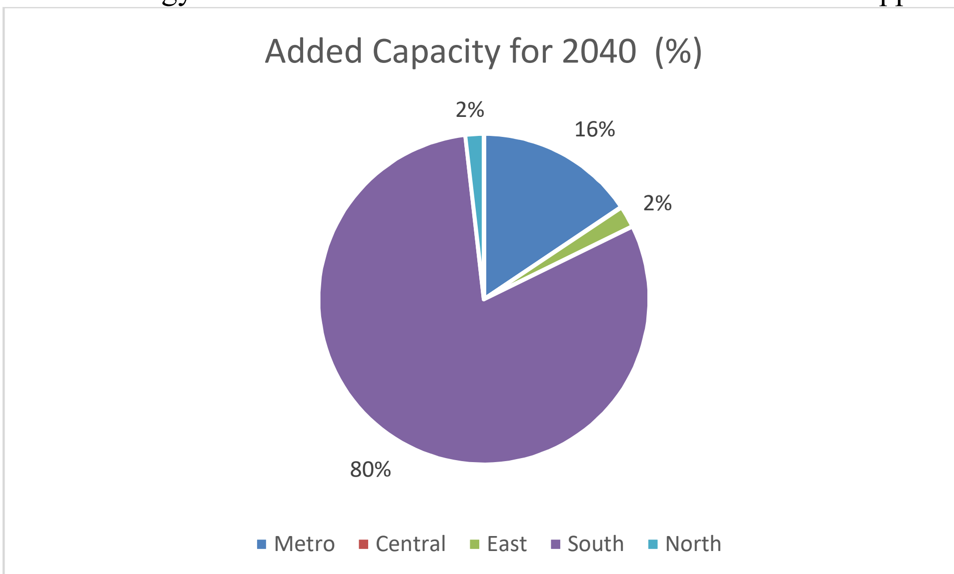

Figure 4.7: Added Capacity per System in 2040. Source: Created by Maria J Martinez at the University of Texas at Austin

Most of the added interconnection capacity in this estimation is from the South System towards the Metro System and Central System. On the other hand, the current ANDE's Master Plan 2014-2023 focuses on the transmission expansion from the East System to the Metropolitan System to utilize the existing installed capacity fully (ANDE, 2014b). Furthermore, the Central system must feed the Metro System in this configuration. The West and North System are fed from the Metro System.

From	To	Added Interconnection Capacity (MVA)
South	Central	5,073
South	Metro	6,274
Central	Metro	1,245
Metro	North	575
Metro	West	404

Table 4.5: Added Interconnection Capacity between Systems. Source: Created by Maria J Martinez at the University of Texas at Austin

Considering the cost of installed capacity of the candidate plants, connection to the grid, transmission, and ANDE'S soft costs at 2014 prices, the costs of transmission expansion for interconnections between systems are approximately 2.82% of the total cost for plants construction. On the other hand, transmission costs are 2.74% of the total construction and transmissions cost of the plants. At today prices, the total cost of the expansion needed by 2040 is around $7,096,860 $/MVA of new generation installed capacity.

4.3.2 Sustainability Indices for the Expansion Case

None of these configurations shows an improvement in the trend of net import and energy reliability indices. In the expansion case in 2025, Paraguay stops being a net exporter. In comparison, in the base case, Paraguay is not a net exporter after 2023. It can be estimated, as in the base case, that Paraguay does not have electricity exports to regional markets after 2026. The trend of the net import index is still decreasing over the study period (See Figure 4.8).

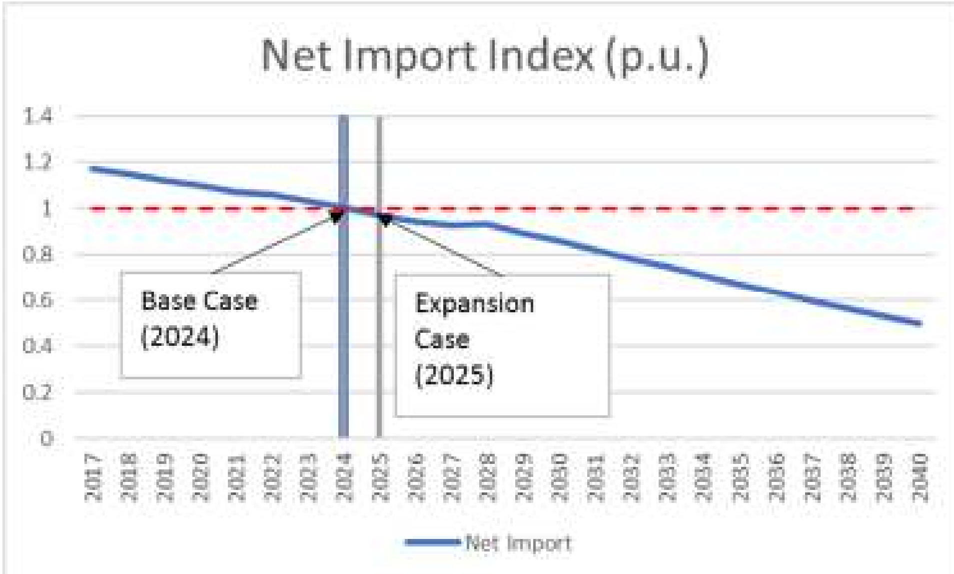

Figure 4.8: Net Import Index Expansion Case. Source: Created by Maria J Martinez at the University of Texas at Austin

One of the Sustainable Energy indices from the World Energy Council includes a metric for diversification of electricity generation sources. In the expansion case, without forcing any other diversification strategies, more than the candidate plants chosen to be considered, by 2026, 26% of the total installed capacity is from solar generation. Consequently, the metric for diversification of electricity generation sources is improving.

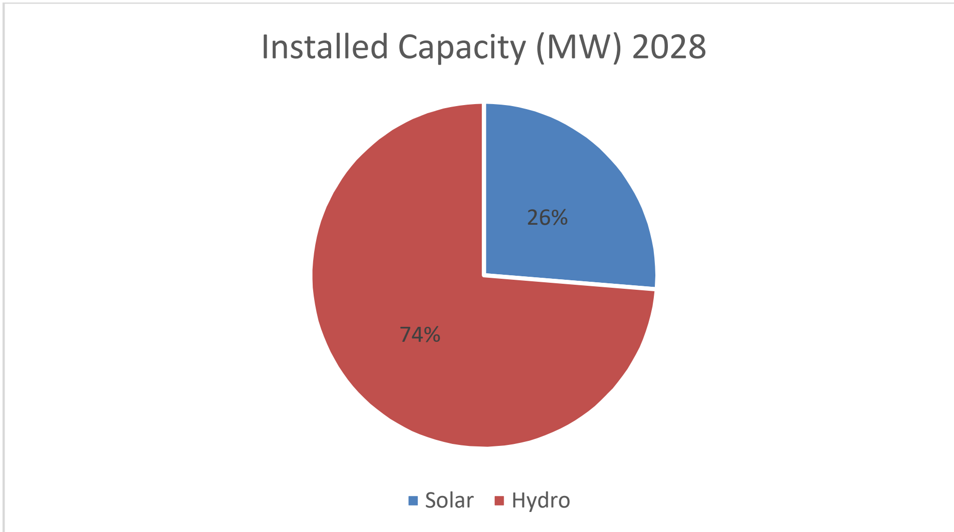

Figure 4.9: Installed Capacity by 2028 (MW). Expansion Case. Source: Created by Maria J Martinez at the University of Texas at Austin

4.4 Conclusion

Using the OPTGEN-SDDP software to solve the new installed generation capacity optimization, after 2029 the transmission system cannot sustain the demand increase. Therefore, only two rolling horizons are analyzed in this optimization. With the plants chosen by 2017-2029 period, 26% of electricity generation in 2028 is from solar generation. This expansion of transmission and generation is just to keep up with the demand, not to improve any sustainability index such as the Net Import index. Nevertheless, there is an overall improvement of diversification considering the original electricity portfolio mix.

