Andrew Mabula

# Optimal use of hydro resources in the Chiriquí Viejo Basin, Panama

Master's thesis in Hydropower Development
Supervisor: Oddbjørn Bruland
July 2019

**Master's thesis**

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# Abstract

The Chiriquí Viejo water basin is located in the Chiriquí province of Panama which shares boarders with Costa Rica on the western borders of the country. It is characterized by an average altitude of 1100 mm and annual precipitation of 2476 mm which makes it suitable for hydropower production. The basin consists mainly of run-of-river schemes, with a daily regulation reservoir.

The study consists of 7 power plants with a generation capacity greater than 20 MW. Five of the powerplants are in operation; Monte Lirio (52 MW) with no upstream storage, El Alto (72 MW), Bajo de Mina (57 MW), Baitun (86 MW) and Bajo Frio (58 MW) and two power plants, Pando (33 MW) and Burica ( 65 MW), planned to be introduced to the system between 2019 and 2023. The main objective of the study is to find strategies for the use of water in the cascade and optimize the hydropower production.

A spreadsheet model and nMAG have been used in the study to simulate and optimize production. Operating the reservoirs at near full capacity increases production by 3.7% (37 GWh) annually with a reduction in operational time of 28% for El Alto, Bajo de Mina, Burica and Bajo Frio powerplants.

nMAG has been used to conduct simulations for the future, current system and climate change impact on production. The introduction of Pando and Burica to the system increases the production of the Chiriquí Viejo basin by 528 GWh annually. The Upstream regulation of Pando will result in increased production at Monte Lirio hydropower powerplant of 0.1% (0.4 GWh) and 0.2 GWh for both Bajo de Mina and Baitun hydropower plants with the production increase mostly in the rainy season.

Simulations based on climate change with the future setup show no significant impact on production. Inflow based on climate change studies from literature with a 12% reduction is still able to meet firm demand based on the strategy in nMAG.

## Acknowledgement

I would like to sincerely thank Professor Oddbjørn Bruland for his guidance and supervision in this study, much would not have been achieved without his effort. I would like to thank my co-supervisor, Professor Knut Alfredsen for effortlessly availing time and support.

I would like to thank Hans Jacob Bull-Berg and the SN Power team in Panama that comprised of Ian Dillon and Jose Calvo for their consistent support, communication and assistance during the study.

Last but not the least, I would like to thank my mother Grace Mukuka Mabula and my family for their encouragement and support throughout the course of my study.

## Table of Contents

# List of Figures

# List of Tables

# Acronym and Abbreviations

| | |
|---|---|
| **ANAM** | Autoridad Nacional del Ambuente de Panamá |
| **ARB** | Automatic Reservoir Balancing |
| **ASEP** | Autoridad Nacional de los Servicios Públicos |
| **CND** | Central National Dispatch |
| **ETESA** | Empresa de Transmission Electrica S.A |
| **FIC** | Fountain Intertrade Cooperation |
| **GDP** | Gross Domestic Product |
| **masl** | Mean above sea level |
| **RGC** | Reservoir Guide Curve |
| **RWL** | Reservoir Water Level |
| **SINTEF** | Stiftelsen for Industriell og Teknisk Forskning |

# 1.0 Introduction

Hydropower in the Panamanian electricity sector accounts for 51 %, shared between small and large hydro schemes with small hydro accounting for 9% of the total share (Wood, 2018). Most of the water for hydropower production is found in the western Province of Chiriquí. The Province has its highest hydropower potential in the Chiriquí Viejo water basin which has an average altitude of 1100 masl and a mean annual precipitation of 2476 mm making it suitable for hydropower development (Diego, 2008).

The Panamanian government approved a National Energy Plan, in March 2016, for the period 2015 to 2050 aimed at diversifying and advancing the energy sector and decarbonization. The plan was to increase renewable energy with a strategy of 7 % by 2020 and 13% in 2030 which has facilitated for investment opportunities in the renewable sector (IRENA, 2018). These factors attracted development of hydropower in Chiriquí Viejo and foreign investment in Panama by SN Power.

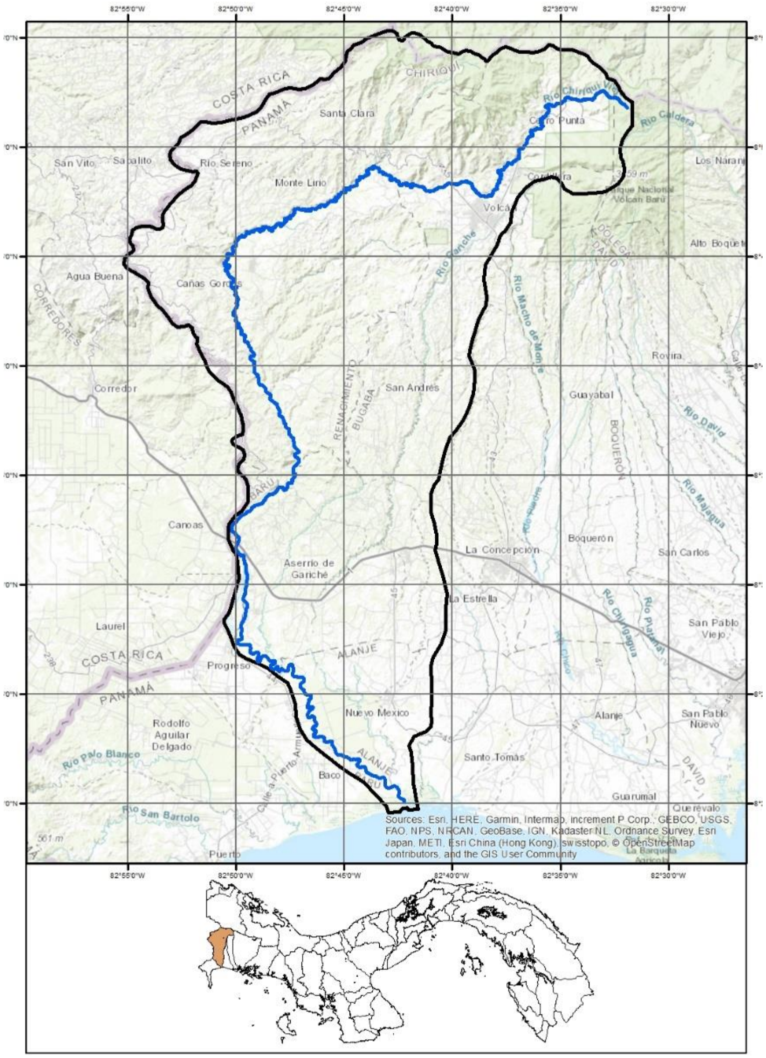
SN Power is owned by Norfund an investment fund for developing countries and Statkraft a state-owned leading power company, entered a joint venture in 2011 with a Panamanian company, Credicorp Group and formed the Fountain Intertrade Corporation (FIC). The purpose of this investment vehicle was to develop and operate the Bajo Frio powerplant in the Chiriquí Viejo water basin. The Bajo Frio powerplant is a runoff the river hydro scheme with an installed capacity of 58 MW.

In 2012, the two companies entered another joint venture to develop Hidro Burica a 63 MW run-of-river scheme, downstream of Bajo Frio. However, operation of the Bajo Frio has not met the expectations of SN Power which intends to increase its investment in the basin. It Is the purpose of this study to find strategies for the use of water in the cascade and optimize the hydropower production.

# 2.0 Study area

## 2.1 Chiriquí Viejo Catchment

The Chiriquí Viejo water basin is between the coordinates 8° 15’ and 9° 00’ N and 82° 30’ and 82° 55’ W. It is located in the western pacific region of Panama and lies on the pacific slope. The total catchment of the basin is 1376 $km^2$ with most of the western divide shared with the border of Costa Rica. The Chiriquí Viejo is the main river having a length of 161 m (ANAM, 2016). It runs in the western direction from in the north part and changes direction southwards towards the outlet into the Pacific Ocean.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

*Figure 2.1 Chiriqui Viejo water basin*

## 2.2 Topography

The western part of Panama is characterized by a central spine of mountains that form a continental divide halfway through the country giving it higher elevation than the eastern side characterized by hills and swamps.

The Chiriquí Viejo has the highest peak in Panama with an elevation of 3 474 masl at Volcán Barú in the north-eastern part. The average altitude of the basin is 1 100 m asl (Diego, 2008).

## 2.3 Climate

Panama is generally classified as a tropical climate characterized by a dry and rainy season. The dry season commences in January up until April with the months of March and April being the hottest. The rainy reason commences in May and prevails until December and is characterized by heavy downpours usually in the evening and early hours of the night. Using climate classification by Köppen-Geiger, 2006 Chiriquí Viejo basin can be classified as tropical monsoon.

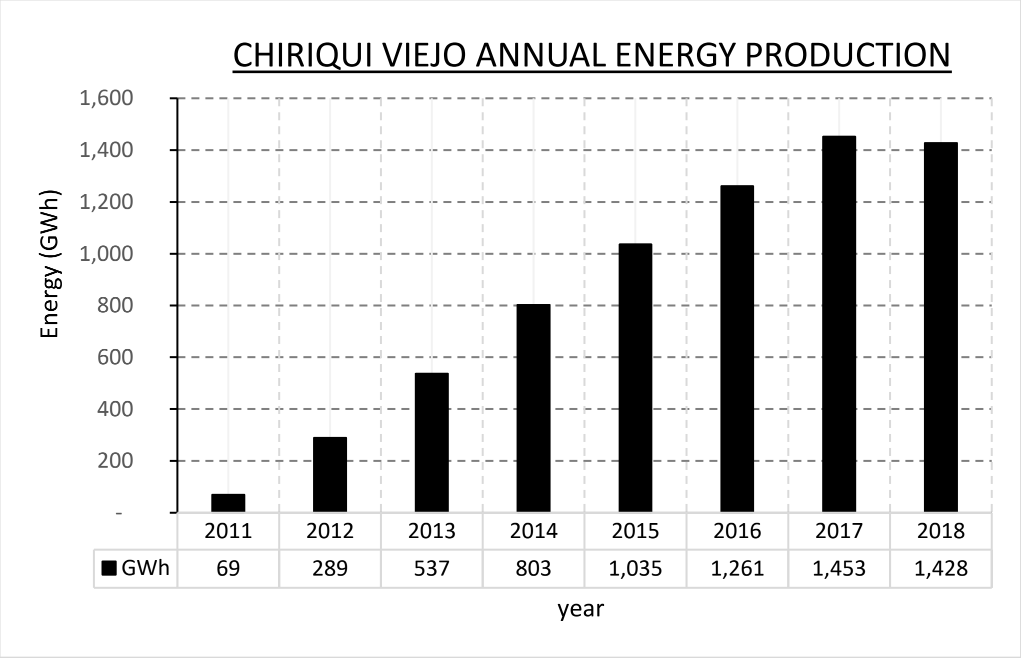
The temperature and relative humidity are uniformly high with diurnal temperature ranging between 24 and 29 ℃ with an average humidity of 80%. However, high altitudes like Volcan have a lower temperature range between 13 and 21 ℃ throughout the year (Cimate-data.org, 2019)

## 2.4 Rainfall

The Mean annual precipitation in the basin is 2 476 mm with a range between 1000 and 3000 mm which may go up to a maximum of 6000 mm (Cimate-data.org, 2019)

## 2.5 Hydropower production

The Chiriquí river currently has six hydroelectric powerplants with a total capacity of 330 MW. The total energy production has been increasing since 2011 from 69 GWh in to 1428 GWh in 2018, figure2.2.



|  | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|
| ■ GWh | 69 | 289 | 537 | 803 | 1,035 | 1,261 | 1,453 | 1,428 |

*Figure 2.2: Annual energy production for Chiriquí Viejo 2011 – 2018*

The table 2.3 and figure 2.4 show the status and location of the power plants considered for the study. All the power plants have been designed to be operated as run-of-river hydro schemes with an upstream pondage, except Monte Lirio, to meet diurnal variation of the demand as well as meeting a firm capacity during the peak period.

*Table 2.1: Hydropower Plants > 20 MW in Chiriquí Viejo watershed*

| No. | HPP | Company | Installed Capacity (MW) | Status | Completion |
|---|---|---|---|---|---|
| **1** | Pando | EISA | 33 | Development | 2019 |
| **2** | Monte Lirio | EISA | 52 | Operation | 2014 |
| **3** | El Alto | PPA | 72 | Operation | 2014 |
| **4** | Bajo de Mina | IDEAL | 57 | Operation | 2012 |
| **5** | Baitun | IDEAL | 86 | Operation | 2012 |
| **6** | Bajo Frio | FHPC | 58 | Operation | 2016 |
| **7** | Hidro Burica | HBSA | 65 | Development | 2023 |

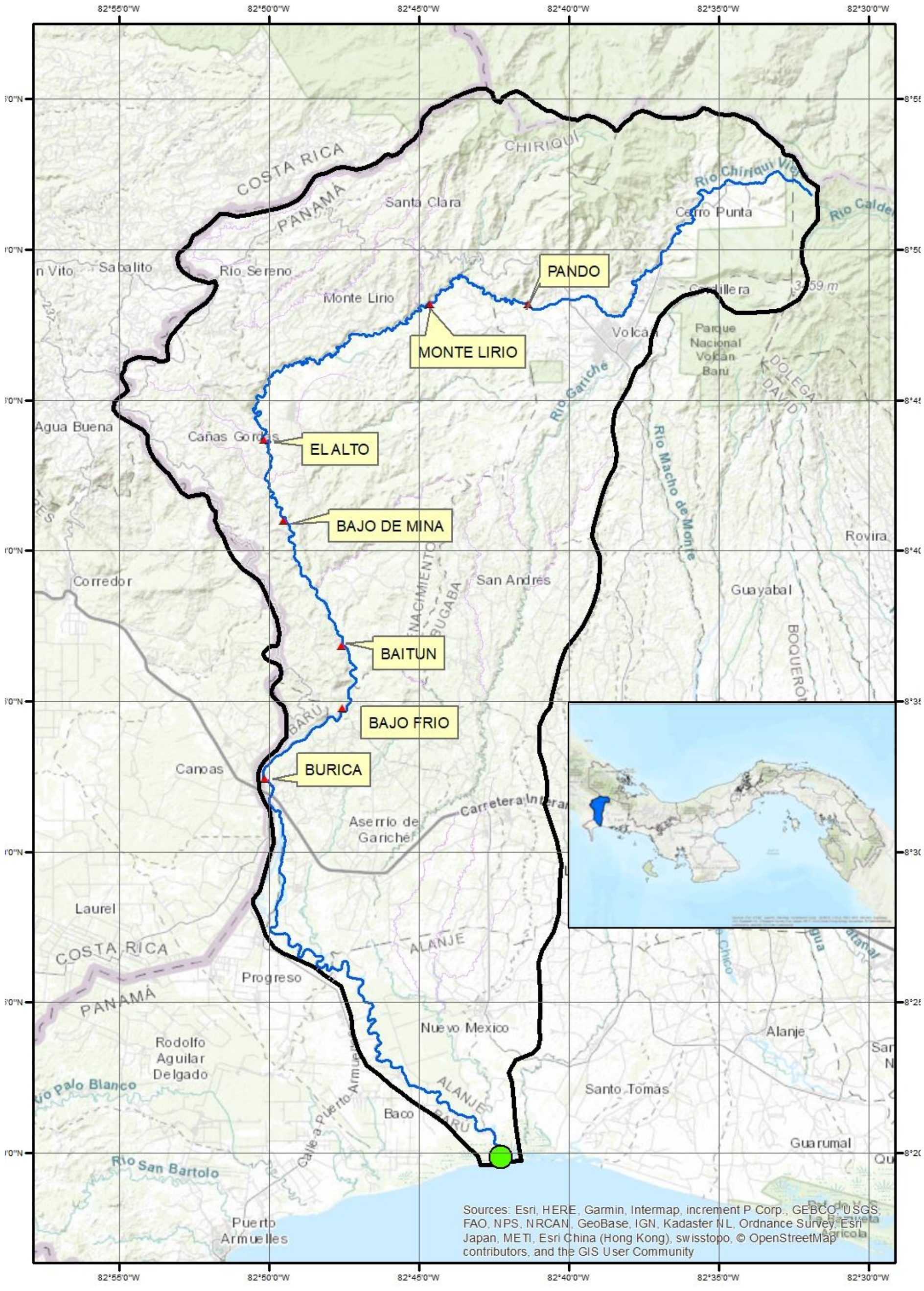


*Figure 2.3: Hydropower plants in the Chiriquí Viejo watershed*

### 2.5.1 Pando and Monte Lirio hydropower plant

Pando and Monte Lirio are two power plants located 8°48'11.3"N 82°44'38.1"W and 8°46'08.1"N 82°49'19.2"W, respectively. Monte Lirio is in operation while Pando is scheduled to be complete in 2019 and the two will be operated in a cascade setup generating a total capacity of 84.25 MW.

Monte Lirio's operation depends on the outflows discharged downstream of Pando and additional river flow. The head pond level is 974 m which is the tailwater of Pando. The rated turbine flow for each is 7 m3/s and has a head of 274 m providing a tailwater level of 673 m. The hydraulic set comprises of an intake and a 7.9 km long tunnel with a surge tank and a 2.8 km long penstock feeding three generators.(CMD, 2018)

*Table 2.2: Pando and Monte Lirio powerplant characteristics*

| | | PANDO | MONTE LIRIO |
|---|---|---|---|
| **Rated Output** | MW | 32.6 | 51.65 |
| **Rated Turbine Q** | $m^3/s$ | 14.5 | 21 |
| **Rated Head** | m | 252.5 | 274 |

### 2.5.2 El Alto hydropower plant

The power plant is located just downstream of the mouth of the river Candela 8°43'40.8"N 82°50'10.2"W. It has a capacity of 72 MW comprising of 3 vertical-shaft Francis turbines and an upstream reservoir of 3.3 million cubic meters. The hydraulic system consists of a headrace tunnel 4.2 m in diameter coated with steel and a surge tank. (CMD, 2014b)

*Table 2.3: El Alto powerplant characteristics*

| | EL ALTO | |
|---|---|---|
| **Rated Output** | MW | 72 |
| **Rated Turbine Q** | $m^3/s$ | 60 |
| **Rated Head** | m | 126 |

### 2.5.3 Bajo de Mina hydropower plant

The Bajo de Mina power plant has a capacity of 56.8 MW located 8°40'59.5"N 82°49'30.6"W. The powerhouse is fitted with two Francis turbines. A storage pondage with a capacity of 0.87 million cubic meters is provided upstream of the powerplant.

The hydraulic setup comprises of 5.4 km long power tunnel with a surge and a 290 m long surface penstock bifurcating into two pressure pipes to a surface powerhouse.(CMD, 2014a)

*Table 2.4: Bajo de Mina powerplant characteristics*

| | BAJO DE MINA | |
|---|---|---|
| **Rated Output** | MW | 56.8 |
| **Rated Turbine Q** | $m^3/s$ | 56.5 |
| **Rated Head** | m | 112.2 |

### 2.5.4 Baitun hydropower plant

The power plant is located 8°36'51.3"N 82°47'36.0"W and has a capacity of 85.6 MW with two vertical Francis turbines. The hydraulic system comprises of 5.9 m tunnel with a 340 m long penstock having a diameter of 5.1 m.(CMD, 2014a)

*Table 2.5: Baitun powerplant characteristics*

| | BAITUN | |
|---|---|---|
| **Rated Output** | MW | 85.6 |
| **Rated Turbine Q** | $m^3/s$ | 75.0 |
| **Rated Head** | m | 129.3 |

### 2.5.5 Bajo Frio hydropower plant

The Bajo Frio power plant is located 8°34'47.0"N 82°47'34.5"W. It has a total installed capacity of 58 MW which is shared between two power houses, La Potra and Salsipuedes each having 28 MW in capacity with La potra having an additional 2.10 MW generating from ecological flow.

An additional 2.10 MW is generated from an auxiliary unit using ecological flow. The plant has three Kaplan turbines with a rated discharge of 100 $m^3/s$. The river at this location has an average annual inflow of 11.8 $m^3/s$. the hydraulic setup comprises of an intake structure, a 5.1 km long tunnel with a surge tank and a 2 km long penstock with a bifurcation to a surface powerhouse. Salsipuedes is downstream of La potra connected by a 2 km canal which runs to a forebay. It has a capacity of 28 MW with a head of 31.19 m..(CMD, 2011)

*Table 2.6: Bajo Frio powerplant characteristics*

| | | LA POTRA | LA POTRA (Aux.) | SALSIPUEDES |
|---|---|---|---|---|
| **Rated Output** | MW | 27.77 | 2.10 | 27.77 |
| **Rated Turbine Q** | $m^3/s$ | 100 | | 100 |
| **Rated Head** | m | 31.19 | 41.00 | 31.19 |

### 2.5.6 Burica Hydro power plant

The powerplant is in the development phase will be located 8°32'25.7"N 82°50'09.6"W. the planned capacity is 65 MW with 2 Francis turbines.

*Table 2.7: Burica powerplant characteristics*

| | BURICA | |
|---|---|---|
| **Rated Output** | MW | 65 |
| **Rated Head** | m | 71 |

# 3.0 Literature review

## 3.1 Panama

Panama is a country in the southern part of Central America which borders Colombia on the east and Costa Rica on the West of the country and located between the north latitude 7- and 10-degrees and the west longitude 77- and 83-degrees. It has a total area of 75,420 with a population of four million. The official language in Panama is Spanish (CIA, 2019).

## 3.2 Economy

There is no central bank in Panama. The Balboa is the country's currency, equivalent to the United states dollar, which is used as the legal tender. Panama relies on the services industry which accounts for more than 75% of the gross domestic product (GDP), with 10% of the GDP being generated from the Panama Canal (Woods, 2009).

## 3.3 Energy in Panama

The Panamanian energy sector relies on fuel and has a high dependency on its import. It's energy demand is represented by four sectors which include Commercial, Public, Industry, Residential and transport. Commercial and Public and residential sectors are the highest consumers of electricity while transport and industry mainly consume oil and oil products. The electricity consumption since 2010 has maintained an annual average growth rate of 6.2% with the commercial and Public sector accounting for 15 % of the total energy consumption (IRENA, 2018)

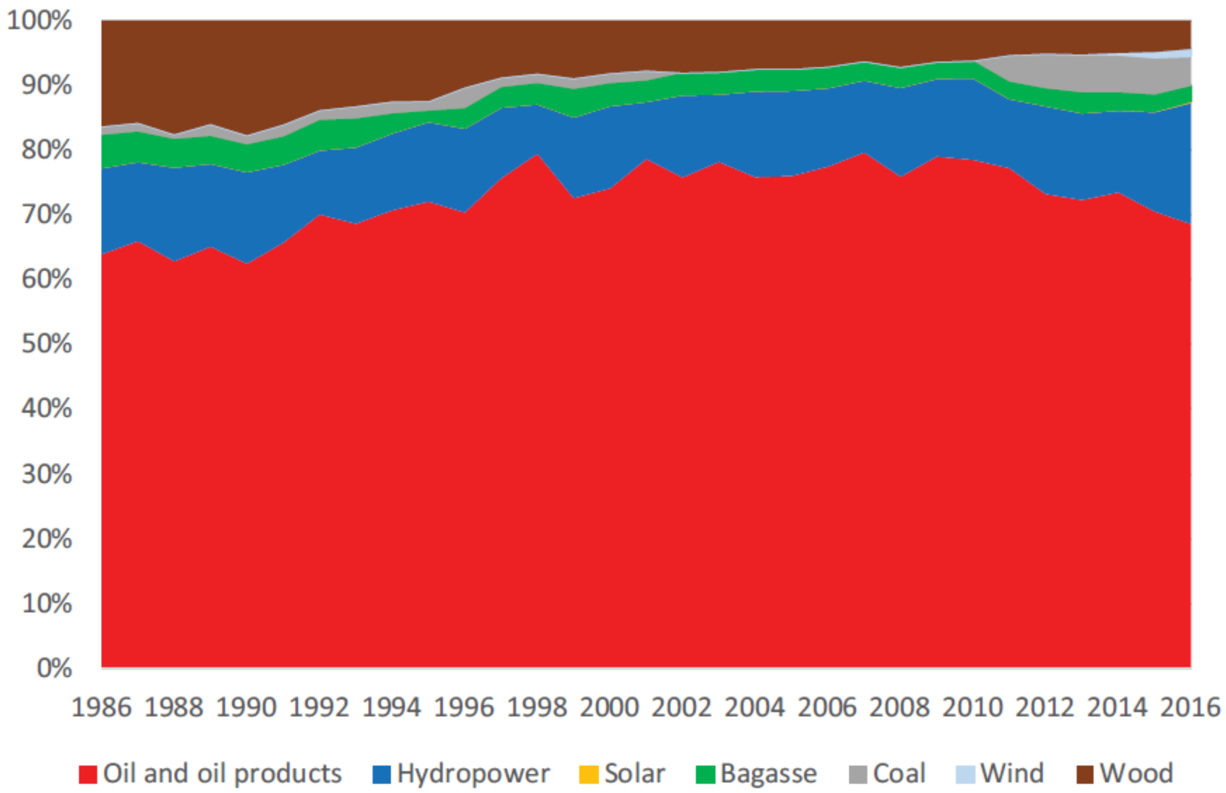


*Figure 3.1: Panama's total primary energy supply, (IRENA, 2018)*

### 3.4 The Electricity sector in Panama

Electricity in Panama was provided by the private sector until 1961 when the state-owned Institute of Hydraulic Resources and Electrification (IRHE) was created which later nationalized private companies. Before 1997, the Institute operated as vertically integrated electricity company until it was unbundled into generation, transmission and distribution units of with the government maintaining ownership of the transmission line while partially privatizing generation and distribution. (IRENA, 2018)

The electricity market in 2017 comprised of a total of 60 generation companies, three self-generators, one transmission company, three distribution companies and twenty-two large consumers on the market. (TECSA, 2018). The both the capacity and energy mix have been growing in quantity and type to include wind and solar energy which were introduced in 2013. This can be seen in the gross electricity production statics of the period 2000 to 2016 in Figure 3.2.

