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System Design and Analysis of Electricity Provision for a Desalination Plant

A Study for Pozo Colorado, Paraguay

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Master of Energy and Environmental Engineering
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Problem Description

This project is focused on fresh water production for Pozo Colorado, a district in the Chaco region in Paraguay. Scarcity of potable water is a challenge in this region due to the dry and hot climate. This is one of the reasons why only 2 % of the population lives here, although the region covers almost two thirds of the country's territory. There are groundwater resources in the area that are not yet exploited but this water has a high grade of salinity.

In this project a desalination plant that applies the technology of reverse osmosis will be studied. A PV-based energy supply for the plant should be suggested and assessed in terms of technical and economic aspects. For Pozo Colorado, a grid-connected PV-system should be evaluated and for areas without grid-connection a stand-alone PV system should be designed. Different operational regimes of the plant should be studied in order to find an optimal configuration for both the plant and the energy system. The simulation tool HOMER should be applied for investigations related to the micro-grid.

An important part of the project is data gathering during a field trip to Paraguay, which will take place in January-February 2014. The project is in collaboration with the non-profit organization Ren-PEACE and Engineers Without Borders (IUG) at NTNU.

Start date: 25th of January 2014

Supervisor: Marta Molinas

"The cure for anything is salt water - tears, sweat, or the sea"

- Isak Dinesen, Seven Gothic Tales

Preface

This master thesis has been written at the Department of Electric Power Engineering at Norwegian University of Science and Technology (NTNU) during spring 2014. The title of the thesis is *System Design and Analysis of Electricity Provision for a Desalination Plant – A Study for Pozo Colorado, Paraguay*.

I would like to thank my supervisor, Professor Marta Molinas at NTNU, and my advisor, Post.Doc. Jon Are Suul at NTNU, for invaluable guidance and support during the whole project period. Aldo Marcos, civil engineer in Asunción in Paraguay, was an excellent guide during the field trip to Paraguay and he has always been available for all the questions I had. Without Aldo this project would never have existed and I am very grateful for his contribution. Next, I would like to thank my fellow student Johannes Waatevik for his cooperation during the whole year, both academically and as my travel buddy in Paraguay. In addition, I would like to thank Stanislas Merlet, solar energy consultant from Multiconsult, for his professional advice and excellent Spanish skills during the field trip, and for his enthusiasm that kept us going even in high temperatures. All the lovely people we met in Paraguay deserve gratitude for everything they did for us, also the dog Chaqui who became the symbol of the project and will continue to grow until the project has been realized. Furthermore, I would like to thank Engineers Without Borders (IUG) at NTNU and Ren-PEACE for giving me the opportunity to write this very interesting project.

I would particularly thank my parents for proofreading my work and for always supporting me. I would also like to thank Astrid, Idun and Alexander for the coffee breaks and good laughs at the department, Joachim for always lending a helping hand, and Inger Johanne for being my fellow adventurer since 2008. And last, but not least, I would like to give special thanks to Trondheim for being the best student town and for giving me memories for life.

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Abstract

Fresh water scarcity and drinking water quality is a challenge in Pozo Colorado, a district in the northern part of Paraguay. Establishing a brackish water reverse osmosis (BWRO) desalination plant that produces potable water from the saline groundwater resources could be a solution to the problem. With high solar intensity in the region, a grid-connected battery back-up PV system could provide a reliable electricity supply to the plant. For areas that lack grid-connection, electricity provision from a stand-alone PV system with diesel generator could be a possibility.

In this master project, a BWRO plant is designed for Pozo Colorado to cover the demand of potable water in the village. Three construction stages are suggested for the plant, with associated energy supply systems. In all stages, grid electricity is the main energy source. In Stage 1, a back-up PV supply with battery storage is designed for the distribution pump only, for reliability reasons. In Stage 2 and Stage 3, the PV system is expanded to 12 kWp and then further to 20 kWp. Cost estimates for the desalination plant and the energy supply systems are presented for every stage. If production over a 25 year period is considered, the water cost in Stage 3 will be 15-30 % lower than the current cost of water in Pozo Colorado. With the current power price in Paraguay it would not be economically feasible to install PV panels in Pozo Colorado without subsidies. From simulations in the software HOMER, it was found that the price would have to increase by as much as 75 % in order to make introduction of PV modules economically viable. By creation of a synthetic electricity market with seasonal variations and higher prices during daytime, it was found that the average price only has to increase by 21 % in order to make PV introduction economically feasible. For a situation where energy is supplied from a stand-alone PV system, different operational regimes for the plant were evaluated. Based on costs of membranes and batteries, it was found that it would be more economical to use water as storage medium for solar energy instead of batteries. A three-step profile with production during the day and no production during night-time was found to be optimal from an economic point of view.

Overall this project reveals that a BWRO desalination plant supplied by a grid-connected PV system is a promising solution for Pozo Colorado. For areas that lack grid-connection, a stand-alone PV supply with diesel generator would be feasible, and in such a situation the operational regime of the plant will highly affect system configuration and costs.

Sammendrag

Mangel på ferskvann og kvalitet på drikkevannet er en utfordring i Pozo Colorado, et distrikt i den nordlige delen av Paraguay. Et anlegg som bruker omvendt osmose til avsalting av det salte grunnvannet (BWRO) kan være en løsning på problemet. Det er høy solinnstråling i området og derfor kan et nettilknyttet solcelleanlegg med batterilagring fungere som energiforsyning. For områder uten nettilknytning kan et frittstående solcelleanlegg med dieselgenerator være en løsning.

I denne masteroppgaven har et BWRO-anlegg blitt designet for Pozo Colorado. Tre utbyggingstrinn er foreslått for anlegget med tilhørende energiforsyning. I alle trinnene er det nettet som er hovedkilden til elektrisitet. Et back-up solcellesystem med et lite batterilager er designet for distribusjonspumpa i Trinn 1, som forsyningssikkerhet. I Trinn 2 og Trinn 3 er solcellesystemet videre utvidet til 12 kWp og deretter til 20 kWp. Kostnadsestimater for avsaltingsanlegg og energiforsyning er presentert for hvert trinn. Dersom man vurderer produksjon over 25-årsperiode vil vannkostnaden i Trinn 3 være 15-30 % lavere enn det den er i Pozo Colorado i dag. Men med dagens strømkostnad i Paraguay vil det ikke være lønnsomt å installere solceller i Pozo Colorado uten subsidier. Simuleringer i programvaren HOMER viste at strømprisen må øke med hele 75 % for å gjøre det lønnsomt å introdusere solceller i energisystemet. Et kunstig strømmarked med sesongbasert variasjon og høyere priser på dagtid ble laget, og simuleringer viste at gjennomsnittsprisen da bare må øke med 21 % for å gjøre solceller lønnsomt. For et frittstående solcellesystem ble ulike produksjonsprofiler for avsaltingsanlegget vurdert. Basert på kostnader for membraner og batterier ble det funnet at det vil være mest lønnsomt å bruke vann som lagringsmedium for solenergi i stedet for batterier. En tretrinnsprofil med produksjon på dagtid og ingen produksjon om natten var den optimale lastprofilen sett fra et økonomisk synspunkt.

Dette prosjektet viser at et BWRO-anlegg med et nettilknyttet solcelleanlegg som energiforsyning er en lovende løsning for Pozo Colorado. For områder uten nettilknytning er et frittstående solcellesystem med dieselgenerator en mulig løsning, og i et slikt tilfelle vil produksjonprofilen til anlegget i stor grad påvirke både systemkonfigurasjon og kostnader.

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Abbreviations

AC	Alternating Current
AF	Annuity Factor
ANDE	Administración Nacional de Electricidad
BWRO	Brackish Water Reverse Osmosis
CF	Compound Amount Factor
CONACYT	Consejo Nacional de Ciencia y Tecnología (National Council of Science and Technology)
d	Day
DC	Direct Current
DOC	Dissolved Organic Carbon
EC	Electrical Conductivity
ERD	Energy Recovery Device
ESS	Energy Storage System
Gs	Paraguayan Guaranis
HP	High Pressure
IUG	Ingeniører Uten Grenser
LP	Low Pressure
MED	Multiple-Effect Distillation
MPPT	Maximum Power Point Tracking
MSF	Multi-stage Flash Distillation
NPC	Net Present Cost

OECD	Organization for Economic Co-operation and Development
PSSH	Peak Sunshine Hours
PV	Photo-Voltaic
PWF	Present Worth Factor
R$	Brazilian Real
RMS	Root Mean Square
RO	Reverse Osmosis
SE/CW	South-East/Central-West
SOC	State of Charge
STC	Standard Test Conditions
SWRO	Salt Water Reverse Osmosis
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
UCSA	Universidad del Cono Sur de las Americas
UNA	Universidad Nacional de Asunción
US$	United States Dollars
VC	Vapor Compression
VSC	Voltage Source Converter
VSD	Variable Speed Drive
Wp	Watt Peak

Symbols

Symbol	Description	Unit
A	autonomy day	days
c	electricity price	c/kWh
C	battery capacity	Ah
E	energy	kWh (J·h/s)
F_{th}	thermal efficiency	-
M	number of membranes	-
P	power	W (J/s)
q	membrane throughput	m^3/membrane
Q	flow rate	m^3/h
U	voltage	V
η	efficiency	-

Chapter 1

Introduction

Water is a basic necessity for all living creatures on Earth. With climate change, increased urbanization and population growth, water scarcity is a growing challenge in many countries. Lack of fresh water is also a problem in the Gran Chaco, a region that covers the northern part of Paraguay, southeastern Bolivia and northern Argentina in South America. Within the borders of Paraguay, the Chaco covers almost two thirds of the country's territory. Despite this, it is home to only 2 % of the population. This can partly be explained by an extreme subtropical climate and the lack of modern infrastructure, but above all it is the scarcity of potable water that impedes settlement in the area.

Pozo Colorado is a small town in the Paraguayan Chaco, situated by the Trans Chaco highway that connects the southern and northern part of the country. Clean potable water is in shortage in the district, like in the rest of the region. Currently, the water supply in Pozo Colorado is surface water, which is rainwater collected in large ponds in the outskirts of town. Due to lack of chemicals for treatment, drinking this water can cause serious health problems and in dry periods water shortage is also a challenge. There are groundwater resources in the area, however, that have not yet been exploited. The problem is that this water is saline and undrinkable unless it is treated.

Building a desalination plant in Pozo Colorado that produces fresh water from the saline groundwater resources could be a solution to the problem of poor water quality and water scarcity. Reverse osmosis (RO) desalination is a widely used technology in the World today. RO is both energy efficient and has low investment costs compared to other desalination methods. The desalination process requires electricity, however, in particular to obtain the high pressure that enables RO. Fortunately a new 22 kV supply line was connected to Pozo Colorado in January 2014. The region also has high levels of solar irradiation and a PV supply could therefore be implemented in the energy system in order to increase reliability. The solar resources could also be exploited in a stand-alone PV system for areas without grid-connection.

This project was initiated by the non-profit organization Ren-PEACE in 2013. It is also in partnership with the student division of Engineers Without Borders (IUG) at Norwegian University of Science and Technology and it is one of IUG's "Meaningful Masters". IUG funded a field trip to Paraguay that took place in January and February 2014. This master thesis is based on a specialization project that was written during autumn 2013 [1]. The project report is used as a background for writing this thesis. Initially, the project was based on a study conducted by Aldo Marcos at National University of Asunción in 2005 [2]. Marcos' work was a feasibility study for establishing a brackish water reverse osmosis (BWRO) plant in Pozo Colorado, in order to supply fresh water for cattle production. As energy supply for the plant, Marcos considered a hybrid stand-alone system of solar PV and wind energy, with a diesel generator as back-up generation.

Unlike the project of Marcos, it is the provision of potable water for the villagers in Pozo Colorado that is the focus in this master project. Since a grid-connection is recently established, a battery back-up grid-connected PV system is designed as energy supply for the plant. Next, a stand-alone PV system with diesel generator is designed as a prototype for other areas in the Chaco that lack grid-connection. Johannes Waatevik, master student at NTNU, has in his master thesis modelled the power systems in detail [3], and some of his work is applied in this project.

This work includes a total of 8 chapters. Chapter 2 gives an overview of Paraguay and the existing water and electricity supply situation in Pozo Colorado. It also comprises information about the field trip to Paraguay, in addition to theory about RO desalination and battery back-up grid-connected PV systems. In Chapter 3, a desalination system design is presented for Pozo Colorado, with three possible stages of construction. For the stages suggested, energy supply systems are recommended in Chapter 4, including introduction to the simulation tool HOMER. Load profiles are developed as input parameters to the program based on data from an existing desalination plant visited in Paraguay. The energy supply systems are grid-connected, but includes introduction of PV modules in Stage 2 and 3. Simulation results are presented in Chapter 5, with system size and economic figures for both energy system and desalination system. The configurations are compared in terms of system costs and water costs in the same chapter. In Chapter 6, future electricity price development in Paraguay is evaluated. A synthetic electricity market model is created with hourly variations and reduced costs during daytime when solar irradiation is high. In the end of this chapter it is studied whether fluctuating power costs will have an impact on PV feasibility, from simulations in

HOMER. In Chapter 7, the applicability of a stand-alone PV supply is considered. An optimal operational regime of the desalination plant is determined based on costs of membrane and batteries. Hence, it is assessed whether it is most economical to utilize water or a battery bank as storage for solar energy. The optimal load profile is simulated in HOMER and energy system size and cost figures are presented at the end of Chapter 7. Chapter 8 includes a discussion of the project results, followed by a conclusion and suggestions for further work in the end.

Chapter 2

Background and Theory

2.1 Paraguay

2.1.1 Country overview

The Republic of Paraguay is a landlocked country situated in Central South America. It borders on Brazil to the east and northeast, Argentina to the south and southwest, and Bolivia to the northwest, as can be seen from the map in Figure 2.1.

Figure 2.1 Map of South America [4]

Paraguay has a small population and territory compared to its neighbors. In 2012, the country had 6.687 million inhabitants and with an area of 400,000 km^2 it has only about 5 % of the territory of Brazil. The majority of the population lives in the southeast region. 61% of the people are considered to live in urban areas, a number that is steadily increasing. The capital and largest city is Asunción close to the border with Argentina. Asunción is home to about 1.9 million people, nearly one third of the country's population. As a large part of the population has native heritage, there are two official languages in the country: Spanish, and the indigenous language Guarani [5].

Paraguay is a developing country, and about one third of the population lives below the poverty line. On average, the gross national income per capita was US$ 3,290 in 2012, well below the average of US$ 8,999 for developing countries in Latin America [6]. The weak economy affects the living standards of the Paraguayan people. Only 66 % of the rural population in the country is considered to have access to an improved water source, and as few as 43 % of the people living in rural areas have access to improved sanitation facilities [5, 6].

2.1.2 The Chaco and Pozo Colorado

The Paraguayan Chaco is a rural region in the northern part of Paraguay, as can be seen in Figure 2.2. It occupies almost two thirds of the country's territory, but is only home to 2 % of the population. The reason for this is the extreme subtropical climate and the lack of modern infrastructure. However, it is particularly the scarcity of potable water that impedes large scale colonization of the region. The annual mean precipitation in the region is between 800 and 900 mm, but most of this rain falls during the warm summer months [7]. In comparison, the capital, Asunción, has a mean annual precipitation of about 1300 mm [8]. Summer is a very hot period in the Chaco, with average temperatures close to 30°C for several months [7]. This is the period of the year with the highest plant growth rate, which means that also the transpiration from trees and plants and evaporation from the soil is at its highest. Hence, much of the rainfall evaporates directly and cannot be captured.

Figure 2.2 Map of Paraguay and the Chaco [5]

Pozo Colorado is a district in the Chaco region, 271 km northwest of Asunción, as can be seen on the map in Figure 2.2. The district is located in the department of Presidente Hayes and the closest big city, Concepción, is situated about 150 km to the east. Pozo Colorado is linked to other parts of the country by roads that connect south to north and east to west. The whole district has 17,727 inhabitants (2002 census), of whom 1,700 live in the town center [2]. More detailed data about Pozo Colorado is presented in Appendix A, which also includes a town plan. One of the streets in the center of town can be seen in Figure 2.3.

Pozo Colorado is no exception regarding the poor availability of water resources in the Chaco region. The balance between precipitation and evaporation is challenging and there is low access to potable water in the area. Nevertheless, the electricity production in the country is largely based on hydro resources in eastern and southern regions.

Figure 2.3 Street in Pozo Colorado

2.1.3 Current electricity situation

Paraguay is a large producer of hydroelectric power, most of it originating from the Itaípu dam on the border to Brazil in the south-east and the Yacyretá dam on the border to Argentina in the south. In total, the electricity production in Paraguay was 57.6 TWh in 2011, nearly 100 % comprised by hydropower. Out of this, only 13 % was consumed within the country and the majority of the remaining was exported to Brazil and Argentina. The residential sector is the dominant electricity consumer in Paraguay with 42 % of the demand. 23 % is consumed in industry and the remaining 35 % in commercial and public services. Per capita, the consumption was 1,230 kWh/year in 2011, well below the consumption in the neighboring country Brazil, where it is around 2,440 kWh/capita/year [9]. Figure 2.4 depicts the development in electricity consumption per capita per year for Paraguay and the non-OECD American countries from 2000 to 2011. The non-OECD countries include every country in America, excluding the US, Canada and Chile. One can detect that consumption in Paraguay is well below the regional average but there is a steady increase in consumption through the whole period.

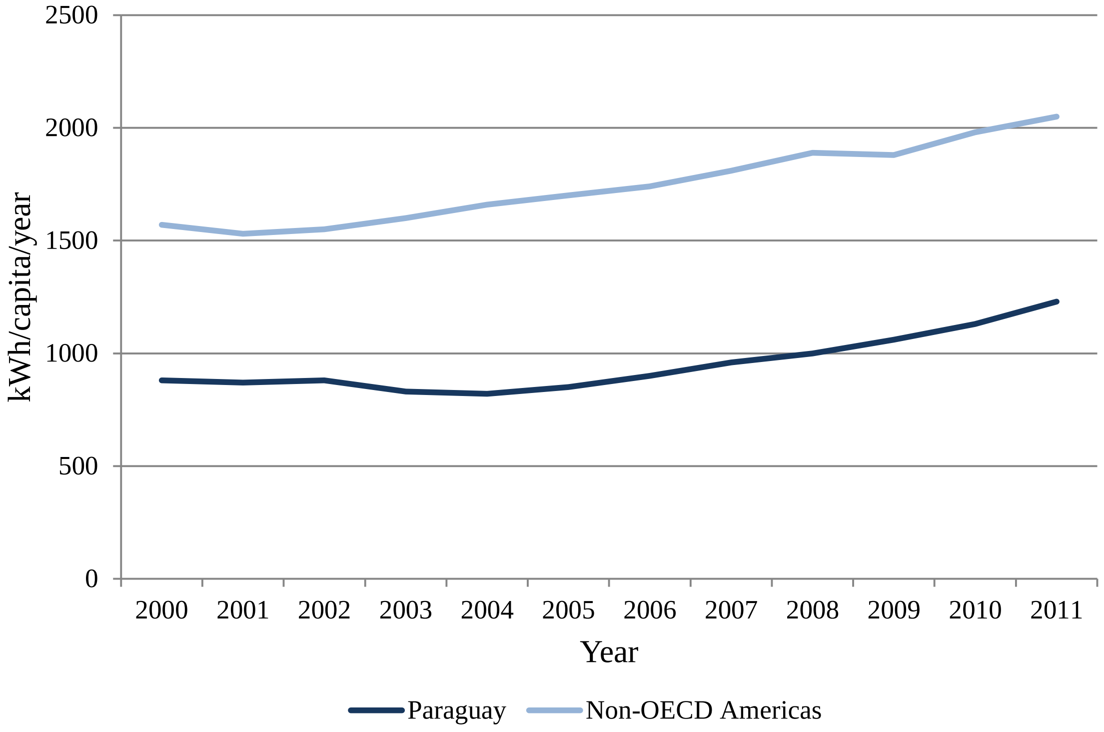

Figure 2.4 Electricity consumption per capita per year in Paraguay and non-OECD Americas from 2000-2011 [9, 10]

Although electricity consumption has risen steadily per capita in the period from 2000-2011, the increase differs from sector to sector. Figure 2.5 illustrates the development in electricity consumption distributed on the industrial sector, the residential sector and the sector of commercial and public services. It can be observed that industry has had a slow and steady growth in electricity consumption through the whole period. Consumption in the residential sector has more fluctuations, while commercial and public services have experienced a large increase in consumption after 2009.

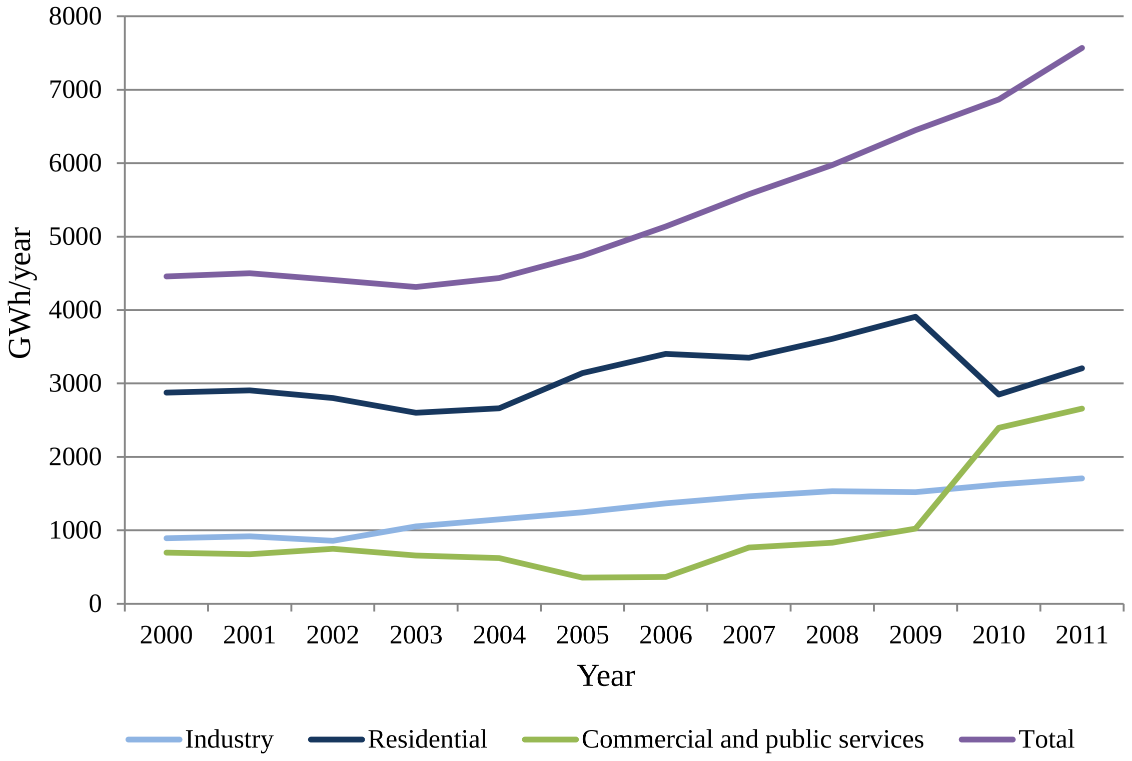

Figure 2.5 Electricity consumption per sector per year in Paraguay from 2000-2011 [11]

Unlike most of the countries in Latin America, Paraguay still has a public monopoly on electricity. The electricity market, including generation, transmission and distribution, is controlled by Administración Nacional de Electricidad (ANDE), which also determines the electricity tariffs. Power prices have been relatively constant over the past 5 years in Paraguay. Figure 2.6 depicts the development in power prices from 2007 to 2011 for six different sectors in Guaranis (Gs), in 2013 prices. Only average price data was available for 2013. It can be observed from the figure that the average price has been quite stable during the period although there has been a clear growth from 2011 to 2013. During these two years, the average price increased by as much as 16 %. Residential, commercial, industrial and general prices have seen a slight increase, while costs in the public lighting sector have declined. Costs in the governmental sector were slightly lower in 2011 than in 2007 but prices were lower in 2009 and 2010, as illustrated in the figure.