The resultant generation is in line with Paraguay's energy diversification policy. Paraguay does not have a target for this diversification, even though it is part of its energy policy. The study of feasibility of this amount of solar generation on the grid is beyond the scope of this thesis, but it is a topic that should be carefully considered for the Paraguayan system.

With the limitation of transmission, the demand increase rate of 9.84% points to a need for more generation and transmission expansion by 2040 than the original candidates in ANDE's Master Plan. The installed capacity needed after the original pool of candidate plants is 6,000 MW. By 2040, there is a 13,571 MVA transmission expansion to connect mostly South system to the Metro system. At 2014 prices, that represents a cost of $ 7.1 million per MVA of new generation installed capacity. Furthermore, future studies on the Paraguayan system can be approached as first optimizing the generation expansion, and then considering transmission expansion, as only around 3% of the total cost of new generation installed capacity is due to transmission expansion cost.

Beyond costs and reliability, at this point, other criteria in the energy policy of interests of the stakeholder have not been analyzed. The next chapter explains how to implement other criteria in Paraguay's generation and transmission expansion planning.

Chapter 5

Multicriteria Generation Expansion

5.1 Introduction

This chapter explores how to incorporate socio-environmental responsibility inside OPTGEN, as part of Paraguay's productive development, diversification of domestic energy sources, and other stakeholders' considerations. Section 5.2 explains the methodology for optimizing what plants should be prioritize in a socio-environmental context. Section 5.3 presents OPTGEN results using these priority plants.

5.2 Optimization

5.2.1 Methodology

The final objective to this approach is to represent socio-environmental data to estimate a proxy to expand a cost-base Generation and Transmission expansion optimization model. A bibliographic review reveals various multicriteria optimization algorithms to take in account these aspects, such as multi objective decision making and multiple attribute decision making (Meza, 2006). In this methodology, a multiple attribute decision making approach was based on a linear additive utility model. In economics, a utility function is a mathematical strategy to model consumer's preferences, but can be used in other contexts such as multicriteria optimization (Meza, 2006). Assuming individual attributes to the utility function are independent from the others, the preference functions for individual attributes can be added (Keeney & Raiffa, 1995). The solution can be interpreted as the ranking of candidates by their expected utility value (Voropai & Ivanova, 2002). The proposed methodology allows to use mixed-integer linear programming. In this case study, this optimization was implemented using Excel's

Simplex LP solver method because it is rapid, and by using the branch and bound method, it supports integer and binary constraints (FrontlineSolvers, 2017).

Figure 5.1 is a diagram of the proposed approach. All the social-environmental and technology aspects to be considered are inside the "Decision Module", built outside the optimization software. This approach seeks to maximize the utility function that could represent the positive social impact, the minimum environmental impact, type of technology considerations, and other aspects that stakeholders could take in account as important for the candidate plants. For a large set of projects and constraints, this optimization algorithm approach helps to find a priority order. This order of priority can be added to OPTGEN in multiple ways, such as precedence constraints or scaling investment costs.

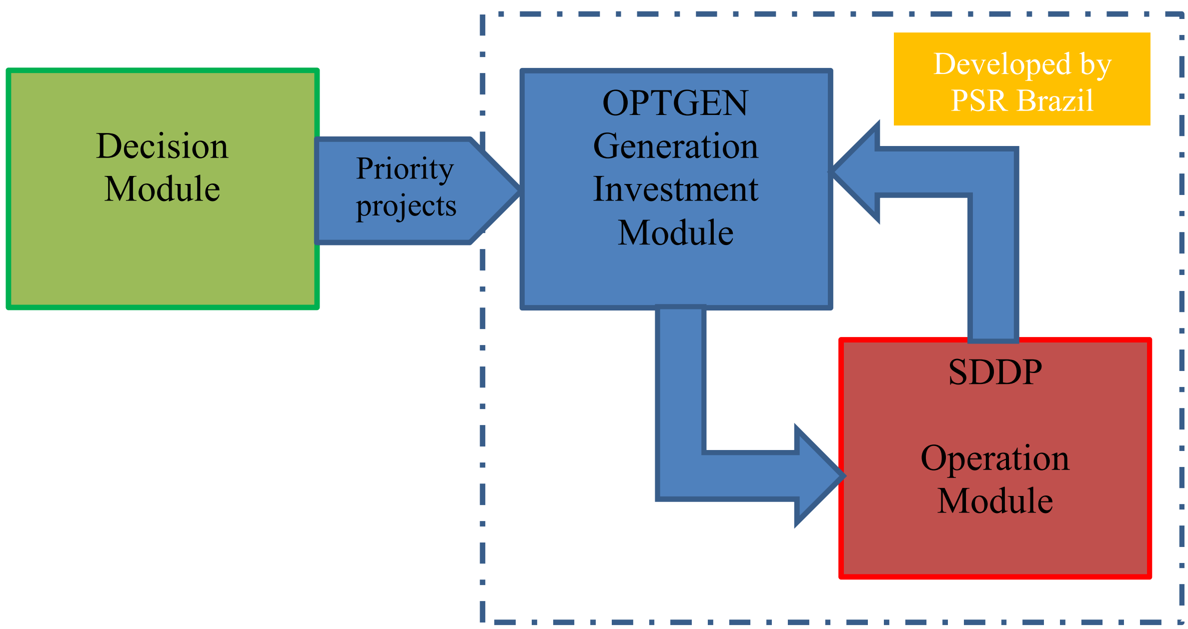

Figure 5.1: OPTGEN-SDDP- Decision Module Flowchart. Source: Created by Maria J Martinez at the University of Texas at Austin

Optimization Problem

Table 5.1 lists the nomenclature of the optimization problem. The utility function for the plant i is the product of the utility of the plant times the decision vector variable of the plant (if it is constructed or not). Following the OPTGEN approach, the x_i decision vector variables can be binary or continuous depending of the candidate plant's type of technology. The objective of the optimization function is to maximize the total sum of the utilities to find the priority projects (Equation 5.1).

Objective function: $\max(\sum_{1}^{I} U_i * x_i)$ … (5.1)

The constraints are equivalent to the ones considered to the Base Case on OTPGEN. As alternative constraints, one plant should not be constructed if the other one is constructed; adding both decision variables should be less or equal to 1. In the plants with construct constraints, the decision variable is always equal to 1. For the no construct constraints plant, the decision variable is always equal to 0 (Equation 5.3 and Equation 5.4). Equation 5.5 represents how to construct a plant before the other; the decision variable of the first should be larger or equal to the decision variable of the second plant to construct.

Alternative Constraints: $x_n + x_m \leq 1$ … (5.2)

Construct constraint: $x_l = 1$ … (5.3)

No construct constraints: $x_p = 0$ … (5.4)

Construct "plant r" before "plant s": $x_r \geq x_s$ … (5.5)

To clarify, Paraguay doesn't have a target for diversification, even though it is part of the energy policy. Equation 5.6 represents diversification constraints; it can be added to the multicriteria optimization if stakeholders deem it important. The percentage of total installed capacity (p) is the target amount of a type of source; for example, 5% electricity from solar. The total new installed capacity of one technology type must be more or equal of the target installed capacity for that technology.

$$\sum_1^V c_v * x_v = p * (C + \sum_1^I c_i * x_i) \quad \ldots (5.6)$$

Where:

Symbol	Description	Unit
i	index hydroelectric plants	
I	number of plants	
U_i	utility function for the candidate plant.	
x_i	decision vector	
x_n	alternative to plant m	
x_m	alternative to plant n	
x_l	obligatory plant	
x_p	plant not to be constructed	
c_i	capacity of the candidate plant	MW
p	percentage of the total installed capacity	%
C	Existing installed capacity	MW
V	number of plants of one type of technology	
x_v	decision vector for one type of technology	
c_v	capacity for one type of technology	

Table 5.1: Nomenclature for Multiple Attribute Decision Making. Source: Created by Maria J Martinez at the University of Texas at Austin.