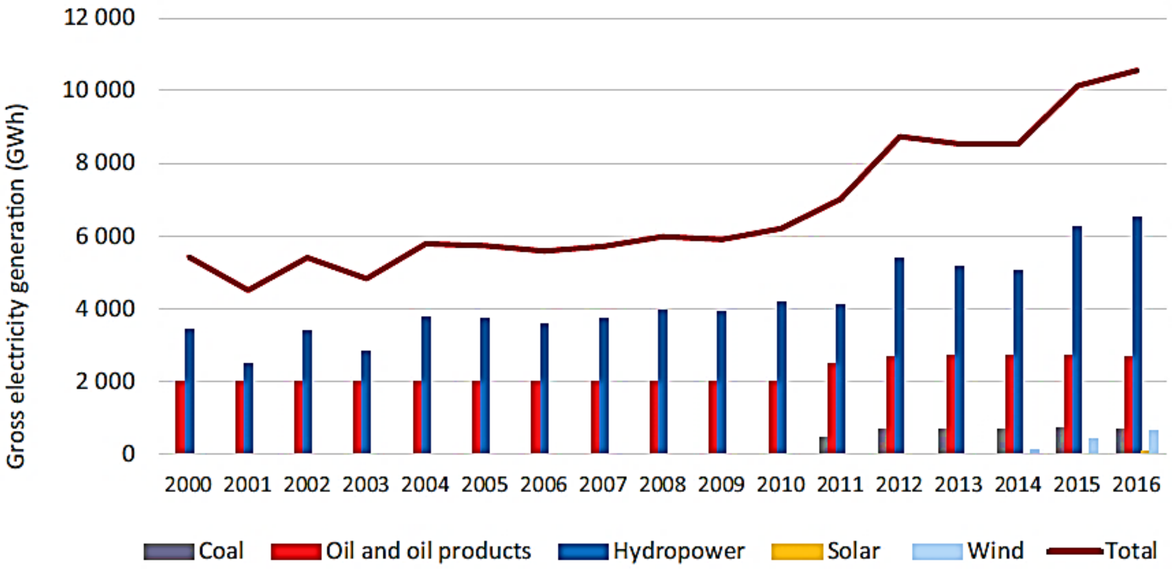


*Figure 3.2: Gross Electricity generation in Panama (IRENA, 2018)*

The 2017 statists indicate hydropower maintaining the largest source of energy in the sector with an installed capacity of 1 715 MW which accounts for 51% of the total installed capacity, thermal energy with an installed capacity of 1 239 MW and an addition of wind capacity of 270 MW and solar energy of 118 MW (TECSA, 2018). Figure 3.3 presents a summary of the total capacity of electricity generation by fuel source.

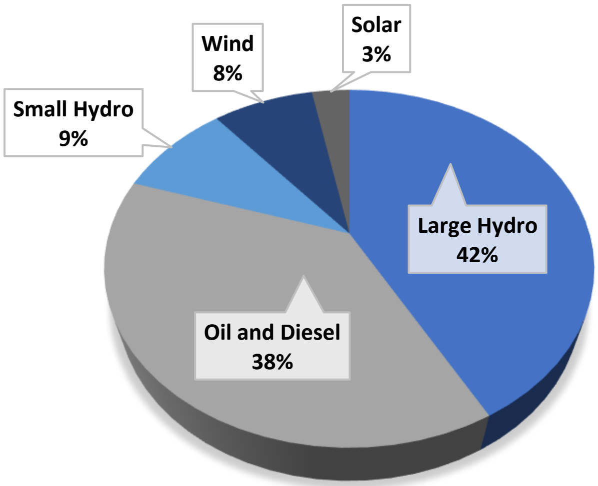


*Figure 3.3: Panama Electricity generation by fuel source, 2016*

Panama is demarcated into three concession Zones which are each supplied by a distribution company. Empresa de Dsitribucion Electrica Chiriquí, S.A. (EDECHI) which supplies the western zone, Empresa de Distribucion Electrica Metro Oestra, S.A. (EDEMET) supplies the central zone and Elektra Norste, S.A. (ENSA) which supplies the eastern zone.

Transmission of electricity is done by Empresa de Transision Electrica S.A (ETESA). Figure 3.4 shows the main transmission grid. In addition, there are interconnectors to Colombia and Costa Rica.

*Figure 3.4: Main Transmission system in Panama (ETESA, 2017)*

### 3.4.1 Electricity market in Panama

The privatization and change of the Panamanian energy sector in 1998, lead to the creation of a wholesale market. The wholesale market comprises of a contract market and occasional market. In the contract market, medium- and long-term energy and/or power transactions are agreed between the market agents for prices of energy and power.

The occasional market provides an opportunity for hourly energy and power transactions considering the surplus and deficiencies that arise as a result of the dispatch, contractual commitments and the reality of the demand and supply (ASEP, 2019).

### 3.4.2 Electricity prices

Consumer prices in Panama are considered stable since distribution companies are obliged to contract 100% of the energy that they forecast. Peak demand in panama is usually experienced during the day due to the use of air conditioning systems.

The spot price on Panamanian Electricity market is heavily influenced by oil prices. When oil prices are low, thermal powerplants sell their energy on the spot market influencing a lower spot price as the marginal cost reduces. Figure 3.5 shows the relationship between marginal cost, oil prices and hydropower contribution.

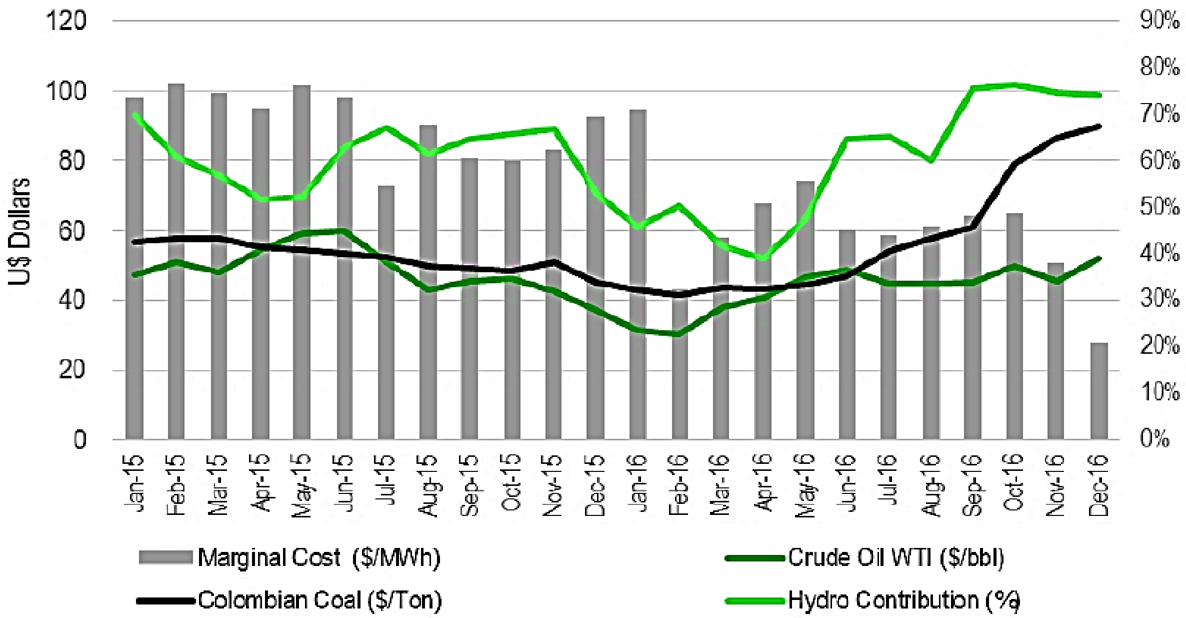


*Figure 3.5: Marginal Costs vs International fuel costs and Hydrological contribution (TECSA, 2018)*

Generally, the price of electricity in panama has ranged between 15 to 20 U$ cents/kWh as shown in the historical average electricity price in figure 3.6.

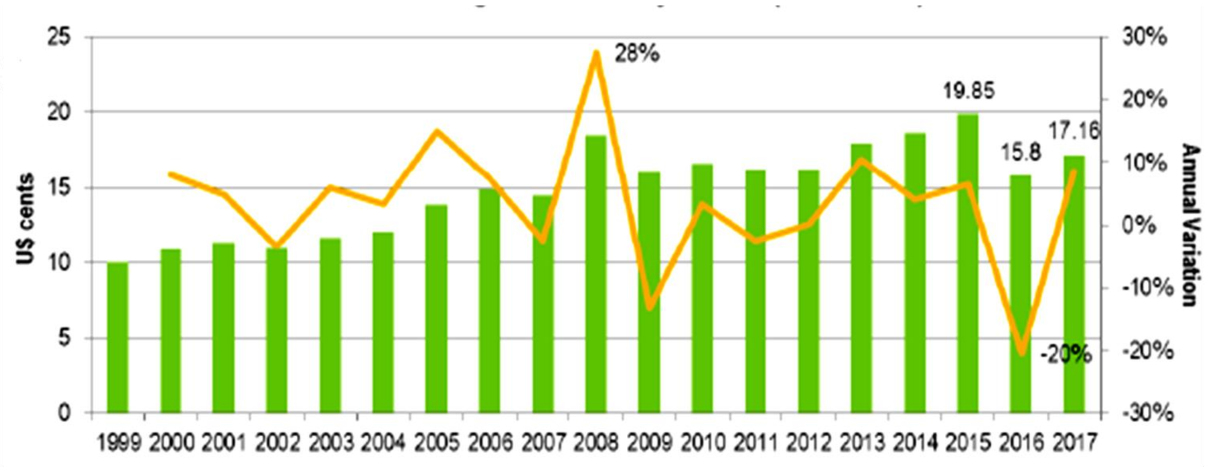


*Figure 3.6: Historical average electricity price (U$ cents) (TECSA, 2018)*

### 3.5 Optimization of hydropower systems

Optimization is the maximization or minimization of a function to find the best result possible under given circumstances (Astolfi, 2006).

In hydropower systems, optimization of reservoir operations is a process that involves the allocation of resources, development of streamflow regulation strategies and operating rules as well as real-time release decision making which are set within the guidelines of the operating rules. Optimization models are used to determine values for a set of decision variables by maximizing or minimizing the objective functions subject to constraints (Wurbs, 1993).

The objective function and its constraints can be represented mathematically as linear or non-linear functions of the decision variable depending on the complexity of the system. Wurbs (1993) categorized objective functions into three main groups;

- Economic benefits and costs
- Water availability and reliability
- Hydroelectric power generation

The decision variables can be release rates while constraints include storage capacities, diversion or stream flow requirements and mass balances.

Literature with regards to optimization models and application to reservoir operations is extensive. Reservoir system studies are unique, and selection of the model depends on a number of considerations which include the characteristics of the application, analysis capabilities provided by alternative models and the background and preferences of the analysis (Wurbs, 1993). The following chapters provide an overview of optimization and simulation models; Vansimtap (EMPS) and prodrisk (commercial) and nMAG (open source) which have been developed in Norway.

### 3.5.1 Vansimtap

The vansimtap is a hydropower and reservoir operation simulation model which was developed by SINTEF. It has a two-step optimization and simulation solution of strategy evaluation and simulation of operational decisions. The strategy evaluation computes incremental water value based on the water value method for each market area by utilizing a combination of Stochastic dynamic programing (SDP) and heuristic approach for treating the interconnection between areas while the simulation conducts generation decisions based on the incremental values. (Warland et al., 2016).

The water value method is based on dynamic programing which evaluates future inflow conditions and the power market to estimate an economic value of water in a reservoir. Simulation in Vansimtap is based on modules which can be combined in series or parallel as a description of the physical structure of the model (Killingtveit, 1995).

The model is suited for long term scheduling which is aimed at evaluating the seasonal and multi/annual reservoirs. The seasonal model can be connected to a short-term production optimization (SHOP) for short-term planning of one to two weeks. The main input data is inflow time series, firm power demand and the spot-market.

### 3.5.2 Prodrisk

Prodrisk is a SINTEF model which is used for long and mid-term scheduling for a general detailed hydro representation. It is based on stochastic dual dynamic programming (SDDP) and uses a time resolution of one week and can be divided into load blocks of hourly resolution.

The model consists of a backward recursion and forward simulation were weekly decision problems are solved for each price, combination of the state for the previous time step, and combination of inflow. (Warland et al., 2016). Prodrisk uses a similar market and detailed hydro module as vansimtap which means they can both solve the same scheduling problem.

### 3.5.3 nMAG

nMAG is a simulation model for multiple reservoir hydropower production systems which was developed by Hydrotechnical Laboratory. Simulations in nMAG are based on the water balance equation in which the program runs an iterative procedure to determine a reservoir volume in each time step (Killingtveit, 1999).

The model uses modules or nodes to represent the various components of the power system represented in in figure 3.7. The modules are connected by links defining the movement of water in the production system.

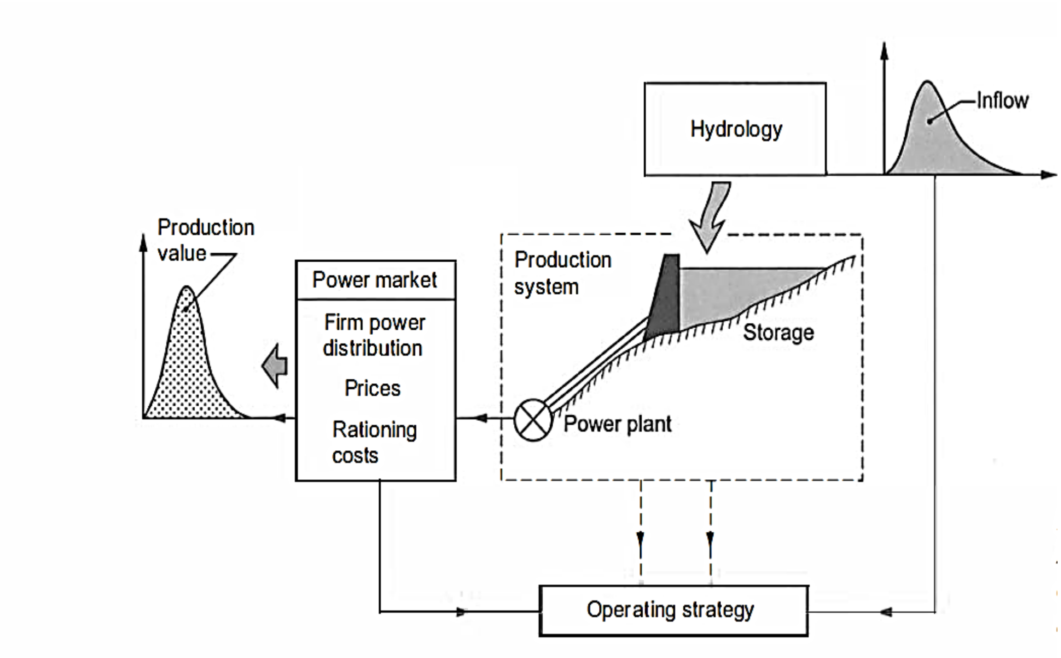


*Figure 3.7: Hydropower system simulation components ((Killingtveit, 1995)*

nMAG consists of 4 module types that comprise of the Reservoir, Power plants, Interbasin transfers and control points.

### 3.5.4 Power plant

nMAG calculates the power and energy using the equation below.

Energy: $E = Q(t) * 3600 * dt * EEKV$ (KWh)

Equivalent Energy: $EEKV = \eta * \rho * g * H_n / (1000*3600)$ (KWh/$m^3$)

Power: $P = E/ dt$ (KW)

Where $Q(t)$ is the discharge through the turbine during the time-step dt ($m^3/s$). dt is the length in hours of the one time-step. η total efficiency. ρ density of water (1000 kg/$m^3$). G gravity constant (9.81 m/$s^2$). $H_n$ net head of water (m)

nMAG provides a more detailed description of the power plant with an option for optional data comprising of;

- Nominal head (m)
- Intake level (masl)
- Tailwater level (masl)
- Head loss coefficient ($s^2/m^5$)
- Total power plant efficiency

This is relevant only for power plants that operate with varying head or large variations of the maximum and minimum discharge. This means that the efficiency curve will not be constant and will therefore depend on the optimal data provided.

### 3.5.5 Energy market

nMAG has a simplified market with a constant price, different demand curves will be used to observe their effect on production. The demand curve distributes the firm energy over a period of time. nMAG provides three options for firm power distribution which consist of;

- Constant Firm Power,
- Daily load and
- Variable firm power

The Constant firm power distributes the energy equally over the period used for the simulation either day or week. The daily load specifies directly a percentage for each day with a simulation period of 365 days. For a varied seasonal distribution, the Variable firm power provides a distribution for a range of days in the simulation period.

### 3.5.6 Operational strategy

The operational strategy is key in optimizing the water resources. nMAG offers three operational strategies;

- Automatic reservoir balancing
- Reservoir release specification and
- Reservoir guide curve

Using the Automatic reservoir balancing, nMAG selects a water level that will optimize the output of the production. This is suited for small reservoirs where it can be a challenge to specify guide curves. As the name of the strategy specifies, there is no need for input to run it.

The reservoir release specification is used to specify average planned releases from the reservoir in terms of the volumetric flow rate with an annual distribution in percent.

The reservoir guide curve strategy is used to specify the amount of water the reservoir can contain at a time step throughout the year for economical use of the water. For this strategy, nMAG first assumes unconditional firm power demand. It then compares the deviation between actual reservoir volume with the reservoir guide curve and decides whether a curtailment is needed, for a negative deviation, or to produced dump power for a positive deviation (Killingtveit, 1999).

### 3.6 Run-of- river schemes and climate change

Run-of-river hydropower schemes do not have large reservoirs for water storage as a result they generate much less energy than hydroelectric dams. These schemes can be used to provide baseload requirements and also respond to meet peak demand (Lindstrom, 2012).

During dry periods the production can reduce significantly due to depleted water levels which in turn has an impact on the plant capacity factor. It is therefore expected to have low production in the dry season. However, in the rainy season, the capacity factor increases due to high flow and this essential makes them suitable to contribute to base load in a mixed energy market.

One major impact on these schemes is that of climate change. During dry periods this significantly reduces the capacity factor of powerplants which directly impacts on revenue.

Climate change is considered as a phenomenon that affects the distant future. Studies on climate change in Central America show a reduction of future water resources. One such study conducted by Maricarmen (2016), shows an increase of 1°C in temperature and a decrease in rain and water resources for most of the countries in Central America. The decrease in water resources has been estimated on average as 12% for the period between 2020-2039 and 16% between 2040-2059.

# 4.0 Data and data analysis

The purpose of this chapter is to present the data provided and data analyses.

## 4.1 Hydrology data

The amount of water flowing in a river is essential for evaluating the water resource potential of a catchment. The quality of data determines the reliability of results in water resources evaluation. The Chiriquí Viejo basin has 4 hydrological stations used for volumetric flow rate monitoring. The stations are monitored by ETESA's hydrometeorology management. Table 4.1 shows the characteristics and data availability of the stations.

*Table 4.1: Characteristics of gauging stations in Chiriquí Viejo watershed*

| Number | River | Location | Drain Area (Km$^2$) | Elevation (m) | Years Active | Days missing |
|---|---|---|---|---|---|---|
| **102-01-01** | CHIRIQUI VIEJO | VOLCAN | 108 | 1533 | 1957 - 2019 | 406 |
| **102-01-02** | CHIRIQUI VIEJO | PASO CANOA | 788 | 85 | 1957 -2018 | 1242 |
| **102-01-03** | CHIRIQUI VIEJO | BAITUN | 720 | 380 | 1957 - 2016 | 2213 |
| **102-02-01** | CANDELA | RIO SERENO | 56.8 | 870 | 1980 - 1998 | 204 |

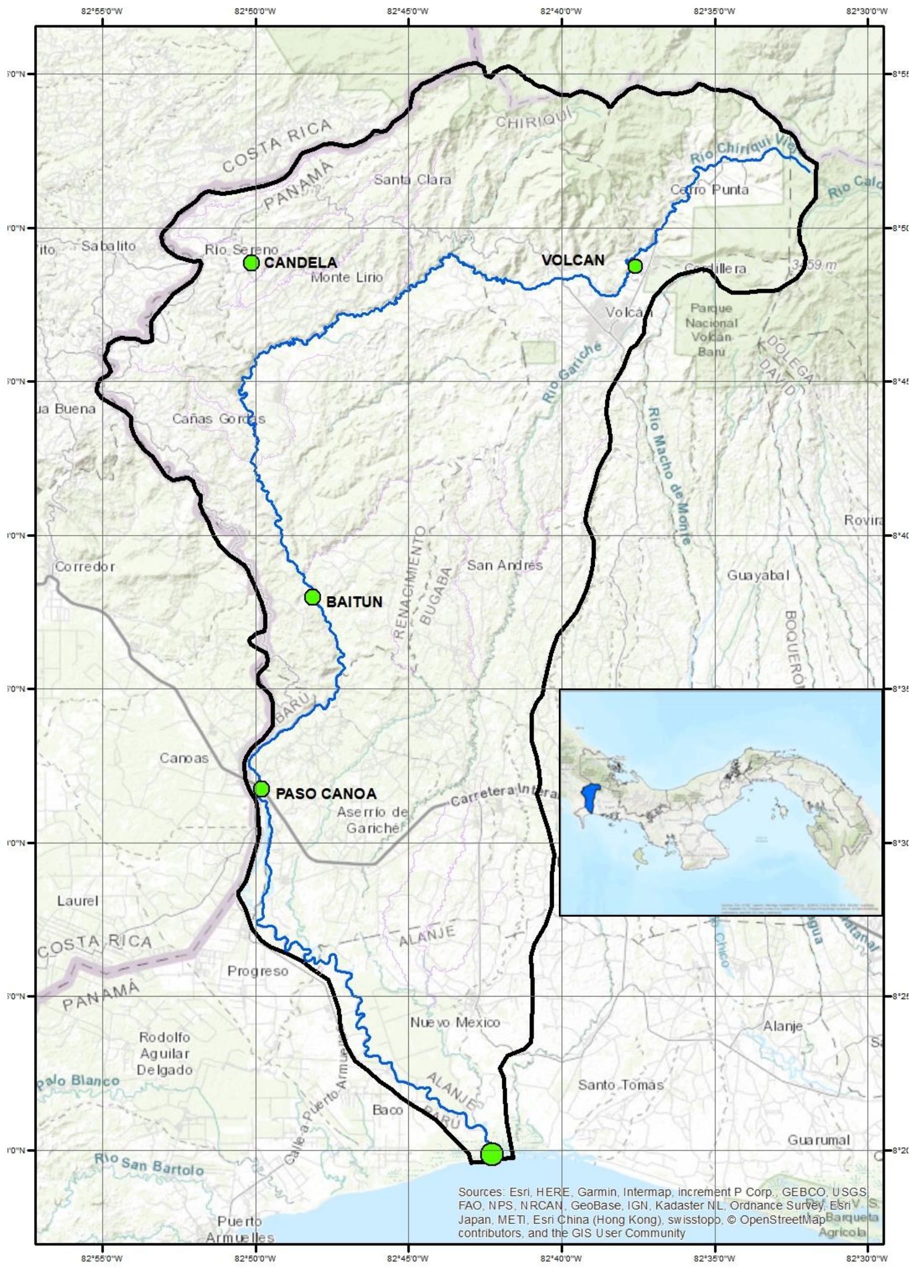


*Figure 4.1: Hydrological stations in Chiriquí Viejo Watershed*

Candela gauging station has records of up to1998 while Baitun, upstream of Bajo Frio ends in 2016. Volcan and Paso Canoas have data available up to 2019 and 2018, respectively, however Paso Canoas has no data for 2013 and 2014 and missing 508 data points between 2012 and 2018.