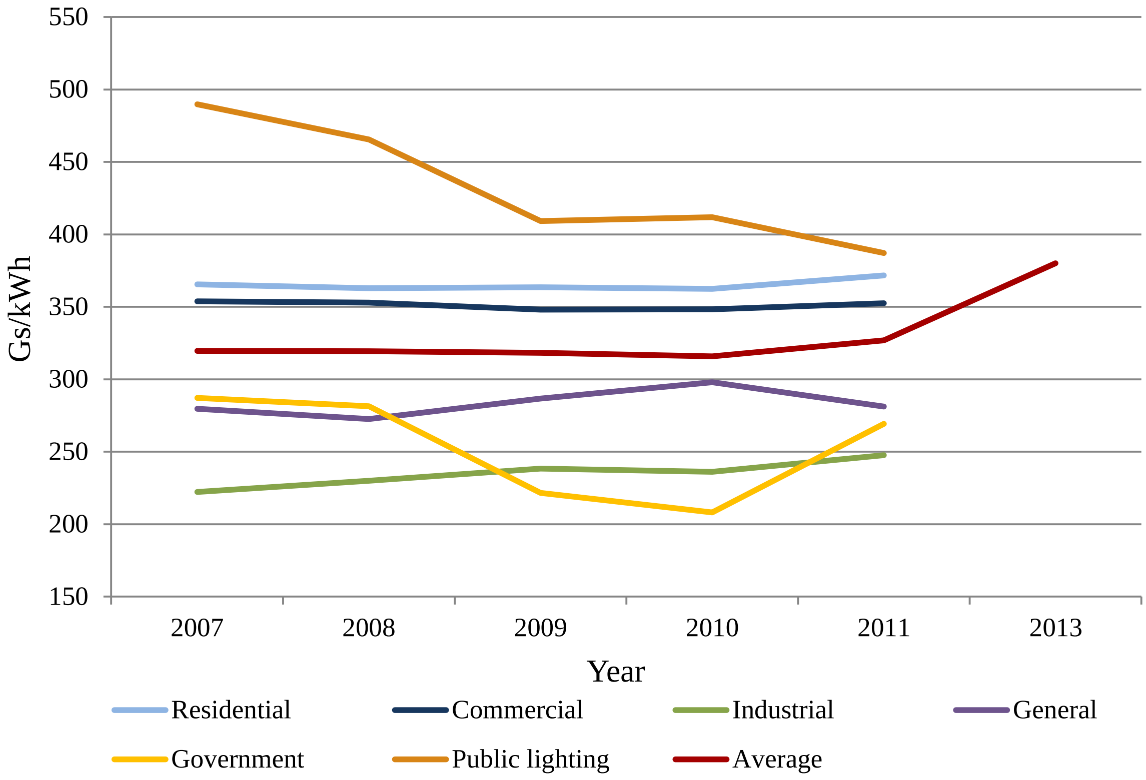

Figure 2.6 Power price development in Paraguay per sector, in 2013 prices[12-14]

The transmission grid in Paraguay is mostly centered in the areas around the capital, where the majority of the population lives. As illustrated in Figure 2.7, there are mostly 220 kV lines in the south, as well as one 500 kV supply line. In the more scarcely populated northern areas, there is one main 220 kV line supplying Loma Plata with electricity in the occidental region. As indicated on the map, Pozo Colorado has no high voltage electricity supply. However, in January 2014, a new 23 kV line was installed from Concepción, in addition to an existing 23 kV line from Asunción. This expansion will improve the electricity situation in Pozo Colorado, resulting in a more stable supply in harsh weather conditions and in periods of high electricity demand. With an expected economic growth and more energy-intensive industries, the electricity demand in Paraguay is anticipated to increase in the future. This is reflected in the report of grid expansions published by ANDE. According to this report, reliability will be further increased by 2023 with a new 220 kV line being connected to Pozo Colorado from Concepción [15].

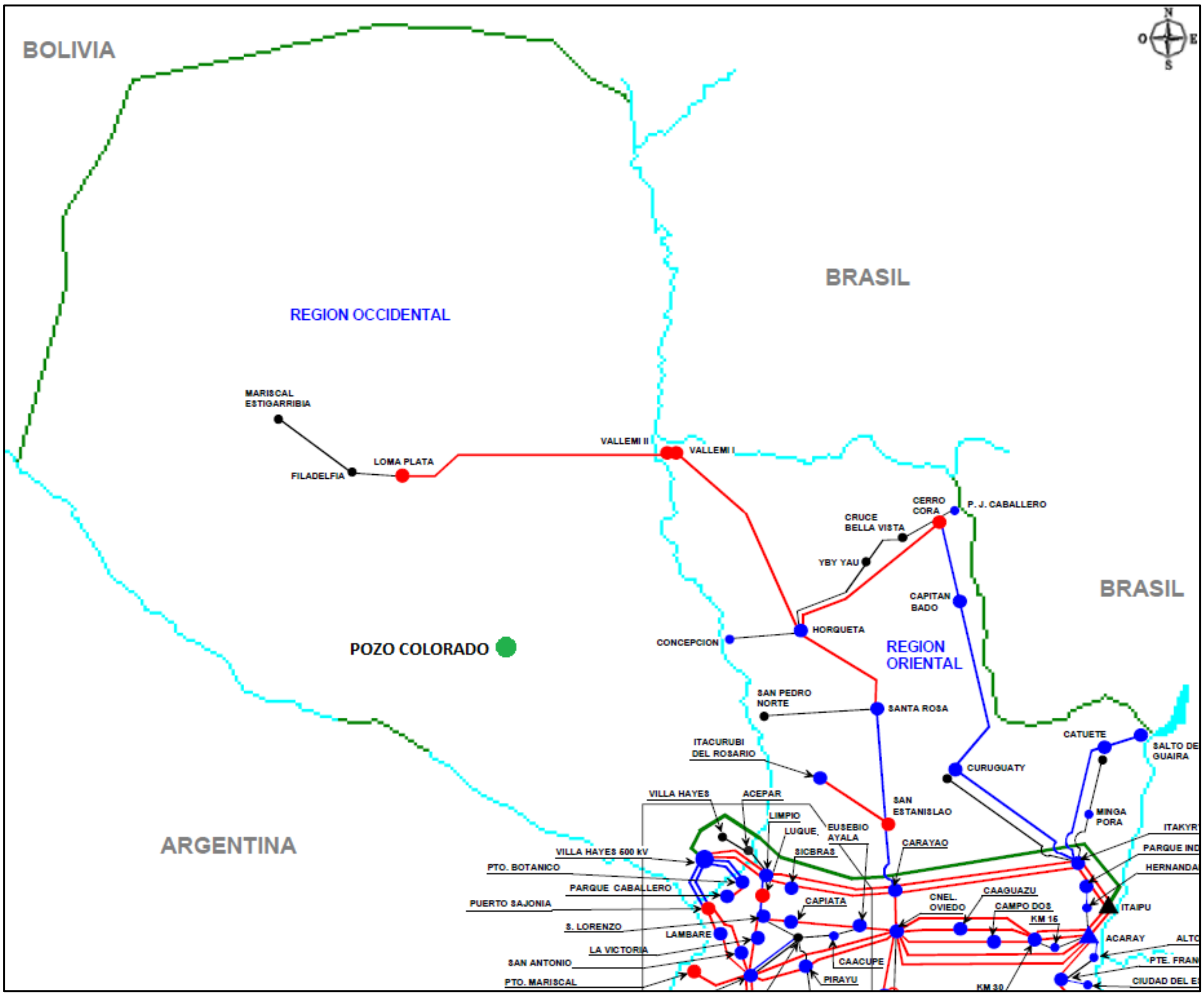

Figure 2.7 Map of high-voltage transmission lines in Paraguay in January 2014(green = 500 kV grid, red = 220 kV grid, black = 66 kV grid, blue = planned grid expansion during 2014) [15]

2.1.4 Renewable energy potential

With a warm climate, there are high levels of solar irradiation in the Chaco region. For Pozo Colorado, the annual average irradiation is 4.97 kWh/m^2/day. In comparison, Quito in Ecuador, which is situated almost on the equator, has an average of 5.46 kWh/m^2/day on a yearly basis [16]. The bars in Figure 2.8 indicate the variation in irradiation through the year for Pozo Colorado. It can be observed that the average irradiation for January is as high as 6.6 kWh/m^2/day, whereas June has an average of about 3 kWh/m^2/day. Yet solar irradiation is not the only renewable energy resource in the region. There are also wind resources present, indicated by the line graph in Figure 2.8. It can be observed that the wind speeds are at maximum between May and October, when irradiation levels are lower. The inverse correlation between these two energy resources could be benefited from in a renewable energy system. Due to time limitations it is only the solar resources of Pozo Colorado that are considered in this project.

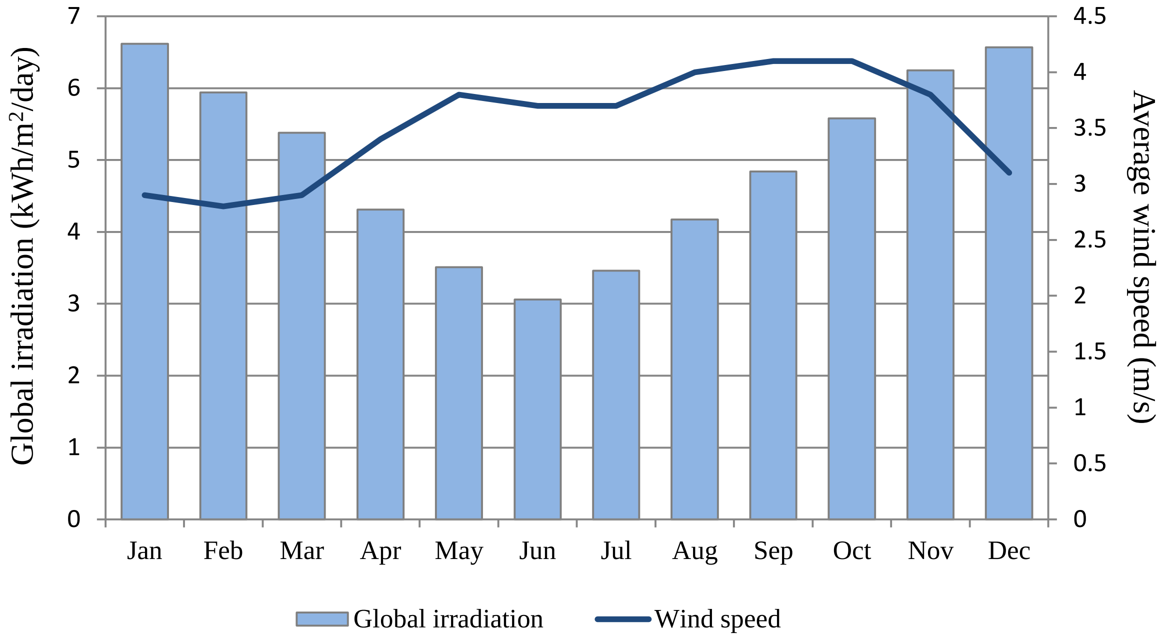

Figure 2.8 Average daily solar irradiation and average wind speeds in Pozo Colorado [2, 16]

2.2 Previous work

In 2005, Aldo Marcos submitted his master thesis "Fresh water production in Pozo Colorado, Paraguayan Chaco: by Reverse Osmosis using alternative energies, aeolic and photovoltaic - Technical and Economic feasibility study" [2] at the National University of Asunción. This is a study of the possibility of establishing a desalination plant in Pozo Colorado, using RO technology to treat the high salinity groundwater resources in the area. Marcos found that a hybrid system consisting of solar PV, wind turbines, diesel generator and battery storage would be a promising energy supply for the desalination plant. The purpose of the plant was to produce 600 m^3 fresh water daily for cattle production in the area. The use of renewable energy sources in this work provides valuable information for further investigation, and the concept of a RO plant for Pozo Colorado is elaborated in this master project.

2.3 Partner organizations

This project is written in cooperation with two organizations. First of all, it is in collaboration with the non-profit organization Ren-PEACE. Ren-PEACE is an organization that develops “micro-grid projects” in partnership with universities, and their aim is to provide energy from renewable energy sources in order to alleviate extreme poverty [17]. This project work is in close cooperation with Ren-PEACE, and the possible realization of the project is expected to be financed by funds gathered by this organization.

The student organization Engineers Without Borders at NTNU (IUG) is also involved in this project. IUG supports students writing “meaningful masters”; master theses where students use their engineering knowledge to improve the lives of people in need. IUG NTNU gives advice and field trip funding to students who are interested in involvement in development work during their final year at NTNU. This project is one of the meaningful masters that IUG provides in 2014. IUG sponsored a field trip to Paraguay during winter 2014, which will be furthered described in section 2.4.

2.4 Field trip to Paraguay

In collaboration with members in Ren-PEACE and with funding from IUG, a field trip to Paraguay and Pozo Colorado took place in January-February 2014. Participants on the trip were Johannes Waatevik, student at NTNU, Stanislas Merlet, solar energy consultant from Multiconsult, and the author. Aldo Marcos, civil engineer, member of Ren-PEACE and author of the master thesis presented in section 2.2, was a guide and advisor during the three-week stay in Paraguay.

The objective of the field trip was to gather as much data as possible for further work with the project. The data collected was both quantitative and qualitative. Quantitative data was either obtained by own measurements, like available space, or by interviewing people. As far as possible, information obtained from the citizens of Pozo Colorado was validated by asking several people to avoid misinterpretations due to the language barrier. Some quantitative information was particularly challenging to obtain, for example water consumption per household, and hence an average number was used if there was dissenting information from the inhabitants. Data collected about water consumption and the existing water supply system in Pozo Colorado is described in section 2.5.

A visit to an existing RO desalination plant in Filadelfia, called Aguamin, gave valuable data about plant equipment and component costs. This will be further elaborated in section 2.6.4. Qualitative data involved general feasibility of the project and evaluation of the site in Pozo Colorado. The feasibility of connecting an additional load to the new grid was discussed with José Vallejos from ANDE. An overview of the most important qualitative and quantitative data collected during the field trip is presented in Table 2.1.

Table 2.1 Quantitative and qualitative data gathered during field trip to Paraguay

Quantitative data	**Qualitative data**
Number of inhabitants	Willingness of local population
Water consumption	Feasibility of grid-connection
Available space, distances	Practical evaluation of site (shading etc.)
Costs of grid-connection, building, water	Configuration of current water supply system
Surface water composition	Experience from Aguamin RO plant
Properties of Aguamin RO plant	

Next to data collection, an important part of the field trip was to establish contacts that could be relevant for realization of the project. In order to successfully implement project plans it is essential to involve the local administration and it could also be beneficial to include research staff at universities at an early stage. When in Pozo Colorado, a meeting with the head of the village, Gregorio Riveros, and the local doctor, Cesar Mareco, gave interesting and important information about the local conditions. A picture from the meeting is included in Figure 2.9. Meeting the owner of Aguamin RO plant, Ricky Hockh, was crucial to understand the challenges of RO desalination in the region, and Hockh could be a useful contact both during project implementation and plant operation. Presentation of the project plans at Universidad Nacional de Asunción (UNA) and Universidad del Cono Sur de las Americas (UCSA), both in Asunción, was rewarding and important contacts have been established in the field of research. A photo from the meeting at UCSA is presented in Figure 2.10.

Figure 2.9 Meeting with Gregorio Riveros and Cesar Mareco in Pozo Colorado 27th of January 2014

Figure 2.10 Meeting with professors at Universidad del Cono Sur de las Americas 6th of February 2014

2.5 Existing water supply system in Pozo Colorado

During the field trip to Pozo Colorado the existing water supply system was inspected. This was a result of a European Union project from 2009 that was initiated to improve the drinking water supply of the village. The system pumped water from a pond of surface water into three storage tanks of 10,000 liters each. In the tanks the water was treated chemically with aluminum sulfate, before being stored in a 20,000 liter underground tank. From there it was pumped to an elevated tank with a volume of 10,000 liters prior to being distributed to the consumers through an underground piping system. The system failed to work properly after short time in operation. Parts of the distribution system were unable to withstand the high pressure and were therefore damaged. In September 2012 there were no more chemicals to be used for treatment.

Since then, the water has been untreated and some of the villagers have had to walk to the pond to fetch water in buckets due to damage on the pipelines. Some people treat the water with chlorine at home while others drink the water untreated. Based on information from one of the villagers, the water consumption per capita is around 55 l/day, which yields a total demand of 93,500 l/day for 1,700 inhabitants. Every household has to pay a monthly fee for being connected to the distribution system, in addition to costs of chemicals. Based on an average chlorine consumption of 0.234 l/household/month and a fixed connection fee of 3.3 \$/household/month, the cost of water is about 0.38 $\$/m^3$. This is based on an average number of 5 people in each household in the village [18]. Details about water consumption and cost of water are summarized in Table 2.2.

Table 2.2 Water consumption and cost of water with the current system in Pozo Colorado [18]

Consumption per capita	0.055 m^3/d
Consumption village	93.5 m^3/d
Approximate cost of water	0.38 $\$/m^3$

The configuration of the existing water supply system is sketched in Figure 2.11. As status is today, the underground storage tank is not in use and neither are the elevated tanks of 1,000 liters each. A photo of the source of surface water can be seen in Figure 2.12, the elevated storage tanks are shown in Figure 2.13 and the storage tanks on ground are depicted in Figure 2.14. Results from a water analysis of the surface water are included in Appendix A.

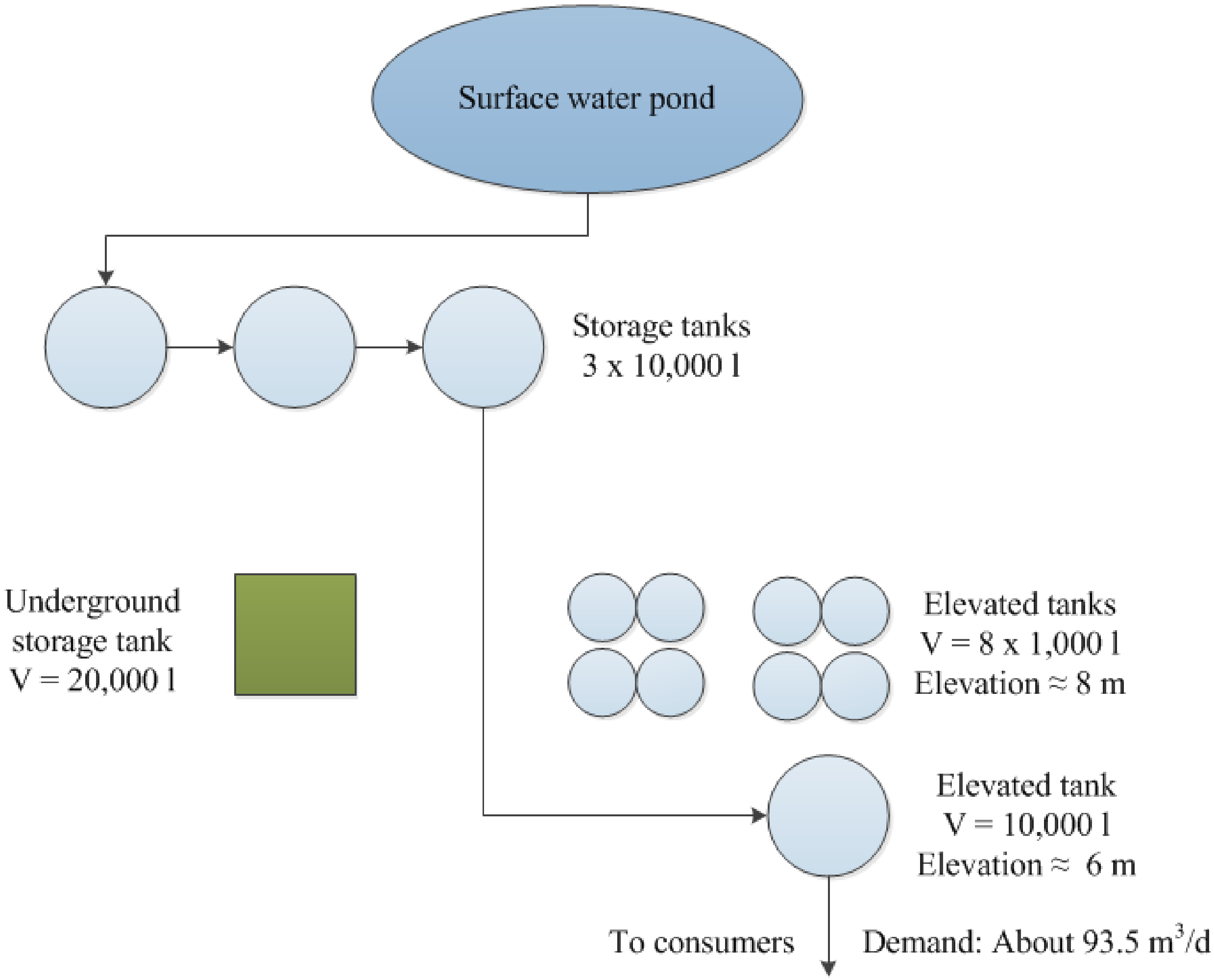

Figure 2.11 Configuration of the existing water supply system in Pozo Colorado

Figure 2.12 Surface water pond in Pozo Colorado

Figure 2.13 Elevated storage tanks in Pozo Colorado

Figure 2.14 Three storage tanks of 10,000 liters each in Pozo Colorado

The current system is not optimal as it is neither a secure nor safe water supply. Without chemicals for treatment, the water is not considered to be a safe source of drinking water. According to Cesar Mareco, the doctor of Pozo Colorado, there have been several cases of diseases due to the poor drinking water quality and there have been incidents of dehydration [19]. In addition, the availability of water from the pond is limited in periods of very hot weather when evaporation rate is high. In these periods, there are trucks from the government driving from Concepción to cover the needs of the people in Pozo Colorado [18]. The water distribution system is also a challenge and upgrading the pipes is crucial to obtain a well-functioning water supply.

There are, however, groundwater resources in the area that could be extracted and applied for drinking purposes. The challenge is that the salinity of this water is high and it is undrinkable unless it is desalinated. Compared to typical brackish water, the salinity of the groundwater in the area is in the higher-end bracket. As described by Marcos in 2005 [2], a RO desalination plant that produces potable water from the groundwater resources could therefore be a solution to the problem.

2.6 Reverse osmosis technology

2.6.1 Concept of reverse osmosis

Osmosis is the natural process where water from a solution with low concentration of dissolved solids flows through a membrane to a solution with higher concentration of dissolved solids. Figure 2.15 illustrates the direction of flow. The membrane placed between the compartments is semipermeable, which means that it will let water and some ions flow through it, while it is impermeable to most dissolved substances. Water will continue to flow through the membrane until equilibrium is reached and the solute concentration is equal on both sides. At equilibrium, there is no more net flow between the compartments. Now, the side that once had the higher concentration will have a higher water level than the other compartment. As Figure 2.16 indicates, the difference in height between the two compartments corresponds to the osmotic pressure of the solution. This is the pressure applied on the surface of the semipermeable membrane [20].

The process of RO occurs when a pressure greater than the osmotic pressure is applied to the compartment that first contained the high-concentration solution. Due to resistance in the membrane, the applied pressure has to be considerably higher than the osmotic pressure. As a result of the pressure increase, water will flow in the reverse direction. This is illustrated in Figure 2.17. The water that flows through the membrane will be relatively pure and the dissolved solids will remain on the side where the pressure is applied. As a consequence, there will be purified water on one side and there will be a concentrated solution in the other compartment [20].