5.2.2 Utility Function

The utility function to analyze is the core of the multiple attribute decision making approach. This function helps to reflect what the stakeholders deem important. For example, the analysis can involve the number of people below the poverty line plus the economic aspects of the candidate plants (Medaglia, et al., 2006). This thesis expands the idea of the social index based on number of people below the poverty line to other aspects. The following section is a description of factors in this case study; with some considerations, these could be expanded to fit other criteria. Each index can be from 0 to 1, where 1 represents a higher utility function. These indices are suggestions of how to consider different socio-environmental aspects. They can be modified and weight to represent multiple stakeholders' considerations. Appendix D.1. presents a full index table.

5.2.2a Social Considerations

Paraguay's governmental policy includes poverty reduction programs. Resources for doing this are limited, and one approach could be to define spending priorities by targeting people with the largest needs. According to Elbers 2004, without considering any local political-economy consideration or the resources within the area, targeting smaller administrative units, such as districts, yields positive results in poverty reduction programs. (Elbers, et al., 2004). , Based on similar reasoning, this thesis target poverty reduction to a district level not in a departmental or regional electric system level.

In Paraguay, one of the means for poverty reduction is the generation of income from agricultural and non-agricultural jobs (STP, 2017). Non-agricultural jobs include public projects of local impact. In that context, power plants might have the potential to generate these types of jobs, if contract clauses include hiring local workers. In that way, Elbers observations can comply and programs such as this can have positive results. This approach considers the resources within the area because these are important for the project of the candidate power plants. Some indices are affected by the location of the plant and where the plants feed the National Interconnected System. Then, the objective is to construct the power plant where the sum of both indices is the highest.

5.2.2b GINI

The GINI index is chosen because is one of the most common measure of wealth inequality. It is reported by district for the Paraguay's Census Direction as a measure for income distribution. A value closer to 0 represents more equality. In this approach, a value near 1 represents more inequality in the district. This gives a higher index weight to the candidate plant on this district to be chosen (Santander & Robles, 2004). That way, the optimization is targeting the districts with the highest inequality.

5.2.2c Poverty

Poverty can be represented by the percentage of the people below the poverty line. (Medaglia, et al., 2006). This data comes from the Paraguay's National Census. For this case study, the interpretation for the social index is like the GINI index. A value closer to 1, represents a district with high poverty levels. That way, the optimization is targeting the districts with the highest poverty levels.

5.2.2d Population

Population is considered to estimate the amount of people affected by the project. Also, it helps to determine where to choose the location based on access to labor for the candidate plants (Sachs, 2013). This regional population is represented as a ratio of the country's population. It can be assumed that the impact on the population is only positive, because most social negative impacts are included in the following environmental impacts metric and in the soft cost in the OPTGEN expansion model. After that, and again, values closer to 1 represent a district with a potential for a higher positive social impact.

5.2.2e Technology and Diversification Criteria

The electricity portfolio might include different types of technologies involving different costs, practical and construction facilities and environmental impacts. These indices can be added to a utility function. In this example, four indices are chosen, operation and maintenance cost, environmental impact proportional to investment, mobility and diversification.

The operation and maintenance cost index (O&M) represents an estimate of the expenditures within the district for that plant. From IRENA, there is an estimated of the O&M cost per technology of the power plant. This index cost can be represented by a ratio between the plant's O&M cost and the largest O&M cost, that is the large hydropower plant cost as seen in Table 5.2.

O&M Index		
Type	O&M $/KW-year*	Index
Small Hydro	83	0.48
Hydropowe r plant	172	1.00
Solar	14	0.08

Table 5.2: Operation and Maintenance Index. Source: Created by Maria J Martinez at the University of Texas at Austin from data by Renewable Power Generation Costs in 2014 (IRENA, 2015)

As a first estimation, the environmental impact index is proportional to investment cost, following the reasoning behind the economic input-output life cycle analysis method. This method measures the effect of changing the output of a single sector by defining the economy where the sectors are embedded (Carnegie Mellon University Green Design Institute, 2008). The environmental impact is defined as a proportion of the largest investment value. In the Expansion Case, the candidate solar plant is the alternative to Corpus Christi (CCS). In that case, the impact is 1. To have the similar interpretation of desirability than the other indices, the environmental impact index for the utility function is environmental impact minus 1.

Two advantages of a solar installations are its modularity, and that it can be closer to the load centers. This is measure in the mobility index, being 1 for solar, and zero for hydropower as a first assumption.

For diversification, any criteria such as percentage of solar penetration on the generation mix portfolio can be added on OPTGEN if the plants are not all modeled as having renewable sources. Due to this, diversification criteria can be added to reach a specific target in the study period.

5.2.3 Results

The full optimization spreadsheet table is in Appendix D.2, and a summary of the indices are in Appendix D.3. The results for the Multicriteria Generation expansion do not represent any precedence criteria. These candidate plants are in target districts and have a lower environmental impact, therefore they are chosen to be constructed first. The final order of deployment is optimizing inside OPTGEN. With this consideration, the list of candidate plants without diversification criteria and with diversification criteria is shown in Table 5.3. Because "Mobility" is defined to consider the difference between technologies for this analysis, it is also compensating the environmental impact index difference between hydro and solar projects. Then, the results to compare include results with the mobility index and without it.

Results		
Criteria	**Diversification**	**No Diversification**
Mobility Index	Ypane I Solar Pirapo Solar Itacora Itati Solar U:(18.046)	Ypane I Solar Ypane II Solar Pirapo Solar U:(18.584)
No Mobility Index	Ypane I Solar Itacora Itati Solar Corpus Christi U:(15.399)	Ypane I Solar Corpus Christi Ypane I U:(16.237)

Table 5.3: Results for the Multicriteria Generation Expansion. Source: Created by Maria J Martinez at the University of Texas at Austin

5.3 OPTGEN Results

OPTGEN was run a last time. To run the optimization expansion module, the optimization result used was the "no diversification result with the mobility index". This result was chosen because if the original expansion problem had 26% of solar then a diversification constraint is not needed. Thus, the plants to be constructed first are: Ypane I Solar, Ypane II Solar, Pirapo Solar.

The results of the multicriteria optimization is set inside OPTGEN to be built first. To do this, the investment prices of these plants are established at a tenth of their original price to force OPTGEN to build then first. The interconnection cost is not scaled down. Under this assumption, the chosen plants are the same as the original expansion case with two differences: the three solar sites are built first in the second rolling horizon, and the solar Corpus Christi plant is 44 MW smaller in this case. All the chosen plants are shown in Table 5.4.

Plants						
Rolling Horizon	Date	Name	System	Technology	Decision %	Added Capacity (MW)
1	12/2019	Ypane III	North	Small Hydro	100	12
	01/2022	Acaray III	East	Hydro	100	300
2	01/2024	Pirapo Solar	South	Solar	100	10
	01/2024	Ypane I Solar	North	Solar	100	18
	01/2024	Ypane II Solar	North	Solar	100	16
	01/2026	Brazo Ana Cua	South	Hydro	100	273
	01/2027	Rio Paraguay I SH	Metro	Small Hydro	100	30
	01/2027	Pirapo	South	Solar	100	4
	01/2027	CCS	South	Solar	3	230
	01/2027	Corpus SH	South	Small Hydro	100	30
	01/2027	Itacora SH	South	Small Hydro	100	30
	01/2027	Carapa I	East	Small Hydro	100	10
	01/2027	Carapa II	East	Small Hydro	100	30
	01/2027	Ypane I	North	Small Hydro	100	7
	01/2027	Ypane II	North	Small Hydro	100	8
	01/2027	Jejui	Central	Small Hydro	100	9
	01/2027	Rio Paraguay II SH	North	Small Hydro	100	30
	01/2028	CCS	South	Solar	42	2,944
Total						**3,990**

Table 5.4: Schedule for new installed Capacity. Multicriteria Optimization Expansion. Source: Created by Maria J Martinez at the University of Texas at Austin

Again, most of the new installed capacity is in the South System as seen in Figure 5.2. On the other hand, there is an increment of the amount of installed capacity by 34 MW in the North System if compared with the original expansion problem, due to both Ypane I and Ypane II solar sites.