Different methods have been applied to fill the data pending on the severity of the data set. For single point missing data an average of the previous and adjacent value has been applied based on the equation below.

$$Q_m = (Q_{m-1} * f_i/f_{i-1} + Q_{m+1}*f_i/f_{i+1})*0.5$$

Where $Q_m$ is the missing daily value

$Q_{m-1}$ is the previous day value

$Q_{m+1}$ is the adjacent value

$f_i$ is the distribution factor

for values greater than a month the filling has done by using the average of the time series for that particular month.

$$Q_m = Q_{m+1} * f_i/f_{i-1}$$

Where $Q_m$ is the missing monthly value

$Q_m$ is the missing monthly value

There is an annual variation of 1500 million cubic meters between the lowest and highest annual average inflow for Paso Canoas and 220 million cubic meters for Volcan. Volcan inflows are approximately 10 % of Paso Canoas which is relative its location in the catchment.

Figure 4.4 shows the daily distribution of the inflow at Volcan and Paso Canoa. The daily distribution is similar to the annual distribution in which Volcan has an almost flat curve compared to Paso Canoa.

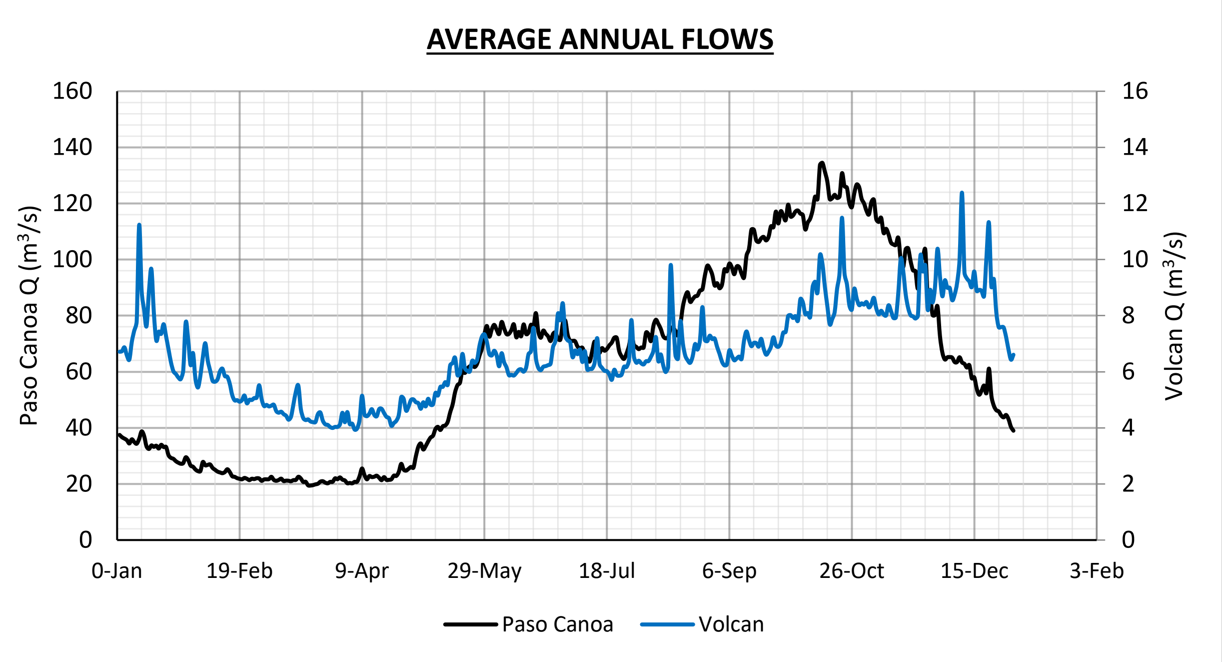


*Figure 4.2: Annual Average flows for Paso Canoas and Pando (1957-2018)*

It is essential to check the consistency of data as there can be changes in the operation of a gauging station due to changes in river sediment, physical temperament of measuring instruments and other factors that can cause erroneous data which can affect discharge computations. An accumulative Mass Curve has been used to check the consistency of data. Using visual inspection, Figure 4.3 shows no significant variation to indicate a shift in the discharge curve.

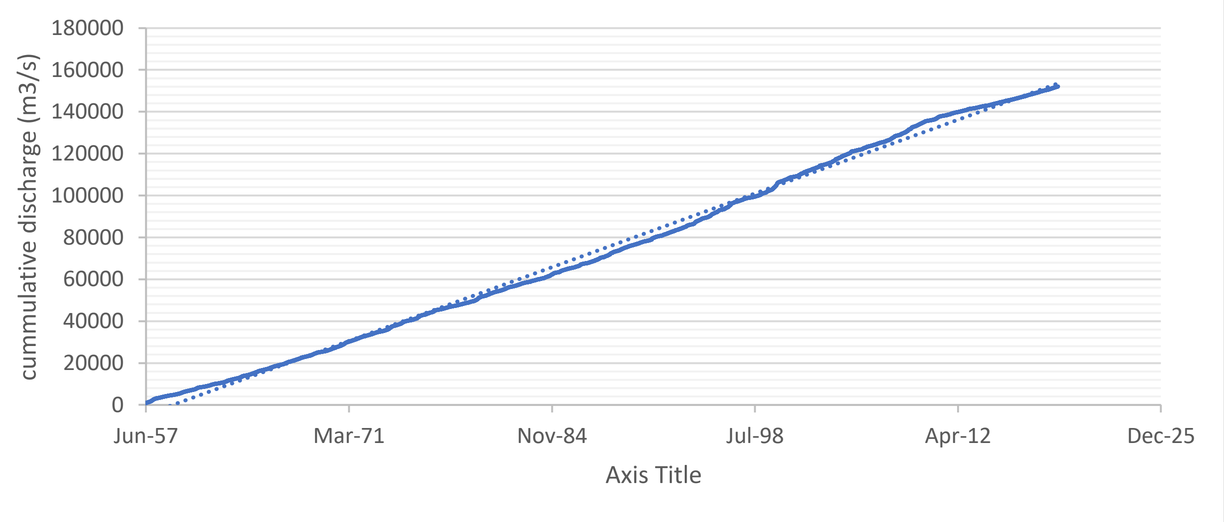


*Figure 4.3: Accumulated Mass curve for Volcan (1957 – 2018)*

### 4.1.1 El Alto Inflow

Hourly inflow has been provided by Hydro Caisan S.A. which runs the EL Alto power plant from 2014 to 2018. A cumulative plot shows seasonal undulations but no significant bend to indicate a shift in the Hydrograph.

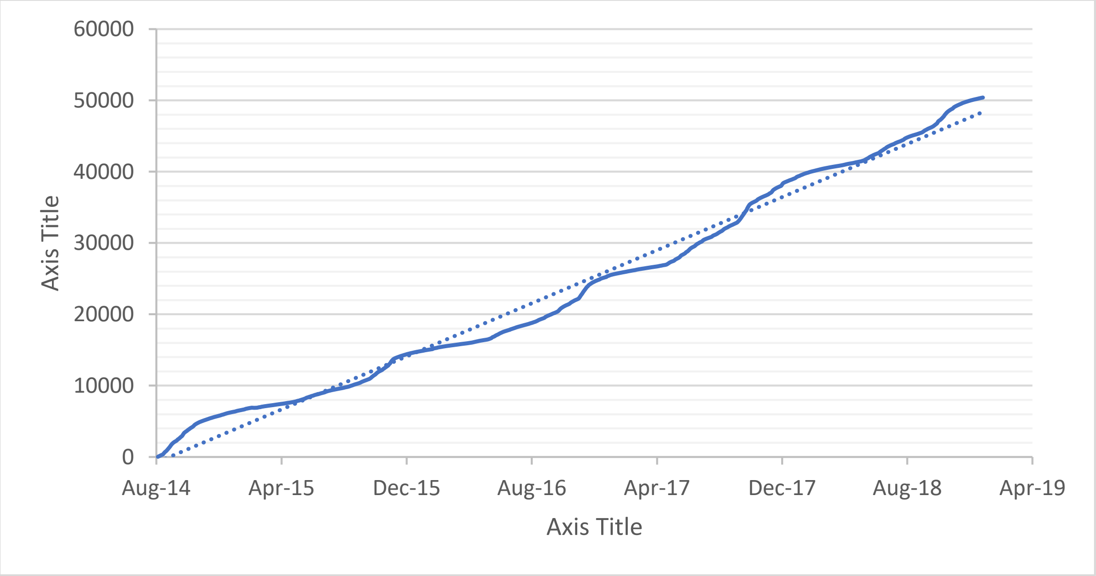


*Figure 4.4: Accumulated Mass curve for El alto inflow*

## 4.2 Runoff scaling

Not every section of the river or stream can be measured. Gauging stations are located such that they can record the river flow based on a specific purpose. Scaling is a method used to transfer the flow from a point with observed data to a point of study. The scaling equation below has been used for scaling.

$$Qs/(A_s*F_s) = Q_{obs}/(A_{obs}*F_{obs})$$

Where Q is the runoff

A is the Area

F is the mean annual runoff

Figure 4.5 shows the scaled El Alto inflow against the actual Pas Canoas flows

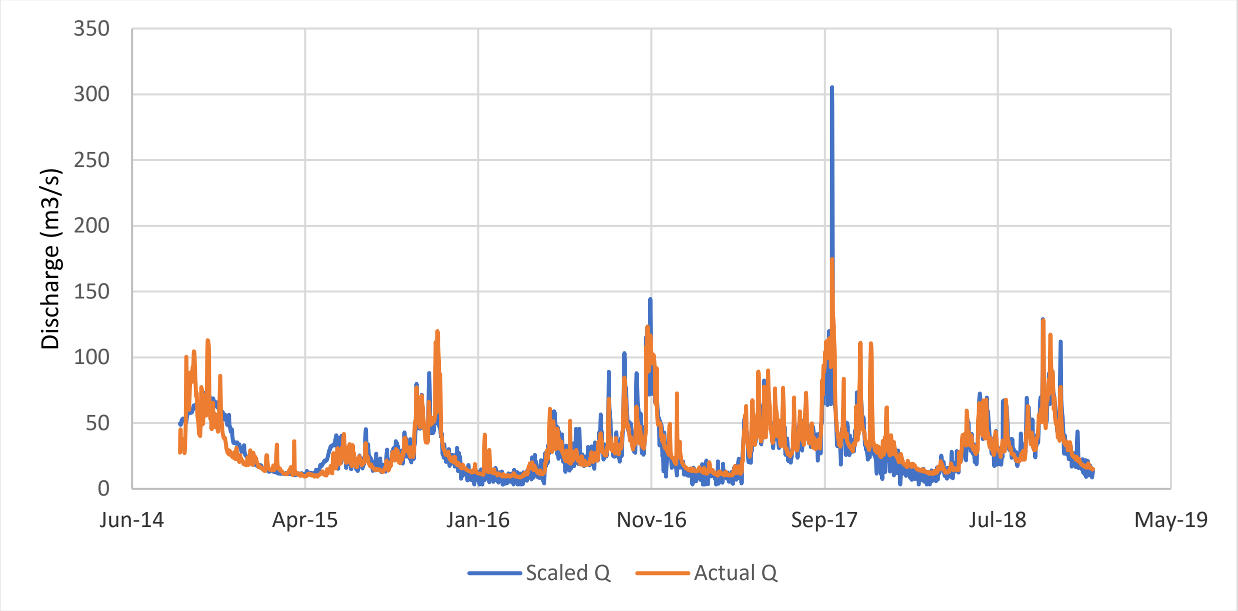


*Figure 4.5: Scaled inflow (EL Alto) vs Actual inflow (Paso Canoas)*

## 4.3 Generation and spot price data

Hourly generation data and spot prices has been provided by CND for the five power plants considered in the study. The data has a period from 2014 to 2018. Figure 4.6 illustrates the average daily average spot price for each year.

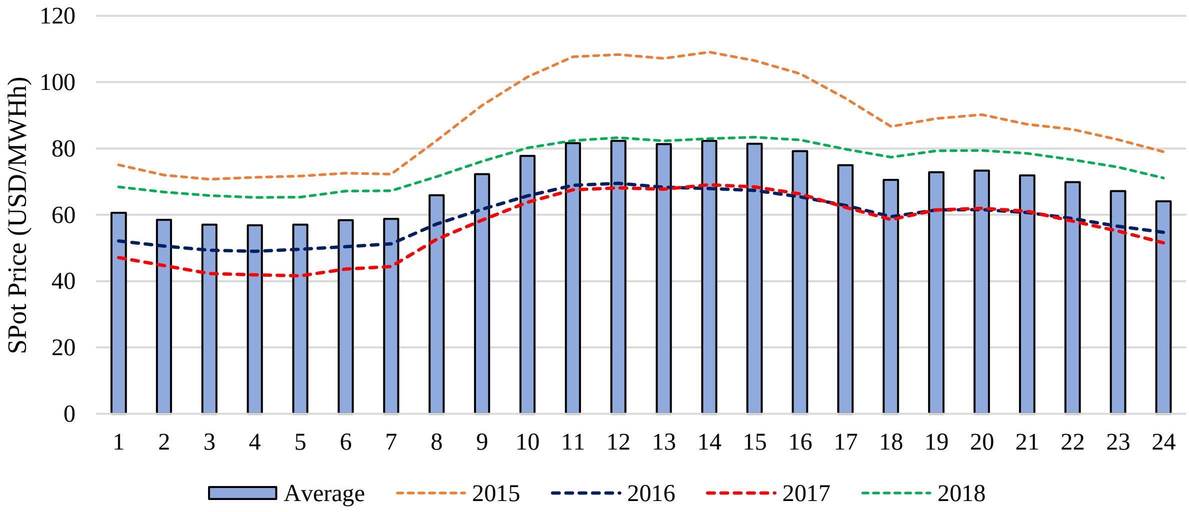


*Figure 4.6 Daily average Spot Price Variation (USD/MWh)*

## 4.4 Turbine efficiency curves

Most of the plants have a Francis turbine installed. Efficiencies have not been provided except for a Hill turbine for the Bajo Frio powerplants. A typical turbine efficiency curve based on literature (Vinnogg, 2003) has been used, figure 4.7.

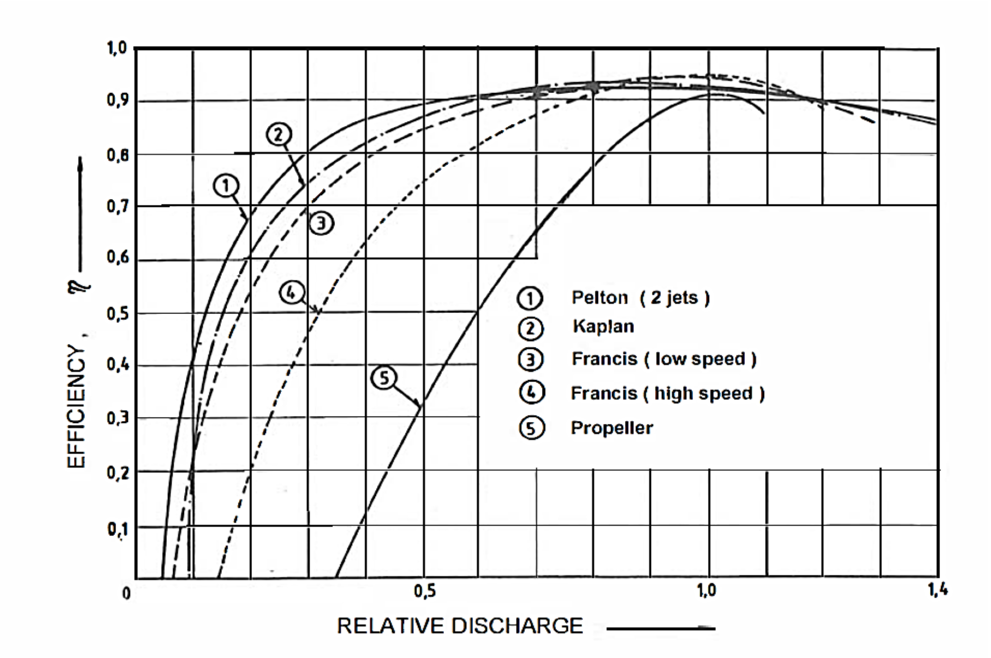


*Figure 4.7: Typical turbine efficiency curves*

## 4.5 Head loss

In most cases, the head loss has not been provided. The alternative has been to estimate using the Manning's equations, which also used in nMAG, and data obtained from literature (CDM, 2011, 2014, 2018) to estimate the coefficient.

$hl = kf * Q^2$

Where kf is the head loss coefficient calculated as

$$kf = \frac{L}{n^2 * A^2 * R^{\frac{4}{3}}}$$

where A and L are the area and length of the conveying structure, i.e. pipe, tunnel. n the manning's number and R the hydraulic radius.

# 5.0 Spreadsheet model

One limitation of the study was accessibility of commercial programs. A spreadsheet model was therefore developed using Microsoft excel program to optimize hourly production and find strategies for production. The aim is to conduct simulations, test different reservoir strategies and to optimize production. The following chapters describe the model structure, simulation and optimization the reservoirs powerplants in the Cascade.

## 5.1 Model structure

The production system setup is such that each reservoir has inflow and releases from the reservoirs are used for energy production. Excess water in the reservoir is considered as spill. The reservoir is connected to a power plant that has a turbine.

The model comprises a number of spreadsheets which produce a specific output by utilizing different parameters, functions, including inflow, outflow, reservoir, Production, firm distribution, price, Optimizer and Results spreadsheets.

Four powerplants have been used in the model to simulate, strategize and optimize their reservoirs. Monte Lirio has no storage and is not included in the model. There are 4 modules which are described under the subsections of Hydrology, Reservoir operation, Production, Energy market, Optimization and Results modules.

### 5.1.1 Hydrology

**Inflow**

Inflow for all the power stations is based on hourly inflow from El Alto. The inflow for the downstream powerplants is computed by the summation of the total outflow of the upstream powerplant releases and local inflow to that power plant. Local inflow is computed by scaling of El Alto inflow using the equation presented in chapter 4.2.

$Q_{in.} = Q_{out}. + Q_{local}$

Where $Q_{out.}$ is the total water released from the upstream power plant and $Q_{local}$. the inflow from the local catchment

**Outflow**

The total outflow is evaluated by using a mass balance of the production releases, the environmental flow and the spill.

$$Q_{out.} = Q_{turb}. + Q_{spill} + Q_{env.}$$

Where $Q_{out.}$ is the total water released to the downstream power plant. $Q_{prod}$. the turbine releases. $Q_{spill}$ the water spelt and $Q_{env.}$ Representing environmental releases.

### 5.1.2 Reservoir operation

The purpose of this module is to conduct simulation of the reservoirs using mass balancing of the inflows, outflows and storage fluctuations. The Continuity equation presented below has been used for each reservoir and in each time step to conduct a reservoir water balance.

$$S(t) = S(t\text{-}1) + Q_{in}.\,(t) - Q_{turb.(}t) - Q_{spill}(t) - Q_{env.}(t)$$

S(t) the volume stored in the current time step. S(t-1) the volume of water in the previous time step. $Q_{in.}(t)$ is the volume of water flowing into the reservoir in the current time step. $Q_{turb.}(t)$ the volume of water released through the turbines in the current time step. $Q_{spill.}(t)$ the volume of water spill in the current time step and $Q_{env.}(t)$ which accounts for environmental flows.

In addition to the continuity equation, several functions and have been developed represented by non-equation relationships, that specify the limits and conditions for water release.

**Reservoir storage**

A boundary condition has been set for the reservoir to operate between the minimum and maximum reservoir storage which allows for spilling when at maximum and filling at minimum storage. The condition operates as follows;

If (S(t-1) + X(t)) >= Smax. Spill; otherwise store water

X(t) which specifies the gain or loss of water in that timestep computed by

$X(t) = Q_{in.}(t) – Q_{spill}(t) – Q_{env.}(t)$

S(t) the volume stored in the current time step. S(t-1) the volume of water in the previous time step. $Q_{spill.}(t)$ the volume of water spill in the current time step and $Q_{env.}(t)$ which accounts for environmental flows.

**Reservoir runtime**

The reservoir run time is a series of functions and conditions used to check if the amount of water in the reservoir is enough to run at full capacity. Two functions have been used to operate this criterion. The first function is used to compute the ratio of total outflow which includes the turbine capacity at full production and restrictions against the water available in storage in the previous time step and returns a value to either operate at full capacity on not.

If (storage(t-1)/(Turbine (t) + Env. Q(t)) >= 1) return 1 if TRUE, 0 if FALSE

**Minimum HPP runtime**

The second function checks if the water available in storage for the previous time step can be used to operate at maximum production for a specific number of hours designated as the minimum runtime. If the power plant can only operate at full capacity when the minimum runtime of say, two hours, is specified then this function will check if this condition is fulfilled and allows the next two or more timesteps to operate at full capacity.

If (reservoir runtime >= min runtime) return >min runtime, otherwise return 0

## Regulation function

The regulation function is used to decide the amount of water that can be released to the power plant. The function operates by checking;

> if ($Q_{in../firm}$ + $Q_{env.}$) >= S(t-1)
>
> where $Q_{in./firm.}$(t) is the volume of water, the greater between the inflow to the reservoir or the firm capacity in the current time step. $Q_{env.}$(t) the environmental flow in the current time step and S(t-1) the volume of water in the previous time step

which if met checks whether the powerplant can run on full capacity from the minimum runtime. If not met the power plant can run on the maximum of firm and river inflow.

## Production Capacity function

The variable of optimizing production is the amount of turbine releases in each planning period. The optimization in this study is based on the criteria of reservoir regulation where the most water is stored and allocated to a time of value, the time of value in this case is when either the spot price is either high or the reservoir storage is high.

An objective function defining the amount of release has been treated with weighting factors that depend on the reservoir and historical spot prices. The purpose of this function is to decide whether to allocate releases to the power plant or to store the water. The function is tested with different weights to determine the optimal release that can be achieve in the simulation period.

Water release have been set as a function of two variables, the reservoir filling criteria and the spot price difference. The two variables are used as the weighting factor to determine the optimal releases. The reservoir filling criteria determines how the reservoir will be operated by specifying the minimum reservoir operating capacity. The spot price difference is used to control releases depending on the difference in spot price of the current and next prices. The decision is met by using an OR function that releasees water to the power plant if one of the two conditions is met as follows

> If OR(S(t-1)/$S_{max.}$ >= R, P(t-1)/$P_{av.(}$24) >= P) Release, Otherwise store

Where S(t-1) the volume (mill. $m^3$) of water in the previous time step. (R) reservoir filling criteria defining specifying the reservoir operating zone for the powerplant. P(t-1) (USD/MWh) is the spot price in the current time step. Pav.(24) average spot price (USD/MWh) for the next 24 hours and (P) spot price difference variable defining the ratio between the spot price in a time step against the average for the proceeding 24 hours which is used to decide if the average spot price is higher in the next time steps and decides whether or not to produce.

### 5.1.3 Energy calculations

**Energy production**

The production module is used to compute the energy generated from the releases from the reservoir module. The water released to the powerplant is first checked if it meets the minimum and maximum production capacity which when satisfied is used to compute the energy using the energy equation.

$$P = \rho g Q H \eta$$

Where $\rho$ is the density of water ($Kg/m^3$), g is the acceleration due to gravity ($m/s^2$), Q is the water release to the turbines (m3/s), H is the net head (m) of water and $\eta$ is the total efficiency.

The net head is the summation of the gross head and the total head losses with the total head loss evaluated using the manning's equation.

$$hl = kf * Q^2$$

Where kf is the head loss coefficient calculated as

$$kf = \frac{L}{n^2 * A^2 * R^{\frac{4}{3}}}$$

where A and L are the area and length of the conveying structure, i.e. pipe, tunnel. n the manning's number and R the hydraulic radius.