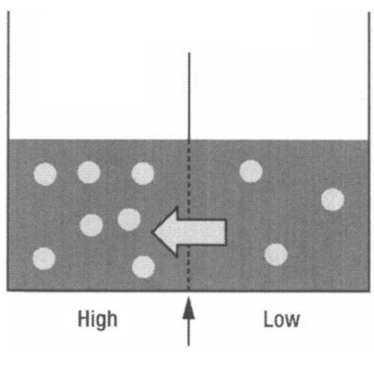

Figure 2.15 Water flow to equalize concentration on the two sides of the RO membrane [20]

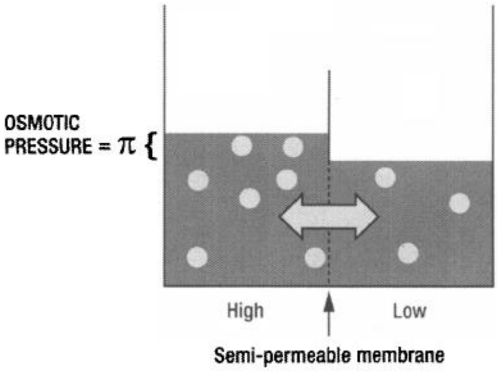

Figure 2.16 Pressure difference on each side of a RO membrane due to the osmotic pressure difference [20]

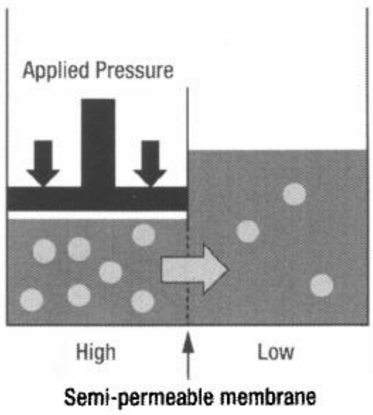

Figure 2.17 A pressure greater than the osmotic pressure is applied on the high-concentrate side and water flows to the compartment with lower concentration [20]

The osmotic pressure is a function of the concentration of total dissolved solids (TDS). For every 100 mg/l of TDS an osmotic pressure of about 1 psi (≈0.07 bar) will be created. That means that brackish water, which typically has a TDS of 3,000 mg/l, would have an osmotic pressure of about 2.1 bar, and seawater with a typical TDS of 35,000 mg/l would have an osmotic pressure of about 24.5 bar. Hence, the lower salinity of the source water, the less energy intensive the purification process will be. Temperature and target product water quality are also factors that will affect the energy use. Furthermore, TDS concentration is often monitored by measuring electrical conductivity (EC) expressed in micro Siemens per centimeter (μS/cm). The TDS/EC ratio in source water is site dependent but is usually between 0.67 and 0.70 [21].

In Figure 2.18, the layout of a typical RO membrane is illustrated. The membrane in the figure is spiral-wound, which is the dominating membrane element for brackish and seawater desalination plants. The outer part of the membrane consists of 40 to 42 flat membrane sheets, which are assembled into 20 to 21 membrane envelopes. The envelopes are separated by a feed spacer that is approximately 0.7 to 0.9 mm thick. A feed spacer facilitates mixing and passage of the feed water along the length of the membrane. In the desalination process, pressurized saline feed water is applied on the outer surface of the membrane envelopes. Permeate, or fresh water, is collected between the two sheets of the envelope and directed towards the center of the membrane element. Permeate from all envelopes is collected in the central permeate collector tube, as indicated in Figure 2.18, and from there it is evacuated out of the element. The concentrate, or brine, leaves the membrane through the outer parts of the tube [21]. Due to risk of fouling, there is a limit to how much fresh water that can be recovered in a RO membrane system. For BWRO plants it is typically between 65-85 % [21, 22].

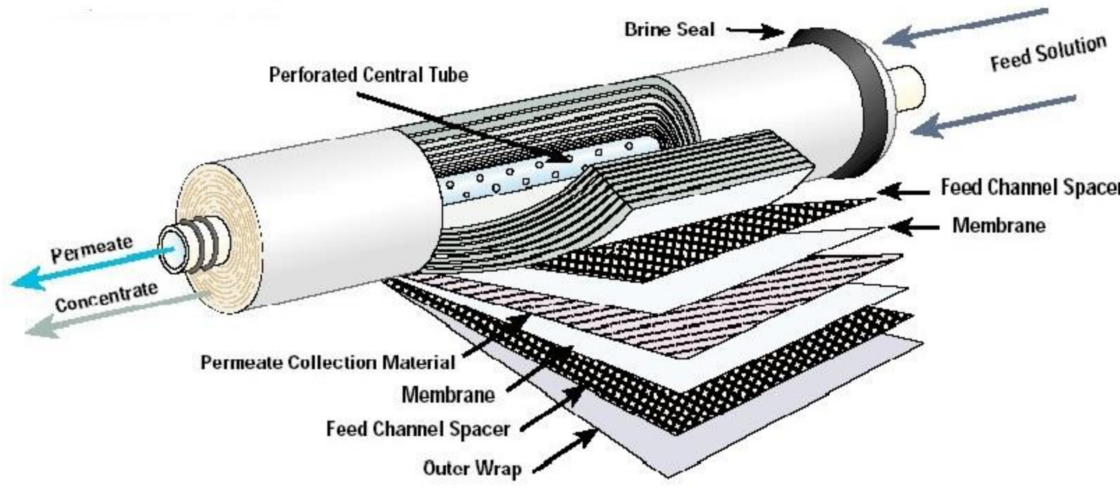

Figure 2.18 Spiral-wound RO membrane configuration [23]

Compared to other desalination processes, the RO process is very energy efficient. Energy consumption per cubic meter of fresh water is presented in Table 2.3, for five different desalination technologies. Compared to the other three, BWRO and sea water reverse osmosis (SWRO) are clearly the most energy efficient methods.

Table 2.3 Energy use for alternative desalination technologies (MED = Multiple-effect distillation, MSF = Multi-stage flash distillation, VC = Vapor compression, BWRO = Brackish water reverse osmosis, SWRO = Seawater reverse osmosis) [21]

	MED	**MSF**	**VC**	**BWRO**	**SWRO**
Total energy use (kWh/m^3)	5.7-7.8	12.7-15.0	8.0-12.0	0.3-2.8	2.5-4.0

2.6.2 Key components in a reverse osmosis plant

A RO plant consists of a number of components that are designed to perform the required desalination process. Larger plants would typically have more sophisticated and expensive components, whereas smaller plants would normally require fewer and less expensive equipment. Regardless of size, the basic system configuration is the same for all RO plants. The main components in a RO plant are presented in Figure 2.19. The combination of these components, including valves, couplings and fittings, can function independently and is referred to as a RO train [21].

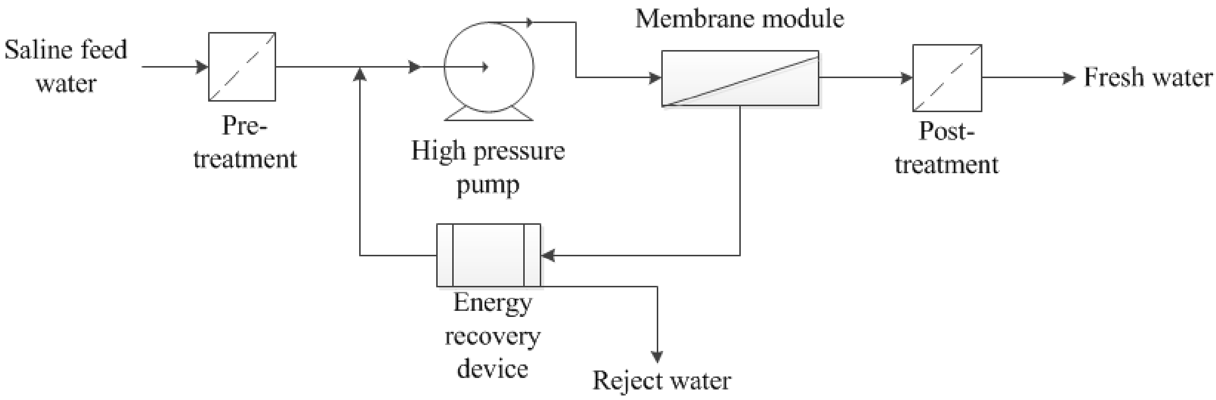

Figure 2.19 Schematic diagram of a RO system with energy recovery device, modified from [24]

As can be seen from Figure 2.19, the saline feed water has to be treated before entering the membranes to avoid fouling and thereby reduction of membrane performance. Therefore, the first stage is the pre-treatment process. Depending on the source water quality, this stage involves different water treatment processes, like various filtration methods, screening and chemical conditioning [21]. Next, the treated water enters the high pressure (HP) pump, where the required pressure is obtained. Centrifugal HP pumps are used for all desalination plant sizes, however reciprocating pumps are sometimes used for plants with a fresh water production lower than 4,000 m^3/day [25]. A RO plant can consist of one large HP pump or several smaller pumps. According to [21], one pump is usually considered to be more efficient, but several pumps could be used for reliability concerns or if the plant has to be operated in a wide range of production flows.

After the pressure is increased, the water flows through the membrane modules. The membrane type is chosen according to the source water quality, the required product water quality and the desired membrane properties. Available on the market are membranes that are high-rejection, low-energy, low-fouling or high-productivity membranes. The most common spiral-wound membrane that was presented in Figure 2.18 on page 23 has a standard diameter of 200 mm and a length of 1.0 m. In a RO plant, the membranes are installed in pressure vessels that typically contain 6 to 8 membrane elements each. These vessels are tube-shaped and are usually made of plastic or metal [21]. Figure 2.20 presents a series of pressure vessels containing membrane elements.

Figure 2.20 Pressure vessels containing RO membrane elements [26]

The concentrate produced by the RO system has a high pressure and thereby a high energy content. Through an energy recovery device (ERD), some of this energy can be recovered and thereby the overall energy requirement can be reduced. A system without an ERD would normally use two to three times more energy and this will increase for larger systems [24]. Different ERDs are available, but the two main types are centrifugal and isobaric ERDs. The centrifugal device converts the energy in the concentrate into rotational energy which is used directly to run the HP pump. An isobaric ERD, on the other hand, applies a piston to deliver the energy to pump new source water into the system and is decoupled from the HP pump. The feasibility of installing an ERD is mainly dependent on the plant size and ERDs are generally not installed in smaller plants [21].

The product water exiting the membrane elements is fresh water. Before it is drinkable, however, the water has to go through a post-treatment process. In this stage, the water is re-mineralized and disinfected, depending on the quality requirement on the product water. After this process, the fresh water is ready to be distributed to the consumers [21].

2.6.3 Operational regime

For desalination plants powered by renewable energy sources the operational regime becomes an issue due to the unsteady power delivery and thereby the need for energy storage systems (ESS). As the most essential and expensive components of the desalination plant, the RO membranes have to be taken into account when the mode of operation is determined. Experience from RO desalination plants reveals that it is preferable to operate the membranes with a constant water flow in order to protect the membranes. According to [27], varying the flux outside of membrane specifications for can cause lower product water quality and also reduce the lifetime of the membranes. Hence, a variable production is feasible if entire sections of RO membranes are taken out of operation at lower production rates [28]. Little research has been conducted on how start and stop in production affects membrane fouling. According to [27, 29], membranes can easily tolerate start and stop, as long as flushing of the membranes is performed within the first five to ten minutes after shut-down. For flushing, fresh water from the operating part of the system can be applied.

The system pumps should also be considered when determining the operational regime of a desalination plant. In recent years, the variable speed drive (VSD) technology has developed and become more prevalent. Adjusting the speed of a drive according to the load can increase efficiency and reduce energy consumption. In addition it allows for gentle start-up and shutdown which can expand the lifetime of the equipment. In many applications a VSD can reduce energy consumption by as much as 30-60 % [30]. With a VSD the system efficiency could be maintained on a high level regardless of the required pumping capacity [31]. Hence, it would be technically feasible for the pumps in the system to have a variable production profile, although optimal membrane operation would result in a relatively constant pumping rate.

2.6.4 Example of a reverse osmosis desalination plant in the Chaco

During the field trip to Paraguay, an existing BWRO desalination plant was visited. Aguamin desalination plant is located in Filadelfia, the capital of Boquerón Department in the Gran Chaco of Western Paraguay. Filadelfia is placed 191 km north-east of Pozo Colorado along the Trans Chaco highway and is also considered to be the capital of the Paraguayan Chaco. Like in Pozo Colorado, the groundwater in Filadelfia is of high salinity. According to Ricky Hockh [29], owner of the desalination plant, the conductivity of the groundwater is around 13,000 μS/cm. The plant produces water to partly cover the needs of the people living in the town center of Filadelfia and has been in operation since 1998. The maximum production capacity of the plant is 240 m^3/d, which is considerably higher than the demand in Pozo Colorado. The water is distributed to the local consumers via a piping system and in tankers for larger distances.

At Aguamin there are two membrane trains of 12 4-inch membranes each, and a pressure of about 50 bar is obtained by two HP pumps in series configuration. In the pre-treatment stage an anti-crystallization chemical is added to prevent scaling in the membranes, followed by a sand filter and a particle filter. According to Hockh, the product water is of high quality and therefore only a carbonate filter is necessary as post-treatment. The product water is pumped into elevated storage tanks with a capacity of around 1/3 of the daily production, and from there it is distributed to the consumers. About 50 % of the feed water can be recovered as fresh water and the remaining is brine discharge. The discharge is pumped back into the ground to a well deeper than the extraction well. The plant configuration is further specified in Figure 2.21 and the HP pumps and pressure vessels can be seen in Figure 2.22. No ERD is installed in the plant as it is not economically viable for this size [29]. Membrane and pressure vessel suppliers are listed in Table 2.4 with the associated lifetimes of the components for the use at Aguamin [29].

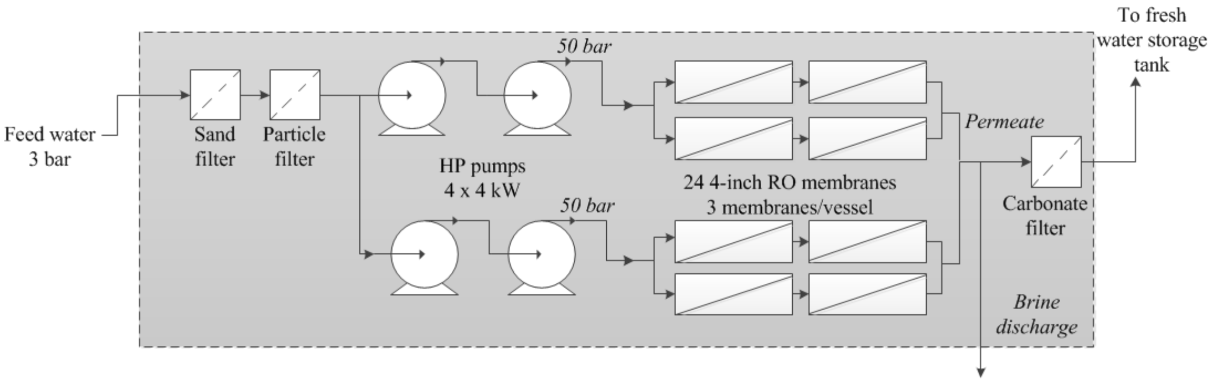

Figure 2.21 Configuration of Aguamin reverse osmosis desalination plant in Filadelfia, Paraguay

Figure 2.22 High pressure pumps and pressure vessels at Aguamin desalination plant

Table 2.4 Brand and lifetimes of membrane and pressure vessels at Aguamin desalination plant

Component	**Brand**	**Lifetime (years)**
RO membrane	Hydranautics	1
Pressure vessel	Codeline	5

2.7 Battery back-up grid-connected PV systems

2.7.1 General about battery back-up grid-connected PV systems

In regions where there is high risk of power outage, a battery back-up grid-connected PV system could be a useful solution. Such systems would be suitable in places where grid reliability is generally poor or in locations where natural disasters occur frequently.

In Figure 2.23 a basic battery back-up grid-connected PV system is illustrated. The system is DC-coupled, which means that the PV array and the battery bank are connected to a common DC bus, and there is an inverter to connect the DC and AC bus. In order to prevent the battery bank from being overcharged or too heavily discharged, a charge controller is a crucial component [32]. As can be seen from the figure, the battery bank is either charged by energy from the PV array or from the grid. The PV array, battery storage and inverter in Figure 2.23 are further described in section 2.7.2, 2.7.3 and 2.7.4.

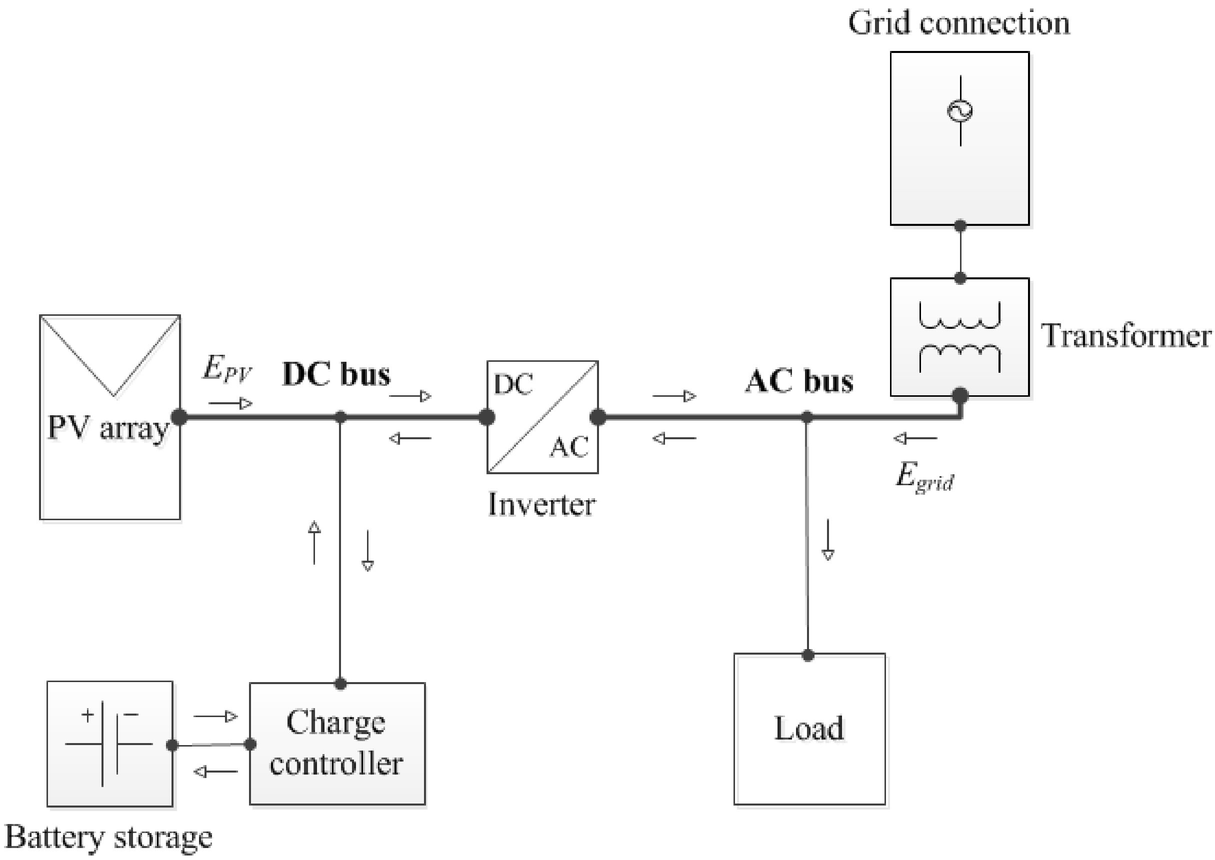

Figure 2.23 Block diagram of a basic DC-coupled battery back-up grid-connected PV system, modified from [32]

2.7.2 PV modules

There is continuous development in the field of PV cell technology and there are many cell technologies available on the market. The most commonly used PV cells today are based on silicon and are designed in the form of mono crystalline or polycrystalline. The mono crystalline cells are more expensive in manufacturing and the module efficiency is typically between 12 and 16 %. Modules consisting of polycrystalline wafers have a slightly lower efficiency, normally between 11 and 15 %, but are lower in cost [33].

The PV array capacity depends on the energy demand that has to be covered in case of grid failure. It may be an advantage to establish which periods of the year when power failures are most likely to occur, since this is the period when the PV array has to produce energy. The PV system has to be designed in such a manner that it can operate as a stand-alone system. When sizing the system, loss factors have to be taken into consideration. By applying equation (2.7.1) from [32], the peak power of the PV array, in kWp, can be determined:

$$P_{peak} = \frac{E}{PSSH \cdot F_{th} \cdot \eta_b \cdot \eta_{inv} \cdot \eta_w \cdot \eta_c} \tag{2.7.1}$$

where E is the average daily energy consumption in kWh, F_{th} is the thermal factor of the PV array, η_b is the battery efficiency, η_{inv} is the efficiency of the inverter, η_w represents the system wiring loss factor and η_c is the efficiency of the charge controller. PSSH is the average peak sunshine hours per day, which is the length of time in hours that the sun's irradiance is 1000 W/m^2, obtained by integration of irradiance over all daylight hours. Thermal losses could be up to 15 % in a worst case scenario and the inverter losses are normally around 6 %. Battery charging losses are typically about 10 % and the system wiring losses could be as high as 4 %. Losses in the charge controller would normally be around 2-4 % [32]. If all these loss factors are applied, the total efficiency will be around 68 % in a worst case scenario. When the peak power of the PV array is known, the number of modules can be found, depending on the module sizes that are available.

2.7.3 Battery storage

When determining the size of the battery bank the daily energy demand has to be evaluated. Next, the autonomy time of the system has to be considered, which is the time that the system can supply energy to the load without solar irradiation, starting with fully charged batteries. In addition, it has to be taken into consideration that the batteries are rechargeable and cannot withstand deep discharges. Deep discharges can cause irreversible damages to the batteries and can reduce the lifetime of the batteries considerably. A charging state lower than 30 % is considered a deep discharge for lead-acid batteries, which is the most common battery type in PV systems [32, 34], and this must be counted when sizing the battery package [35].

Although lead-acid batteries can be designed for deep discharges, the number of operating cycles depends on the depth of discharge during normal operation. Figure 2.24 indicates how the number of cycles decreases with an increasing depth of discharge, for a lead-acid battery from the supplier Rolls. This battery could withstand up to 5000 cycles with a 20 % average daily discharge, whereas a 60 % average daily discharge would result in only 2800 cycles. For clarification, a 100 % discharge is here equal to the maximum allowable discharge, which is usually set to 70 %.

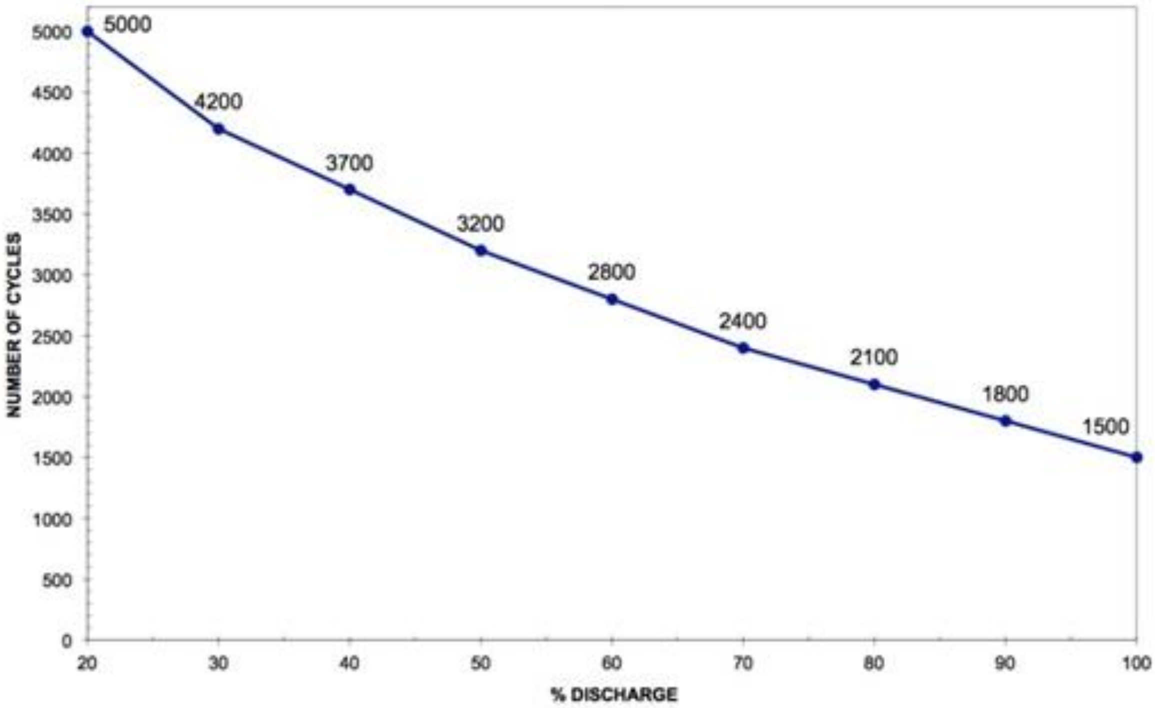

Figure 2.24 Cycle life vs. depth of discharge for a flooded lead-acid battery, Rolls series 5000 [36]

The energy consumption, the number of autonomy days and the maximum depth of discharge are used to calculate the required storage capacity. The battery capacity, C, in Ah, can be determined by equation (2.7.2), from [35]:

$$C = \frac{E \cdot A}{0.7 \cdot U} \cdot 1000 \qquad (2.7.2)$$

where E is the average daily energy consumption in kWh, A is the number of autonomous days and U is the nominal voltage of the battery. The factor 0.7 is a result of the maximum deep discharge of 30 % for lead-acid batteries. A typical lead-acid battery would have a charging efficiency of around 90 %, which implies that only 90 % of the energy that enters the battery leaves the battery [32]. The PV array has to make up for these losses, as represented by η_b in equation (2.7.1).