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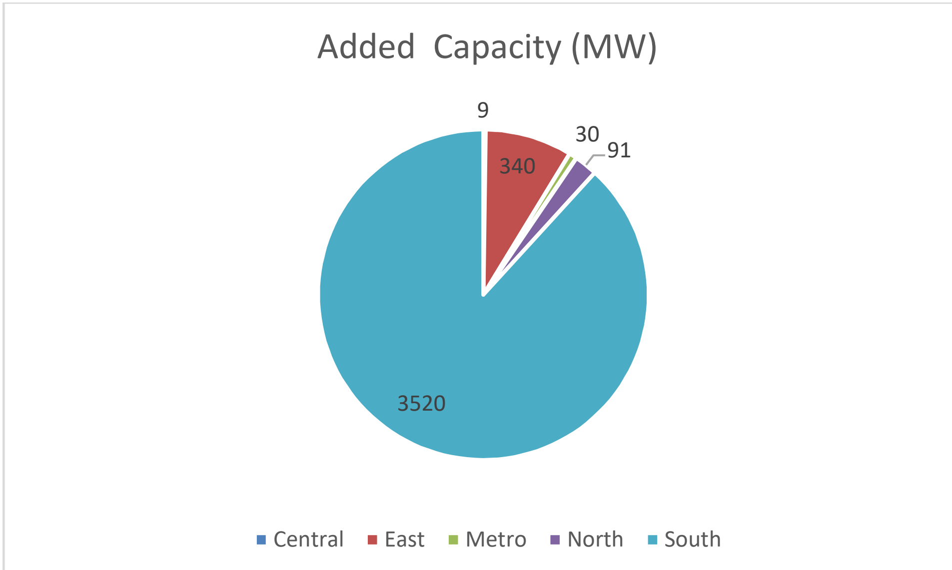


Figure 5.2: Added Capacity per System. Multicriteria Optimization Case. Source: Created by Maria J Martinez at the University of Texas at Austin

Another similar result to the original Expansion Case is that the deficit risk is increasing after 2024, and new plant cannot be built after the second rolling horizon due to transmission constraints. As seen in Figure 5.3 the reserve margin needed is more than 1.2 times the installed capacity till 2026. After that, the peak demand is still less than the installed capacity till 2029, but the reserve margin capacity needed is not met in the 2026-2027 period. During 2028, the installed capacity is larger than the reserve margin, but again after 2029, the installed capacity never reaches the desire reserve margin. Generation expansion is still needed but not constructed, due to transmission constraints.

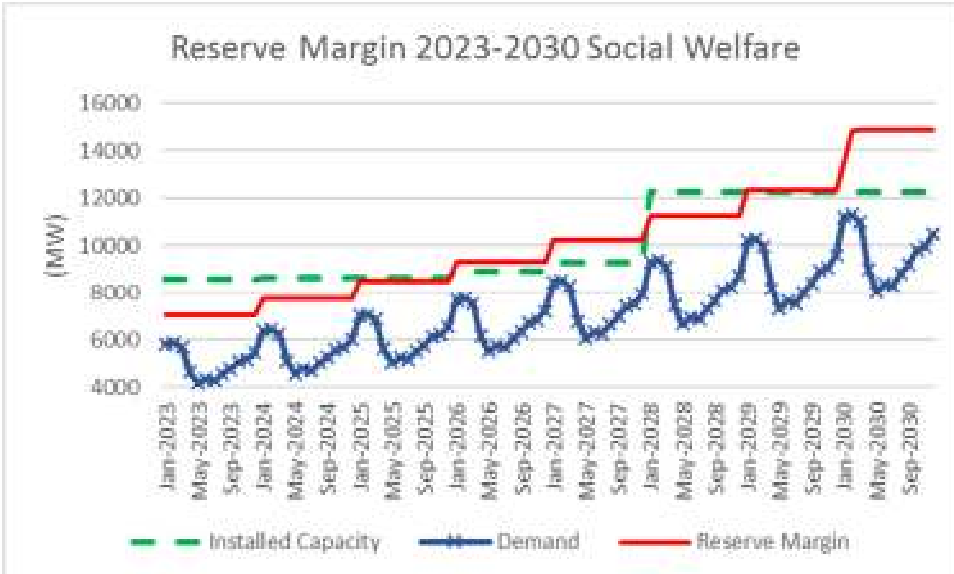


Figure 5.3: Reserve Margin 2023-2030. Multicriteria Optimization Case. Source: Created by Maria J Martinez at the University of Texas at Austin

Over the two-rolling horizons run by OPTGEN, comparing the cost of both expansion plants with the actual prices, the investment cost of the multicriteria optimization case represents a $49 million (0.0161%) extra of operation costs if compared to the Base Case. Nevertheless, the investment is around $20 million (0.069%) less. The $20 million includes the transmission expansion estimated in the original expansion problem (See Table 5.5).

	Investment	Connection red	Transmission	Total	Operation Cost	Unit
Welfare	27,571,683,566	215,819,845	531,571,964	28,319,075,376	305,729,060,000	$
	6,909,561	54,085	133,213	7,096,860	76,616,78	$/MVA
Original	27,583,998,666	215,939,150	538,708,997	28,338,646,814	305,679,970,000	$
	6,909,601	54,091	134,942	7,098,635	76,573,138	$/MVA

Table 5.5: Cost for the Multicriteria Optimization Vs Expansion Case Source: Created by Maria J Martinez at the University of Texas at Austin

5.3.1 Sustainability Indices

The sustainability indices for the Multicriteria Optimization case result do not behave any different from the original Expansion Case. The deficit risk is still increasing after 2024. There are transmission constraints that do not allow expansion; there is no improvement in the reliability index. On the other hand, because there is no substantial difference between both cases, the net import index still has a decreasing tendency over the study period. Finally, this case presents the same behavior for diversification as the Expansion Case, seen in Figure 5.4: 26% when considering solar penetration.