### 5.1.4 Energy market

The energy market module consists of the firm power distribution and historical spot price inputs. The daily firm distribution curve is based on the average production distribution for the four plants in the cascade and redistributed hourly with an adjusted form curve

The spot price module comprises of the historical spot prices and another series of the averaged 24-hour spot prices from the next 24 hours

### 5.1.5 Optimization and Results

A macro has been used to run different sets of price difference and reservoir filling criteria. For each price difference, the macros test a range of the reservoir criteria and outputs the total production (GWh), average daily gross revenue (USD/day) which is the product of the energy and spot price over the simulation period, operation hours (%) and spill (%).

## 5.2 System setup

The simulation setup has been done for the four power plants as shown in figure 5.1. Inflows from El Alto have been used from 2016 to 2018 while turbine efficiency is based on the typical turbine curves, chapter 4.4.

*Figure 5.1: Spreadsheet simulation setup*

## 5.3 Calibration and validation model

The setup for the simulation is based on hourly inflow from El alto and a runtime of two hours. The main parameters adjusted are the reservoir filling criteria and the maximum power (MW). The filling criteria for all the reservoir has been set to start at 10% for all the reservoir. The calculated head loss coefficients have been adjusted to meet the maximum hourly observed energy.

The Panamanian market has zero spot prices. There is however no correlation between the zero prices and actual energy production as power plants are still producing during these hours. Two simulations have been tested to see the effects of zero pricing on production. Simulations have been tested on EL Alto power plant. Simulation one has a function that restricts the release of water when prices are zero while simulation two allows for firm production during zero pricing. Figure 5.2 shows the results of the two simulations.

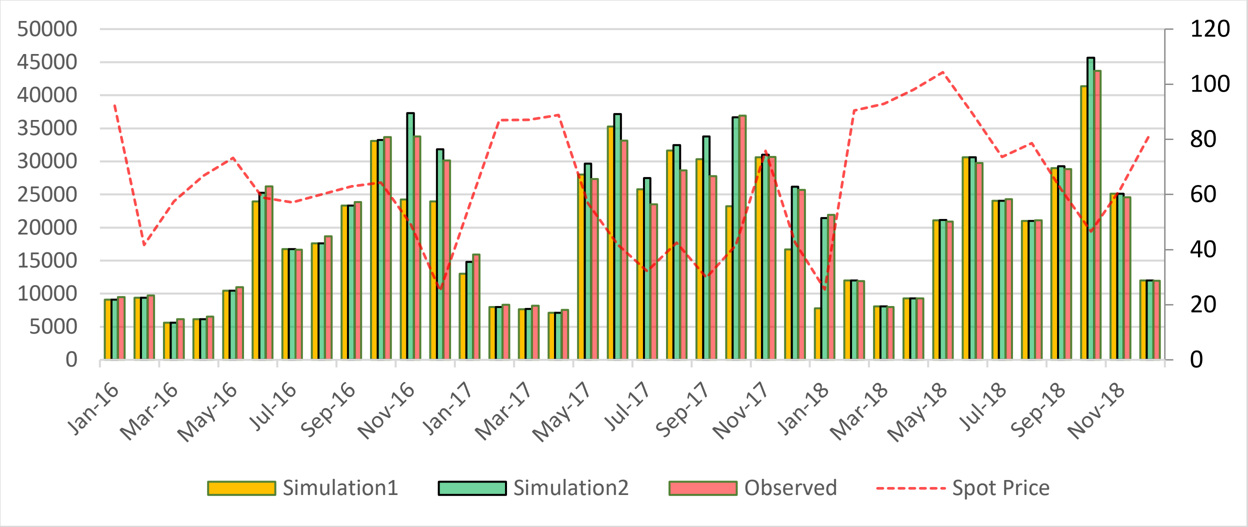


*Figure 5.2 Monthly Energy (MWh) comparison of simulations for zero pricing (USD/MWh)*

The simulation with zero pricing, simulation one, gives a lower production at the end of the years 2016 and 2017. However, it gives a closer distribution between the May and September of 2017. Using correlation comparison between the simulated and observed, figure 5.3,

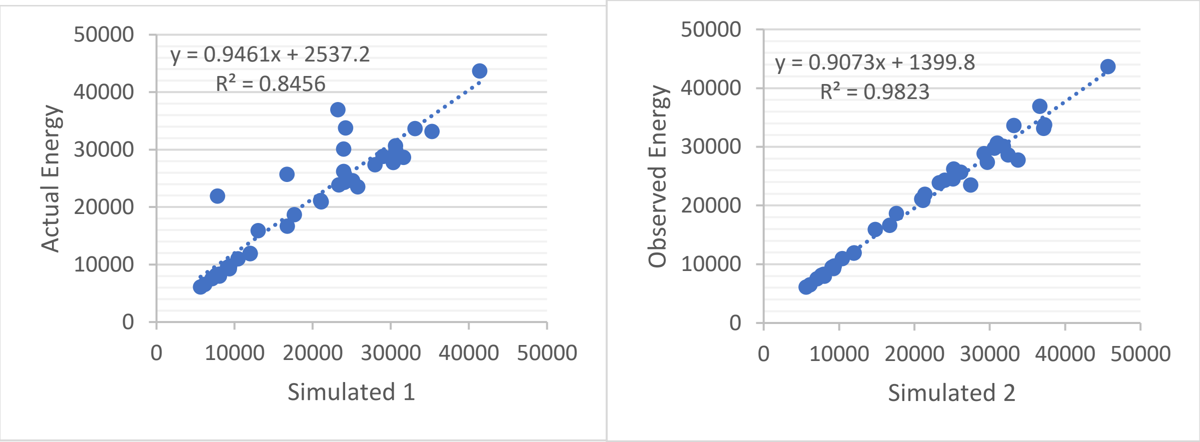


*Figure 5.3 Scatter plot comparison for zero pricing simulations (MWh)*

Simulation two gives a better correlation with the observed and performs better for the years 2016 and 2018. Therefore, the setup producing simulation two results has been adopted.

### 5.4 Simulation results and discussion

Running the initial setup produces a total generation of 100 GWh of the four power stations over the entire simulation period. The strategy generates a higher gross revenue of 9.4 million USD which is 5% more than the observed with a lower average power plant operation time of 4% when compared to the observed.

*Table 5.1: Simulation Results for the period 2016 - 2018*

| | **TOTAL GENERATION (GWH)** | | **AV. SPILL (%)** | **AV. OPERATIONAL HOURS (%)** | | **AV. GROSS REVENUE (MILL. USD)** | |
|---|---|---|---|---|---|---|---|
| | Simulated | Observed | Simulated | Simulated | Observed | Simulated | Observed |
| **EL ALTO** | 778 | 756 | 9.0 | 78 | 88 | 43.59 | 43.29 |
| **BAJO DE MINA** | 709 | 686 | 14.0 | 79 | 84 | 41.57 | 39.21 |
| **BAITUN** | 1074 | 1063 | 11.2 | 78 | 79 | 63.36 | 60.44 |
| **BAJO FRIO** | 679 | 636 | 15.7 | 82 | 81 | 40.76 | 36.93 |
| **TOTAL** | **3 240** | **3 140** | **12** | **79** | **83** | **189** | **180** |

The distribution of production for the power plants is similar with Bajo Frio producing 1% less which is taken up by Baitun, Figure 5.4

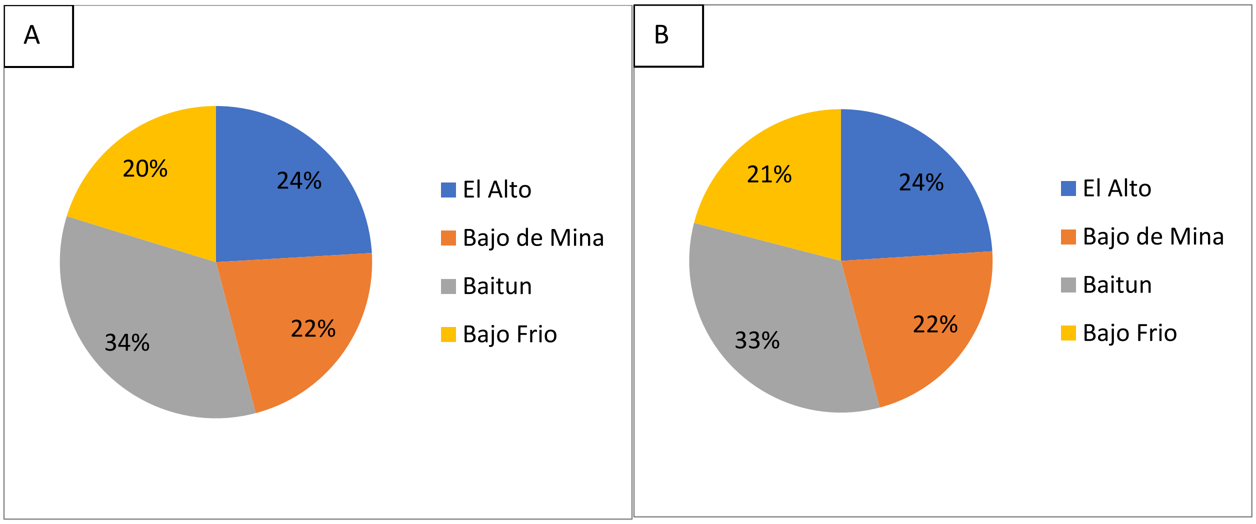


*Figure 5.4: Total Generation: A is the simulated Energy (GWh) production. B. is the observed Energy production*

Figure 5.5 shows the total monthly Energy production for the cascade.

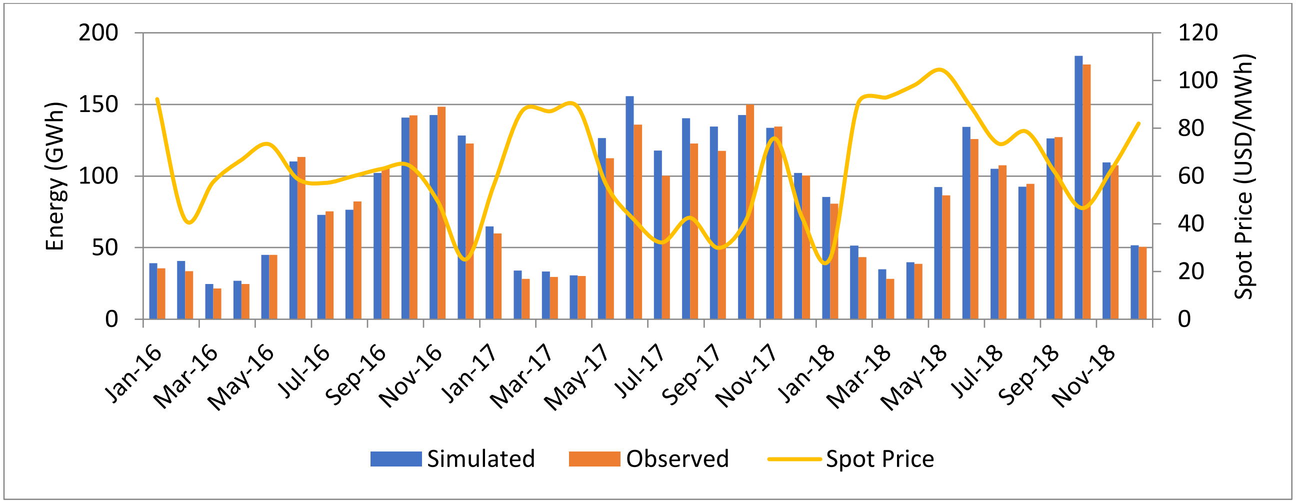


*Figure 5.5: Total Monthly Energy (GWh) for the El Alto, Bajo de Mina, Baitun and Bajo Frio and Monthly Average Spot Prices (USD/MWh)*

Based on the 3-year simulation the initial model setup generates an average annual energy of 45 GWh, 4.3 % more than the observed production and a gross annual average of 6.4%.

### 5.5 Optimization results and discussion

Two optimization criteria of optimization have been tested to study the system. The first criteria is to maximize the production for the specified simulation period. The second criteria is to maximize the computed average daily revenue which has been used as the main criteria for optimization. The purpose is to, both, analyses the system response as well as the influence of the weighting factors on the reservoir and production based on the model's operation detailed in the previous sections.

#### 5.5.1 Production maximization

Optimization of production gives a range of operation of the reservoirs in the cascade between 60 and 80% of the total volume. The weighting factor representing the price difference ranges between 1.2 and 1.8.

*Table 5.2: Optimal price difference and reservoir regulation criteria variables*

| | RUN TIME | PRICE DIFF | RES FILLING |
|---|---|---|---|
| | (hrs) | (%) | (%) |
| **EL ALTO** | 2 | 1.3 | 0.6 |
| **BAJO DE MINA** | 2 | 1.5 | 0.5 |
| **BAITUN** | 2 | 1.2 | 0.6 |
| **BAJO FRIO** | 2 | 1.8 | 0.8 |

The Bajo Frio powerplants produces the highest variable combination with a reservoir filling criterion of 0.8 and a price difference of 1.80, table 5.2. The reservoir must be kept high to reduce losses with frequent releases even at lower prices to maximize production as can be seen in figure 5.6 were the reservoir is being kept above 0.8 million cubic meters with the plant running several start/stop generation sequences.

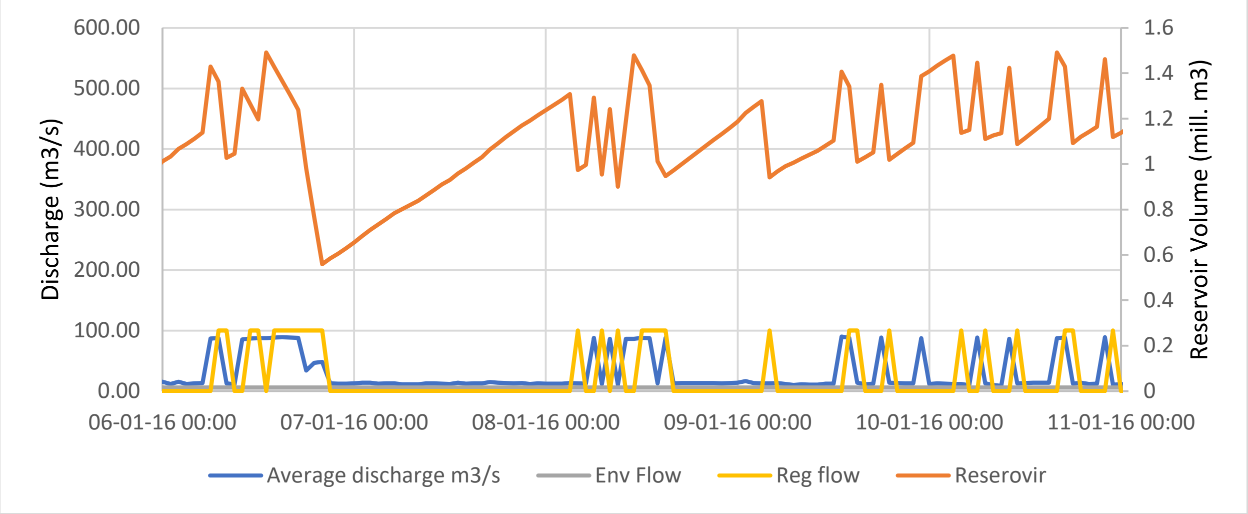


*Figure 5.6 :Optimized Bajo Frio reservoir water balance*

Bajo de Mina also uses a high price difference variable, this trend is seen for small reservoirs with a lower peaking capacity. Baitun with a larger reservoir and peaking capacity produces the least price difference. table 5.3

*Table 5.3: Reservoir Peaking hours*

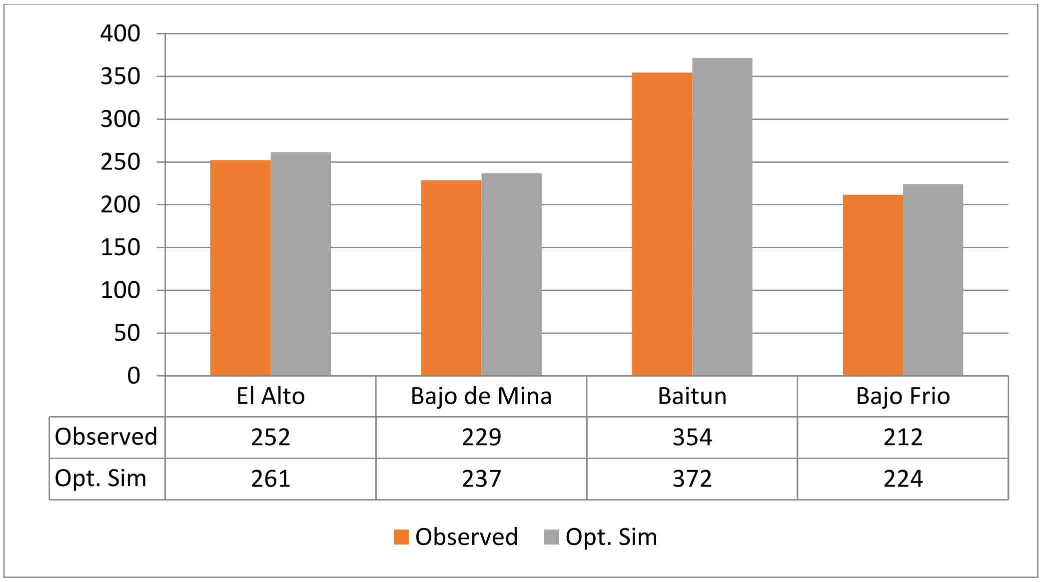
| | CAPACITY (M3/S) | RESERVOIR VOLUME (MILL. M3) | PEAKING CAPACITY (HRS) |
|---|---|---|---|
| **EL ALTO** | 60 | 1.1 | 5 |
| **BAJO DE MINA** | 56.5 | 0.87 | 4 |
| **BAITUN** | 75 | 2.48 | 9 |
| **LA POTRA** | 100 | 1.5 | 4 |

The operation time reduces on average by 31% when compared to the observed production in table 5.1 with a total increased production of 154 GWh for the entire simulation period.

*Table 5.4:Optimization Results for the period 2016 - 2018*

| | **TOTAL GENERATION (GWH)** | | **AV. SPILL (%)** | **AV. OPERATIONAL HOURS (%)** | | **AV. GROSS REVENUE (MILL. USD)** | |
|---|---|---|---|---|---|---|---|
| | Simulated | Observed | Simulated | Simulated | Observed | Simulated | Observed |
| **EL ALTO** | 784 | 756 | 9.6 | 48 | 88 | 45.93 | 43.29 |
| **BAJO DE MINA** | 710 | 686 | 15.0 | 54 | 84 | 43.61 | 39.21 |
| **BAITUN** | 1115 | 1063 | 12.6 | 53 | 79 | 70.01 | 60.44 |
| **BAJO FRIO** | 686 | 636 | 14.6 | 53 | 81 | 43.04 | 36.93 |
| **TOTAL** | **3 294** | **3 140** | **13** | **52** | **83** | **203** | **180** |

Figure 5.7 shows the annual average generation for the based on the optimized production.



| | El Alto | Bajo de Mina | Baitun | Bajo Frio |
|---|---|---|---|---|
| Observed | 252 | 229 | 354 | 212 |
| Opt. Sim | 261 | 237 | 372 | 224 |

*Figure 5.7: Annual Average Energy (GWh) production maximization*

In summary, using the production maximization increases the annual average production by 47 GWh which is 4.5 % higher than the observed and with an increased revenue of 12% for the simulation period.

### 5.5.2 Revenue maximization

Two strategies have been used for revenue optimization. The initial simulation setup is based on operating the power plant with a firm strategy and surplus which has been used for the first strategy. The second strategy is based on the assumption that the power plant will only operate at full capacity.

**Strategy 1**

Table 5.13 shows the variables for revenue optimization. The price difference variable decreases while the reservoir filling criteria reduces when compared to the production maximization.

*Table 5.5: Optimal price difference and reservoir regulation criteria variables (Strategy 1)*

| | RUN TIME | PRICE DIFF | RES FILLING |
|---|---|---|---|
| | hrs | No. | No. |
| **EL ALTO** | 2 | 1.1 | 0.9 |
| **BAJO DE MINA** | 2 | 1.1 | 0.7 |
| **BAITUN** | 2 | 1.0 | 0.9 |
| **LA POTRA** | 2 | 1.1 | 0.8 |

Bajo Frio and Bajo de Mina use a lower reservoir filling variable. The reservoir at Bajo Frio can be observed to be more stable than the one in figure 5.8 with longer production releases and less intermittent peaking.

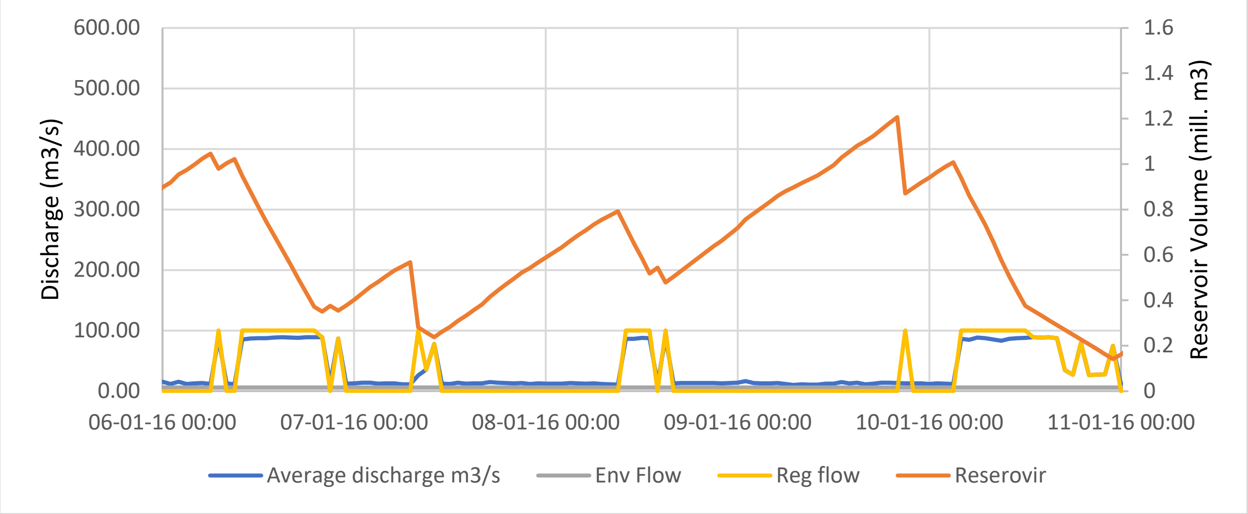


*Figure 5.8: Optimized Bajo Frio reservoir water balance (strategy 1)*

The total generation is 115 GWh more than the observed, Table 5.6.

*Table 5.6: Optimization Results for the period 2016 – 2018 (strategy 1)*

| | **TOTAL GENERATION (GWH)** | | **AV. SPILL (%)** | **AV. OPERATIONAL HOURS (%)** | | **AV. GROSS REVENUE (MILL. USD)** | |
|---|---|---|---|---|---|---|---|
| | Simulated | Observed | Simulated | Simulated | Observed | Simulated | Observed |
| **EL ALTO** | 773 | 756 | 10.5 | 58 | 88 | 48.00 | 43.29 |
| **BAJO DE MINA** | 708 | 686 | 15.0 | 54 | 84 | 45.80 | 39.21 |
| **BAITUN** | 1105 | 1063 | 13.2 | 54 | 79 | 72.29 | 60.44 |
| **BAJO FRIO** | 669 | 636 | 14.6 | 54 | 81 | 44.20 | 36.93 |
| ***TOTAL*** | **3,255** | **3,140** | **13** | **55** | **83** | **210** | **179.87** |

The Energy production and revenue of the cascade increases by 3.7 %, and 17%. Figure 5.5 shows the annual average generation based on the optimized production. The total average energy increases by 37 GWh.