2.7.4 Inverter

For a grid-connected PV system an inverter will be necessary to produce AC from the DC produced by the PV array. For grid-connected PV systems, the inverter must be capable of switching from grid-synchronized current source to internally synchronized voltage source in cases of grid failure. The inverter is sized according to the maximum instantaneous power requirements of the load. Inverter efficiencies vary with the quality of the inverter but a pure sine inverter could have efficiencies above 96 %. An inverter is specified by power rating and input and output voltage, as well as harmonic distortion and surge capacity [32].

Chapter 3

Desalination System Design for Pozo Colorado

3.1 Site for desalination plant

The current location of the water treatment system in Pozo Colorado is indicated on the photo in Figure 3.1. On the southern side of the pond there is a large open space that is owned by the local community. This site is indicated by the white circle in Figure 3.1. It was estimated during the field trip that this space covers an area of approximately 300 m^2, which could be further extended towards the west. The location close to the existing storage tanks and the proximity to the road would make this a suitable site for a desalination plant. Also, the town center is close by and the fresh water would not have to be distributed across very long distances to reach the consumers. There are no high trees of significance in the area that could cause shading for solar PV panels.

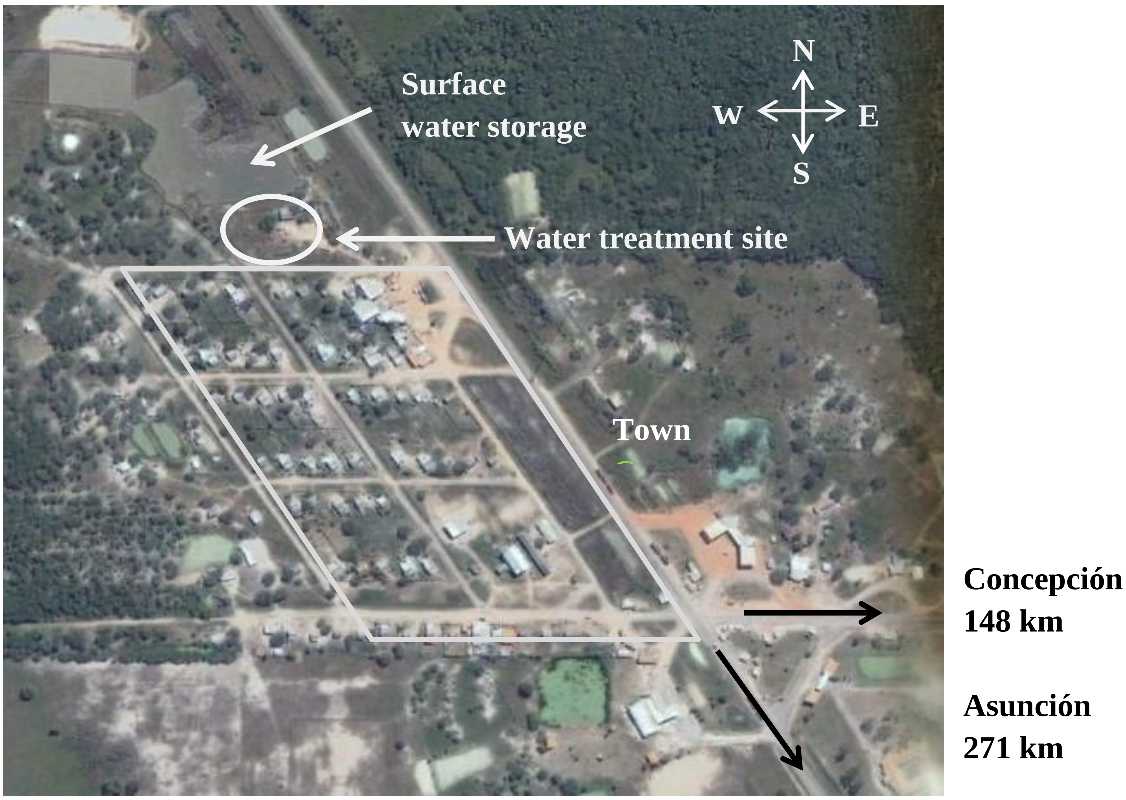

Figure 3.1 Pozo Colorado overview with water storage pond and water treatment site

3.2 Reverse osmosis desalination plant configuration

A preliminary design for the RO plant in Pozo Colorado has been created, based on the theory presented in section 2.6.2, data collected from Aguamin desalination plant presented in section 2.6.4 and discussion with Hockh [29]. A possible configuration is presented in Figure 3.2, where the area inside the dashed rectangle indicates the components that are part of the desalination process. The inner rectangle represents one RO train, which includes 2 HP pumps in series and the associated membrane modules. The diagram shows that there are 5 pumps in the system: 1 well pump, 1 low pressure (LP) pump, 2 HP pumps and 1 distribution pump. The well pump extracts groundwater from a well into the feed water storage tank. In this tank, the sand in the feed water will sink to the bottom, preventing sand particles from clogging the system, before it is pumped into the desalination plant by the LP pump.

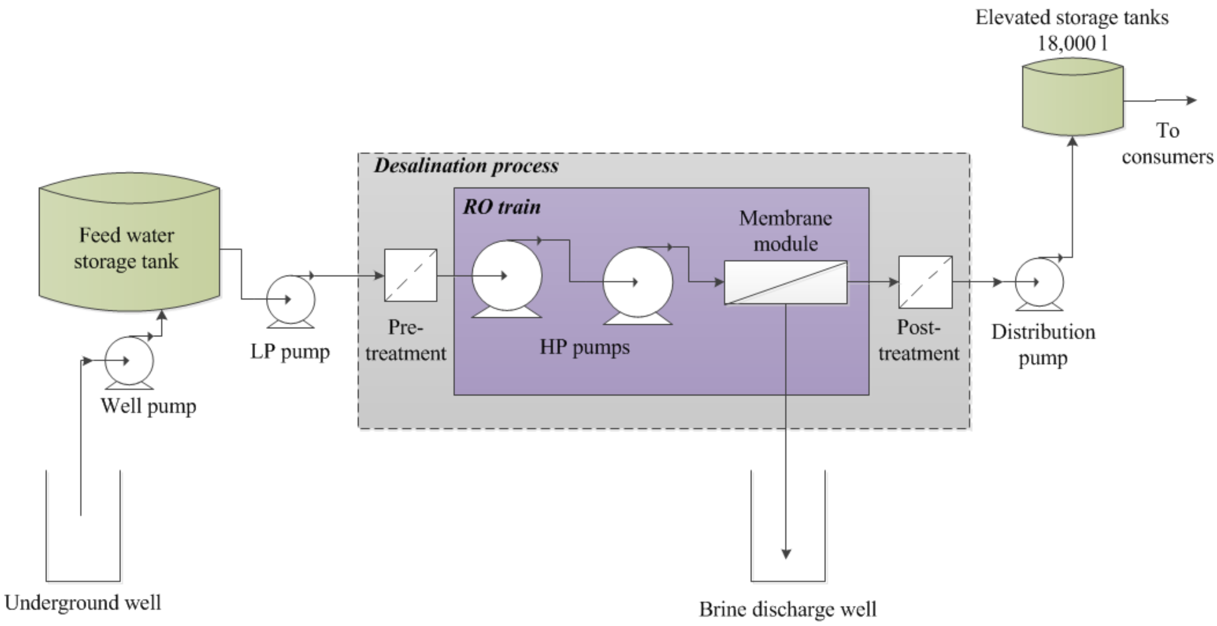

Figure 3.2 Preliminary design of a reverse osmosis desalination plant for Pozo Colorado

The RO process is equivalent to the process presented in section 2.6.2, with pre-and post-treatment, HP pump and membranes. As for Aguamin, the HP pumps are configured in series, each of the pumps raising the pressure by a certain amount. To take care of the brine that is left-over from the RO process, a discharge well or tank is necessary. If it can be justified from a hydrogeological perspective, the brine could be pumped back into the ground as it is done at

Aguamin. After post-treatment, the fresh water is pumped to elevated storage tanks and from there it is distributed to the consumers. The size of the feed water storage tank is not considered here, but according to observations from Aguamin it should be around 1/3 of the daily fresh water production. The existing elevated storage tanks with a total volume of 18,000 l could be included in the system, as indicated in the figure. In addition to the components presented in the figure, a technical office will be necessary to house the desalination units, pumps, motors and a control system for monitoring the plant.

3.3 Construction stages

The desalination plant could possibly be built in three stages, where production in the first stage almost covers the current fresh water demand in Pozo Colorado. This would allow for testing the desalination technology on a small scale and learning from any faults that could occur. For the second and third stage, the desalination plant could be easily expanded with additional RO trains. This could allow for an increase in water consumption, and in addition enable distribution of fresh water to people living outside the town center in Pozo Colorado. A possible plan for expansion is presented in Table 3.1 and is presented graphically in Figure 3.3.

In Stage 1, the production is 88.6 m^3/d, which almost covers the current demand of 93.5 m^3/d. It can be observed that production in Stage 2 is double the production in Stage 1, and Stage 3 can produce triple the amount of Stage 1. The RO membrane type that is considered is equivalent to the membranes that will soon be taken into use at Aguamin: Hydranautics SWC4+B, with a diameter of 8 inches and a permeate flow rate of 24.6 m^3/day [37]. This type is chosen based on the assumption that the groundwater conditions are close to similar in Pozo Colorado and Filadelfia. Further membrane specifications are presented in Appendix C. With this membrane type, 4, 8 and 12 membrane units are required for Stage 1, 2 and 3, respectively, to obtain the desired water production. Based on experience from Aguamin, each membrane train includes 2 HP pumps. It is assumed that the plant availability is 90 %, as it is usual for desalination plants to have some down-time through the year [21]. In the following chapter the power system that supplies energy to the desalination plant will be considered.

Table 3.1 Project stages for the desalination plant in Pozo Colorado

Project stage	**Stage 1**	**Stage 2**	**Stage 3**
# RO trains	1	2	3
# Membrane units	4	8	12
# HP pumps	2	4	6
Production capacity (m^3/d)	88.6	177.1	265.7

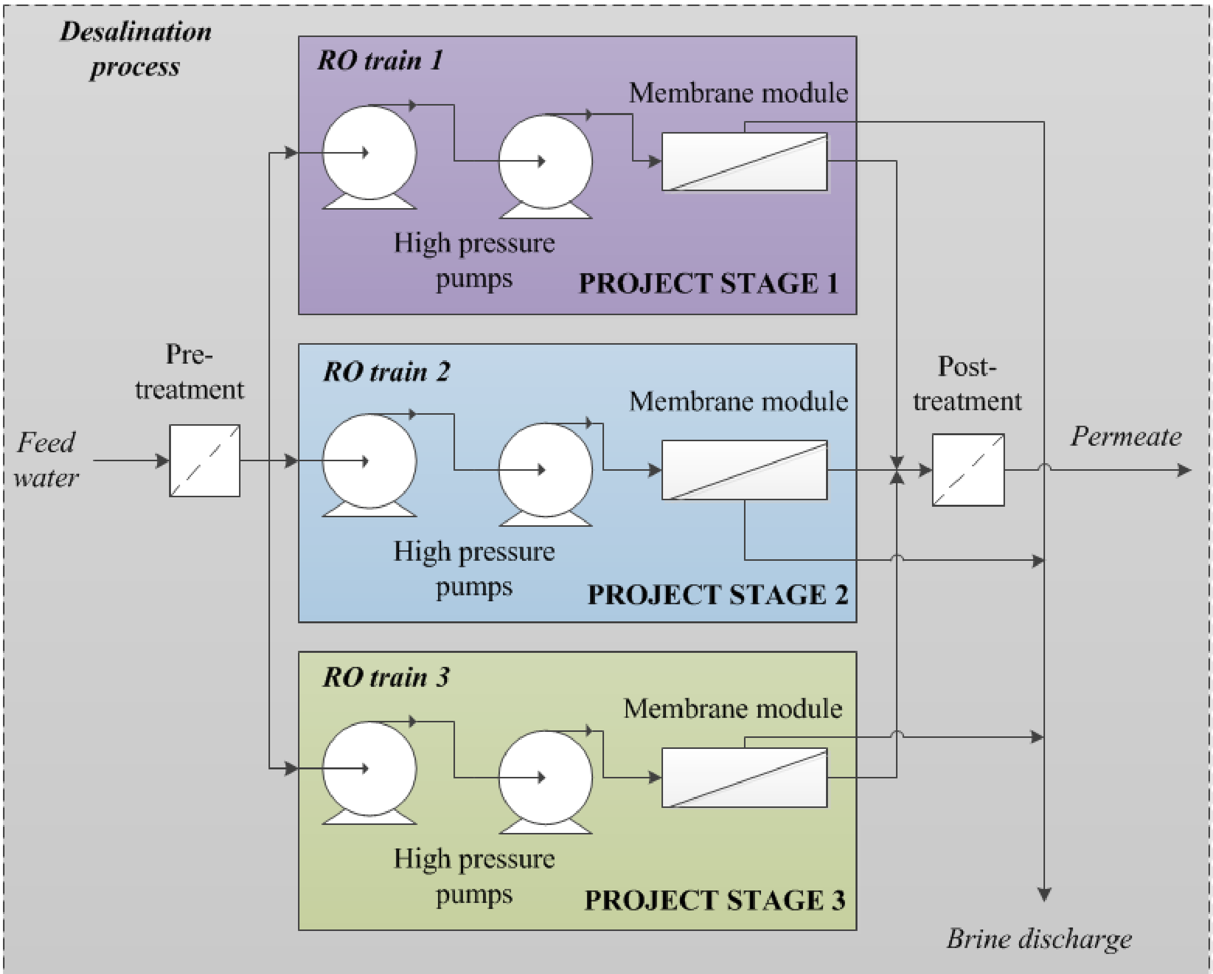

Figure 3.3 Project stages for the desalination plant in Pozo Colorado

Chapter 4

Micro Power System Modeling

4.1 About HOMER

HOMER is a micro power optimization model that can be applied to simulate energy systems for a variety of applications. Both off-grid and grid-connected power systems can be evaluated, and the preferred system set-up is defined by the user. An example of a schematic diagram is presented in Figure 4.1, where a grid-connected PV system with converter is illustrated.

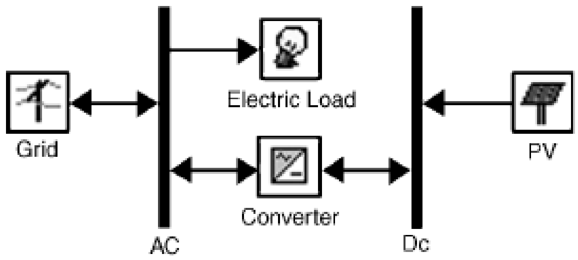

Figure 4.1 Schematic diagram of a grid-connected PV system in HOMER [38]

For input parameters on technology options, resource availability and component costs, HOMER performs three main tasks: Simulation, optimization and sensitivity analysis. In the simulation process, energy balance calculations are performed for different system configurations in hourly time steps throughout the year, and the life-cycle cost of each arrangement is calculated. Next, it is determined whether the system configuration is technically feasible, which means if the system is capable of meeting the electric demand under the specified conditions. In the optimization process, the different system configurations are sorted according to the net present cost (NPC). In order to evaluate the effect of a change in certain factors, like economic conditions or resource availability, a sensitivity analysis can be performed. In this manner, possible future scenarios can be assessed and qualified decisions can be made [38]. The relationship between the simulation, optimization and sensitivity analysis is presented in Figure 4.2. As the figure indicates, a single optimization can include multiple simulations, and a sensitivity analysis consists of multiple optimizations.

Solar irradiation data can either be implemented as hourly or monthly values in HOMER. If there are only monthly values available, HOMER will synthetically generate hourly data based on a built-in algorithm. By applying statistical properties that reflect global averages, the program creates solar data for every hour in one year [38].

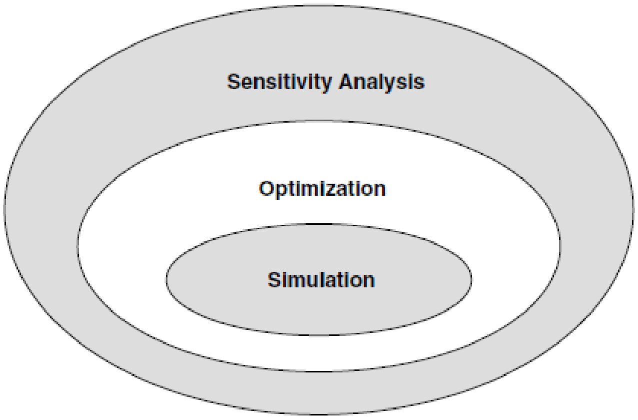

Figure 4.2 Conceptual relationship between simulation, optimization and sensitivity analysis in HOMER [38]

4.2 Input parameters

4.2.1 Energy resources and economics

Prior to simulations in HOMER, there are a number of parameters that need to be defined. First of all, the availability of energy resources is the basis for establishing an energy supply system. Since measured solar irradiation data was not available, monthly data for Pozo Colorado was obtained from the NASA database [16] and implemented in the model. These values are presented in Appendix A. From the monthly irradiation data, HOMER generates synthetic hourly solar data that are applied in the simulations.

Next, a series of economic figures have to be defined in the program. For a grid-connected system, economic data on the unit price of electricity, grid-connection cost, demand rate and transformer cost have to be identified. This information was gathered during the field trip to Paraguay and relevant cost figures are presented in Table 4.1.

Table 4.1 Cost components of electricity, grid-connection and solar PV system in Paraguay

Cost component	**Cost**	**Unit**	**Lifetime (years)**	**Reference**
Electricity	0.08	$/kWh	-	[14]
Grid-connection	200 for distance < 15 m	$	-	[14]
Demand rate	8	$/kW/month	-	[14]
100 kVA transformer	3000	$	25	[14]
PV system (array, wires, mounting)	2.2	$/Wp	25	[39]
Converter	0.3	$/Wp	25	[39]
Battery bank	150	$/kWh	5	[40, 41]

The applied unit electricity cost is the current annual average for Paraguay. This is slightly higher than the electricity cost at Aguamin desalination plant in Filadelfia, which is likely since Filadelfia is situated in a region with better grid infrastructure than Pozo Colorado. For grid-connection it is estimated that the distance to the closest connection point is less than 15 m. The presented transformer cost is for a 100 kVA transformer, which is larger than the energy system considered, but a transformer of this size allows for system expansion. For the PV system, an overall price for PV modules, wires and mounting is applied per Watt peak

(Wp). Converter costs are separated from the PV system. The lifetime of the PV modules and converter was set to 25 years [42]. It was assumed that there is no maintenance costs related to the PV system and that 2-axis tracking is applied to gain more solar irradiation according to the height of the sun. The cost of batteries was not implemented in HOMER but is presented since those costs are applied for a back-up energy supply for the distribution pump. Due to a hot climate in Pozo Colorado that causes stress on batteries, a lifetime of 5 years is estimated for the battery bank.

In order to discount future costs to present value, an interest rate has to be determined. For the simulations, the standard real interest rate in HOMER of 6 % was applied. The lifetime of the project was set to 25 years, as the useful lifetime of a desalination plant is normally between 25 and 50 years [21].

4.2.2 Load profiles and constraints

For appropriate sizing of the energy supply system, load profiles are essential. The ratings applied for each of the stages, from now on denoted by “cases”, are presented in Table 4.2, Table 4.3 and Table 4.4. The ratings of the HP pump and the LP feed pump were estimated from the pumps that are used at Aguamin desalination plant, assuming a linear correlation between flow and capacity rating. For the well pump and distribution pump, the very same capacity ratings are used as at Aguamin, as these are standard pumps that are readily available off the shelf and can be operated according to their capacity. Based on experience from Aguamin, it is estimated that additionally one well pump and one feed pump will be required for every membrane train. The electrical load of the technical office housing the desalination equipment is estimated to be equivalent to the suggestion in [2]. Due to the available electrical grid, constant load profiles are considered 24 h/day for all three stages. It is assumed that there is no random variability for the load profiles.

Table 4.2 System loads for Case 1

Component	Load/piece (kW)	No. pieces	Total load (kW)
HP pump	1.5	2	3.0
Well pump	2.2	1	2.2
LP feed pump	0.75	1	0.75
Distribution pump	2.2	1	2.2
Technical office	2	1	2.0
Total load (kW)			**10.15**

Table 4.3 System loads for Case 2

Component	Load/piece (kW)	No. pieces	Total load (kW)
HP pump	1.5	4	6.0
Well pump	2.2	2	4.4
LP feed pump	0.75	2	1.5
Distribution pump	2.2	1	2.2
Technical office	2	1	2.0
Total load (kW)			**16.1**

Table 4.4 System loads for Case 3

Component	Load/piece (kW)	No. pieces	Total load (kW)
HP pump	1.5	6	9.0
Well pump	2.2	3	6.6
LP feed pump	0.75	3	2.25
Distribution pump	2.2	1	2.2
Technical office	2	1	2.0
Total load (kW)			**22.05**

Introduction of PV modules is considered for reliability reasons and also for creating an energy supply system that could partially be replicated in areas without grid-connection. For two of the energy supply configurations, some constraints are implemented in HOMER in order to stimulate PV penetration in the system. This is necessary due to the low electricity price in Paraguay, which does not favor PV systems without subsidies, as will be further described in section 5.2. These limitations will not be incorporated in a real system and are only implemented in the simulation program. In order to obtain the values for maximum grid purchase, it was estimated that the PV modules can cover the energy demand for the additional HP pumps in Case 2 and Case 3 for 8 hours per day, when solar irradiation is at maximum. The remaining demand will be covered by electricity from the grid. The grid purchase limit was set according to equation (4.2.1):

$$E_{grid,\max} = E_{tot} - E_{PV} \quad \text{, for Case 2 and Case 3} \tag{4.2.1}$$

where $E_{grid,max}$ is the maximum annual limit for grid purchase in kWh, E_{tot} is the total energy demand per year in kWh and E_{PV} is the energy supplied annually by the PV modules in kWh. E_{PV} was estimated according to equation (4.2.2):

$$E_{PV} = \begin{cases} 2 \cdot P_{HP} \cdot t \text{ for Case 2} \\ 4 \cdot P_{HP} \cdot t \text{ for Case 3} \end{cases} \tag{4.2.2}$$

where P_{HP} is the capacity of the high pressure pump in kW and t is the number of hours where energy is supplied to the HP pumps from the PV system. A value of t = 8 h was used for the calculations, as this is the time when solar irradiation is at maximum. The limitations on grid purchase from all cases are presented in Table 4.5.

Table 4.5 Maximum electricity purchase from grid per year for all cases, applied in HOMER simulations

Case	$E_{grid,max}$ (kWh)
1	Unlimited
2	120,231
3	163,593

Prior to simulations in HOMER, the preferred configuration of the energy supply has to be determined. In the following, configurations for the three cases are presented.

4.3 Energy supply for the project stages

4.3.1 Energy supply considerations

During the field trip to Paraguay the current electricity supply to Pozo Colorado was inspected; a 23 kV three-phase supply from Asunción, 271 km to the south-east. According to Marcos [2], the reliability of this grid was an issue in 2005 and would not serve as a safe power supply. As described in section 2.1.3, a new 23 kV supply line was connected from Concepción in January 2014. This connection increases the security of supply considerably. According to José Vallejos from the planning department of ANDE, connecting an additional load of about 50 kW to the new grid would not pose any problems [14]. Based on this information, three energy supply systems are suggested in the following: Case 1, Case 2 and Case 3. The three energy systems are designed to cover the electricity demand of Stage 1, Stage 2 and Stage 3 presented in section 3.3.

The general energy supply system design is similar for all three cases and is presented in Figure 4.3. The configuration is based on the design in the master thesis by Waatevik [3].