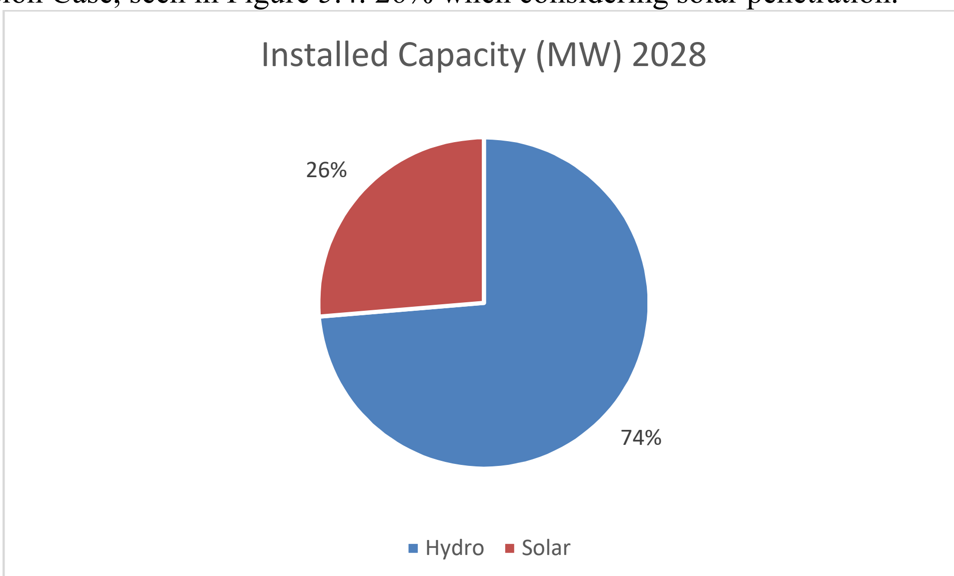


Figure 5.4: Installed Capacity by 2028 (MW). Multicriteria Optimization Case. Source: Created by Maria J Martinez at the University of Texas at Austin

5.4 Conclusion

This chapter considers a simple mix-integer linear optimization to ponder several conditions from Paraguay's energy policy and stakeholder's consideration to expand the base optimization expansion-operation module as presented in OPTGEN-SDDP. This thesis analyses the multicriteria expansion problem using a utility function to consider socio-economical, technological, and environmental criteria. The advantage of this approach is that criteria can be expanded and weighted in the algorithm to reflect stakeholders' interests. The result of this optimization is added in OPTGEN by scaling the cost of the plants to force the model to construct them first. Variations of this approach can be made by changing the period in which the plants are built.

With the original pool of candidate plants, like the original expansion case, there is no improvement of any sustainability index. After considering this, the political decision to follow the multicriteria expansion plan seems straightforward. The investment needed in the multicriteria expansion plan is less than the original expansion plan. Furthermore, the multicriteria expansion plan is constructed targeting districts with the highest population and necessity between the original pool of districts. In present value terms, the consequences of this decision are $49 million of operation costs until 2040. Overall, the original expansion plan is cheaper but the difference between the cost of this one and the multicriteria plan is less than 0.1%. In the end, it is in the hands of the planner committee to make this call or not.

Chapter 6

Conclusion

Paraguay's electricity supply has many problems, such as regular outages and high system losses in the distribution and transmission system. There have been some steps taken to ameliorate these problems by ANDE and other stakeholders who participated in the development of Paraguay's recent energy policy program to target problems in the energy and electricity sectors. This thesis proposes a tool to measure and model different commands of the policy and to interpret and evaluate results inside a holistic framework that includes more than cost considerations.

The proposed generation and transmission-expansion planning methodology is guided by Paraguay's energy policy by analyzing the net import index to measure Paraguay's energy exports to regional markets. The approach allows an analysis to promote the generation of economic value from domestic hydroelectric power. Building a multicriteria optimization case (promoting energy security with criteria of self-sufficiency, efficiency, minimum cost, with socio-environmental responsibility) facilitates sustainable economic development. To develop other types of energy technologies and contribute to energy security, in case it is needed, sources of electricity diversification criteria can be added inside the multicriteria optimization case. Analyzing the environmental impact of the hydropower plants allows an analyst to include both social and environmental responsibility within the harness of hydropower potential of river basins. The impact and risk of the dependency between the electricity sector and the Parana river basin can be estimated by expanding the Base Case, with help of SDDP.

The methodology to study the generation and transmission expansion from 2017 to 2040 includes the development of the Base Case. The Base Case is a worst-case scenario for the SIN, with an increase in demand at a rate of 9.84% per year. Based on this Base Case, system expansion would be needed within the study period. Using OPTGEN-SDDP software to solve the new installed generation capacity optimization, after 2029 the transmission system cannot sustain the demand increase. Due to this, only two rolling horizons are analyzed by the optimization. With the plants chosen for the 2017-2029 period, 26% of electricity generation in 2028 is solar. By 2040, the rate of demand increase suggests a need for more generation and transmission expansion than the original candidates in ANDE's master plan, due to limitation of transmission capacity. The installed capacity needed after the original pool of candidate plants is 6,000 MW. Also by 2040, there is 13,571 MVA transmission expansion to connect mostly South systems to the Metro system. At 2014 prices, the generation and transmission expansion is at a cost of $ 7.1 million per MVA of new generation installed capacity. As only around 3% of the total costs of new generation installed capacity are due to transmission expansion cost, future expansion studies on the Paraguayan system can be approached as optimizing generation expansion first and then considering transmission expansion.

A mixed-integer linear optimization model is built to analyze several conditions from Paraguay's energy policy and stakeholder's considerations to expand the base optimization expansion-operation module as presented in the OPTGEN-SDDP software. The multicriteria expansion problem is analyzed using a utility function to consider socio-economic, technological and environmental criteria. The advantage of this approach is that the criteria can be expanded and weighted in the algorithm to reflect stakeholders' interests.

Three sustainability indices were considered: diversification, net import, and reliability. The net import index, the ratio between energy production and demand, has a decreasing trend in the period of study. Due to transmission constraints, the reliability index cannot be improved without transmission expansion. The resultant generation portfolio in both expansion problems is also in line with Paraguay's energy policy of diversification of the energy matrix

A political decision to follow the multicriteria expansion plan could be useful from a political and economic standpoint because the investment needed in the multicriteria expansion plan is slightly less than the original expansion plan. Furthermore, it is constructed by targeting districts with the highest population and necessity among the original pool of districts. In present value terms, the consequences of this decision are $49 million more in operation costs until 2040. Overall, the original expansion case is cheaper. The difference between its cost and the multicriteria optimization case is the less than 0.1%. In the end, it is in hand of the stakeholders' committee to make this decision.

Small hydro and solar generation sources are a viable alternative to build an electricity generation portfolio mix for the Paraguayan electricity market, by using both a welfare economics optimization and an extended welfare economics optimization with a multi attribute decision making approach. But transmission constraints are still a major issue for the full exploitation of these resources.

6.1 Future Work

The following are the recommendations for future work:

1. Generation:

- The effect of ramping on hydraulic machines due to intermittent renewable sources.
- Consideration of distributed generation on Paraguay's grid.
- Consequences of high penetration of renewables in the Paraguayan SIN.

2. Transmission:

- N-1 Transmission Expansion: Add criteria of reliability such an N-1 transmission expansion to this analysis.
- Diversification with thermal power plants and storage combined to candidate solar and hydropower plants.

3. Stakeholders:

- Add stakeholder-driven scenarios to the negotiations of generation and transmission expansion and their analysis.

4. Water Resources:

- Comprehensive and open source hydrology data is needed to evaluate hydropower projects, and to minimize risk of these types of endeavors.
- Analysis of value of the water for Paraguay and its regional partners.

5. Electrical Market

- Investigating the consequences of opening up the market for electricity distribution and generation with ANDE as the market and operations regulator.