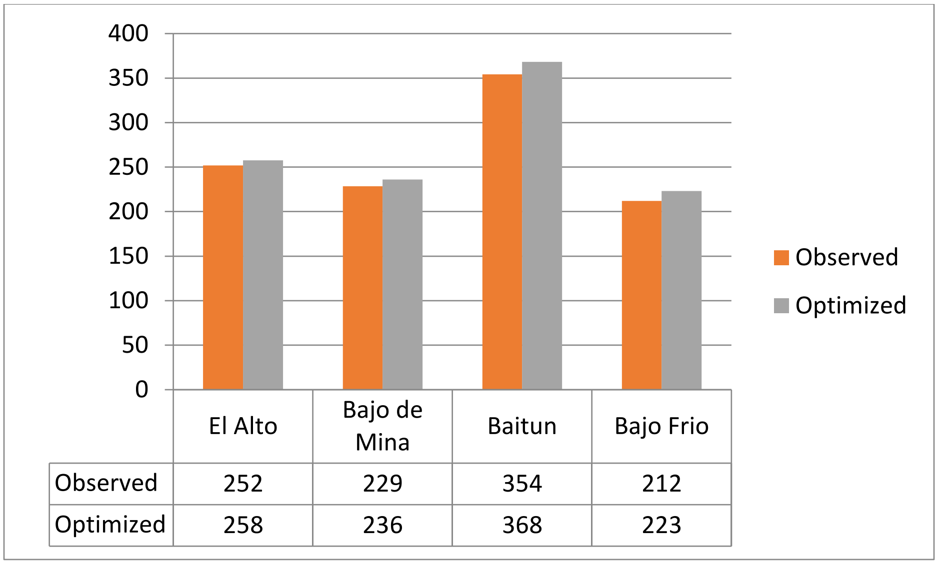


*Figure 5.9: Annual Average Energy (GWh) for revenue maximization*

## Strategy 2

Table 5.7 presents the optimization variables from the second strategy. The values produced are the same as strategy one.

*Table 5.7: Optimal price difference and reservoir regulation criteria variables (Strategy 1)*

| | RUN TIME | PRICE DIFF | RES FILLING |
|---|---|---|---|
| | hrs | No. | No. |
| **EL ALTO** | 2 | 1.1 | 0.9 |
| **BAJO DE MINA** | 2 | 1.1 | 0.7 |
| **BAITUN** | 2 | 1.0 | 0.9 |
| **LA POTRA** | 2 | 1.1 | 0.8 |

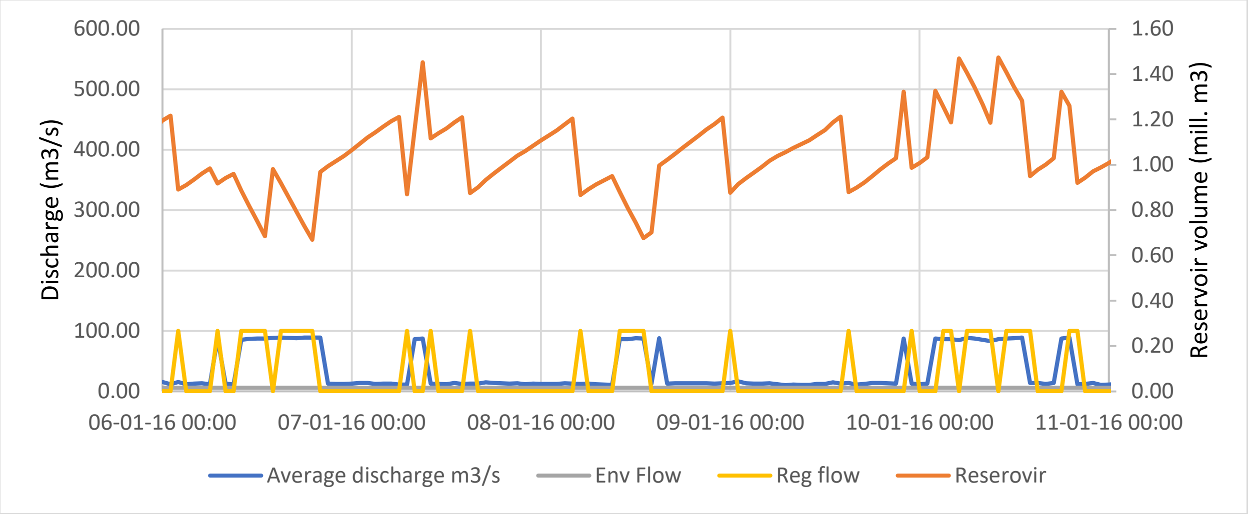


*Figure 5.10: Optimized Bajo Frio reservoir water balance (strategy 2)*

The reservoir during the same period is showing more peaks compared to strategy one. However, the reservoir volume is kept more stable than strategy two.

The total annual energy is 115 GWh higher than the observed which is the same as strategy two.

*Table 5.8: Optimization Results for the period 2016 – 2018 (strategy 1)*

| | **TOTAL GENERATION (GWH)** | | **SPILL (%)** | **OPERATIONAL HOURS (%)** | | **GROSS REVENUE (MILL. USD)** | |
|---|---|---|---|---|---|---|---|
| | Simulated | Observed | Simulated | Simulated | Observed | Simulated | Observed |
| **EL ALTO** | 775 | 756 | 10.7 | 46 | 88 | 47.47 | 43.29 |
| **BAJO DE MINA** | 706 | 686 | 15.5 | 52 | 84 | 45.22 | 39.21 |
| **BAITUN** | 1105 | 1063 | 13.3 | 51 | 79 | 72.09 | 60.44 |
| **BAJO FRIO** | 669 | 636 | 14.8 | 52 | 81 | 44.06 | 36.93 |
| | | | | | | | |
| **LA POTRA** | *338* | *315* | *14.8* | *52* | *81* | *22.20* | *18.24* |
| **SALSIPUEDES** | *331* | *320* | | *52* | *81* | *21.86* | *18.69* |
| | **3,255** | **3,140** | **14** | **50** | **83** | **209** | **179.87** |

However, strategy 2 produces 3.6% annually and a revenue of 16 % which is near to but lower than strategy one. The optimal strategy is to operate the cascade using strategy one.

# 6.0 NMAG Model

The purpose of this section is to review and study the entire powerplant system, compare the simulated production of the current and future setup and the impact of climate change on the production. A simulation for the entire production system has been run based on inflow and average demand distribution for the period 2016 to 2018 with the designed firm power demand.

## 6.1 nMAG system setup

The following section presents some of the considerations made for setting up the cascade in nMAG

### 6.1.1 El Alto Inflow

nMAG scales inflow based on the average annual runoff for a given time series. A time series of not less than 30 years is recommended for average annual inflow. The inflow provided by the powerplant companies is based on a historical time series. Since Inflow at El Alto is available from 2014, the time series was extended by scaling using Paso Canoas time series as explained in chapter 4.2. figure xx Shows the extended time series.

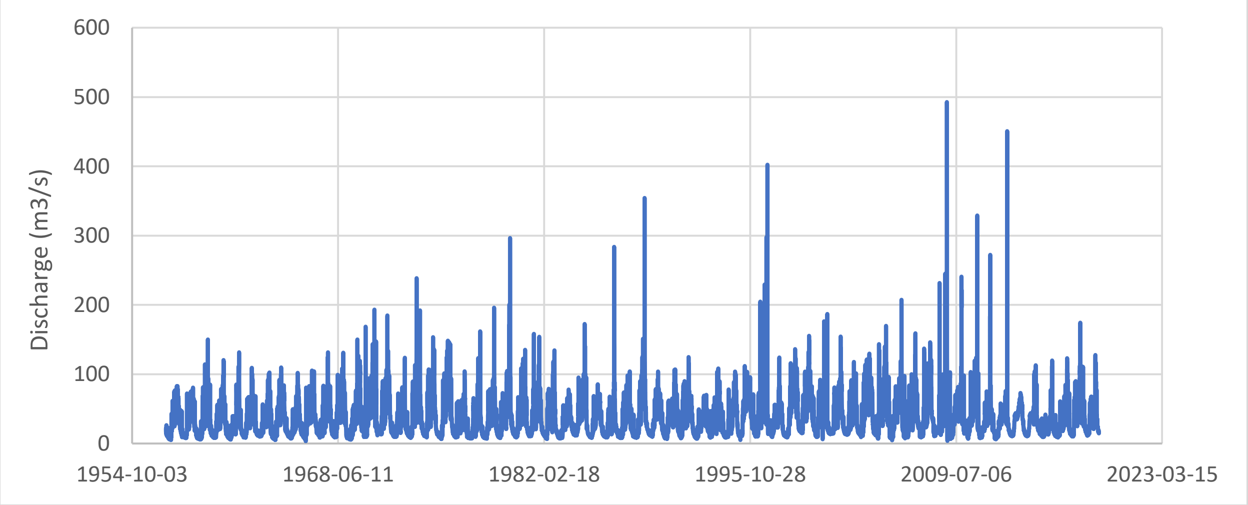


*Figure 6.1: EL Alto extended inflow (1957 -2018)*

### 6.1.2 Monte Lirio inflow

nMAG conducts water balance computations and transfers outflows to the next station. The inflow used at an upstream station will significantly affect the receiving station. Monte Lirio has no reservoir, the production is based on the inflow. The scaling of its inflow in is based on the hydrology from Volcan and El alto. The Using only the Volcan gauging station produces a near flat distribution between the dry and rainy season. El Alto has a better distribution that is similar to the actual production but produces a lower energy production in the dry season. Different weighting factors have been used to find the combination that gives a suitable distribution.

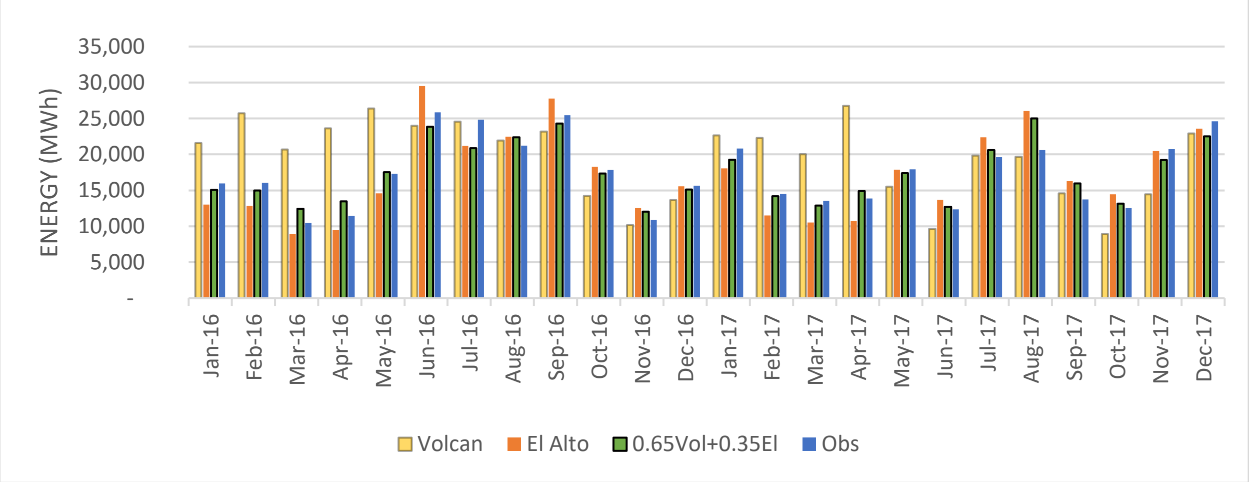


*Figure 6.2: Reservoir guide curve for El Alto*

A combination of the two stations has been used to adjust the inflow using weighting factors of the two stations. A combination of 35% of flows from El Alto and 65% from Volcan gives a suitable distribution which is tested against two other cases.

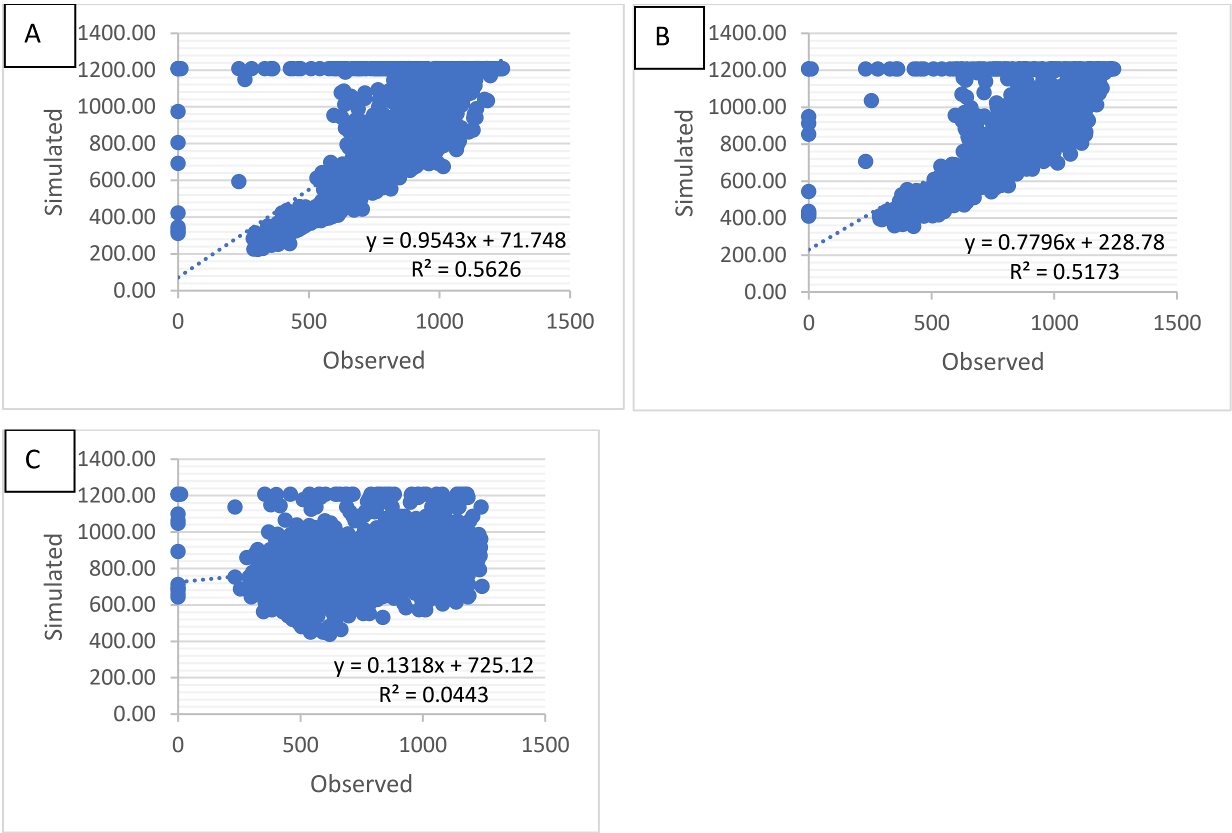


*Figure 6.3: Simulated vs Observed Energy (MWh) for Monte Lirio, A. Based on El Alto inflow, B., 35% El Alto and 65% Volcan, C Volcan.*

El Alto inflows are found to give a better correlation with the observed daily energy and have been used in the simulations. The rest of the power plants have been scaled in nMAG using El Alto inflow.

### 6.1.3 Firm Energy and distribution

The firm energy of the entire system is based on an allocated Firm power for each plant. Generally, all the power plants have a plant factor between the range of 0.40 and 0.50 except for Paso Ancho which is as high as 0.75. A firm distribution has been used based on the average of the 3 years used in the simulation.

### 6.1.4 Operational strategy

The operation strategy used is the automatic balance strategy which is recommended for small reservoirs in nMAG. The strategy is to produce the most energy from the available water.

## 6.2 Current production System

Figure 6.5 shows the nMAG setup of the current production system. La Potra auxiliary is used for generating energy from environmental flows. However, generation for this power plant is not include, since the generation data was not provided.

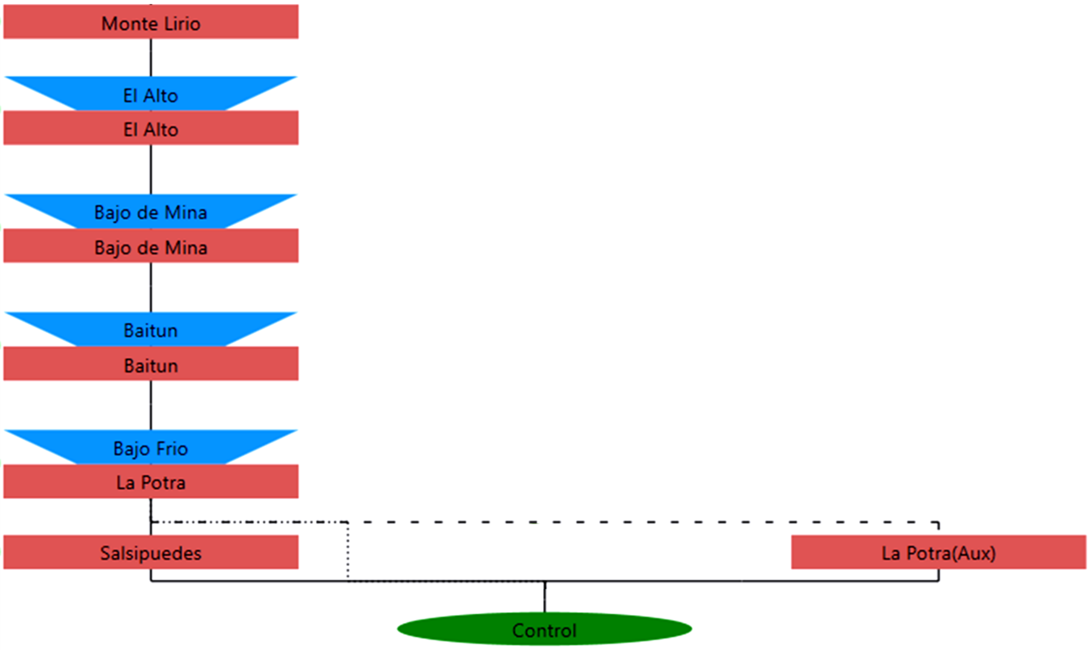


*Figure 6.4: NMAG schematic representation of current system*

An annual firm energy of 1157 GWh has been used in the simulation.

#### 6.2.1 Simulation results and analysis

Figure 6.5 shows the total monthly simulated results for the 5 power plants. The production strategy in nMAG generates 8.7% (345 Gwh) more energy compared to the observed for the simulation period 2016 – 2018.

*Table 6.1: Simulated vs Observed Total Annual Energy (MWh)*

| | SIMULATED | OBSERVED | DIFFERENCE |
|---|---|---|---|
| **2016** | 1,244 | 1,205 | 39 |
| **2017** | 1,646 | 1,400 | 247 |
| **2018** | 1,427 | 1,367 | 60 |
| **TOTAL** | 4,317 | 3,971 | 346 |

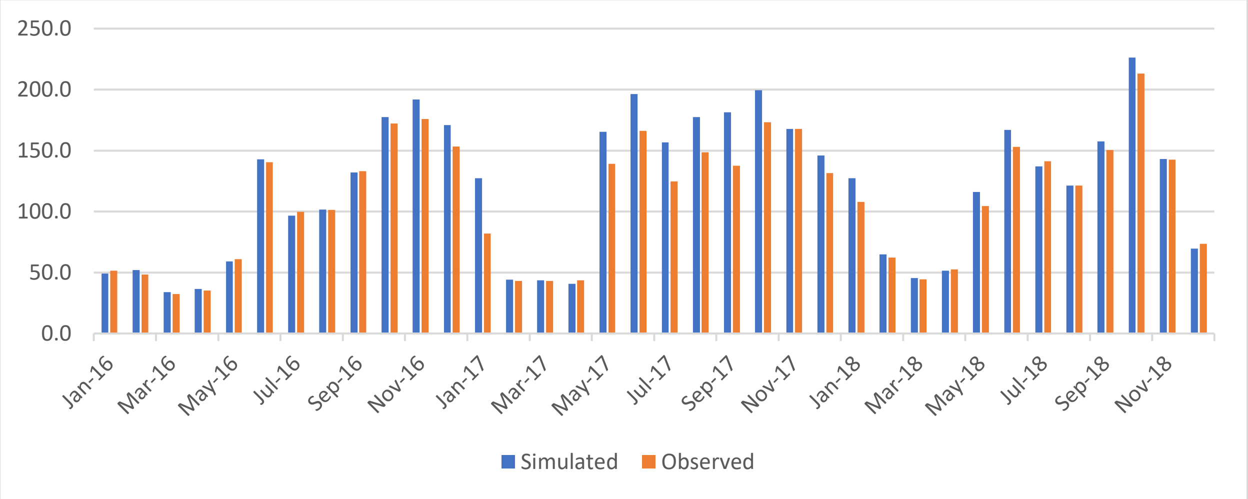


*Figure 6.5: Total Energy (GWh) Monte Lirio, El Alto, Bajo de Mina, Baitun and Bajo Frio*

The trend is similar to that generated from the spreadsheet model were 2017 is producing more Energy compared to the other two years. The months of May to September 2017 show a deviation from the observed data as shown in figure 6.6 with 2017 giving the highest deviation.

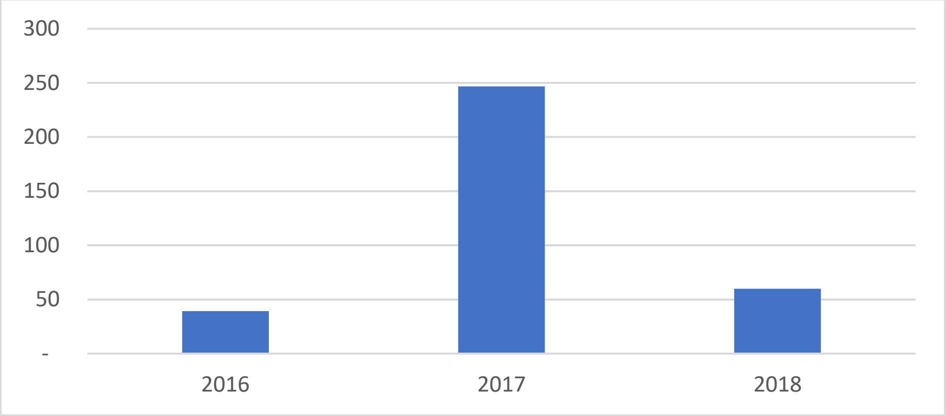


*Figure 6.6: total Annual Energy (GWh) difference of Observed from Simulated Energy*

Table 6.2 shows the annual average generation of the powerplants.

*Table 6.2: Annual Average Energy (GWh)*

| | AVERAGE ANNUAL ENERGY (GWH) | |
|---|---|---|
| | Simulated | Observed |
| **MONTE LIRIO** | 291 | 277 |
| **EL ALTO** | 276 | 252 |
| **BAJO DE MINA** | 244 | 228 |
| **BAITUN** | 384 | 354 |
| **BAJO FRIO** | 230 | 212 |
| **TOTAL** | **1425** | **1324** |

EL Alto power plant has been used to compare the daily production as it has the actual inflow. nMAG is constantly generating for some months with high inflow in all the years which gives a much higher annual average energy of 101 GWh (8%) more than the observed.