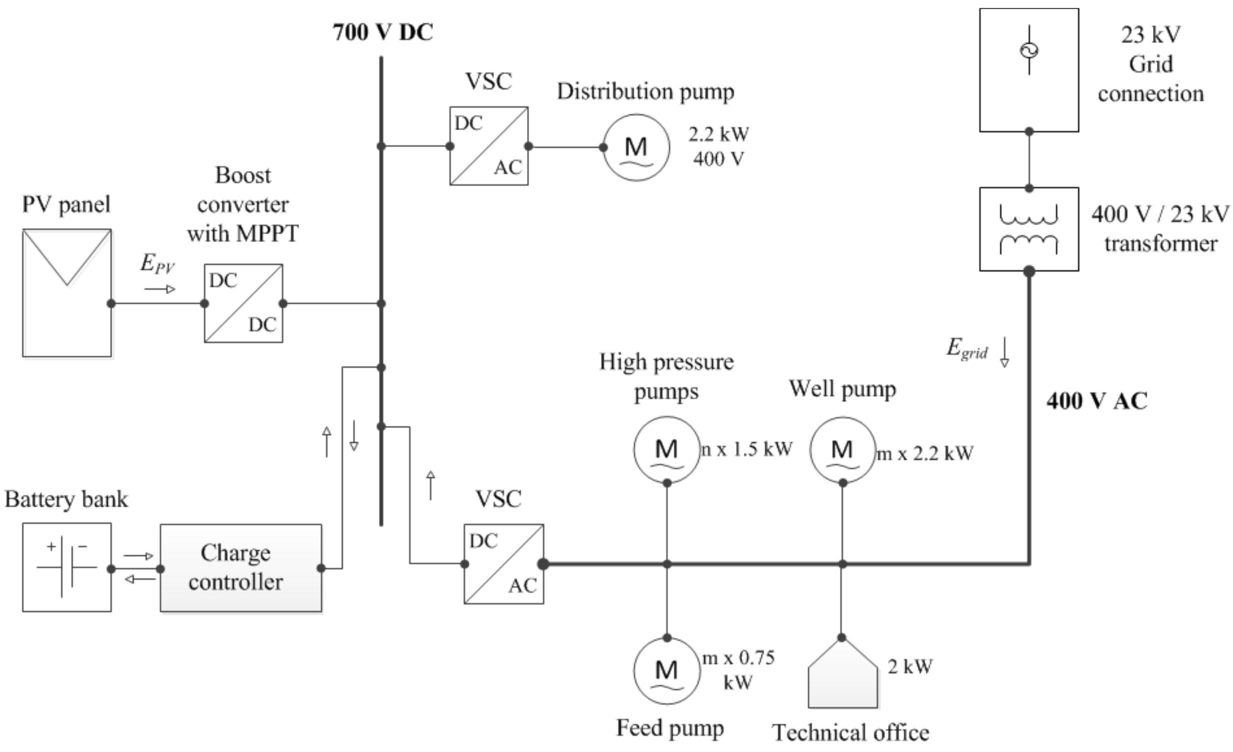

Figure 4.3 General configuration of a grid-connected PV system to be implemented in HOMER

As can be seen from the figure, the system is connected to the 23 kV grid through a transformer providing voltage reduction to 400 V AC. The well pump, feed pump, technical office, as well as the VSDs for the HP pumps are connected to the common AC bus at 400 V. The pumps are rated for 3-phase 400 V RMS voltage, while the technical office is supplied by single-phase 230 V RMS. The AC bus feeds a voltage source converter (VSC) and the drive for the distribution pump is connected to a 700 V DC bus through a dedicated VSC. This VSC has to be dimensioned to tolerate the inrush current that occurs at motor start-up, which could be about 6 times the nominal current of the motor [43]. The DC bus is also connected to a small PV system with a battery bank for energy storage. This is to provide a back-up energy supply for the distribution pump, in order to secure the water supply for the village in case of power outage. The PV system is connected to the DC bus through a DC-DC converter with a maximum power point tracking (MPPT) algorithm. For Case 2 and Case 3, the PV array capacity is increased to cover a larger part of the main load. The number of HP pumps, well pumps and feed pumps varies from case to case and is represented by m and n in the figure.

For all cases, the energy supply can be described by equation (4.3.1), if losses are neglected:

$$E_{tot} = E_{grid} + E_{PV} \tag{4.3.1}$$

where E_{tot} is the total energy supplied to the plant, E_{grid} is the energy supplied from the grid, and E_{PV} is the energy provided by the solar panels. E_{grid} and E_{PV} are indicated in Figure 4.3. The configurations implemented in HOMER for every case are described in the following.

4.3.2 Case 1

For Case 1, only the grid-connected system is simulated in HOMER, as the back-up PV supply is connected to provide energy for short periods only. Figure 4.4 depicts the system that was simulated in HOMER, with a grid-connected load. The peak load of the system is 10 kW and the energy demand is 244 kWh/day.

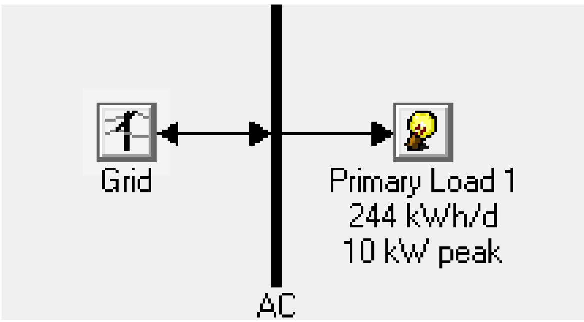

Figure 4.4 HOMER set-up for Case 1

4.3.3 Case 2

For Case 2, the energy supply system has the same configuration as for Case 1, although a PV array is introduced in the HOMER simulations for Case 2 in addition to the grid-connection. The peak load is 16 kW for this case and the daily energy requirement is 386 kWh, as can be seen in Figure 4.5. A converter is necessary in order to provide AC supply to the load.

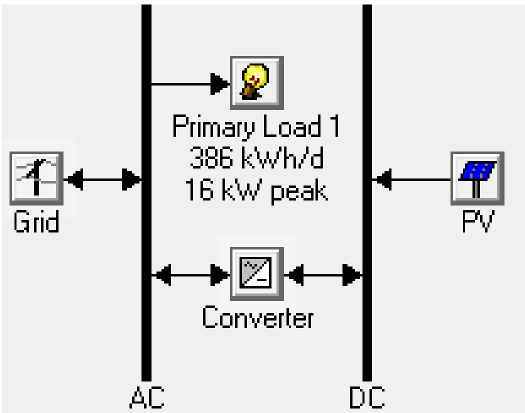

Figure 4.5 HOMER set-up for Case 2

4.3.4 Case 3

For Case 3, the energy supply system has the same configuration as for Case 2, although the PV array will be designed for a larger production rate. The peak load is 22 kW for this case and the daily energy requirement is 529 kWh, as depicted in Figure 4.6. As for Case 2, a converter is necessary in order to provide AC supply to the load.

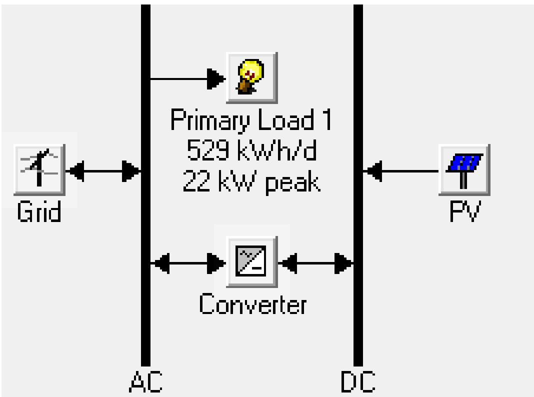

Figure 4.6 HOMER set-up for Case 3

Chapter 5

Economic Aspects

5.1 Costs of desalination system components

In order to evaluate the costs of the desalination plant, economic figures for system components, maintenance and labor have to be identified. For membranes and pressure vessels, the very same lifetimes and supplier as for Aguamin desalination were applied. The pumps are standard types that suit their respective purpose and it is estimated that the lifetime of the pumps are 25 years if maintenance is conducted regularly [29]. Costs of the main components were found on the website of the respective suppliers and are presented in Table 5.1. Cost information of building a house in Paraguay is from civil engineer Marcos in Asunción [44] and a 50 year lifetime is estimated. The area of 50 m^2 is based on the size of the technical office at Aguamin. Costs related to piping and valves are not included as these are considered to represent a minor contribution to the total cost compared to the other components.

Table 5.1 Investment costs and lifetimes for the desalination plant

Cost item	**Brand**	**$/piece**	**$/m²**	**Lifetime (years)**	**Reference**
HP pump 1.5 kW	Grundfos	2,044	-	25	[45]
Well pump 2.2 kW	Franklin	2,655	-	25	[46]
LP feed pump 0.75 kW	Grundfos	1,578	-	25	[45]
Dist. Pump 2.2 kW	Grundfos	2,464	-	25	[45]
Membranes 8-inch	Hydranautics	1,005	-	1	[47]
Pressure vessel	Codeline	1,750	-	5	[48]
Technical office 50 m^2	-	-	450	50	[44]

In addition to the system components, there are other cost items associated with the desalination plant, presented in Table 5.2. Chemical water treatment and plant maintenance is necessary, as well as transport of material and personnel to control and operate the plant. Costs of chemicals are low at Aguamin desalination plant and the equivalent cost is estimated for Pozo Colorado. For transport of material, a gross estimation is made, assuming that all transport occurs at the beginning of the project. This cost could be higher or lower. Maintenance costs include expenditures associated with routine maintenance of equipment, building and piping, in addition to emergency maintenance. An estimation based on average maintenance costs presented in [21] is applied for this cost. In order to operate and control the plant it is estimated that one person working 50 % is sufficient, as the plant size is relatively small and the level of complexity is low [21].

Table 5.2 Other cost items associated with the desalination plant

Cost item	**Cost**	**Reference**
Chemicals	10 $/m^3$ of product water	[29]
Transport	$10,000 for Case 1 and $5,000 for Case 2 and Case 3	-
Maintenance	0.048 $/m^3$ of product water	[21]
Labor 1 employee 50 %	2,500 $/year	[49]

For the economic figures presented in section 5.3-5.7, an excel file is enclosed electronically to this thesis with further details, as described in Appendix G. This file includes estimations on costs of desalination system, energy system and water.

5.2 Feasibility of solar PV in Pozo Colorado

With the power price as low as 8 c/kWh in Paraguay, a solar PV system might not be economically viable. However, with a growing economy in the country and thereby an increasing power consumption [15], it is likely that the cost of electricity will be higher in the future. By applying solar irradiation data for Pozo Colorado and the economic figures presented in section 4.2.1, a simulation was conducted in HOMER to observe the feasibility of a PV system for different power prices. Figure 5.1 illustrates the results, with the power price on the x-axis, the PV array capacity on the primary y-axis and the actual energy cost on the secondary y-axis. It can be observed that it would be economically feasible to start installing PV panels if the power price was 0.14 $/kWh, which is 75 % higher than the price of today. A cost of $2.5/Wp was applied in the simulations for the PV system, including converter.

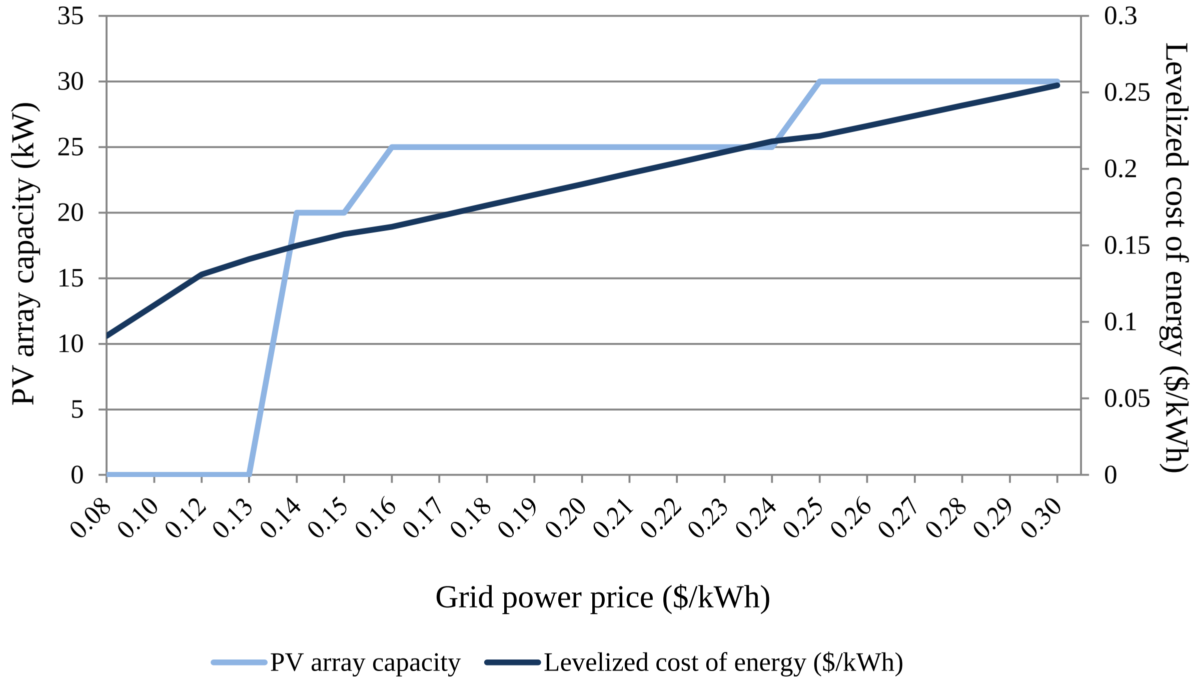

Figure 5.1 Relationship between power price, PV array capacity and levelized cost of energy for an increasing power price, from HOMER simulations

Even though HOMER simulations indicate that a PV supply is not economically viable in Pozo Colorado with the current electricity price, a PV-based energy supply system could be very relevant in other areas that lack grid-connection. For remote areas far from the main highways in the Chaco, a PV-powered RO desalination plant could serve as a reliable source of fresh water. Therefore, introduction of PV modules will be studied for Case 2 and Case 3, as presented in section 4.3. Total costs for Case 1-3, including both energy system and desalination system, are studied in the following.

5.3 Case 1

5.3.1 Energy system costs

For Case 1, a simple HOMER simulation yields the investment cost of the system as well as the annual operating costs for purchase of electricity from the grid for a 25 year period. The PV panels and the battery bank that serve as a security supply for the distribution pump were not included in the HOMER simulations but their respective capacities were estimated by applying equation (2.7.1) and (2.7.2). The sizing procedure for the PV system and battery bank is presented in Appendix D.

Resulting from HOMER simulations and PV system sizing, investment costs, operational costs and replacement costs for the energy system were established. The economic figures are presented in Table 5.3, with the associated energy consumption per produced water volume. For the entire energy system, the investment costs are around $9,100. Among the investment costs, the cost of the back-up battery bank is dominating next to costs of grid-connection and transformer. Operation and maintenance costs for the energy system are only related to the yearly electricity costs. Every 5th year there will be expenses related to replacement of the battery bank, assuming deep cycling and that the warm climate in Pozo Colorado will shorten the battery lifetime considerably [50]. For every cubic meter of produced water, about 2.75 kWh is necessary. The distribution of the nominal costs for the energy system over a 25 year period is illustrated in Figure 5.2. In year 25, the negative cost represents the salvage value of the battery bank.

Table 5.3 Energy system costs and energy consumption for Case 1, 25 year period

Component	Investment cost ($)	O&M ($/year)	Replacement cost ($/year)	kWh/m^3
Electricity from grid (89,067 kWh/year)	3,200	8,101	-	-
Back-up PV system (670 Wp at $2.5/Wp)	1,675	0	-	-
Back-up battery bank (28.2 kWh at $150/kWh)	4,230	0	846	-
Total	**9,105**	**8,101**	**846**	**2.75**

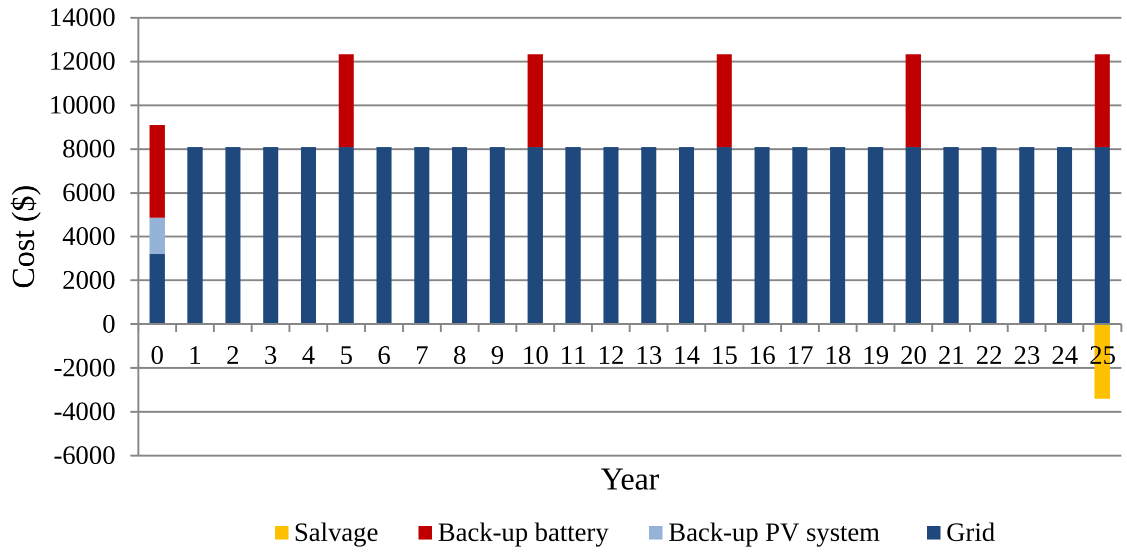

Figure 5.2 Nominal costs over 25 years for the energy system in Case 1

5.3.2 Desalination system costs

Based on the cost figures and lifetimes of the components presented in section 5.1, the costs of the desalination system for Case 1 were estimated for a 25 year period. Cost details are presented in Table 5.4 and Figure 5.3 gives a graphical representation of the costs for the whole period. It was estimated that the investment costs for the desalination system are close to $50,000 and the operational costs are around $10,000/year including costs of replacement. A cost of $1,750 for pressure vessel replacement has to be accounted for every 5th year. The negative cost in year 25 represents the salvage value of pressure vessels.

Table 5.4 Costs of desalination system for Case 1

Component	# pieces	$/piece	Investment cost ($)	Fixed cost ($/year)	Replacement cost ($/year)
HP pump 1.5 kW	2	2,044	4,088	-	-
Well pump 2.2 kW	1	2,655	2,655	-	-
LP feed pump 0.75 kW	1	1,578	1,578	-	-
Dist. pump 2.2 kW	1	2,464	2,464	-	-
Membranes 8-inch	4	1,005	4,022	-	4,022
Pressure vessel	1	1,750	1,750	-	350
Chemicals	-	-	-	1,000	-
Technical office 50 m^2	1	22,500	22,500	-	-
Transport	-	-	10,000	-	-
Maintenance	-	-	-	1,552	-
Labor 50 % (1 employee)	-	-	-	2,500	-
Total	-	-	**49,057**	**5,052**	**4,372**

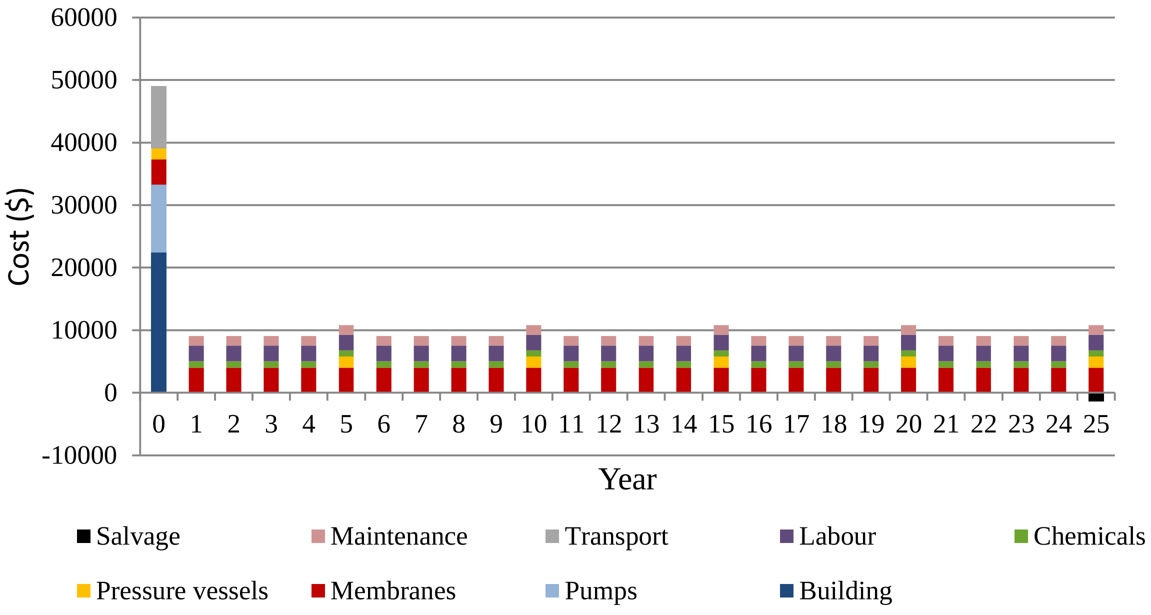

Figure 5.3 Nominal costs over 25 years for the desalination system in Case 1

5.3.3 Total costs

The nominal costs for the whole system in Case 1 over a 25 year period are presented graphically in Figure 5.4. For both desalination and energy system, the investment costs are estimated to be close to \$60,000. Costs for operation, maintenance and replacement of equipment vary between \$17,000 and \$23,000 per year. For a constant water production over the whole 25 year period, the cost of product water is 0.359 \$/m^3, which is 2.1 cents lower per m^3 than the average price of water from the present system.

In Figure 5.5, the cost distribution for all system costs are presented. In the diagram, investment costs include costs for both the desalination plant and the energy supply system. These costs equal 27 % of the total. Energy costs have the highest share of 41 % and the rest is distributed on labor, maintenance, chemicals and replacement costs.

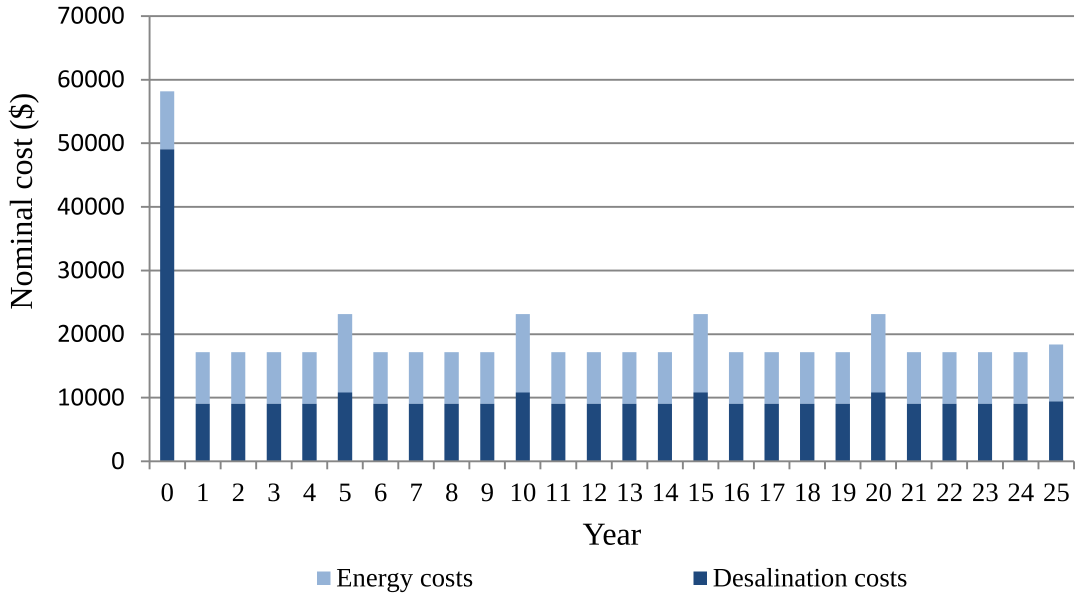

Figure 5.4 Nominal costs over 25 years for the energy system and desalination system in Case 1

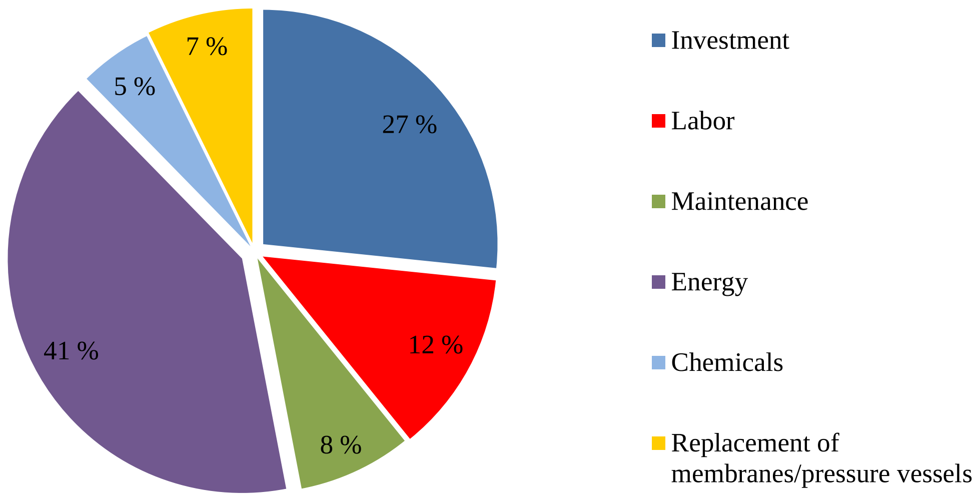

Figure 5.5 Cost distribution for Case 1

5.4 Case 2

5.4.1 Energy system costs

For Case 2, simulations in HOMER yield a PV and converter capacity, investment costs of the system as well as the annual operating costs for purchase of electricity from the grid for a 25 year period. As for Case 1, the back-up PV supply with battery bank is not included in the simulations but is still part of the energy supply system. Table 5.5 presents capacity ratings of the PV modules and the converter that is suggested by HOMER, the amount of PV production and grid purchase in kWh per year and the demand coverage per energy source. A PV capacity of 12 kW yields a production of about 23,400 kWh/year, which is a demand coverage of 16 %. The remaining electricity is supplied from the grid. HOMER estimated a converter of 10 kW to be optimal in the system. The energy consumption is 2.20 kWh/m^3 of produced water, slightly lower than for Case 1.