Appendices

A. Wind and Solar Resource

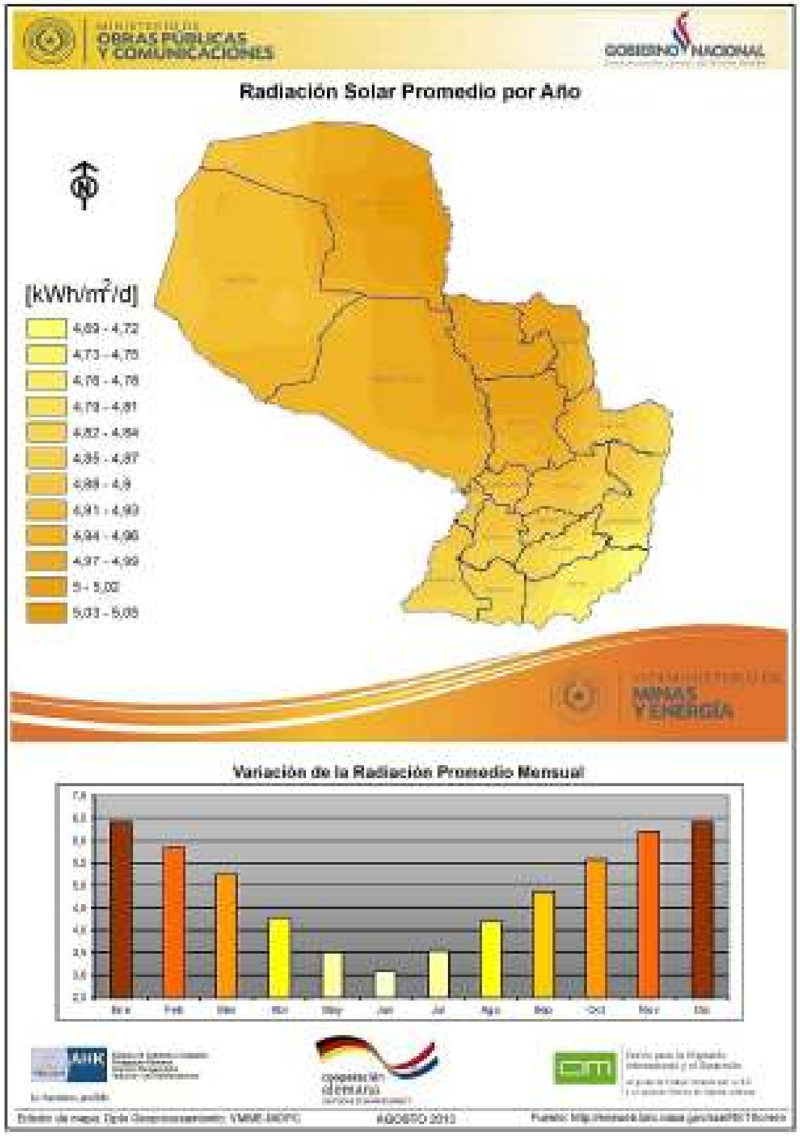


Figure A.1: Monthly Solar Radiation Paraguay. Source: Eolica y Solar (VMME, 2015)

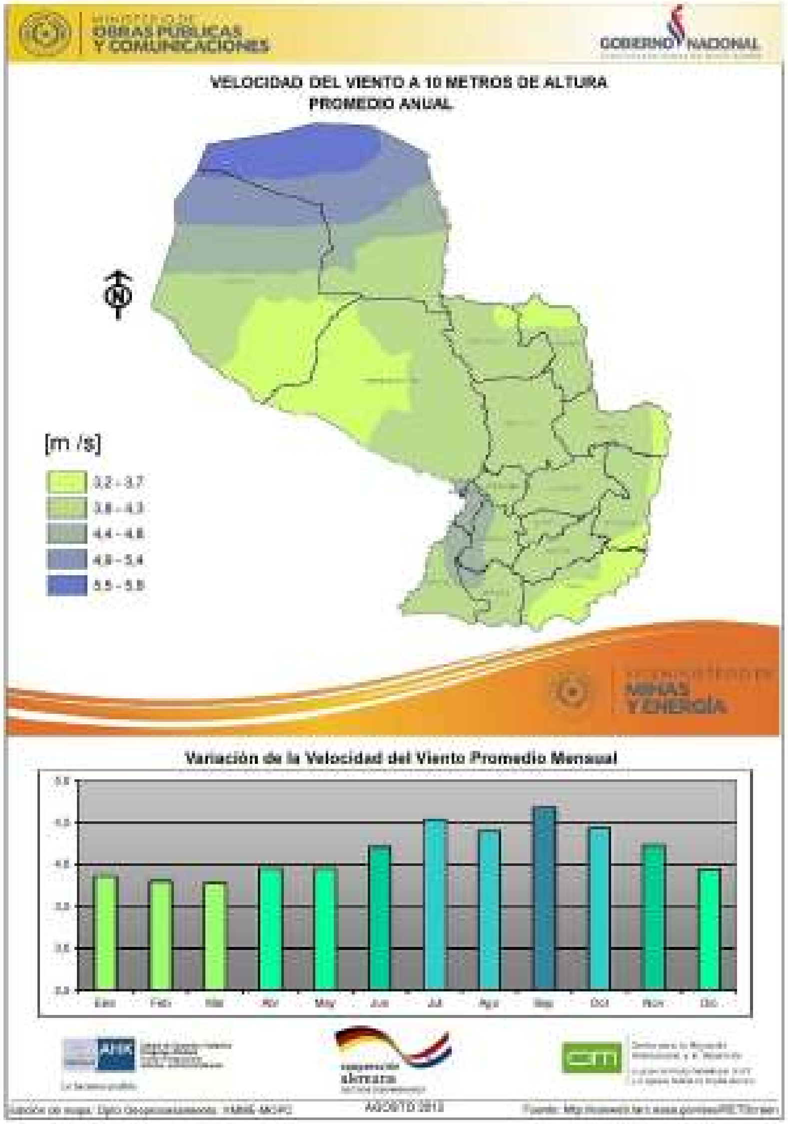


Figure A.2: Monthly Solar Radiation Paraguay. Source: Eolica y Solar (VMME, 2015)

B. Model Data

Paraguayan Interconnections							
#	Name	From	To	Existing or Future	Capacity (MW)		Entrance Year
					From to To	To to From	
61	East-Central 1	East	Central	Existing	550	0	
62	East-Central 2	East	Central	Existing	191	0	
63	East-Central 3	East	Central	Existing	300	0	
64	East-Central 4	East	Central	Existing	191	0	
65	Central-Metro 1	Central	Metro	Existing	272	0	
66	Central-Metro 2	Central	Metro	Existing	272	0	
67	Central-Metro 3	Central	Metro	Existing	230	0	
68	Central-Metro 4	Central	Metro	Existing	240	0	
69	East-Metro 1	East	Metro	Existing	2,000	0	
610	South-Metro 1	South	Metro	Existing	238	0	
611	South-Metro 2	South	Metro	Existing	238	0	
612	Central-North	Central	North	Existing	270	0	
613	North-West 1	North	West	Existing	270	0	
614	South-Metro 3	South	Metro	Future	2,000	0	2022
615	South-Central	South	Central	Future	2,000	0	2022
616	Central-Metro 5	Central	Metro	Future	2,000	0	2019
617	East-Central 5	East	Central	Future	2,000	0	2019
618	East-Central 6	East	Central	Future	2,000	0	2023
619	East-North 1	East	North	Existing	250	0	
620	East-North 2	East	North	Existing	350	0	
621	Metro-North	Metro	North	Future	350	96	2019
622	North-West 2	North	West	Future	350	0	2018
623	North-West 3	North	West	Future	350	0	2021

Table B.1: Regional System's Interconnection Lines. Source: Created by Maria Jose Martinez at the University of Texas at Austin from data by Plan Maestro de Generacion y Transmision 2014-2023 (ANDE, 2014b)