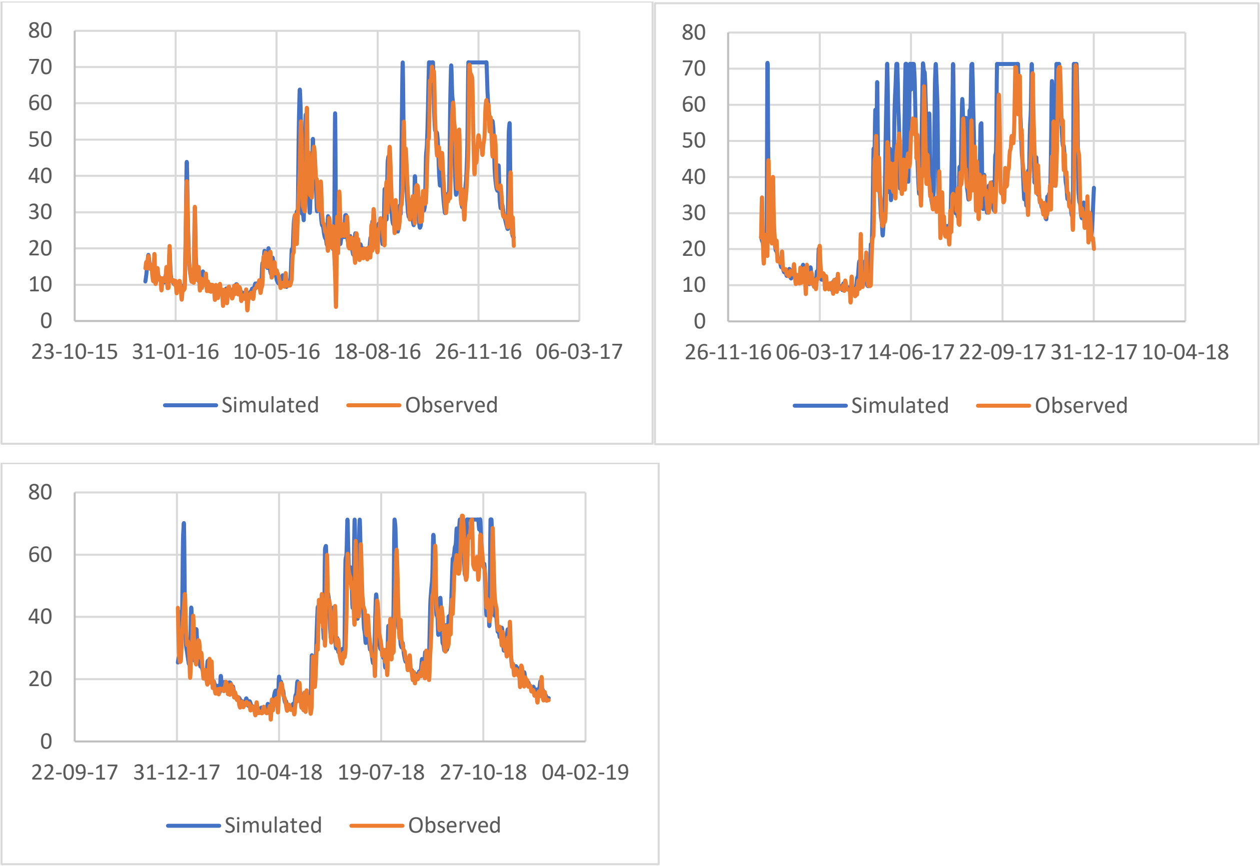


*Figure 6.7: El Alto Average Daily Simulated vs Observed Production (MW)*

### 6.3 Future production system

The future production system will include Pando and Burica which have been added to the current system setup in nMAG. Figure 6.8 shows the layout of the powerplants in the future.

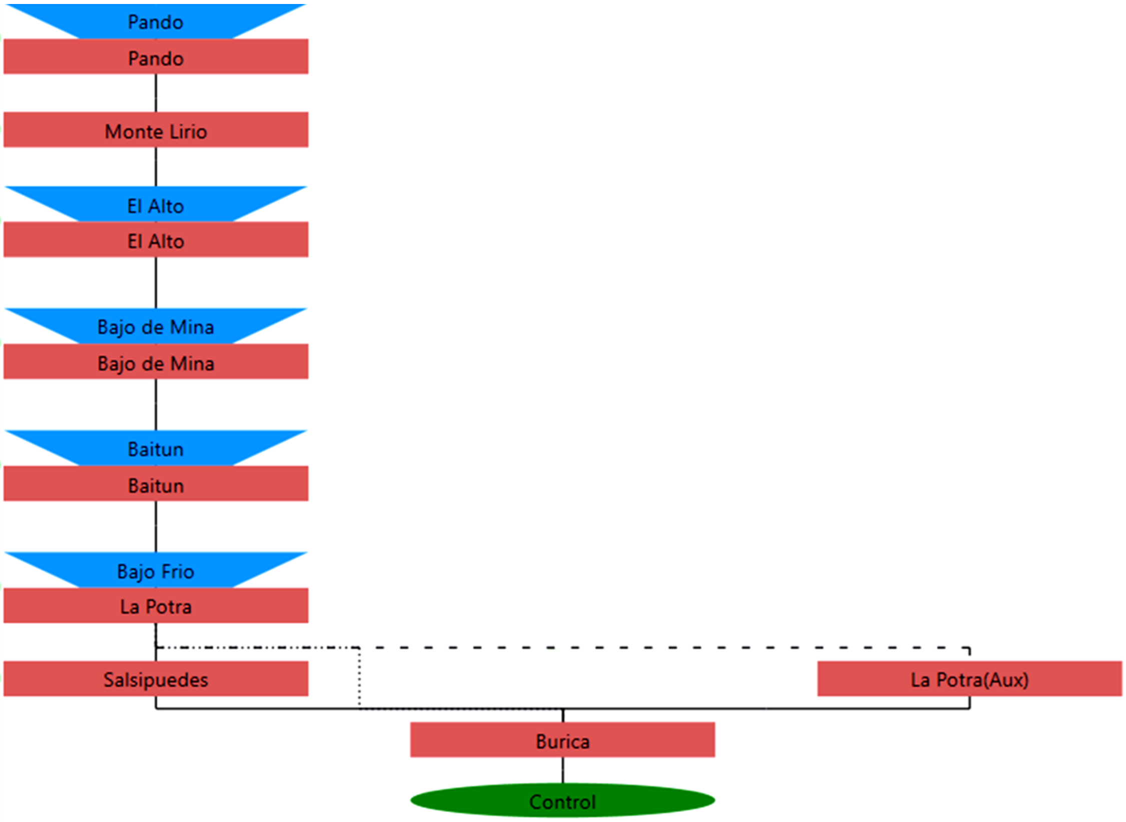


*Figure 6.8: NMAG schematic representation of Future system*

The future system has been set with the same firm distribution as the current setup but with a firm Energy allocation of 1656 GWh.

### 6.3.1 Simulation results and analysis

The Annual average production of the Chiriquí Viejo basin increases by 528 GWh annually based on these power plants in the study. The introduction of a regulation at Pando power plant upstream of Monte Lirio increases production at Monte Lirio by 0.4 GWh (0.1%) and 0.2 GWh for both Bajo de Mina and Baitun.

*Table 6.3: Annual Average Energy (GWh) - Current vs Future Production System*

|  | ANNUAL AVERAGE (GWH) |  |  |
|---|---|---|---|
|  | Current | Future | Difference |
| **PANDO** |  | 231.1 |  |
| **MONTE LIRIO** | 290.8 | 291.2 | 0.40 |
| **EL ALTO** | 275.8 | 275.8 | - |
| **BAJO DE MINA** | 244.2 | 244.3 | 0.10 |
| **BAITUN** | 384.1 | 384.2 | 0.10 |
| **BAJO FRIO** | 230.2 | 230.2 | - |
| **BURICA** |  | 296.6 |  |
|  |  |  |  |

Comparing the difference in production of Monte Lirio based on the Current and Future setup shows increased production in the rainy season. Since there will be regulation taking place at Pando, the effect of storage increases production to Monte Lirio based on the strategy in nMAG.

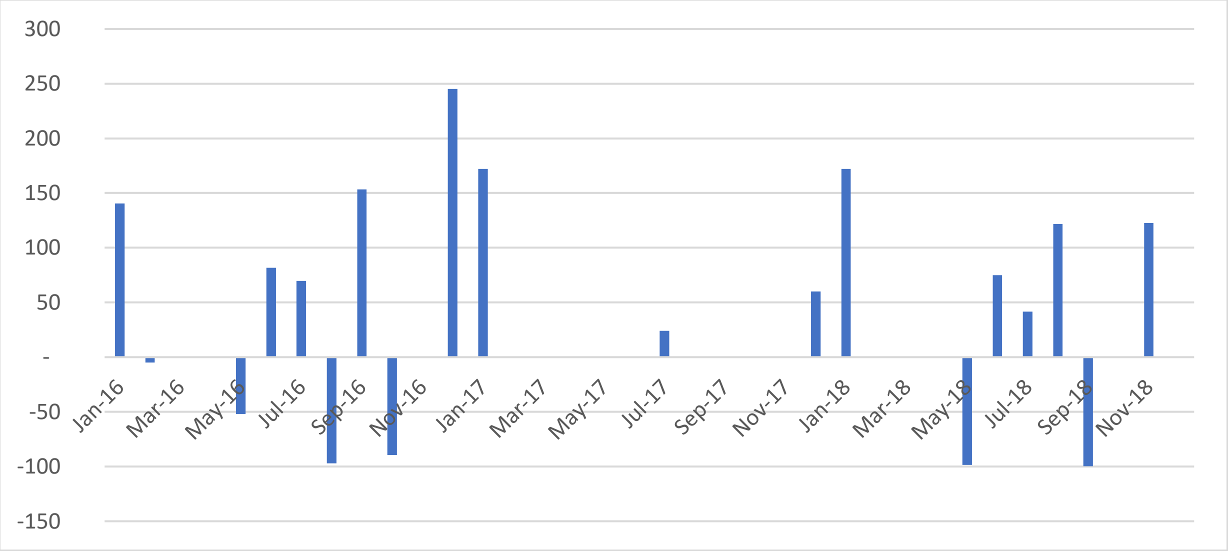


*Figure 6.9: Monte Lirio difference in production between current and future system (MWh)*

### 6.4 Climate change impact on Production

nMAG has been used to conduct simulations of production based on these estimates with the future setup created in chapter 6.3. The simulation is based on the year 2039 with a 12% reduction of inflow and assuming all the power plants will be in operation after 40 years.

The 12% reduction in inflow reduction does not significantly change the future production as shown in table 6.4. Therefore, using a strategy of maximizing production will be able to meet the demand unless otherwise affected by changes in consumption needs and energy regulation.

*Table 6.4: Impact of Climate change on Future production*

| | ANNUAL AVERAGE (GWH) | |
|---|---|---|
| | Current | Future (climate) |
| **PANDO** | 231.1 | 231.1 |
| **MONTE LIRIO** | 291.2 | 291.2 |
| **EL ALTO** | 275.8 | 275.8 |
| **BAJO DE MINA** | 244.3 | 244.3 |
| **BAITUN** | 384.2 | 384.2 |
| **BAJO FRIO** | 230.2 | 230.2 |
| **BURICA** | 296.6 | 296.6 |

# 7.0 Conclusion and recommendations

A spreadsheet model and nMAG have been used to simulate and optimize production in the Chiriquí Viejo basin. The optimal reservoir operation is found to be between 50% and 90% of reservoir capacity on average for the cascade. The Annual average energy for four power plants with storages is increased by 3.7% (37 GWh) with reduced operational time of 28% when revenue is optimized.

Using the production strategy in nMAG generates high annual average production as it generates as much as possible with the water available giving an increased annual average energy of 101 GWh which is 8% more than the observed. The generation for the four power plants with storage in nMAG produces 88 GWh more of the actual annual average energy which is twice the amount generated in the spreadsheet.

The spreadsheet model is seen to improve the daily generation distribution in the months nMAG is producing at maximum throughout a period, the model takes into consideration factors of pricing, hourly demand, and reservoir filling considerations to determine production releases. However, both models are simplified and based on linearity using production models with dynamic modelling capabilities and advanced optimizers can provide for a better optimal production and economic benefit.

Climate change simulations in chapter 6.4 show no significant influence on the production. The strategy in nMAG is capable of utilizing the reduced inflow and meet firm demand.

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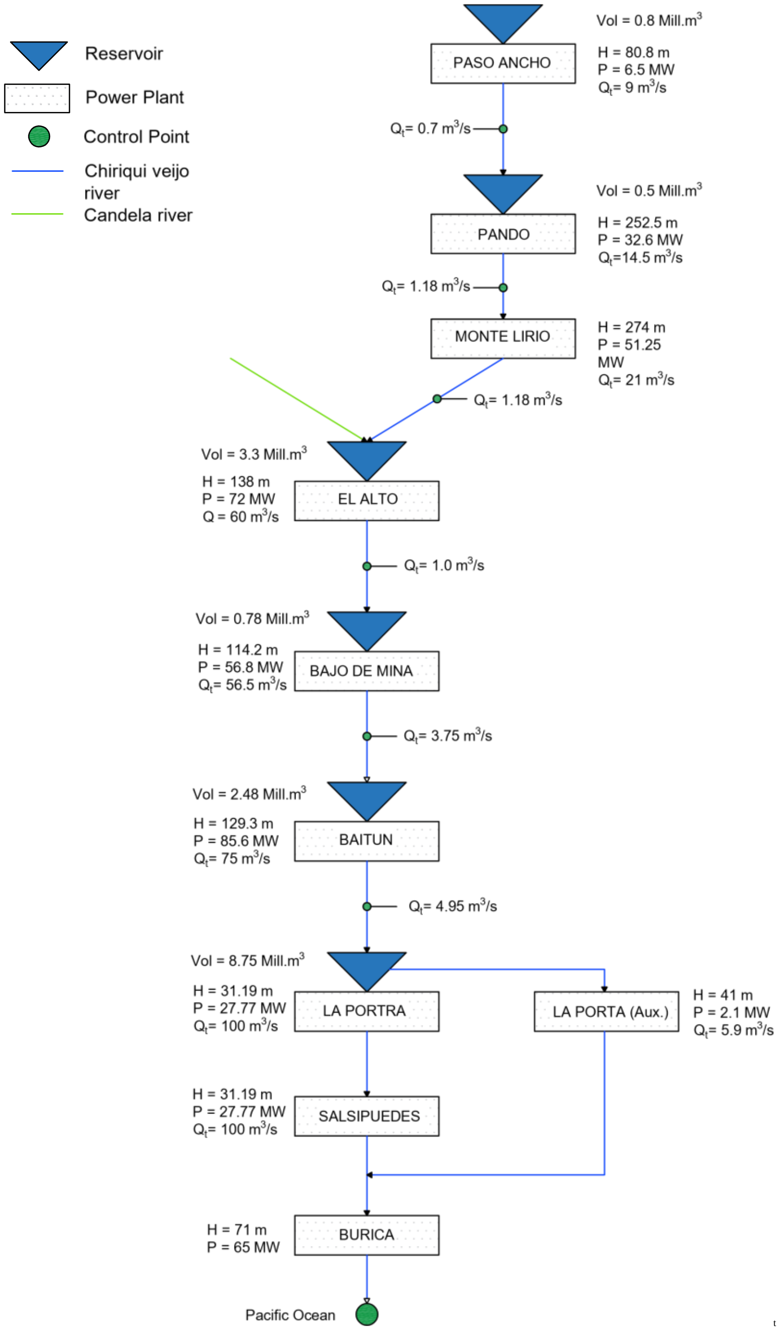
# 9.0 APPENDIX

# Appendix I

## Systematic layout of hydropower plants in Chiriqui viejo



# APPENDIX II

## Daily Summary Of El Alto Inflow (m3/s)

| year | month | day | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 2016 | 1 | 16.8 | 11.7 | 11.9 | 11.8 | 16.3 | 30.5 | 29.2 | 17.9 | 35.2 | 27.0 | 55.9 | 96.9 |
| 2016 | 2 | 15.6 | 11.6 | 11.6 | 11.7 | 15.7 | 47.8 | 23.3 | 21.3 | 30.1 | 33.5 | 50.8 | 84.4 |
| 2016 | 3 | 16.5 | 11.5 | 11.2 | 10.4 | 20.2 | 60.9 | 21.6 | 20.2 | 27.6 | 33.7 | 43.8 | 64.7 |
| 2016 | 4 | 18.4 | 11.5 | 10.2 | 9.4 | 16.5 | 46.9 | 20.9 | 20.3 | 27.0 | 30.6 | 38.3 | 74.0 |
| 2016 | 5 | 16.9 | 11.5 | 11.2 | 9.8 | 14.6 | 29.9 | 24.4 | 19.2 | 28.4 | 32.1 | 34.8 | 91.4 |
| 2016 | 6 | 15.8 | 11.2 | 11.8 | 9.4 | 14.3 | 30.6 | 19.9 | 18.2 | 25.6 | 42.0 | 47.1 | 56.2 |
| 2016 | 7 | 15.7 | 11.4 | 11.1 | 9.1 | 17.8 | 28.4 | 20.5 | 19.7 | 27.6 | 44.6 | 43.0 | 48.9 |
| 2016 | 8 | 15.6 | 10.6 | 11.2 | 9.1 | 16.3 | 45.1 | 51.8 | 19.6 | 25.3 | 54.7 | 37.4 | 51.3 |
| 2016 | 9 | 15.6 | 11.1 | 10.6 | 8.9 | 15.8 | 51.4 | 19.4 | 20.1 | 26.7 | 75.7 | 34.9 | 49.3 |
| 2016 | 10 | 14.6 | 24.5 | 10.6 | 8.8 | 14.8 | 41.0 | 21.5 | 18.8 | 31.8 | 84.6 | 32.5 | 50.0 |
| 2016 | 11 | 14.3 | 41.2 | 10.1 | 9.3 | 13.2 | 39.2 | 24.1 | 20.1 | 29.9 | 79.0 | 31.4 | 49.9 |
| 2016 | 12 | 14.2 | 30.3 | 10.2 | 8.8 | 12.6 | 34.4 | 28.3 | 23.4 | 48.3 | 66.0 | 31.5 | 47.3 |
| 2016 | 13 | 13.8 | 19.0 | 9.4 | 8.7 | 12.1 | 30.1 | 21.7 | 23.4 | 68.5 | 67.4 | 30.8 | 40.1 |
| 2016 | 14 | 13.9 | 15.3 | 11.3 | 8.9 | 12.3 | 37.1 | 23.2 | 27.9 | 40.0 | 49.5 | 35.8 | 37.6 |
| 2016 | 15 | 13.6 | 13.9 | 9.9 | 9.4 | 12.7 | 38.5 | 26.5 | 24.6 | 39.5 | 46.4 | 38.7 | 35.9 |
| 2016 | 16 | 13.4 | 13.2 | 9.7 | 9.8 | 11.4 | 45.7 | 24.4 | 21.9 | 39.1 | 48.7 | 44.2 | 35.5 |
| 2016 | 17 | 13.2 | 12.7 | 9.5 | 10.5 | 14.0 | 38.9 | 23.7 | 20.6 | 35.1 | 47.1 | 107.5 | 40.6 |
| 2016 | 18 | 12.9 | 12.7 | 10.1 | 9.8 | 12.6 | 38.6 | 29.4 | 21.0 | 30.7 | 44.2 | 88.3 | 33.7 |
| 2016 | 19 | 12.6 | 29.6 | 9.5 | 10.8 | 12.5 | 36.9 | 29.4 | 22.7 | 29.0 | 39.2 | 123.1 | 31.2 |
| 2016 | 20 | 12.5 | 18.0 | 9.6 | 12.1 | 11.6 | 30.5 | 23.6 | 27.2 | 29.0 | 36.7 | 106.2 | 32.3 |
| 2016 | 21 | 14.0 | 15.1 | 9.6 | 10.8 | 11.0 | 31.7 | 21.9 | 27.4 | 32.6 | 39.5 | 103.5 | 31.7 |
| 2016 | 22 | 13.5 | 13.6 | 10.5 | 12.1 | 12.3 | 35.1 | 21.1 | 26.5 | 33.1 | 38.2 | 89.7 | 29.5 |
| 2016 | 23 | 12.8 | 12.8 | 10.2 | 12.3 | 11.9 | 35.9 | 23.9 | 24.7 | 28.0 | 34.5 | 107.2 | 28.8 |
| 2016 | 24 | 13.2 | 13.2 | 9.7 | 11.5 | 12.3 | 29.3 | 21.9 | 21.4 | 27.0 | 31.7 | 116.8 | 27.7 |
| 2016 | 25 | 18.9 | 12.0 | 9.5 | 11.1 | 14.1 | 27.0 | 19.7 | 23.0 | 38.6 | 30.0 | 110.5 | 26.7 |
| 2016 | 26 | 14.8 | 11.9 | 9.6 | 13.0 | 19.8 | 26.7 | 18.5 | 35.7 | 33.4 | 32.5 | 102.0 | 26.0 |
| 2016 | 27 | 13.0 | 14.8 | 9.3 | 16.6 | 20.0 | 24.7 | 18.6 | 34.3 | 34.0 | 34.6 | 95.7 | 46.9 |
| 2016 | 28 | 12.7 | 13.3 | 9.9 | 15.9 | 27.2 | 23.4 | 24.7 | 28.5 | 31.3 | 33.7 | 97.9 | 49.2 |
| 2016 | 29 | 12.1 | 12.4 | 10.3 | 19.4 | 29.0 | 22.8 | 22.0 | 41.0 | 28.0 | 35.7 | 101.9 | 28.4 |
| 2016 | 30 | 11.9 | | 10.6 | 17.5 | 22.6 | 21.4 | 20.3 | 42.2 | 26.3 | 56.8 | 101.1 | 25.4 |
| 2016 | 31 | 11.8 | | 10.2 | | 30.3 | | 19.0 | 38.7 | | 62.5 | | 23.9 |
| 2017 | 1 | 23.5 | 14.9 | 11.5 | 10.2 | 12.6 | 54.0 | 54.8 | 42.3 | 36.1 | 110.4 | 34.7 | 38.1 |
| 2017 | 2 | 23.9 | 15.5 | 11.8 | 12.3 | 21.6 | 43.0 | 40.2 | 32.1 | 31.2 | 99.8 | 34.8 | 36.6 |
| 2017 | 3 | 22.7 | 14.1 | 11.8 | 11.5 | 21.1 | 37.5 | 40.0 | 30.1 | 39.1 | 92.8 | 32.9 | 33.7 |
| 2017 | 4 | 21.9 | 13.5 | 15.0 | 12.9 | 31.2 | 36.2 | 39.7 | 32.0 | 32.7 | 108.8 | 32.8 | 33.6 |
| 2017 | 5 | 20.1 | 15.2 | 13.5 | 11.3 | 43.8 | 41.5 | 52.1 | 29.2 | 32.6 | 174.3 | 31.6 | 32.9 |
| 2017 | 6 | 19.9 | 15.2 | 20.1 | 10.4 | 43.0 | 42.2 | 40.7 | 30.5 | 30.3 | 139.4 | 32.6 | 32.6 |
| 2017 | 7 | 18.9 | 14.4 | 18.2 | 10.9 | 55.9 | 38.8 | 34.1 | 40.5 | 30.6 | 130.3 | 30.5 | 30.8 |
| 2017 | 8 | 19.2 | 14.4 | 15.6 | 11.0 | 38.2 | 52.0 | 32.5 | 37.0 | 36.8 | 119.0 | 31.8 | 29.7 |
| 2017 | 9 | 72.6 | 13.4 | 13.3 | 11.0 | 63.0 | 77.4 | 32.9 | 46.1 | 36.3 | 108.2 | 29.0 | 33.2 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2017 | 10 | 34.6 | 13.4 | 13.2 | 10.2 | 35.9 | 71.2 | 36.8 | 58.9 | 35.2 | 84.8 | 28.7 | 86.3 |
| 2017 | 11 | 29.3 | 13.8 | 13.5 | 10.8 | 36.1 | 43.2 | 60.9 | 46.1 | 33.0 | 55.5 | 34.2 | 110.4 |
| 2017 | 12 | 24.7 | 13.3 | 14.3 | 10.8 | 34.4 | 39.3 | 76.8 | 42.0 | 37.7 | 53.6 | 34.0 | 107.3 |
| 2017 | 13 | 24.2 | 13.9 | 12.0 | 10.4 | 29.7 | 54.5 | 58.8 | 44.2 | 31.6 | 46.0 | 34.9 | 77.1 |
| 2017 | 14 | 35.9 | 14.1 | 11.7 | 10.9 | 27.8 | 71.1 | 47.5 | 50.8 | 30.9 | 43.5 | 33.6 | 47.4 |
| 2017 | 15 | 27.4 | 13.8 | 11.8 | 10.2 | 24.3 | 57.2 | 33.6 | 37.1 | 42.4 | 41.1 | 42.9 | 37.3 |
| 2017 | 16 | 23.7 | 14.9 | 12.3 | 10.9 | 27.6 | 90.0 | 30.5 | 35.2 | 43.5 | 36.7 | 63.0 | 34.5 |
| 2017 | 17 | 21.9 | 16.4 | 10.9 | 13.6 | 29.8 | 71.6 | 30.5 | 33.7 | 71.2 | 33.6 | 48.5 | 32.3 |
| 2017 | 18 | 19.8 | 14.7 | 11.4 | 14.0 | 43.3 | 67.6 | 30.9 | 52.7 | 82.8 | 39.2 | 37.4 | 29.6 |
| 2017 | 19 | 19.6 | 14.3 | 11.6 | 16.7 | 58.4 | 59.4 | 28.3 | 54.1 | 71.7 | 32.2 | 40.4 | 28.9 |
| 2017 | 20 | 18.2 | 13.4 | 10.9 | 17.2 | 67.0 | 44.9 | 26.3 | 65.6 | 93.5 | 34.6 | 42.3 | 29.9 |
| 2017 | 21 | 17.5 | 13.7 | 10.1 | 13.4 | 44.6 | 47.0 | 27.0 | 72.6 | 89.1 | 39.8 | 72.8 | 32.8 |
| 2017 | 22 | 17.4 | 14.1 | 12.8 | 11.9 | 36.6 | 41.9 | 27.2 | 53.5 | 94.6 | 39.3 | 89.9 | 27.2 |
| 2017 | 23 | 16.7 | 12.6 | 11.6 | 12.9 | 43.8 | 37.6 | 26.7 | 39.8 | 104.4 | 48.2 | 111.1 | 30.8 |
| 2017 | 24 | 15.9 | 12.2 | 12.3 | 13.2 | 33.5 | 34.9 | 24.8 | 37.6 | 103.9 | 55.5 | 75.7 | 32.2 |
| 2017 | 25 | 16.1 | 15.8 | 13.3 | 16.4 | 38.5 | 38.6 | 25.6 | 40.2 | 112.2 | 83.7 | 56.9 | 30.7 |
| 2017 | 26 | 15.5 | 14.1 | 11.9 | 17.2 | 38.8 | 39.8 | 27.0 | 35.6 | 102.6 | 48.0 | 51.0 | 28.8 |
| 2017 | 27 | 14.9 | 12.5 | 11.4 | 13.9 | 39.3 | 52.2 | 26.9 | 34.5 | 99.3 | 45.4 | 45.7 | 25.0 |
| 2017 | 28 | 14.8 | 12.0 | 11.4 | 11.9 | 54.8 | 76.4 | 28.3 | 37.3 | 105.4 | 39.2 | 44.4 | 24.7 |
| 2017 | 29 | 14.8 | | 11.2 | 11.4 | 59.7 | 61.6 | 36.7 | 38.6 | 106.6 | 39.3 | 44.4 | 24.2 |
| 2017 | 30 | 14.1 | | 10.8 | 11.8 | 88.6 | 61.1 | 48.2 | 49.3 | 114.5 | 42.3 | 42.2 | 26.4 |
| 2017 | 31 | 14.4 | | 11.5 | | 79.4 | | 69.5 | 49.7 | | 37.1 | | 31.4 |
| 2018 | 1 | 36.4 | 26.6 | 14.8 | 12.6 | 15.4 | 32.9 | 42.6 | 39.4 | 28.9 | 56.6 | 41.4 | 22.2 |
| 2018 | 2 | 25.9 | 24.8 | 15.2 | 12.3 | 16.5 | 38.0 | 42.4 | 67.0 | 25.8 | 60.7 | 41.9 | 22.6 |
| 2018 | 3 | 27.6 | 20.6 | 15.1 | 12.1 | 14.2 | 40.7 | 36.7 | 60.8 | 22.2 | 50.7 | 37.1 | 24.3 |
| 2018 | 4 | 28.2 | 21.5 | 14.7 | 14.3 | 14.6 | 36.5 | 34.3 | 44.4 | 22.7 | 61.8 | 75.8 | 23.1 |
| 2018 | 5 | 39.8 | 19.2 | 14.1 | 12.5 | 15.1 | 32.5 | 31.8 | 38.3 | 29.0 | 109.0 | 77.4 | 21.1 |
| 2018 | 6 | 37.3 | 19.4 | 14.3 | 15.3 | 14.7 | 30.1 | 38.6 | 35.8 | 41.1 | 127.7 | 53.4 | 21.1 |
| 2018 | 7 | 61.4 | 18.6 | 13.7 | 16.6 | 15.6 | 33.1 | 35.7 | 35.7 | 44.6 | 82.5 | 46.4 | 22.6 |
| 2018 | 8 | 61.8 | 17.7 | 13.7 | 16.9 | 15.5 | 29.1 | 32.6 | 31.5 | 48.0 | 60.1 | 40.5 | 20.5 |
| 2018 | 9 | 34.2 | 17.8 | 14.1 | 15.2 | 14.3 | 28.9 | 29.8 | 30.4 | 62.9 | 51.4 | 40.5 | 19.5 |
| 2018 | 10 | 31.1 | 18.1 | 15.0 | 14.8 | 14.6 | 27.7 | 29.8 | 31.7 | 54.0 | 46.3 | 38.0 | 18.9 |
| 2018 | 11 | 29.0 | 17.7 | 14.0 | 21.0 | 14.5 | 26.5 | 27.8 | 29.0 | 42.9 | 57.7 | 34.9 | 19.0 |
| 2018 | 12 | 26.9 | 16.6 | 13.2 | 17.1 | 14.5 | 29.9 | 25.8 | 27.2 | 39.2 | 71.5 | 35.2 | 18.2 |
| 2018 | 13 | 25.4 | 21.3 | 14.3 | 19.2 | 27.7 | 27.9 | 26.3 | 26.1 | 39.1 | 67.1 | 33.3 | 17.9 |
| 2018 | 14 | 26.9 | 17.6 | 13.9 | 16.5 | 24.3 | 29.7 | 36.9 | 26.5 | 34.0 | 74.0 | 33.7 | 17.8 |
| 2018 | 15 | 40.5 | 18.5 | 13.1 | 17.0 | 20.0 | 52.4 | 43.4 | 26.1 | 42.3 | 83.3 | 36.0 | 17.1 |
| 2018 | 16 | 35.2 | 19.0 | 13.1 | 15.1 | 24.2 | 57.7 | 40.7 | 26.2 | 42.7 | 72.1 | 34.1 | 17.9 |
| 2018 | 17 | 27.3 | 19.1 | 12.7 | 14.0 | 27.4 | 65.1 | 35.3 | 24.6 | 38.0 | 78.8 | 29.5 | 17.0 |
| 2018 | 18 | 26.6 | 18.5 | 12.9 | 14.2 | 36.1 | 49.8 | 32.0 | 23.5 | 31.9 | 116.7 | 31.1 | 16.4 |
| 2018 | 19 | 26.9 | 17.8 | 12.2 | 12.4 | 40.9 | 45.9 | 30.1 | 23.4 | 31.1 | 101.4 | 29.5 | 17.1 |
| 2018 | 20 | 35.5 | 16.7 | 12.8 | 12.3 | 38.3 | 50.6 | 29.7 | 21.4 | 29.6 | 88.3 | 33.8 | 17.2 |
| 2018 | 21 | 31.6 | 18.9 | 12.6 | 12.6 | 41.2 | 48.1 | 29.3 | 21.1 | 36.7 | 81.1 | 35.5 | 16.1 |
| 2018 | 22 | 30.1 | 19.0 | 11.4 | 12.7 | 40.8 | 40.6 | 27.3 | 22.2 | 29.7 | 89.3 | 32.1 | 17.8 |
| 2018 | 23 | 26.9 | 18.6 | 12.3 | 12.4 | 41.6 | 45.6 | 28.2 | 21.0 | 30.6 | 75.8 | 29.0 | 19.4 |
| 2018 | 24 | 24.7 | 17.8 | 12.4 | 13.2 | 36.9 | 67.2 | 24.2 | 21.6 | 38.8 | 60.5 | 27.8 | 17.1 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2018 | 25 | 24.7 | 17.9 | 12.7 | 13.7 | 33.3 | 42.5 | 27.9 | 20.9 | 38.3 | 69.4 | 25.3 | 17.3 |
| 2018 | 26 | 23.6 | 16.5 | 11.9 | 13.1 | 59.1 | 41.7 | 27.6 | 22.8 | 39.8 | 56.9 | 25.6 | 15.8 |
| 2018 | 27 | 22.5 | 16.0 | 11.4 | 15.6 | 56.0 | 38.6 | 36.4 | 22.7 | 44.8 | 51.1 | 24.3 | 16.0 |
| 2018 | 28 | 21.1 | 15.7 | 11.4 | 16.3 | 40.0 | 56.0 | 33.2 | 24.0 | 56.2 | 49.1 | 24.1 | 15.8 |
| 2018 | 29 | 20.2 | | 11.4 | 19.4 | 43.7 | 67.8 | 32.8 | 27.0 | 52.1 | 51.6 | 24.8 | 15.2 |
| 2018 | 30 | 21.0 | | 11.5 | 17.3 | 41.8 | 49.9 | 33.7 | 24.1 | 56.8 | 45.7 | 23.6 | 14.6 |
| 2018 | 31 | 26.2 | | 13.6 | | 36.0 | | 28.7 | 22.4 | | 39.2 | | 15.1 |