Table 5.5 HOMER simulation results for Case 2, and energy consumption

Component	Capacity (kW)	kWh/year	Fraction (%)	kWh/m^3
PV	12	23,463	16	-
Converter	10	-	-	-
Grid	-	119,658	84	-
Total	**-**	**143,121**	**100**	**2.20**

Cost details for the energy system are presented in Table 5.6. As can be observed from the table, the total investment cost is around $38,500 for the system, considerably higher than for Case 1. Among the investment costs, the cost of the PV system is the dominating component. Operational costs are only related to electricity purchase from the grid and are in total around $11,000/year. The distribution of the nominal costs for the energy system over a 25 year period is illustrated in Figure 5.6, where the negative cost in year 25 represents the salvage value of the battery bank.

Table 5.6 Energy system costs for Case 2, 25 year period

Component	**Investment cost ($)**	**O&M ($/year)**	**Replacement cost ($/year)**
Electricity from grid (119,658 kWh)	3,200	11,117	-
PV system	29,400	0	-
Back-up PV system (670 Wp at $2.5/Wp)	1,675	0	-
Back-up battery bank (28.2 kWh at $150/kWh)	4,230	0	846
Total	**38,505**	**11,117**	**846**

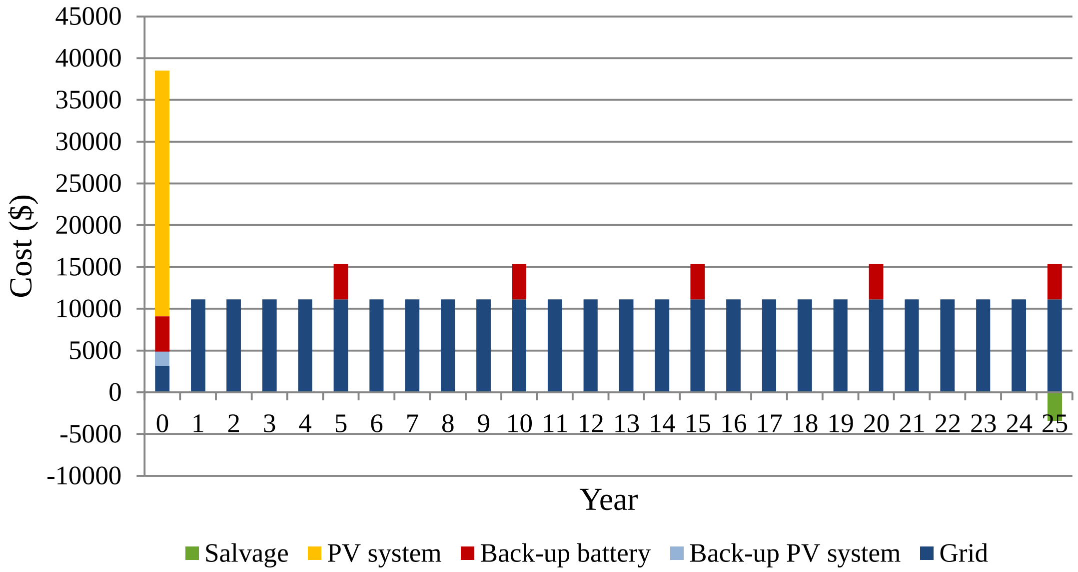

Figure 5.6 Nominal costs over 25 years for the energy system in Case 2

5.4.2 Desalination system costs

Based on the cost figures and lifetimes of the components presented in section 5.1, the costs of the desalination system for Case 2 were estimated for a 25 year period. Cost details are presented in Table 5.7 and Figure 5.7 gives a graphical representation of the costs for the whole period. It is estimated that the investment costs for the desalination system is around $68,000, which also include costs of transport. Operational costs are around $15,000/year including chemicals, maintenance, labor and costs of membrane replacement. A cost of

$3,500 for pressure vessel replacement has to be accounted for every 5th year. Again, the negative cost in year 25 represents the salvage value of the pressure vessels.

Table 5.7 Costs of desalination system for Case 2

Component	**# pieces**	**$/piece**	**Investment cost ($)**	**Fixed cost ($/year)**	**Replacement cost ($/year)**
HP pump 1.5 kW	4	2,044	8,176	-	-
Well pump 2.2 kW	2	2,655	5,310	-	-
LP feed pump 0.75 kW	2	1,578	3,156	-	-
Dist. pump 2.2 kW	1	2,464	2,464	-	-
Membranes 8-inch	8	1,005	8,044	-	8,044
Pressure vessel	2	1,750	3,500	-	700
Chemicals	-	-	-	1,771	-
Technical office 50 m^2	1	22,500	22,500	-	-
Transport	-	-	15,000	-	-
Maintenance	-	-	-	3,103	-
Labor 50 % (1 employee)	-	-	-	2,500	-
Total	-	-	**68,150**	**7,374**	**8,744**

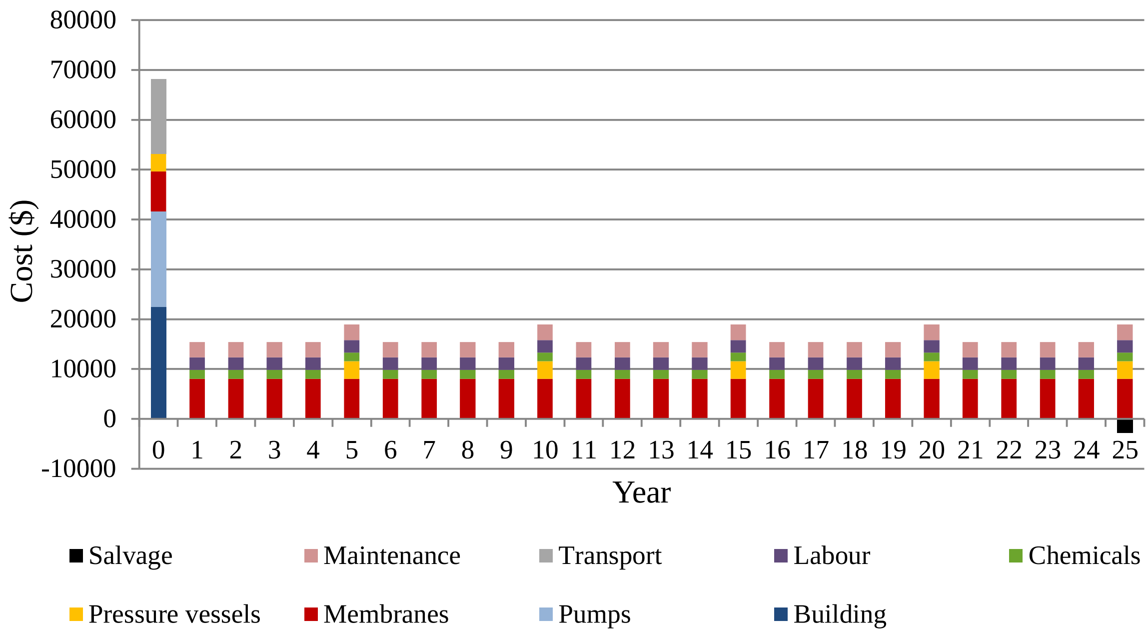

Figure 5.7 Nominal costs over 25 years for the desalination system in Case 2

5.4.3 Total costs

The nominal costs for the whole system over a 25 year period are presented graphically in Figure 5.8. For both desalination and energy system, the investment costs are estimated to be around \$107,000. Costs of operation, maintenance and replacement of equipment vary between \$26,500 and \$34,000 per year. For a constant water production over the whole 25 year period, the cost of product water is 0.286 \$/m^3, which is 9.4 cents lower per m^3 than the average price of water from the present system.

In Figure 5.9, the cost distribution for all system costs are presented. Investment costs equal 25 % of the total and replacement costs represent 24 %. The share of energy costs are lower than for Case 1 with a contribution of 30 %. The remaining costs are distributed on labor, maintenance and chemicals.

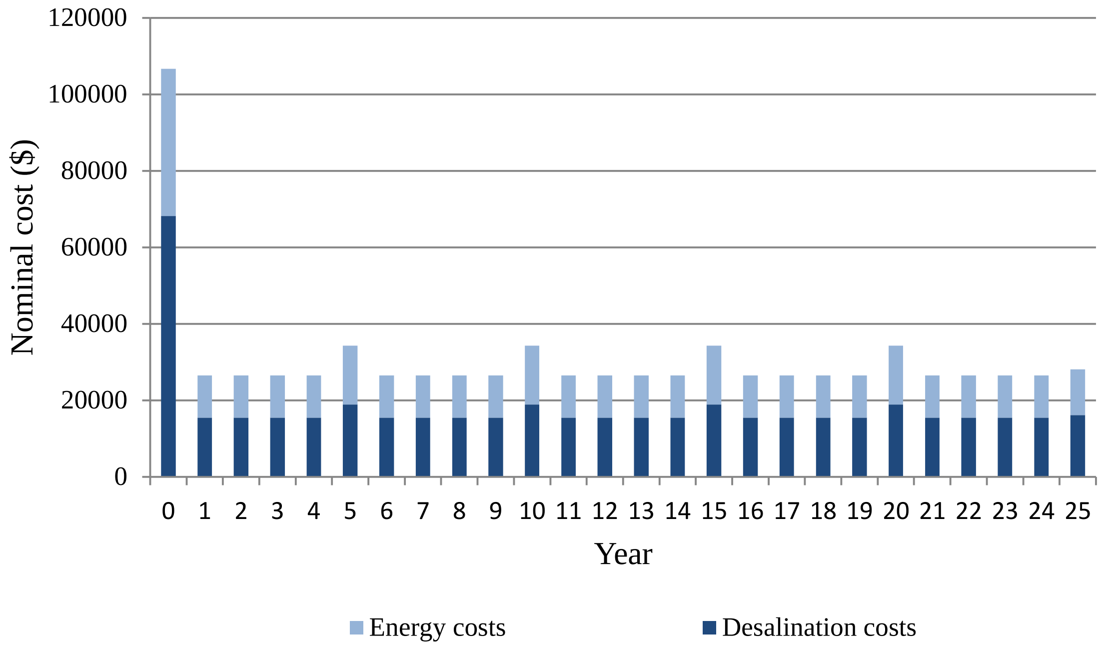

Figure 5.8 Nominal costs over 25 years for the energy system and desalination system in Case 2

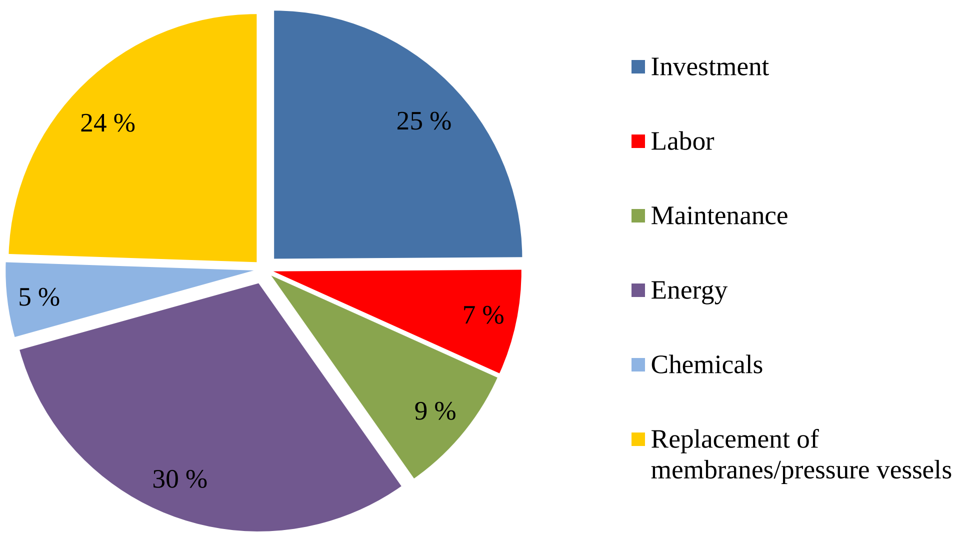

Figure 5.9 Cost distribution for Case 2

5.5 Case 3

5.5.1 Energy system costs

As for Case 2, HOMER simulations yield capacities of PV modules and converter that can cover part of the energy demand in Case 3. In this case, PV modules with a total capacity of 20 kW is found as optimal, which can cover 20 % of the energy demand. HOMER estimated that a converter with a capacity of 16 kW is optimal for the system. The remaining energy demand of 80 % is covered by grid electricity. For this case, only 2.03 kWh/m^3 is necessary. Component details are presented in Table 5.8 and a complete simulation report is attached in Appendix E.

Table 5.8 PV capacity, converter capacity, PV production and grid purchase for Case 3 from HOMER simulations

Component	**Capacity (kW)**	**kWh/year**	**Fraction (%)**	**kWh/m^3**
PV	20	39,405	20	-
Converter	16	-	-	-
Grid	-	157,858	80	-
Total	**-**	**197,263**	**100**	**2.03**

Cost details for the energy system are presented in Table 5.9, including NPC for comparison with later scenarios. The estimation of NPC is based on formulas presented in Appendix B. Investment costs are about $58,000 and the operational costs of about $14,700 per year are related to purchase of grid electricity. The replacement costs are represented by the back-up battery bank that will be necessary to replace every 5th year. For the energy system in total, the NPC is estimated to $255,895. In Figure 5.10 the nominal costs for the energy system are presented graphically over a 25 year period, where the negative cost in year 25 represents the salvage value of the battery bank.

Table 5.9 Energy system costs for Case 3, 25 year period

Component	Investment cost ($)	O&M ($/year)	Replacement cost ($/year)	Net present cost ($)
Electricity from grid	3,200	14,745	-	191,688
PV system	48,800	0	-	48,800
Back-up PV system (670 Wp at $2.5/Wp)	1,675	0	-	1,675
Back-up battery bank (28.2 kWh at $150/kWh)	4,230	0	846	13,822
Total	**57,905**	**14,745**	**846**	**255,985**

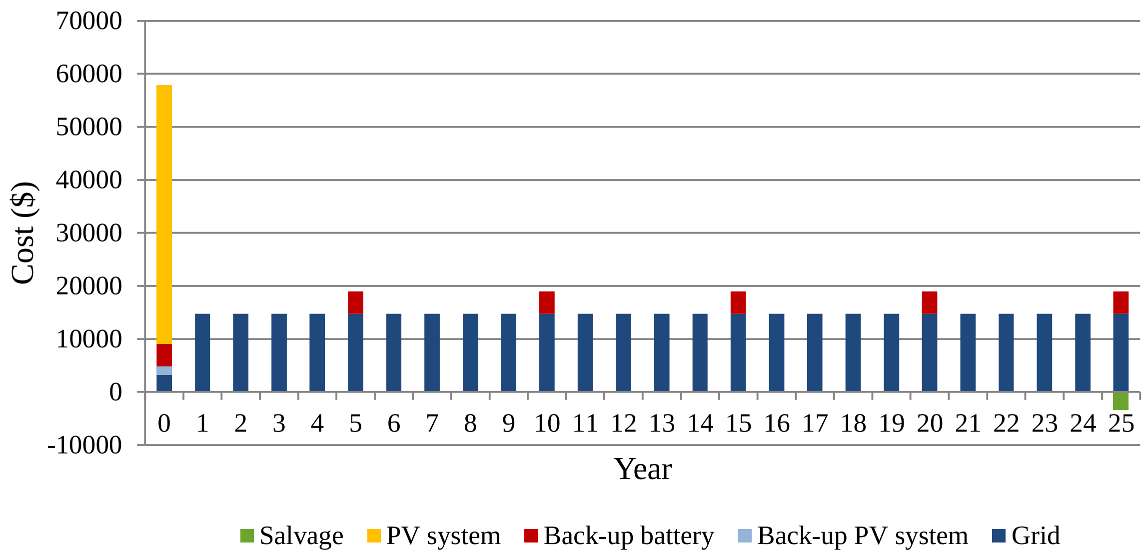

Figure 5.10 Nominal costs over 25 years for the energy system in Case 3

5.5.2 Desalination system costs

Based on the cost figures and lifetimes of the components presented in section 5.1, the costs of the desalination system for Case 3 were estimated for a 25 year period. Cost details are presented in Table 5.10 and Figure 5.11 gives a graphical representation of the costs for the whole period. As can be observed from the table, it is estimated that the investment costs for the desalination system is about $87,000. The operational costs are around $22,000/year. In addition, a cost of $5,250 for pressure vessel replacement has to be accounted for every 5th

year. As for Case 1 and Case 2, the negative cost in year 25 represents the salvage value of pressure vessels at the end of the period of analysis.

Table 5.10 Costs of desalination system for Case 3

Component	**# pieces**	**$/piece**	**Investment cost ($)**	**Fixed cost ($/year)**	**Replacement cost ($/year)**
HP pump 1.5 kW	6	2,044	12,264	-	-
Well pump 2.2 kW	3	2,655	7,965	-	-
LP feed pump 0.75 kW	3	1,578	4,734	-	-
Dist. pump 2.2 kW	1	2,464	2,464	-	-
Membranes 8-inch	12	1,005	12,066	-	12,066
Pressure vessel	3	1,750	5,250	-	1,050
Chemicals	-	-	-	2,657	-
Technical office 50 m^2	1	22,500	22,500	-	-
Transport	-	-	20,000	-	-
Maintenance	-	-	-	4,655	-
Labor 50 % (1 employee)	-	-	-	2,500	-
Total	**-**	**-**	**87,243**	**9,812**	**13,116**

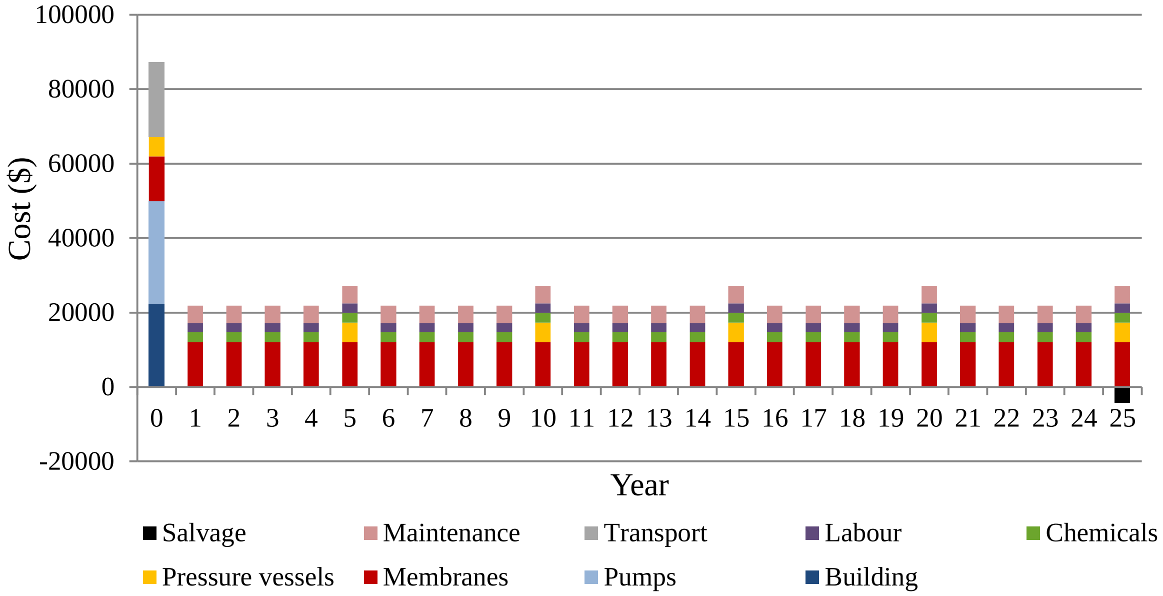

Figure 5.11 Nominal costs over 25 years for the desalination system in Case 3

5.5.3 Total costs

The nominal costs for the whole system over a 25 year period are presented graphically in Figure 5.12. For both desalination and energy system, the investment costs are estimated to be about \$140,000. Costs for operation, maintenance and replacement of equipment vary between \$36,600 and \$46,000 per year. For a constant water production over the whole 25 year period, the cost of produced water is 0.261 \$/m^3, which is 11.9 cents lower per m^3 than the average price of water from the present system.

In Figure 5.13, the cost distribution for all system costs are presented. For this case, investment costs equal 23 % of the total and replacement costs represent 26 %. Energy costs are lower than for Case 1 with a share of 31 %. The remaining costs are distributed on labor, maintenance and chemicals.