Renewable Source Scenarios													
Plant	**Block**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Acaray III	1	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
	2	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Brazo Ana Cua/Brazo Ana Cua SH	1	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	2	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Carapa I	1	0.94	0.75	0.65	0.66	0.85	0.75	0.71	0.62	0.56	0.78	0.86	0.89
	2	0.94	0.75	0.65	0.66	0.85	0.75	0.71	0.62	0.56	0.78	0.86	0.89
Carapa II	1	0.94	0.75	0.65	0.66	0.85	0.75	0.70	0.62	0.55	0.77	0.86	0.89
	2	0.94	0.75	0.65	0.66	0.85	0.75	0.70	0.62	0.55	0.77	0.86	0.89
Corpus Christi/Corpus Christi SH	1	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
	2	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Itacora Itati/Itacora Itati SH	1	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
	2	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81
Jejui	1	0.88	0.71	0.59	0.83	1.23	0.55	0.47	0.42	0.56	1.20	1.32	1.27
	2	0.88	0.71	0.59	0.83	1.23	0.55	0.47	0.42	0.56	1.20	1.32	1.27
Pirapo	1	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
	2	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Rio Paraguay I/ Rio Paraguay I SH	1	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
	2	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Rio Paraguay II/ Rio Paraguay II SH	1	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
	2	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Ypane I	1	0.76	0.96	0.71	0.78	0.77	0.52	0.39	0.36	0.49	0.93	1.08	1.27
	2	0.76	0.96	0.71	0.78	0.77	0.52	0.39	0.36	0.49	0.93	1.08	1.27
Ypane II	1	0.62	0.78	0.58	0.64	0.63	0.42	0.32	0.30	0.40	0.76	0.88	1.04
	2	0.62	0.78	0.58	0.64	0.63	0.42	0.32	0.30	0.40	0.76	0.88	1.04
Ypane III	1	0.76	0.96	0.72	0.78	0.77	0.52	0.39	0.36	0.49	0.93	1.08	1.27
	2	0.76	0.96	0.72	0.78	0.77	0.52	0.39	0.36	0.49	0.93	1.08	1.27
Solar Sites	1	0.30	0.27	0.25	0.20	0.16	0.15	0.16	0.20	0.23	0.26	0.29	0.30
	2	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Table B.2: Regional System's Interconnection Lines. Source: Created by Maria Jose Martinez at the University of Texas at Austin

Peak load		5.66%	per year	increase	rate
Year	**Power**	**Reserve Margin**			
	MW		**Installed Capacity**		
2004	1,241	85.0%	8250	MW	
2005	1,354	83.6%			
2006	1,354	83.6%			
2007	1,521	81.6%			
2008	1,648	80.0%			
2009	1,810	78.1%			
2010	1,892	77.1%			
2011	2,137	74.1%			
2012	2,137	74.1%			
2013	2,425	70.6%			
2014	2,613	68.3%			
2015	2,761	66.5%			
2016	2,917	64.6%			
2017	3,082	62.6%			
2018	3,257	60.5%			
2019	3,441	58.3%			
2020	3,636	55.9%			
2021	3,842	53.4%			
2022	4,059	50.8%			
2022	4,289	48.0%			
2024	4,532	45.1%			
2025	4,788	42.0%			
2026	5,059	38.7%			
2027	5,345	35.2%			
2028	5,648	31.5%			
2029	5,968	27.7%			
2030	6,305	23.6%			
2031	6,662	19.2%			
2032	7,039	14.7%			
2033	7,438	9.8%			
2034	7,859	4.7%			
2035	8,304	-0.6%			

Table B.3: Reserve Margin estimations for 5.66% increase rate. Source: Created by Maria Jose Martinez at the University of Texas at Austin with Data from Memoria Annual 2014 (ANDE, 2014a)

C. Transmission Expansion

Generation Optimization				
System	Max Capacity (MW)	Constraints		Cost (Units)
Metro	3,211	>=	208	5
Central	9	>=	9	5
East	6,940	<=	6,940	1
South	18,341	<=	18,341	1
North	372	>=	372	5
West	-			5
Total	28,873			
	=			
Demand needed	28,873			
	Cost (Units)	43241		

Table C. 1: Optimization of Generation per System by 2040. Source: Created by Maria Jose Martinez at the University of Texas at Austin

					To ↓			
			Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
			Metro	Central	East	South	North	West
From	Node 1	Metro	-	-	-	-	925	404
→	Node 2	Central	4,259	-	-	-	-	-
	Node 3	East	1,332	-	-	-	-	-
	Node 4	South	8,750	7,073	-	-	-	-
	Node 5	North	-	-	-	-	-	-
	Node 6	West	-	-	-	-	-	-
		Total inflow	14,341	7,073	-	-	925	404
		Total outflow	1,329	4,259	1,332	15,823	-	-
		Supply	3,211	9	6,940	18,342	372	-
		Demand	16,223	2,823	5,608	2,519	1,297	404
			-	-	-	0	-	-
Flow Balance		Net **outflow**/**inflow**	**0**	**0**	**0**	**0**	**0**	**0**
Constraints								
Net		**Demand**	**3290**	**572**	**1137**	52	263	**82**
			DN	DN	SN	SN	DN	SN

Arc capacities					To			
			Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
			Metro	Central	East	South	North	West
From	Node 1	Metro	0	8000	8000	8000	8000	8000
	Node 2	Central	8000	0	8000	8000	8000	8000
	Node 3	East	8000	5232	0	8000	8000	8000
	Node 4	South	8750	8000	8000	0	8000	8000
	Node 5	North	8000	8000	8000	8000	0	8000
	Node 6	West	8000	8000	8000	8000	8000	0

	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6
	Metro	Central	East	South	North	West
Metro	0	0	0	0	0	0
Central	0	0	0	0	0	0
East	0	0	0	0	0	55
South	0	0	0	0	1	1
North	0	0	0	1	0	0
West	0	0	55	1	0	0
Cost	$ -					

Table C. 2: Optimization of Interconnection between Systems by 2040. Source: Created by Maria Jose Martinez at the University of Texas at Austin