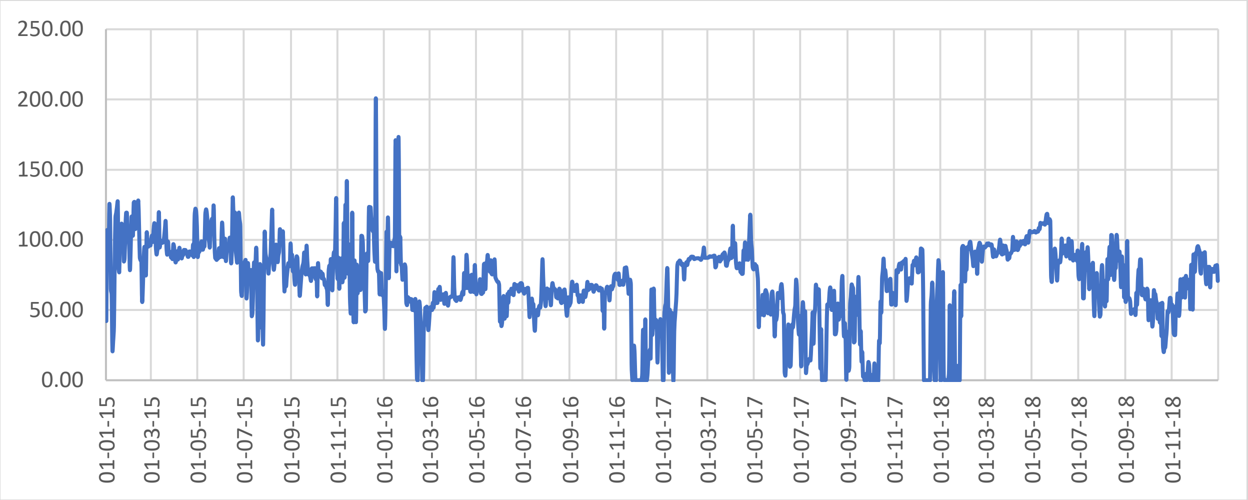
# APPENDIX III

## Monthly Summary of Generation (Mwh)

| Year | Month | Monte Lirio | El Alto | Bajo de Mina | Baitun | La Potra | Salsipuedes |
|---|---|---|---|---|---|---|---|
| 2016 | 1 | 15964 | 9497 | 8512 | 11659 | 2864 | 3022 |
| 2016 | 2 | 16586 | 9711 | 8397 | 10427 | 2409 | 2534 |
| 2016 | 3 | 10502 | 6127 | 5358 | 6586 | 1672 | 1774 |
| 2016 | 4 | 11453 | 6523 | 5573 | 8052 | 2130 | 2247 |
| 2016 | 5 | 17297 | 11003 | 9402 | 14911 | 4616 | 4963 |
| 2016 | 6 | 25861 | 26227 | 23434 | 39280 | 11886 | 12382 |
| 2016 | 7 | 24828 | 16655 | 15396 | 26204 | 8248 | 8853 |
| 2016 | 8 | 21215 | 18662 | 16947 | 27937 | 9030 | 9650 |
| 2016 | 9 | 25434 | 23870 | 22396 | 37144 | 10956 | 11654 |
| 2016 | 10 | 32490 | 33661 | 30876 | 48504 | 14482 | 14842 |
| 2016 | 11 | 26744 | 33752 | 32907 | 51974 | 14695 | 14961 |
| 2016 | 12 | 28366 | 30127 | 27493 | 40976 | 11860 | 12253 |
| 2017 | 1 | 21273 | 15922 | 13930 | 19633 | 5012 | 5360 |
| 2017 | 2 | 14499 | 8334 | 6417 | 8732 | 2272 | 2379 |
| 2017 | 3 | 13552 | 8155 | 7149 | 9263 | 2456 | 2516 |
| 2017 | 4 | 13889 | 7565 | 6593 | 9998 | 2976 | 3051 |
| 2017 | 5 | 29016 | 27358 | 24119 | 37721 | 11543 | 11745 |
| 2017 | 6 | 29959 | 33165 | 29080 | 46041 | 15082 | 12531 |
| 2017 | 7 | 24013 | 23521 | 22174 | 34170 | 10142 | 10051 |
| 2017 | 8 | 25842 | 28645 | 26426 | 42212 | 12621 | 12885 |
| 2017 | 9 | 20706 | 27765 | 25776 | 40430 | 11758 | 11874 |
| 2017 | 10 | 23568 | 36937 | 31265 | 52214 | 14535 | 14931 |
| 2017 | 11 | 32555 | 30672 | 27938 | 46422 | 14545 | 15047 |
| 2017 | 12 | 28553 | 25693 | 22932 | 33181 | 9054 | 9521 |
| 2018 | 1 | 27281 | 21911 | 19414 | 25829 | 6621 | 6823 |
| 2018 | 2 | 20501 | 11579 | 10287 | 13418 | 3356 | 3387 |
| 2018 | 3 | 15139 | 8047 | 7120 | 8999 | 2242 | 2291 |
| 2018 | 4 | 15981 | 9221 | 8355 | 12661 | 3828 | 3777 |
| 2018 | 5 | 20764 | 20386 | 18333 | 28383 | 8501 | 8805 |
| 2018 | 6 | 30980 | 29581 | 27661 | 39509 | 13548 | 13972 |
| 2018 | 7 | 31188 | 24426 | 22908 | 37827 | 11608 | 11967 |
| 2018 | 8 | 24499 | 21365 | 19936 | 32704 | 10710 | 11066 |
| 2018 | 9 | 28779 | 28107 | 26134 | 42735 | 13380 | 13858 |
| 2018 | 10 | 33637 | 44091 | 39517 | 61270 | 17970 | 15903 |
| 2018 | 11 | 29826 | 25053 | 24171 | 38381 | 11321 | 11741 |
| 2018 | 12 | 19905 | 12511 | 11240 | 17598 | 5433 | 5690 |

# APPENDIX III

## Monthly Summary of Spot prices (USD/MWh)



# APPENDIX IV

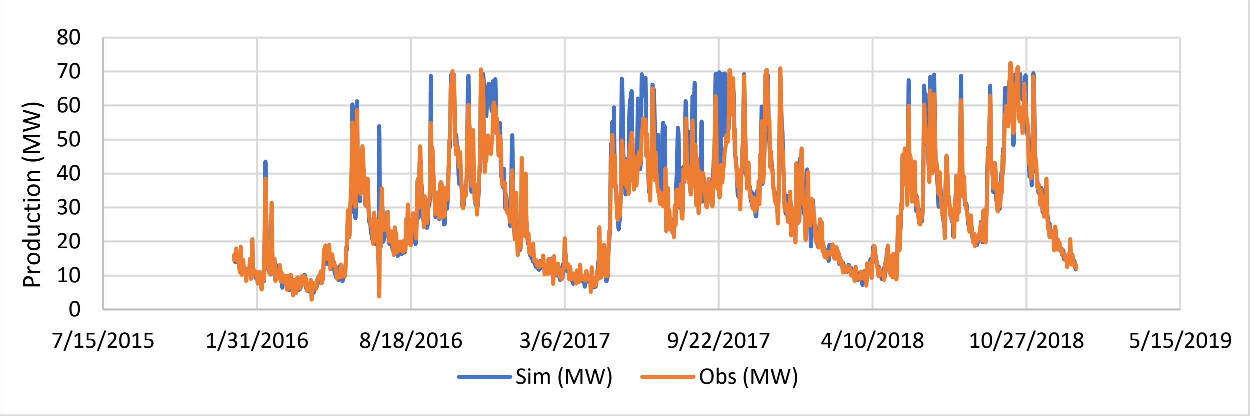
## Optimization Macro

```
Sub test()
   Application.ScreenUpdating = False
    n = 1
 For pdif = 0.5 To 0.8 Step 0.1
    Sheets("reservoir").Cells(5, 6) = pdif
    For fil = 0.5 To 1 Step 0.1
        Sheets("reservoir").Cells(5, 8) = fil
        n = n + 1
        Sheets("OPTIM").Cells(n, 1) = pdif
        Sheets("OPTIM").Cells(n, 2) = fil
        Sheets("OPTIM").Cells(n, 3) = Sheets("reservoir").Cells(2, 17)
        Sheets("OPTIM").Cells(n, 4) = Sheets("reservoir").Cells(4, 19)
        Sheets("OPTIM").Cells(n, 5) = Sheets("reservoir").Cells(4, 17)
    Next fil
  Next pdif
End Sub
```

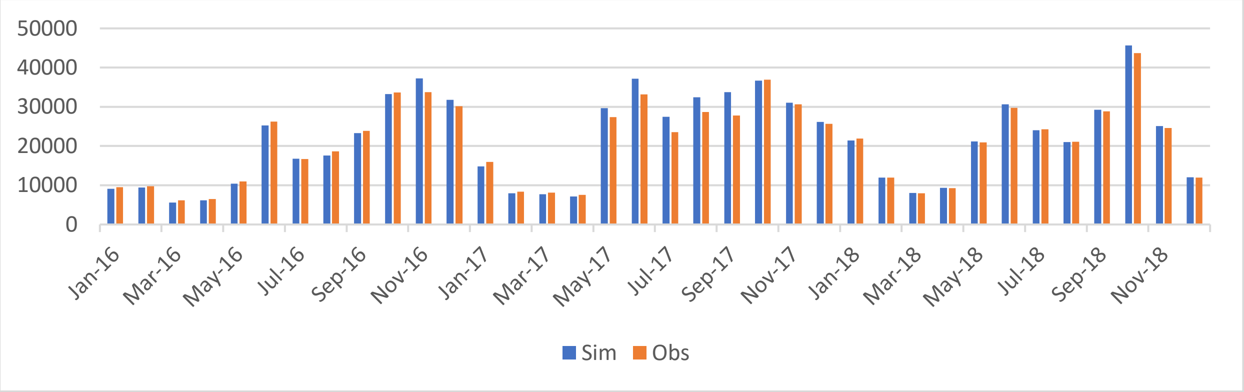
# APPENDIX IV

## SPREADSHEET SIMULATION RESULTS

### EL ALTO DAILY SIMULATION (MW)



### EL ALTO MONTHLY SIMULATION (GWh)



### EL ALTO INITIAL SIMULATION

| | Annual Energy (GWh) | | Gross Revenue (mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 226 | 226 | 12.11 | 12.43 |
| **2017** | 292 | 274 | 13.64 | 13.24 |
| **2018** | 260 | 256 | 17.84 | 17.62 |

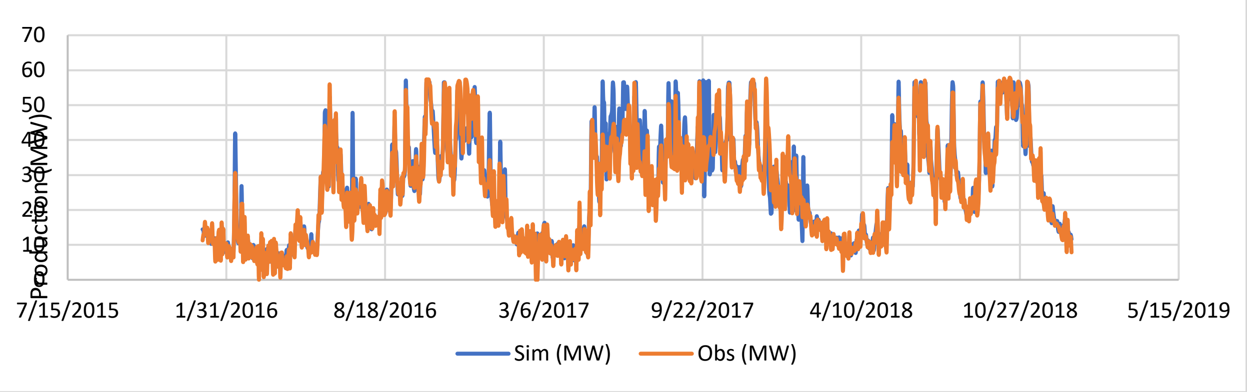
### EL ALTO PRODUCTION MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 229 | 226 | 12.91 | 12.43 |
| **2017** | 292 | 274 | 14.59 | 13.24 |
| **2018** | 262 | 256 | 18.44 | 17.62 |

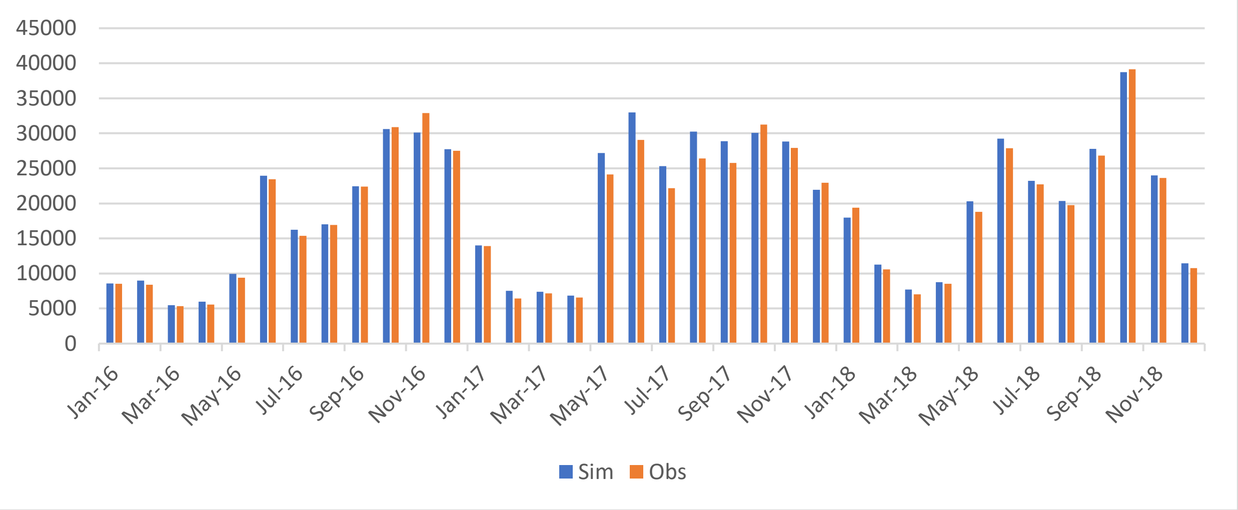
### EL ALTO REVENUE MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 227 | 226 | 13.50 | 12.43 |
| **2017** | 289 | 274 | 15.35 | 13.24 |
| **2018** | 258 | 256 | 19.17 | 17.62 |

### BAJO DE MINA DAILY SIMULATION (MW)



### BAJO DE MINA MONTHLY SIMULATION (GWh)



### **BAJO DE MINA** INITIAL SIMULATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 207 | 207 | 11.53 | 11.20 |
| **2017** | 261 | 244 | 13.01 | 11.84 |
| **2018** | 241 | 235 | 17.04 | 16.17 |

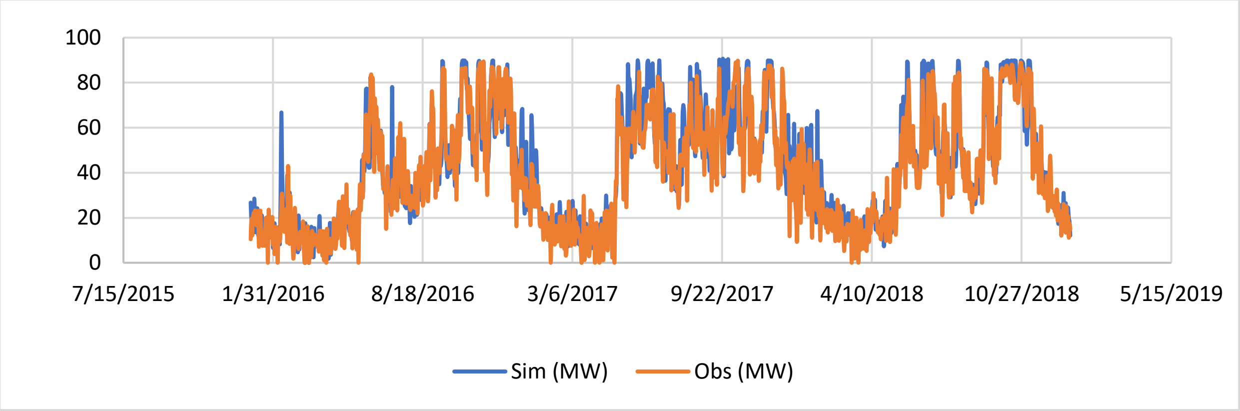
**BAJO DE MINA** PRODUCTION MAXIMIZATION

|  | Annual Energy (GWh) |  | Gross Revenue(mill USD) |  |
|---|---|---|---|---|
|  | Simulated | Observed | Simulated | Observed |
| **2016** | 209 | 207 | 12.28 | 11.20 |
| **2017** | 260 | 244 | 13.91 | 11.84 |
| **2018** | 241 | 235 | 17.41 | 16.17 |