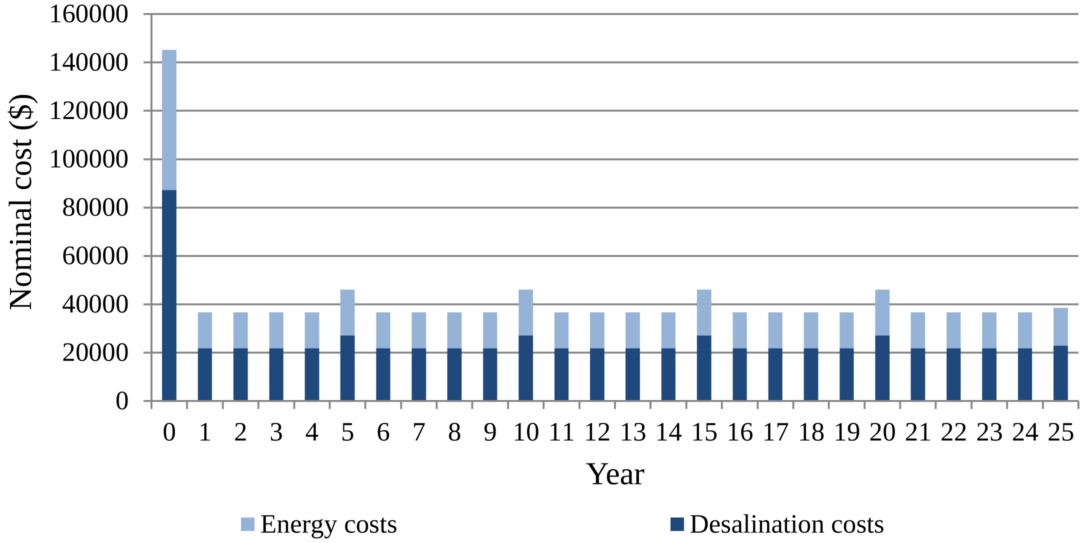

Figure 5.12 Nominal costs over 25 years for the energy system and desalination system in Case 3

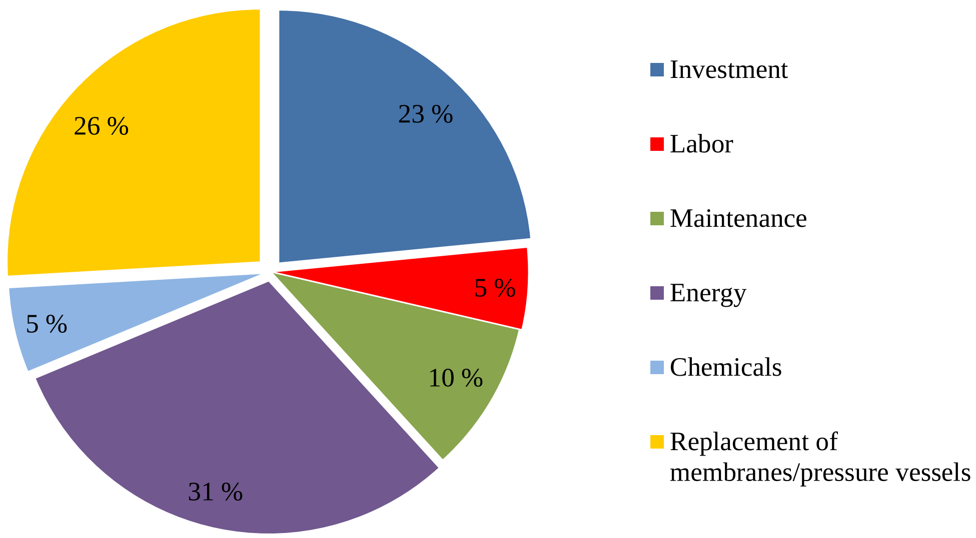

Figure 5.13 Cost distribution for Case 3

5.6 Stepwise system expansion

Combining the costs of Case 1, 2 and 3, a cost prediction for the stepwise system expansion presented in section 3.3 have been developed. It was assumed that the desalination plant, and thereby the energy system, could be expanded every 3 years, in the same procedure as for Case 1, Case 2 and Case 3. For the stepwise system expansion, nominal costs for the whole system over a 25 year period are presented in Figure 5.14. These costs are presented only to give an indication of the magnitude of costs. Investment costs are about \$58,000 for the first step, additional \$50,000 for the next and about \$48,000 for the third stage. For a lifetime of 25 years, this yields a water cost of 0.251/m^3, 12.9 cents lower than for the present system and slightly lower than for Case 3.

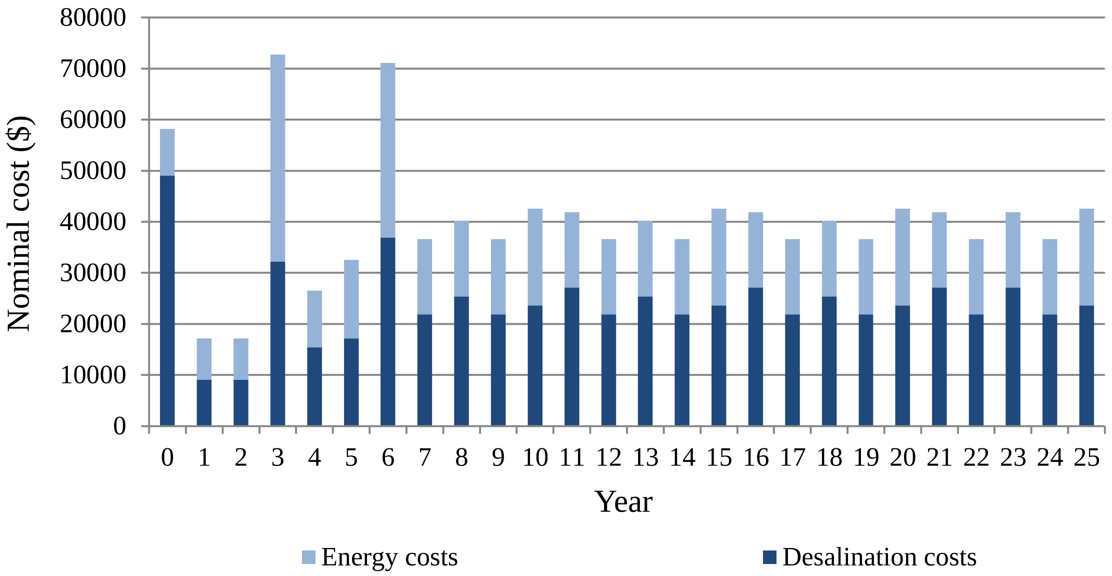

Figure 5.14 Nominal costs over 25 years for the whole system, stepwise expansion

5.7 Comparison of configurations

For Case 1, 2 and 3 it was evident that the cost of water decreases with larger plant size and increasing PV penetration in the energy supply. However, power costs are low in Paraguay; therefore it would be interesting to study the cases for grid-connection only. Figure 5.15 presents the total net present costs in dark blue for all the cases and the associated water costs in light blue. The water costs are calculated by dividing the NPC of the whole system for a

25 year period and the production capacity for the plant over 25 years. The costs of Case 2 and Case 3 with only electricity from the grid, represented by “Case 2 grid only” and “Case 3 grid only” are also included.

It can be observed from Figure 5.15 that the cost of water is slightly lower for both Case 2 and Case 3 with grid-connection only, compared to the systems that include solar PV modules. For Case 2 with grid-connection, the cost of water is 0.274 $\$/m^3$, compared to 0.286 $\$/m^3$ for the investigated Case 2 in section 5.4 where a PV system is embedded in the energy supply. For Case 3, the water cost is 0.251 $\$/m^3$ for grid-connection and 0.261 $\$/m^3$ for the configuration with the PV system. It can be observed from the graph that the water costs in all the investigated scenarios are lower than 0.38 $\$/m^3$, which is the cost of water with the present system.

The system costs presented in the previous sections are only approximate and could be higher or lower. Since there are often unexpected expenses related to a project, a 20 % increase in the NPC of each configuration is evaluated. This is illustrated by the purple bars in Figure 5.15. The associated water costs for each case are represented by the green line. It is clear from the figure that even with a 20 % increase in NPC, the cost of water will still be lower for all but one of the system configurations if compared to the present system. The exception is Case 1, which would have a water cost of 0.431 $\$/m^3$ if there was a 20 % increase in NPC, 0.05 \$ higher than the current water cost.

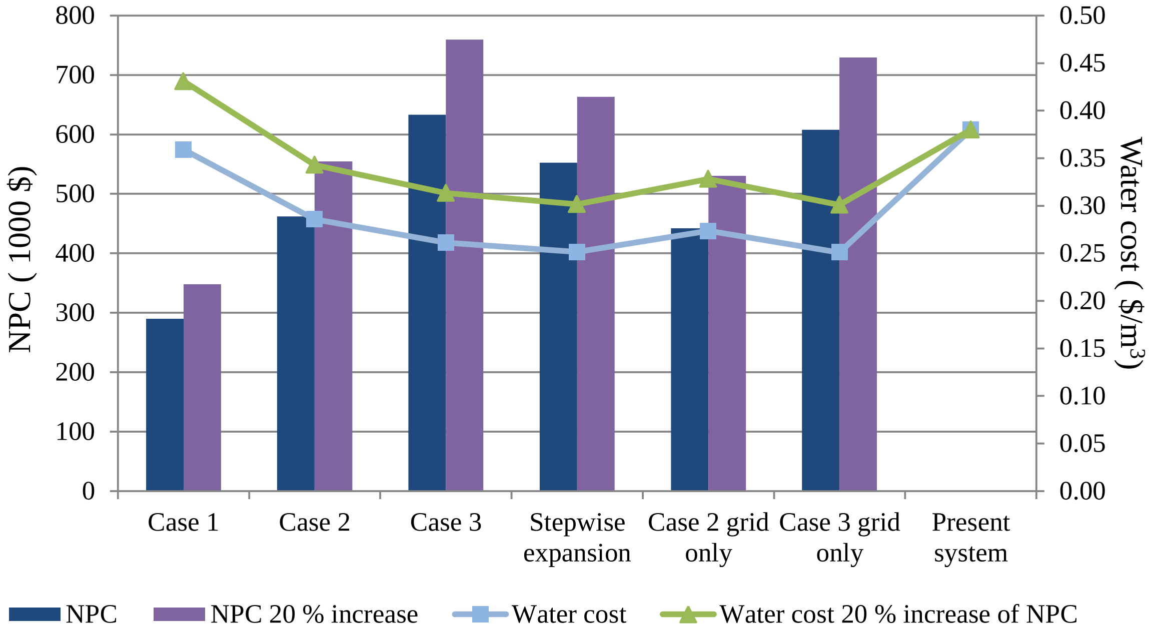

Figure 5.15 NPC for the whole system and associated water costs for the different system configurations, including case of 20 % increase of NPC

In addition to lower water costs for Case 2 and Case 3 with grid-connection only, the investment costs for the energy system are also considerably lower compared to the configurations with PV systems. Figure 5.16 presents a comparison of the energy system investment in year 0 and annual energy costs for Case 2 and Case 3 with PV system and grid-connection only, and the associated water costs. The NPC of the whole energy system over a 25 year period for all cases is also presented. For Case 2, the energy system investment in year 0 is more than 3 times higher than for Case 2 grid only but the annual energy costs are only 6 % lower. With increasing PV system size, the difference is larger. For Case 3, the cost of energy per year is 11 % lower than for Case 3 grid only. Despite this, investment costs for the energy system is more than 5 times higher, as can be observed from the figure. Over a 25 year period, the difference in NPC between the energy systems is not that large. Case 2 grid only has a NPC that is about 10 % lower than Case 2. For Case 3 grid only, the NPC is also about 10 % lower than Case 3.

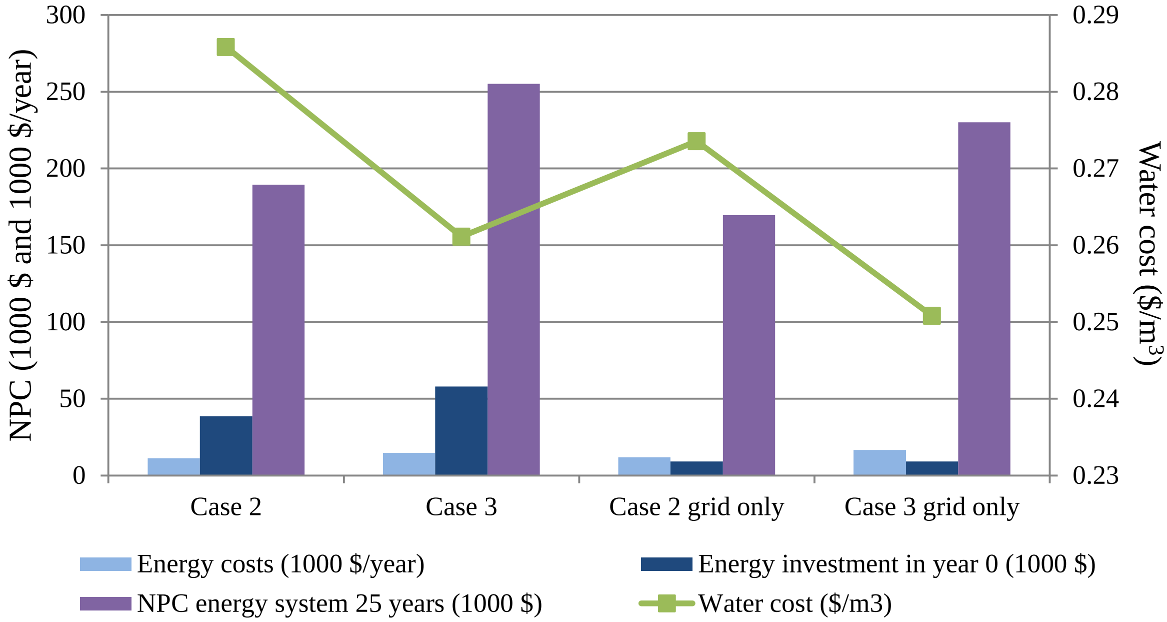

Figure 5.16 Annual energy costs, NPV of energy investment costs, NPC of energy system and associated water costs for the different system configurations

Chapter 6

Applicability in a Future Electricity Market

6.1 Background

As described in section 2.1.3, Paraguay still has a public monopoly on electricity, unlike its neighboring countries. Countries like Brazil, Chile, Colombia and Argentina have been progressive in the development of deregulated electricity markets since the early 1980s (Chile) and 1990s (Brazil, Colombia and Argentina). These are also countries where hydro-power based electricity is dominant or represents a significant share of the electricity mix. Different deregulation models have been introduced in the four countries and hence the result varies between them. For all countries, however, the motivation for introducing a free electricity market was to provide cheaper and more reliable electricity in a more efficient way. After deregulation, price fluctuations are clearly season dependent in all countries and in dry periods prices can be very high due to the large share of hydro power [51].

With a developing economy and an increasing electricity demand, a deregulated electricity market could also be a solution for Paraguay in the future. If a well-functioning deregulation model was introduced, electricity could be delivered in a more efficient way and this could possibly stimulate expansion of the present power distribution system. A fluctuating electricity price could have an impact on the feasibility of solar PV expansion. Therefore, a synthetic electricity market could be created for Paraguay, based on experience from areas with similar energy mix and climate, and where the electricity sector have already been deregulated.

In terms of energy resources, Brazil is the country in South America that is most similar to Paraguay. Hydro-power based electricity comprises about 78 % of the electricity produced in Brazil, while in Paraguay it is close to 100 % [52]. Dry and wet seasons largely influence the power prices in Brazil, although it varies between the four submarkets that the country is divided into. Due to its geographical proximity to Paraguay, the seasonal fluctuations in electricity prices in the submarket of south-east/central-west (SE/CW) Brazil could be a base for constructing a synthetic electricity market for Paraguay. Figure 6.1 indicates the monthly variations in power prices in R$/MWh over a 10 year period in SE/CW Brazil. It can be observed that prices vary according to the seasons and that peaks occur regularly, probably caused by periods of low precipitation in combination with high electricity demand.

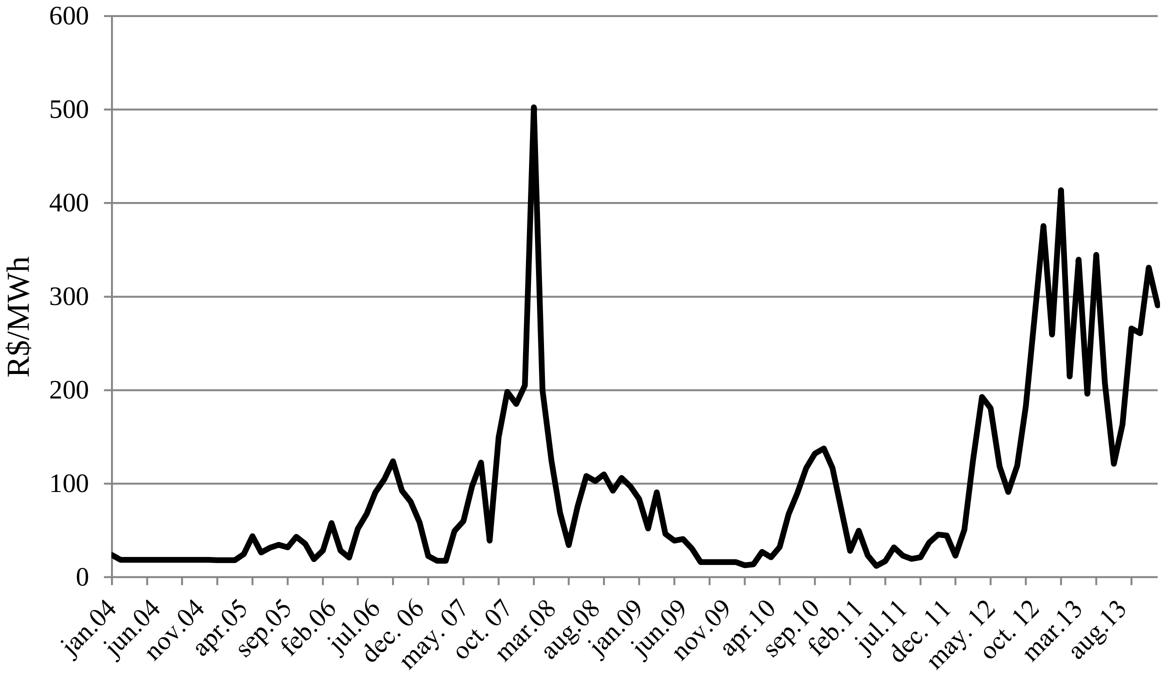

Figure 6.1 Variation in monthly average electricity prices in SE/CW Brazil from January 2004 to January 2013 [53]

Only monthly average electricity prices were available for Brazil. Therefore, an additional country had to be investigated in order to create an electricity market with hourly variations. In a country with a warm climate, electricity prices are likely to rise during hours of high temperatures due to an increased demand of cooling. This occurs in California, where participants in the electricity market can submit hourly bids and prices vary during the day [54]. Typically, prices are higher during the warmest period of the day. This can be observed from Figure 6.2, where variation in electricity price and temperature is depicted for a day in January and a day in July 2011, in San Diego. One can clearly detect a correlation between temperature and cost of electricity, although there is a delay in electricity prices relative to the temperature variations. It can be observed that variations in electricity price are larger in July than in January.

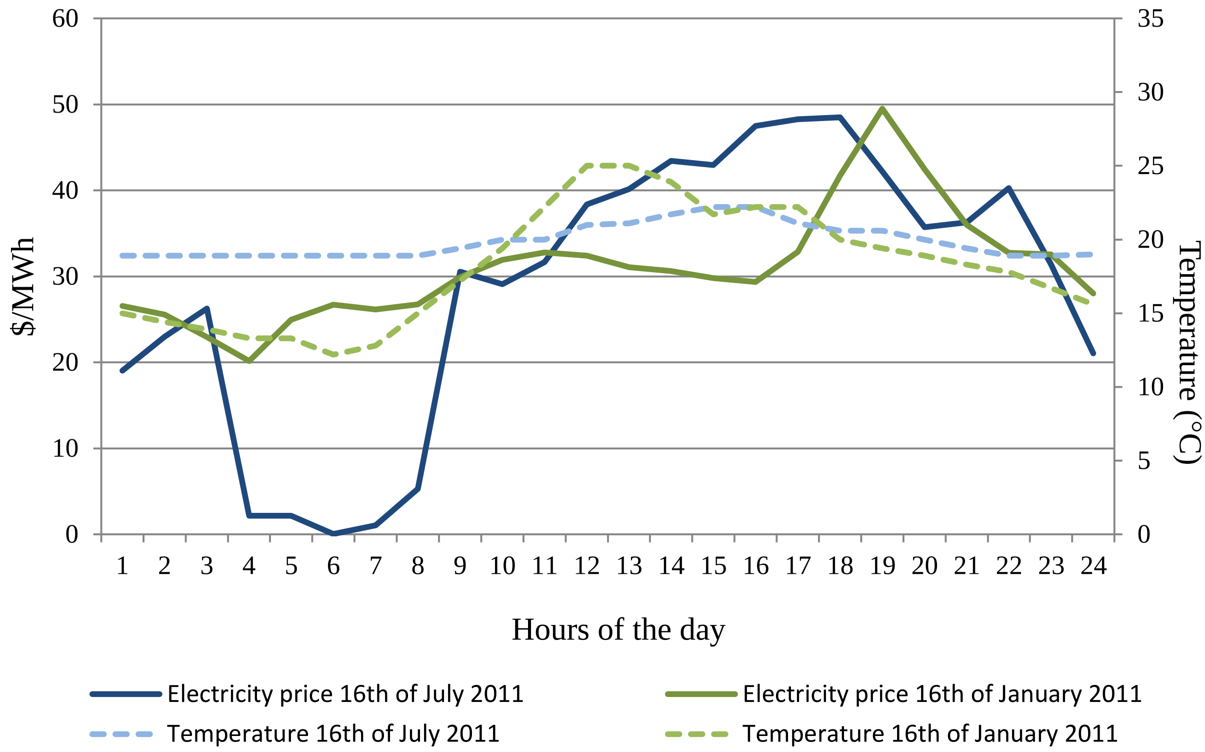

Figure 6.2 Electricity prices and temperature variations in San Diego, California, on 16th of January 2011 and 16th of July 2011 [55, 56]

6.2 Creation of a synthetic electricity market model

Based on monthly price variations in SE/CW Brazil and hourly price variations in San Diego, a synthetic electricity market model was created for Paraguay. Applying price data from the years between 2004 and 2013 from Brazil, typical average monthly variations were estimated for Paraguay, based on an overall average cost of 8 c/kWh [14]. The monthly variations are presented in Figure 6.3. One can detect a price increase during the warmer summer months from October to January.

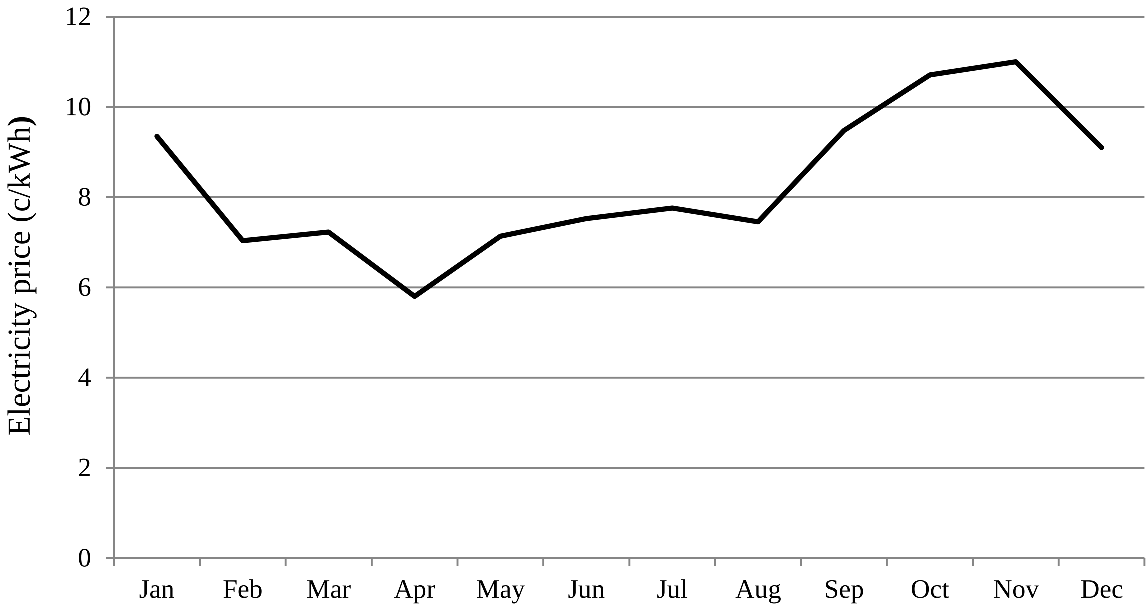

Figure 6.3 Synthetic average monthly variations in power price in Paraguay based on the electricity market in SE/CW Brazil

Hourly price variations in San Diego were applied in order to obtain an electricity market with hourly fluctuations. Price data from one day in every month of 2011 [55] were averaged in order to obtain a price pattern that could be possible if an electricity market was introduced in Paraguay. Typical average hourly price variations for Paraguay are presented in Figure 6.4, also based on an overall average cost of 8 c/kWh. It is clear from the graph that prices increase during daytime and decrease during night-time.