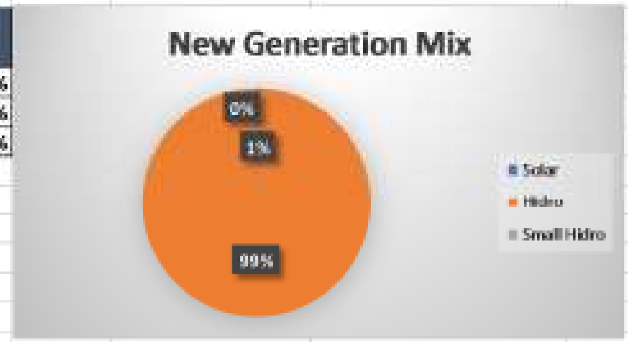
D. Multicriteria Generation Expansion

Data							Social						Technology		Environmental	
Name	Size MW	Expected GWh	District_Input	Distric_Loc	Pop_Input	Pop_Loc	Index_Input	Index_Loc	Poverty_Input	Poverty_Loc	GINI_Input	GINI_Loc	Mobility	Costo		Total_Index
Acaray III	300	2,400	Ciudad del Este	Ciudad del Este	296,597	296,597	0.043	0.043	0.257	0.257	0.506	0.506	-	0.129	0.953	2.694
Ypane I	7	46	Horqueta	Tacuati	60,691	15,776	0.009	0.002	0.630	0.545	0.522	0.543	-	0.001	1.000	3.252
Ypane II	8	43	Concepcion	San Pedro de Ycuamandiyu	83,226	35,021	0.012	0.005	0.438	0.389	0.527	0.502	-	0.001	0.999	2.874
Ypane III	12	79	Horqueta	Tacuati	60,691	15,776	0.009	0.002	0.630	0.545	0.522	0.543	-	0.002	0.999	3.252
Jejui	9	66	Santa Rosa del Aguaray	Santa Rosa del Aguaray	39,763	39,763	0.006	0.006	0.328	0.328	0.527	0.527	-	0.002	0.999	2.723
Carapa	10	66	Salto del Guaira	neral Francisco Caballero Alva	33,444	11,868	0.005	0.002	0.262	0.290	0.613	0.601	-	0.002	0.999	2.774
Carapa II	30	197	Salto del Guaira	neral Francisco Caballero Alva	33,444	11,868	0.005	0.002	0.262	0.290	0.613	0.601	-	0.005	0.998	2.776
Pirapo	4	26	Yuty	Yuty	22,223	22,223	0.003	0.003	0.474	0.474	0.543	0.543	-	0.001	1.000	3.041
Rio Paraguay I	72	613	Villa Hayes	Villa Hayes	48,689	48,689	0.007	0.007	0.255	0.255	0.439	0.439	-	0.033	0.989	2.424
Rio Paraguay II	96	613	Concepcion	Villa Hayes	83,226	48,689	0.012	0.007	0.438	0.255	0.527	0.439	-	0.033	0.985	2.696
Brazo Ana Cua	273	1,800	Ayolas	Ayolas	18,383	18,383	0.003	0.003	0.368	0.368	0.613	0.613	-	0.097	0.957	3.021
Corpus Christi	2,875	18,600	Trinidad	Bella Vista	9,494	13,873	0.001	0.002	0.410	0.228	0.586	0.614	-	1.000	0.551	3.393
Itacora Itati	1,600	11,290	Ayolas	General Jose Eduvigis Diaz	18,383	4,024	0.003	0.001	0.368	0.236	0.613	0.413	-	0.607	0.750	2.991
Bahia negra Solar	1	2	Bahia Negra	Bahia Negra	2,489	2,489	0.000	0.000	0.346	0.346	0.527	0.527	-	0.000	1.000	2.747
Ypane I Solar	18	46	Horqueta	Horqueta	60,691	60,691	0.009	0.009	0.630	0.630	0.522	0.522	1.000	0.000	0.998	4.319
Ypane II Solar	16	43	Concepcion	Concepcion	83,226	83,226	0.012	0.012	0.438	0.438	0.527	0.527	1.000	0.000	0.998	3.952
Jejui Solar	25	66	Santa Rosa del Aguaray	Santa Rosa del Aguaray	39,763	39,763	0.006	0.006	0.328	0.328	0.527	0.527	1.000	0.000	0.996	3.718
Carapa Solar	25	66	Salto del Guaira	Salto del Guaira	33,444	33,444	0.005	0.005	0.262	0.262	0.613	0.613	1.000	0.000	0.996	3.756
Carapa II Solar	75	197	Salto del Guaira	Salto del Guaira	33,444	33,444	0.005	0.005	0.262	0.262	0.613	0.613	1.000	0.001	0.989	3.750
Pirapo Solar	10	26	Yuty	Yuty	22,223	22,223	0.003	0.003	0.474	0.474	0.543	0.543	1.000	0.000	0.999	4.039
Rio Paraguay I Solar	136	358	Villa Hayes	Villa Hayes	48,689	48,689	0.007	0.007	0.255	0.255	0.439	0.439	1.000	0.002	0.981	3.384
Rio Paraguay II Solar	160	422	Concepcion	Concepcion	83,226	83,226	0.012	0.012	0.438	0.438	0.527	0.527	1.000	0.002	0.977	3.933
Brazo Ana Cua Solar	610	1,602	Ayolas	Ayolas	18,383	18,383	0.003	0.003	0.368	0.368	0.613	0.613	1.000	0.007	0.913	3.887
Corpus Christi Solar	7,004	18,406	Trinidad	Trinidad	9,494	9,494	0.001	0.001	0.410	0.410	0.586	0.586	1.000	0.080	0.000	3.075
Itacora Itati Solar	4,215	11,078	Ayolas	Ayolas	18,383	18,383	0.003	0.003	0.368	0.368	0.613	0.613	1.000	0.048	0.398	3.414
Rio Paraguay I SH	30	256	Villa Hayes	Villa Hayes	48,689	48,689	0.007	0.007	0.255	0.255	0.439	0.439	-	0.007	0.998	2.407
Rio Paraguay II SH	30	192	Concepcion	Villa Hayes	83,226	48,689	0.012	0.007	0.438	0.255	0.527	0.439	-	0.005	0.998	2.681
Brazo Ana Cua SH	30	198	Ayolas	Ayolas	18,383	18,383	0.003	0.003	0.368	0.368	0.613	0.613	-	0.005	0.998	2.970
Corpus Christi SH	30	194	Trinidad	Bella Vista	9,494	13,873	0.001	0.002	0.410	0.228	0.586	0.614	-	0.005	0.998	2.844
Itacora Itati SH	30	212	Ayolas	General Jose Eduvigis Diaz	18,383	4,024	0.003	0.001	0.368	0.236	0.613	0.413	-	0.006	0.998	2.637

Table D. 1: Utility Function Table. Source: Created by Maria Jose Martinez at the University of Texas at Austin

Results	
Name	x
Acaray III	0
Ypane I	0
Ypane II	0
Ypane III	1
Jejui	0
Carapa	0
Carapa II	0
Pirapo	0
Rio Paraguay I	0
Rio Paraguay II	0
Brazo Ana Cua	1
Corpus Christi	0
Itacora Itati	0
Bahia negra Solar	0
Ypane I Solar	1
Ypane II Solar	1
Jejui Solar	0
Carapa Solar	0
Carapa II Solar	0
Pirapo Solar	1
Rio Paraguay I Solar	0
Rio Paraguay II Solar	0
Brazo Ana Cua Solar	0
Corpus Christi Solar	0
Itacora Itati Solar	0
Rio Paraguay I SH	0
Rio Paraguay II SH	0
Brazo Ana Cua SH	0
Corpus Christi SH	0
Itacora Itati SH	0

Technology	%
Solar	0.5%
Hidro	99.3%
Small Hidro	0.1%



	Impact	18.584			
	Constraint				
Number of Proyects	5	<=	5		
Alternative	0	<=	1	Rio Paraguay I	
Alternative	0	<=	1	Rio Paraguay II	
Alternative	0	<=	1	Corpus Christi	
Alternative	0	<=	1	Itacora Itati	
Corpus Christi	0	>=	0	Itacora Itati	
Alternative	1	=	1	Brazo Ana Cua	
Alternative	1	=	1	Ypane	
Alternative	0	=	0	Brazo Ana Cua	
Total New Capacity		=	329	MW	
Total Energy		=	1,994	GWh	
Solar	0%		Existing Capacity	8,000	MW
	44	>=	-		
Small Hydro	0%				
	12	>=	-		

Table D. 2: Multicriteria Optimization in Excel. Source: Created by Maria Jose Martinez at the University of Texas at Austin

Multicriteria Optimization Summary		
	Optimization	**Assumptions**
GINI	Max 1 Min 0	Target district with highest inequality
Poverty	Max 1 Min 0	Target district with highest population under the poverty line
Population	Max 1 Min 0	Target districts with the largest population fraction comparing to the total population of the country
O&M cost	Max 1 Min 0	Fraction of the largest O&M cost
Mobility	Max 1 Min 0	1 for solar: 0 for hydropower plants
Environmental Impact Index	Max 1 (Smaller investment cost) Min 0 (largest investment cost)	Proportional to investment cost.

Table D. 3: Multicriteria Optimization Summary. Source: Created by Maria Jose Martinez at the University of Texas at Austin

Glossary

	Meaning
ANDE	National Administration of Electricity
BAC	Brazo Ana Cua
CCS	Corpus Christy Solar site
CLYFSA	Compañía de Luz y Fuerza S.A
DGEEC	Direccion General de Estadisticas, Encuestas y Censos
EII	Electro Intensive Industries
Firm energy	Amount of energy which can be guaranteed to be available at a given time
Gcal	Gigacalories
GDP	Gross domestic product
MOPC	Ministry of Public Developments and Communications
OPTGEN	Optimization Sofware by PSR
Non-firm energy	refers to all available energy above and beyond firm energy.
PSR	Brasilian Energy Modeling Consultation
PYG	Guaranies. Paraguay's currency
SDDP	Stochastic Dual Dynamic Programing
SH	Small Hydro
SIN	National Interconnected System
VMME	Vice Ministry of Mines and Energy
WEC	World Energy Council

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