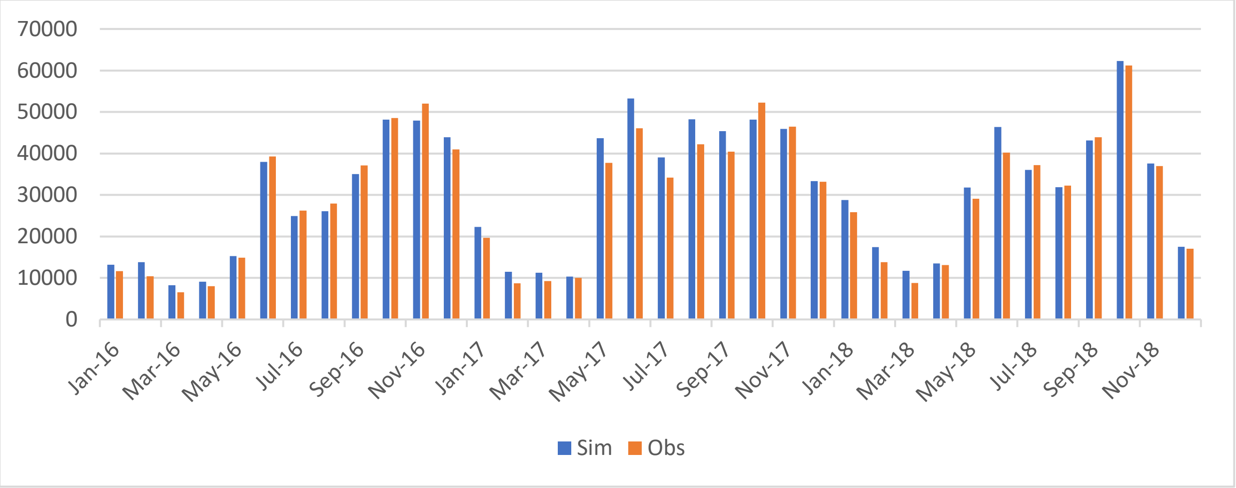
**BAJO DE MINA** REVENUE MAXIMIZATION

|  | Annual Energy (GWh) |  | Gross Revenue(mill USD) |  |
|---|---|---|---|---|
|  | Observed | Simulated | Observed | Simulated |
| **2016** | 208 | 207 | 12.93 | 11.20 |
| **2017** | 259 | 244 | 14.56 | 11.84 |
| **2018** | 241 | 235 | 18.31 | 16.17 |

**BAITUN DAILY SIMULATION (MW)**



**BAITUN MONTHLY SIMULATION (GWh)**



**BAITUN** INITIAL SIMULATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 323 | 324 | 18.15 | 17.56 |
| **2017** | 416 | 380 | 20.87 | 18.28 |
| **2018** | 379 | 359 | 26.97 | 24.59 |

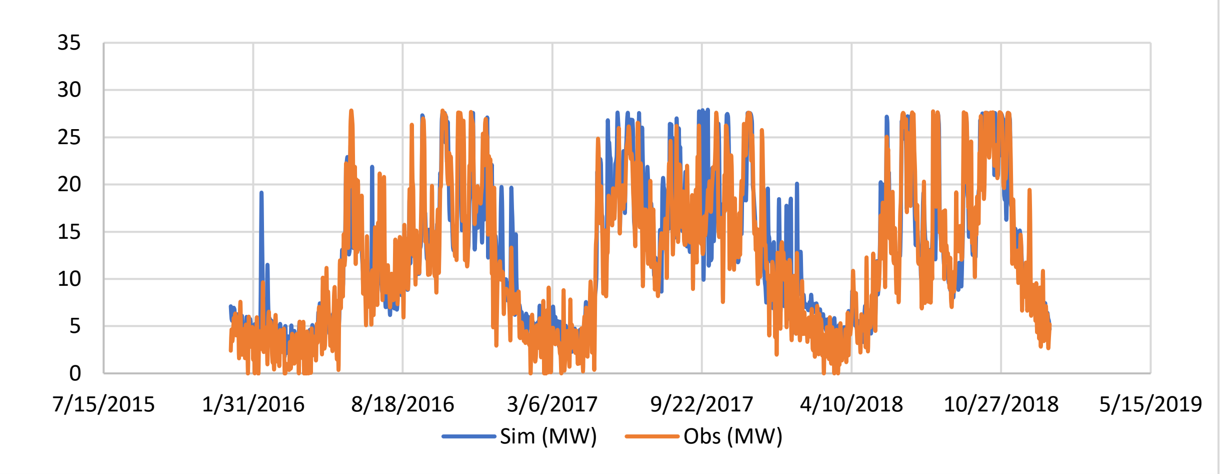
**BAITUN** PRODUCTION MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 326 | 324 | 19.62 | 17.56 |
| **2017** | 411 | 380 | 22.64 | 18.28 |
| **2018** | 378 | 359 | 27.75 | 24.59 |

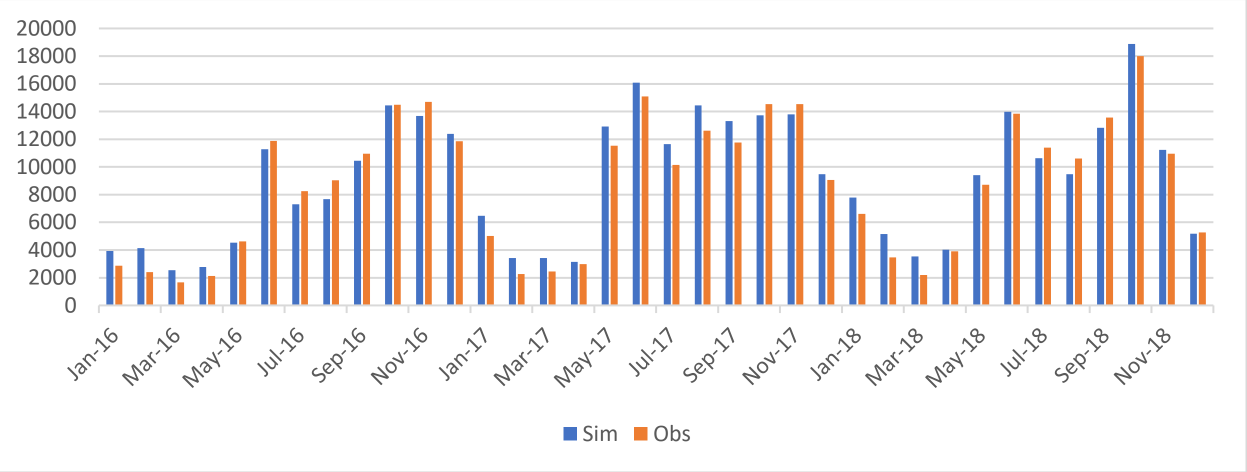
**BAITUN** REVENUE MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Observed | Simulated | Observed | Simulated |
| **2016** | 323 | 324 | 20.33 | 17.56 |
| **2017** | 407 | 380 | 23.18 | 18.28 |
| **2018** | 374 | 359 | 28.79 | 24.59 |

## LA POTRA DAILY SIMULATION (MW)



## LA POTRA MONTHLY SIMULATION (GWh)



## LA POTRA INITIAL SIMULATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 95 | 95 | 5.42 | 5.18 |
| **2017** | 123 | 112 | 6.27 | 5.46 |
| **2018** | 112 | 109 | 8.06 | 7.59 |

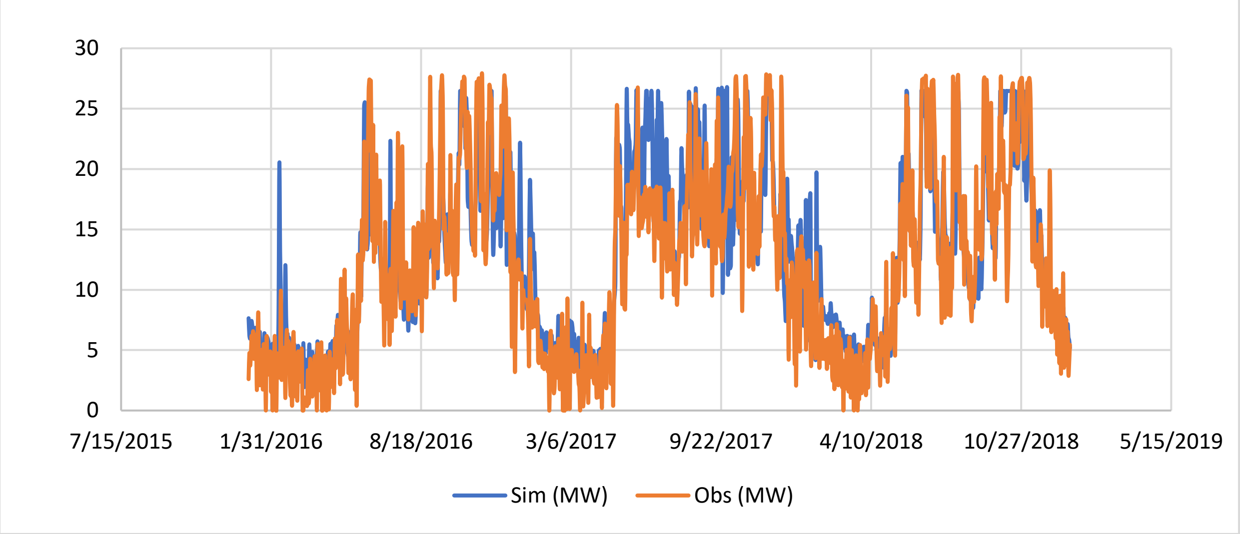
### LA POTRA PRODUCTION MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 100 | 95 | 6.01 | 5.18 |
| **2017** | 124 | 112 | 6.85 | 5.46 |
| **2018** | 116 | 109 | 8.51 | 7.59 |

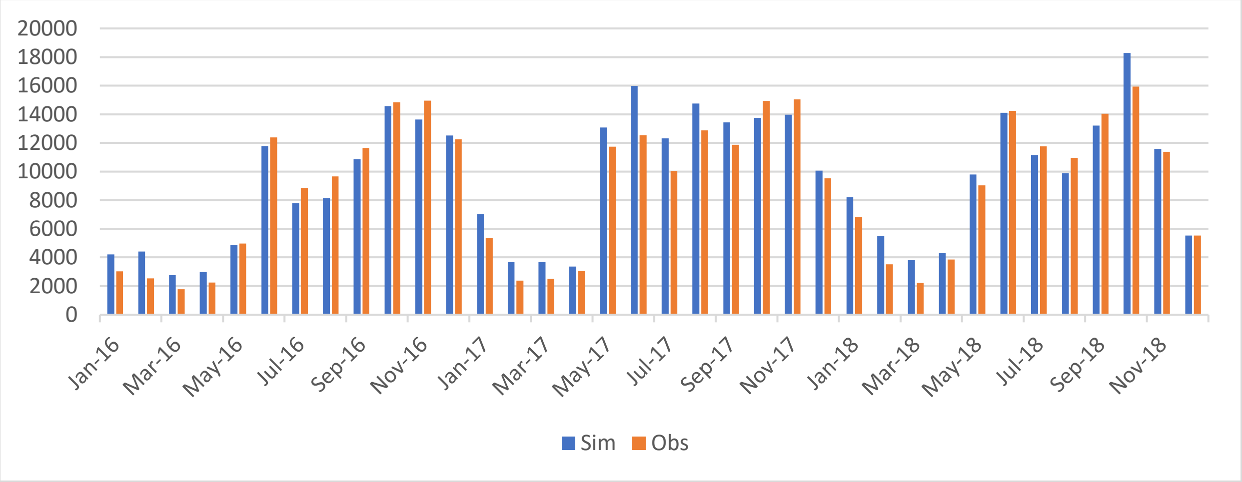
### LA POTRA REVENUE MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Observed | Simulated | Observed | Simulated |
| **2016** | 99 | 95 | 6.30 | 5.18 |
| **2017** | 124 | 112 | 7.15 | 5.46 |
| **2018** | 115 | 109 | 8.90 | 7.59 |

## SALSIPUEDES DAILY SIMULATION (MW)



## SALSIPUEDES MONTHLY SIMULATION (GWh)



## LA POTRA INITIAL SIMULATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 99 | 99 | 5.64 | 5.44 |
| **2017** | 125 | 112 | 6.45 | 5.55 |
| **2018** | 115 | 109 | 8.33 | 7.69 |

## SALSIPUEDES PRODUCTION MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Simulated | Observed | Simulated | Observed |
| **2016** | 97 | 99 | 5.85 | 5.44 |
| **2017** | 121 | 112 | 6.66 | 5.55 |
| **2018** | 113 | 109 | 8.28 | 7.69 |

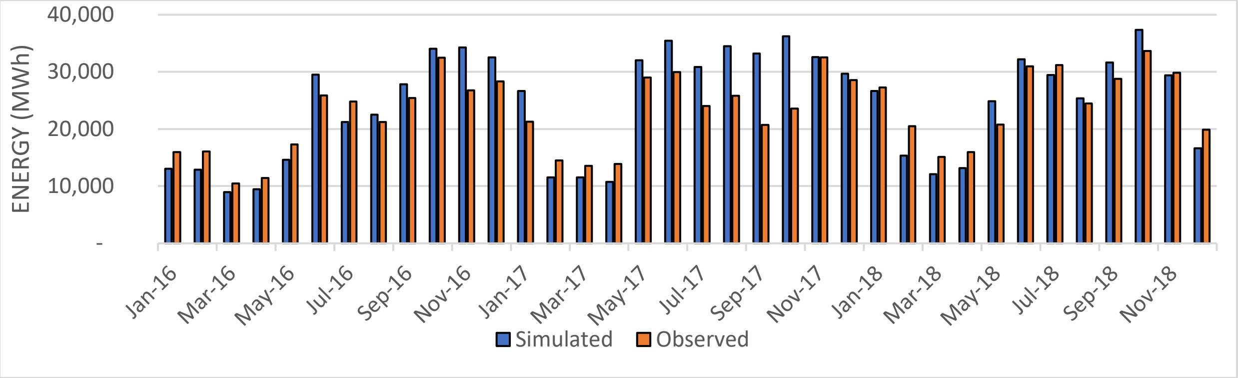
## SALSIPUEDES REVENUE MAXIMIZATION

| | Annual Energy (GWh) | | Gross Revenue(mill USD) | |
|---|---|---|---|---|
| | Observed | Simulated | Observed | Simulated |
| **2016** | 97 | 99 | 6.20 | 5.44 |
| **2017** | 121 | 112 | 7.01 | 5.55 |
| **2018** | 113 | 109 | 8.72 | 7.69 |

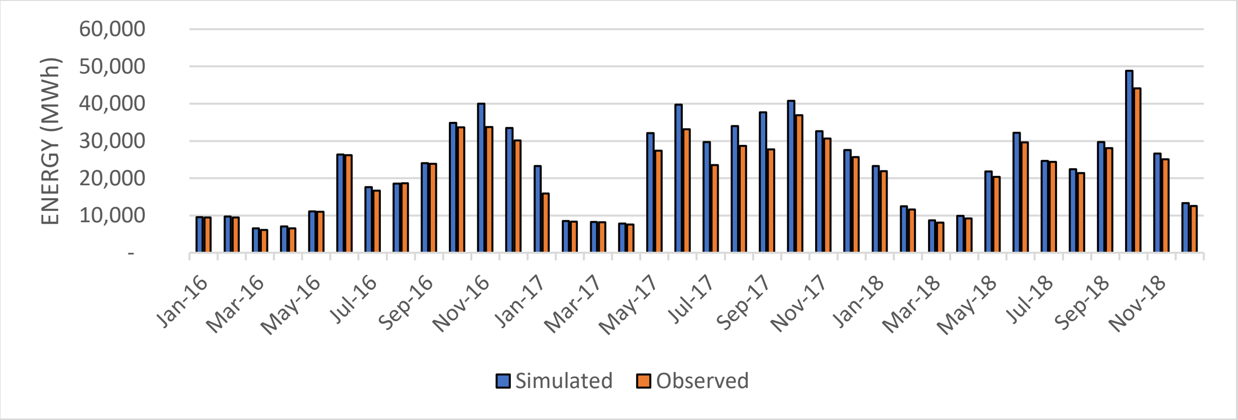
# APPENDIX IV

## NMAG SIMULATIONS

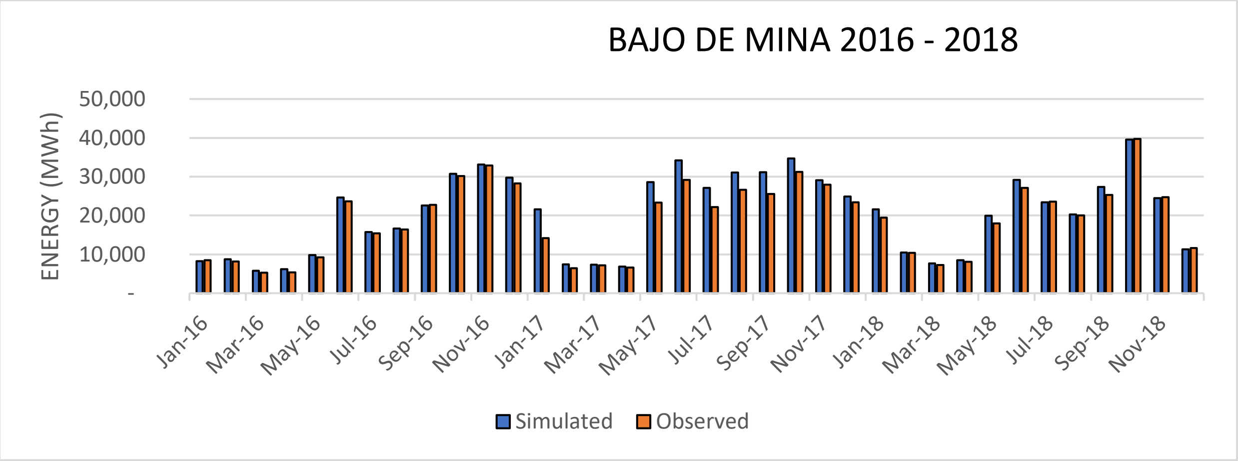
### MONTE LIRIO MONTHLY ENERGY SIMULATION



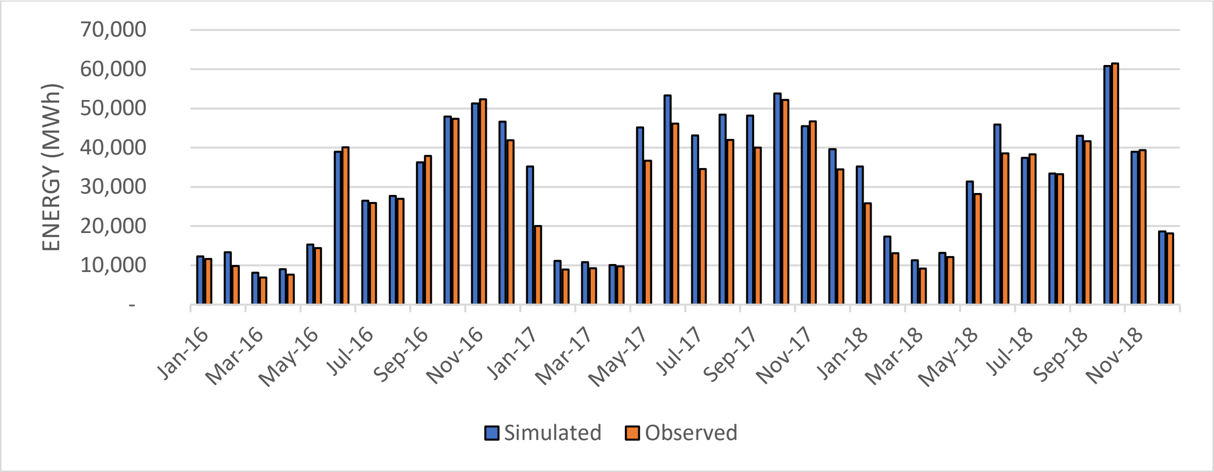
### EL ALTO MONTHLY ENERGY SIMULATION



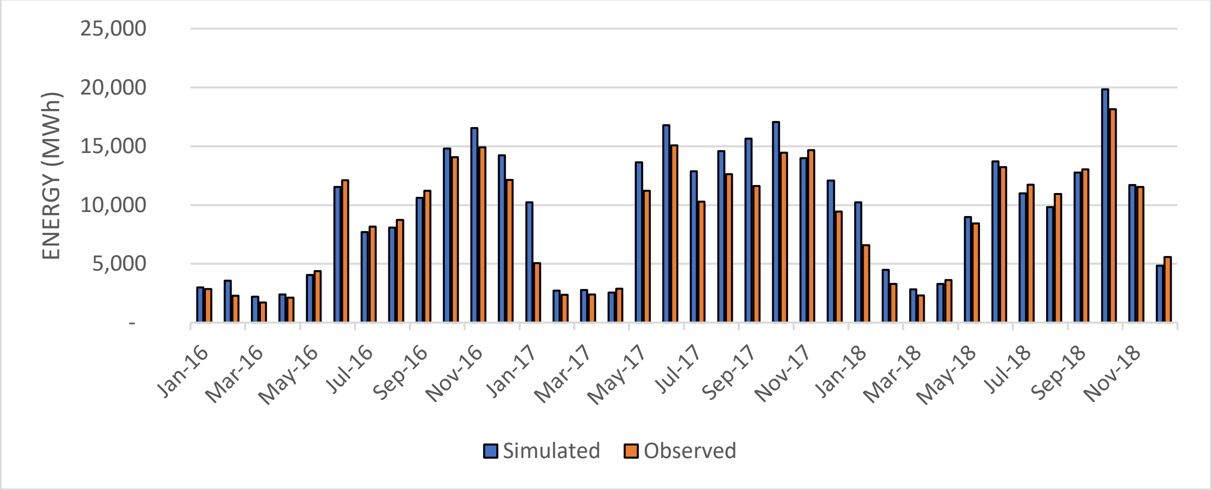
### BAJO DE MINA MONTHLY ENERGY SIMULATION



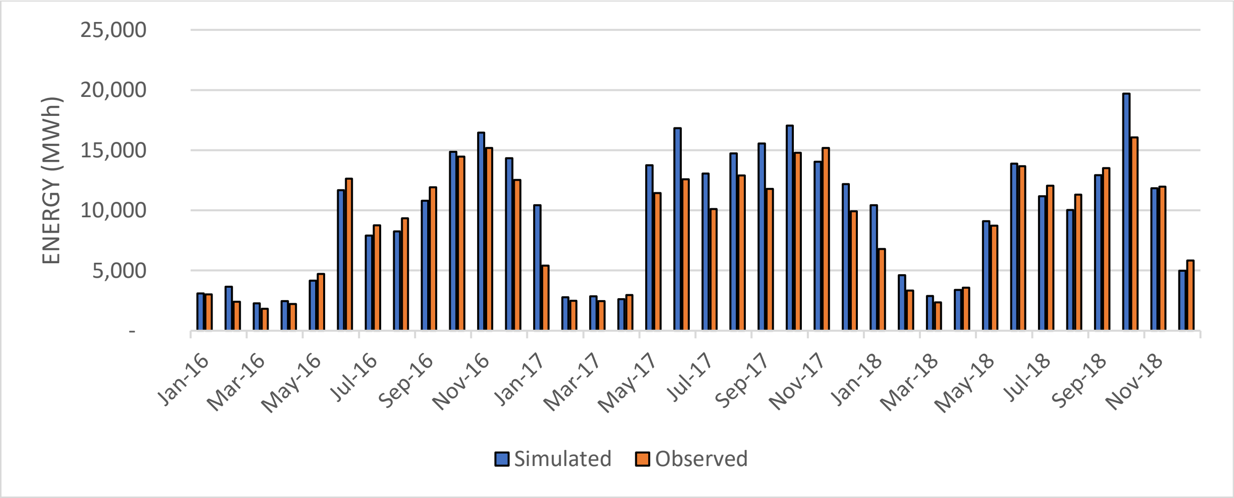
### BAITUN MONTHLY ENERGY SIMULATION



### LA POTRA MONTHLY ENERGY SIMULATION



### SALSIPUEDES **MONTHLY ENERGY SIMULATION**



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Science and Technology