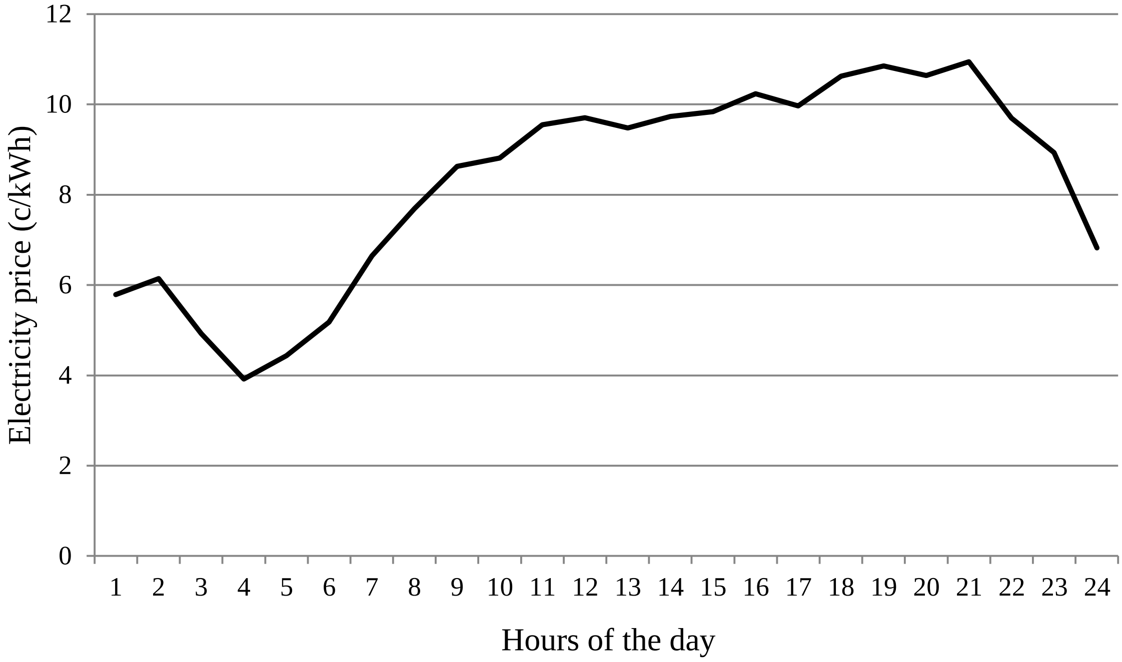

Figure 6.4 Synthetic average hourly variations in power price in Paraguay based on the electricity market in San Diego

Price data from Figure 6.3 and Figure 6.4 were combined in order to create a model of a synthetic electricity market for Paraguay with both monthly and hourly variations. For every day within one month, the hourly variation was modelled to be equal. The electricity price in Paraguay, $c_{m,h}$, in month number m and hour number h was calculated by applying equation (6.2.1):

$$c_{m,h} = c_{avg,Paraguay} \cdot f_m \cdot f_h \qquad , m = 1, 2, \ldots, 12 \text{ and } h = 1, 2, \ldots, 24 \tag{6.2.1}$$

where $c_{avg,Paraguay}$ is the average electricity price in Paraguay today (8 c/kWh) and where f_m is the monthly variation in Brazil relative to the annual average, calculated from equation (6.2.2):

$$f_m = \sum_{y=1}^{y=10} \left\{ \frac{(c_{m,Brazil})_y}{(c_{avg,Brazil})_y} \right\} \cdot \frac{1}{10} \qquad , m = 1, 2, \ldots, 12 \tag{6.2.2}$$

where $(c_{m,Brazil})_y$ is the electricity price in Brazil in month m in year y and $(c_{avg,Brazil})_y$ is the average electricity price in Brazil in year number y. Price data was available for 10 years, hence y goes from 1 to 10. The factor f_h in equation (6.2.1) was calculated from equation (6.2.3):

$$f_h = \sum_{d=1}^{d=12} \left\{ \frac{(c_{d,SD})_h}{(c_{avg,\mathrm{SD}})_d} \right\} \cdot \frac{1}{12} \qquad , h = 1, 2, \ldots, 24 \tag{6.2.3}$$

where $(c_{d,SD})_h$ is the electricity price in San Diego on day d in hour number h and $(c_{avg,SD})_d$ is the average electricity price in San Diego on day d. 12 days of hourly data were chosen from the year 2011, hence d goes from 1 to 12.

From equation (6.2.1) a synthetic variation in electricity prices was created for every month and every hour within one month. The results are presented in Figure 6.5. It can be observed that between September and January, the difference between the minimum and maximum price is highest. The largest difference occurs in November, when there is 9.32 cents difference between minimum and maximum price within the same day. Variations are smaller from February to August. April is the month with the smallest variations, with only 4.85 cents between minimum and maximum. Moreover, October and November are the months when electricity costs are highest, while April is the month of lowest costs. It is obvious from the figure that prices are higher in the summer months when solar irradiation is higher. It can also be observed that costs are higher during the day, which also coincides with hours of sunlight. Further details about creation of the synthetic electricity market can be found in an excel file that is enclosed electronically to this thesis, as described in Appendix G.

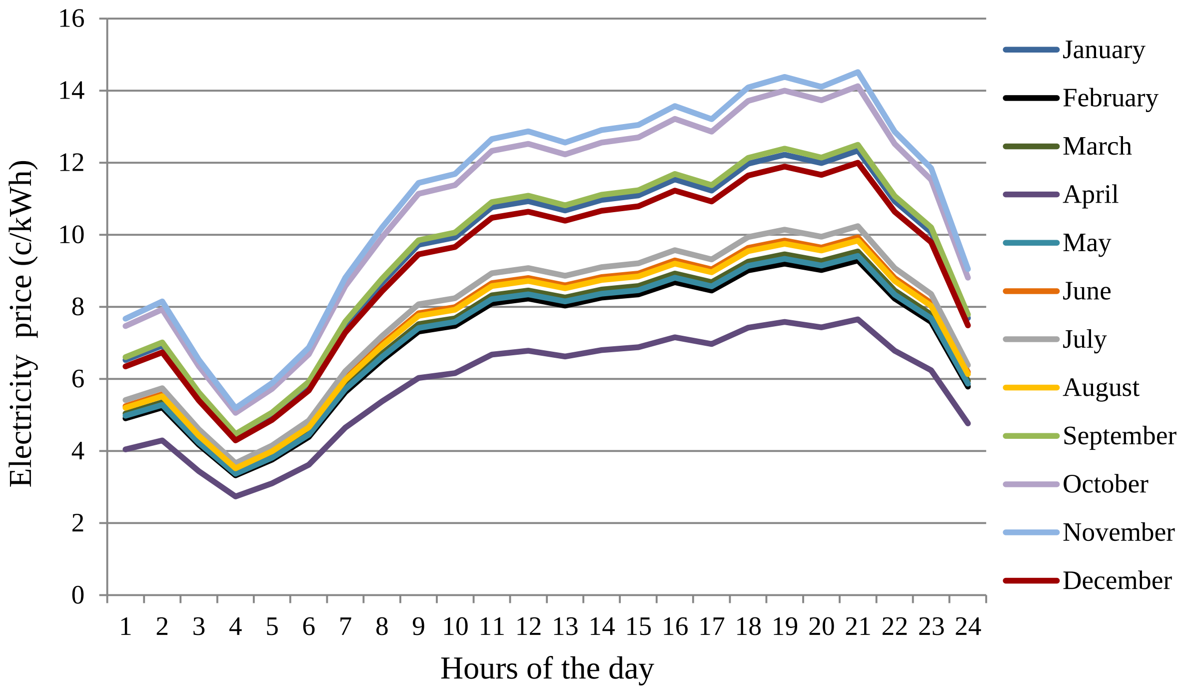

Figure 6.5 Hourly variations in power price for all months in a synthetic electricity market model for Paraguay, based on the electricity markets in San Diego and Brazil

6.3 Applicability in Case 3

The electricity prices presented in Figure 6.5 were implemented in HOMER to study if fluctuating costs would have an effect on PV feasibility. The hourly costs are enclosed electronically to this thesis in a text file, as described in Appendix G. Apart from electricity price data the input parameters were the same as presented in section 4.2. For a grid-connected system the load profile of Case 3 was implemented, with a constant load. In contrast to the previous simulations, no limitations on grid purchase were introduced.

From simulations it was found that even with a fluctuating power price it would not be economically feasible to introduce PV panels in the energy system. However, if prices increase by 21 % HOMER estimates that some energy should be generated by PV modules. With these prices, 25 kW of PV modules would be economically viable in the system, which annually covers about 25 % of the energy demand. Figure 6.6 and Figure 6.7 depict PV production and electricity price for a week in January and a week in July, respectively, from the simulations in HOMER. It can be observed that PV production is higher in January due to more available irradiation, but at the same time this month has high electricity prices. In July, irradiation is lower and hence there is less PV production. This is also a month where electricity costs are lower. The correlation between available solar irradiation and electricity costs is a link that is valuable for introduction of PV. The hourly price data increased by 21 % is also enclosed electronically to this thesis, as described in Appendix G.

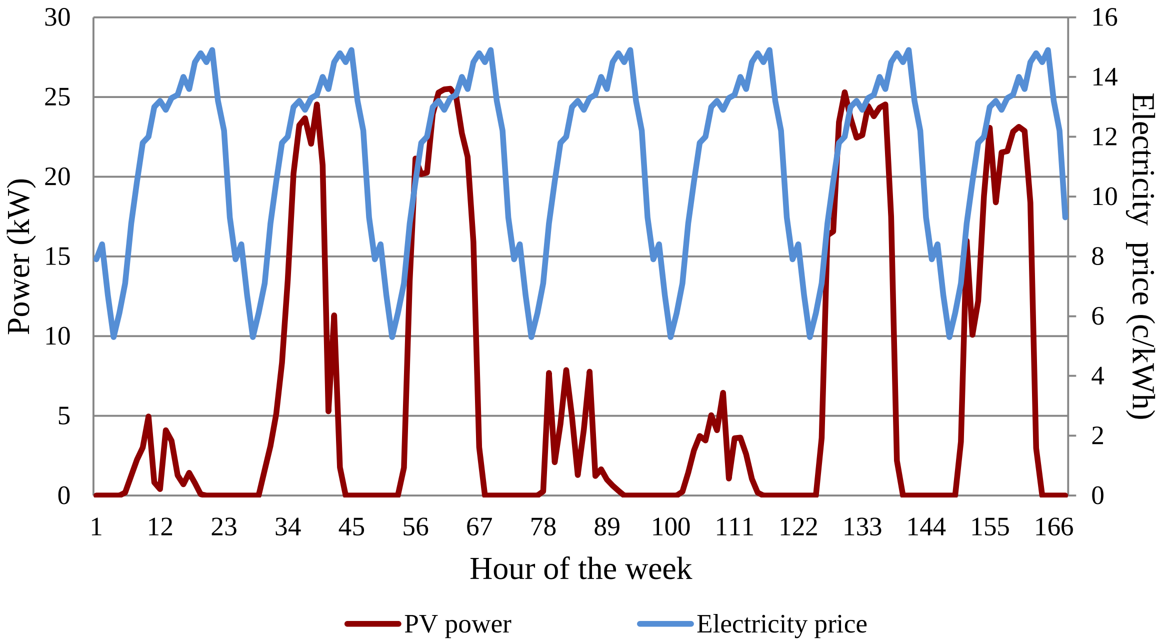

Figure 6.6 Electricity price (increased by 21 %) and PV production for the first week in January, from HOMER simulations

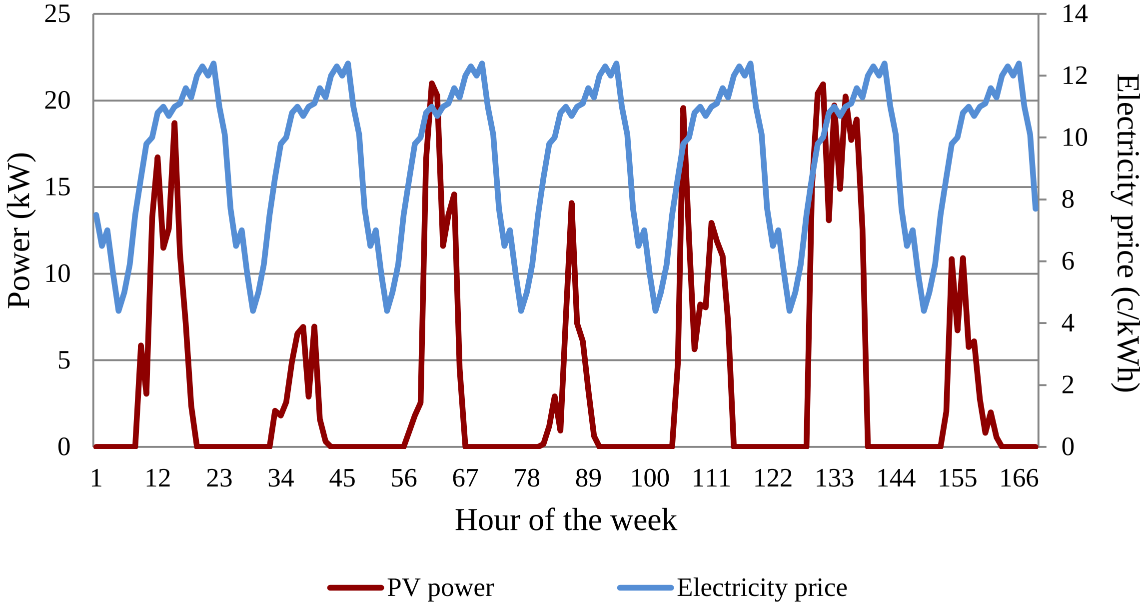

Figure 6.7 Electricity price (increased by 21 %) and PV production for the first week in July, from HOMER simulations

Chapter 7

Applicability in Stand-alone PV Systems

7.1 Stand-alone PV system for the desalination plant

Lack of fresh water is a challenge for the population in large parts of the Chaco region [57]. Unlike Pozo Colorado, however, there are populated areas where there is no access to grid electricity. In such places, establishing RO plants powered by a stand-alone PV system could be a solution, as described in [58]. In order to ensure a reliable electricity supply, an ESS and back-up diesel generators are necessary components in the system. The energy supply to the plant could be described by equation (7.1.1), if losses are neglected:

$$E_{tot} = E_{PV} + E_{gen} \tag{7.1.1}$$

where E_{tot} is the total energy supplied to the plant, E_{PV} is the energy provided by the solar panels and E_{gen} is energy supplied by the diesel generator.

A possible configuration of a stand-alone PV system for the desalination plant is suggested in Figure 7.1. The design is based on the power supply presented in the master thesis by Waatevik [3]. The system has a common DC bus at 700 V feeding a VSC for the pump loads and for supplying AC power to the technical office [3]. The PV array is connected to the DC bus through a DC-DC converter with a MPPT algorithm. Similar to the configuration in Figure 4.3, the pumps are rated for 3-phase 400 V RMS voltage while the technical office is supplied by single-phase 230 V RMS. The diesel generator is connected on the AC side, which is common practice in isolated micro-grids [59, 60]. AC generators are also recommended over DC generators because of maintenance requirements [32]. The converter acts as an inverter in order to convert DC from the PV system and the batteries to AC. When the batteries require charging from the diesel generator, the converter functions as a rectifier. Again, the VSC has to be dimensioned to tolerate the inrush current at motor start-up, as described in section 4.3.1.

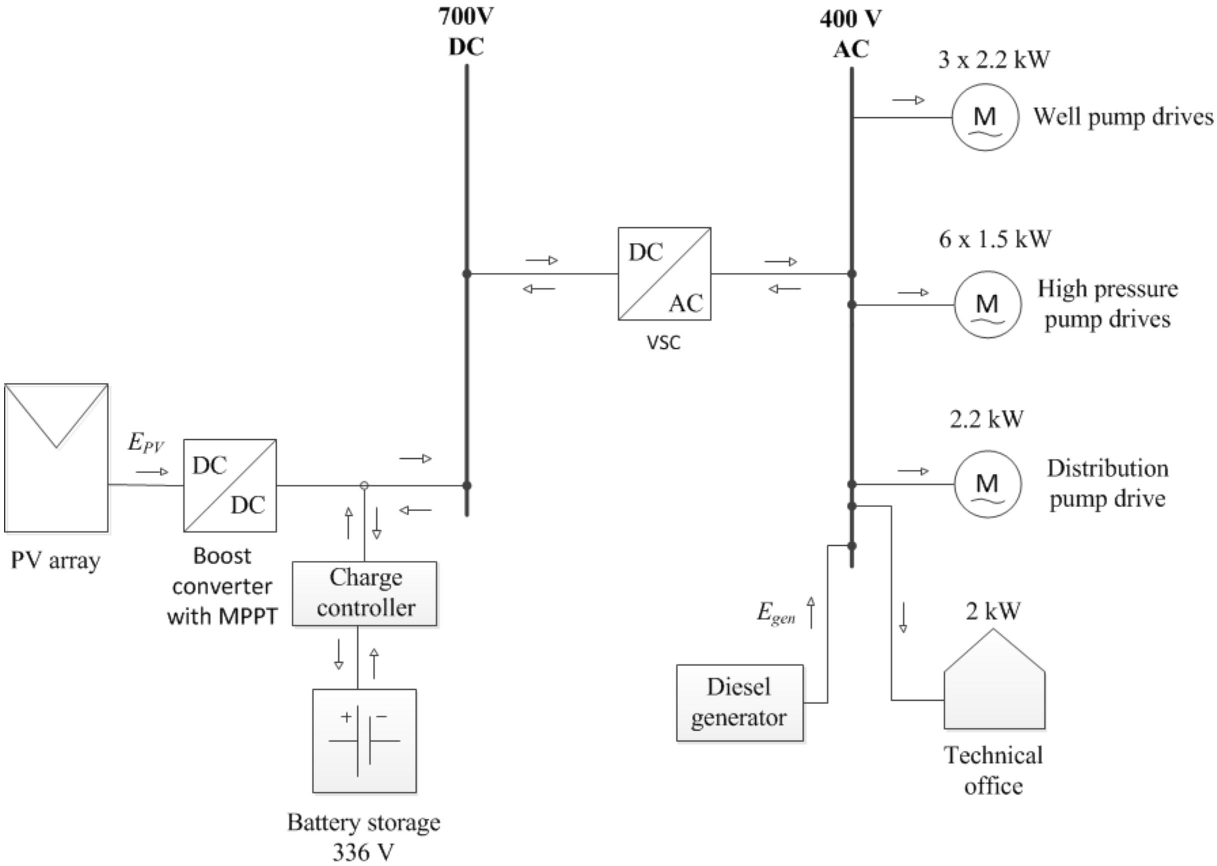

Figure 7.1 Schematic diagram of a stand-alone PV system with diesel generator and battery storage as power supply for a desalination plant, modified from [58]

7.2 Optimal load profile

7.2.1 Load profile cases

For a desalination plant powered by a stand-alone PV system, the operational regime of the plant will highly affect the system configuration, both of the energy supply system and the desalination plant itself. As described in [58], production during night-time will require more battery capacity than for a scenario where production ceases during hours of no sunlight. In the same article it is described that more membrane area is required if the production rate is high during a short period of the day. The article is a publication by the author and is enclosed in Appendix H.

Variation of the production rate through the day is feasible if individual membrane trains are out of operation for certain periods of the day, as described in section 2.6.3. Based on this, six different load profiles are studied to observe the difference in required membrane area and battery storage between the scenarios. All six scenarios yield a daily water production of about 295 m^3/day, with 100 % availability, and are constructed to represent a range of possible production profiles for the desalination plant. An energy consumption of 2 kWh/m^3 was applied in the load profile sizing, based on typical energy consumption for BWRO plants presented in section 2.6.1 and the energy use in the cases from Chapter 5. In the cases where the load is higher during the day, the profile is shaped according to typical global irradiation values for Pozo Colorado, presented in Figure 7.2. It can be observed from the graphs that solar intensity is highest between 8am and 5pm, although its magnitude varies from summer to winter.

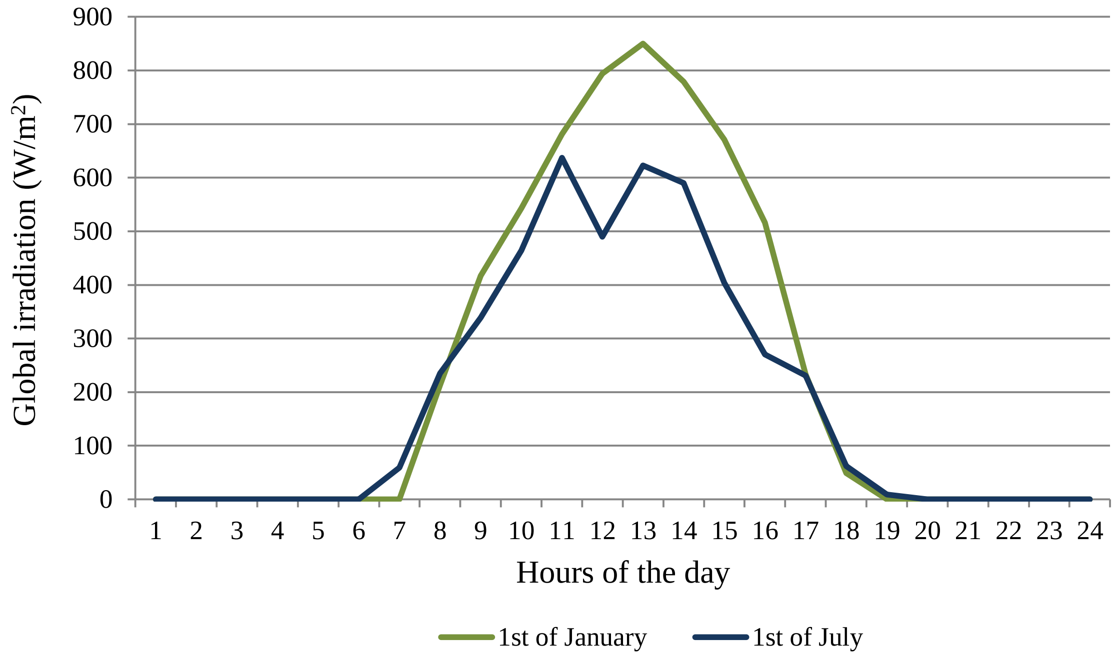

Figure 7.2 Global irradiation in Pozo Colorado for 1st of January and 1st of July [16]

Figure 7.3 presents Scenario 1, where all production occurs between 8 am and 5 pm and stops during night-time. The load profile of Scenario 2 is depicted in Figure 7.4, where production is reduced to half during night-time. In Scenario 3, presented in Figure 7.5, production is constant at all times. Figure 7.6 presents the load profile of Scenario 4, which reduces production to one-third during night-time. For Scenario 5, illustrated in Figure 7.7, production is divided into three steps in order to follow solar irradiation. For this scenario, production is at maximum between 10 am and 3 pm, is reduced to half between 8 am and 10 am and 3 pm and 5 pm, and to one-third at night-time. Scenario 6, presented in Figure 7.8, has a similar production pattern as Scenario 5 but no production during night-time.

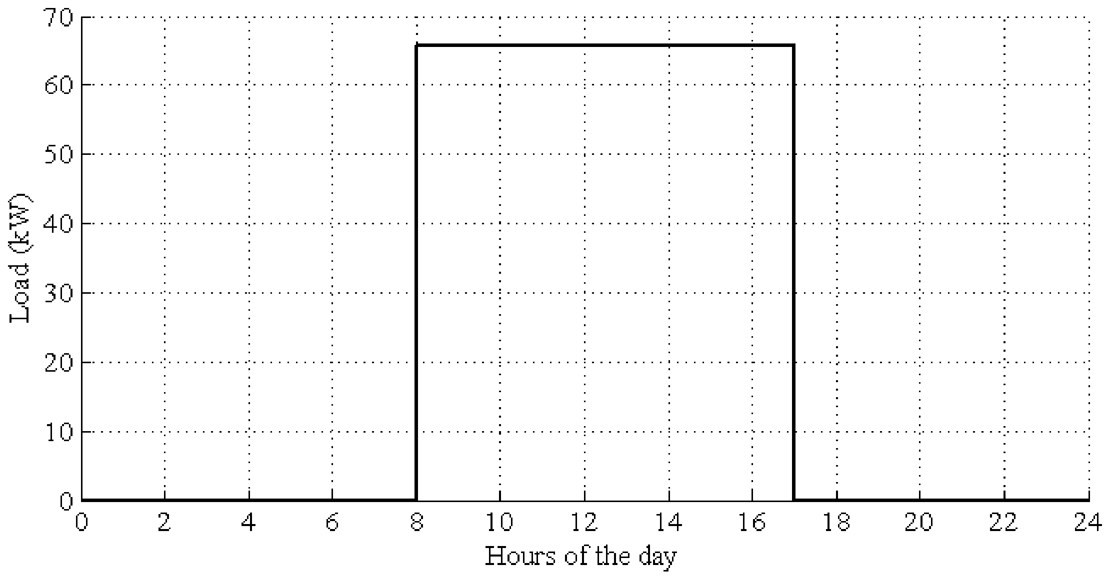

Figure 7.3 Load profile Scenario 1

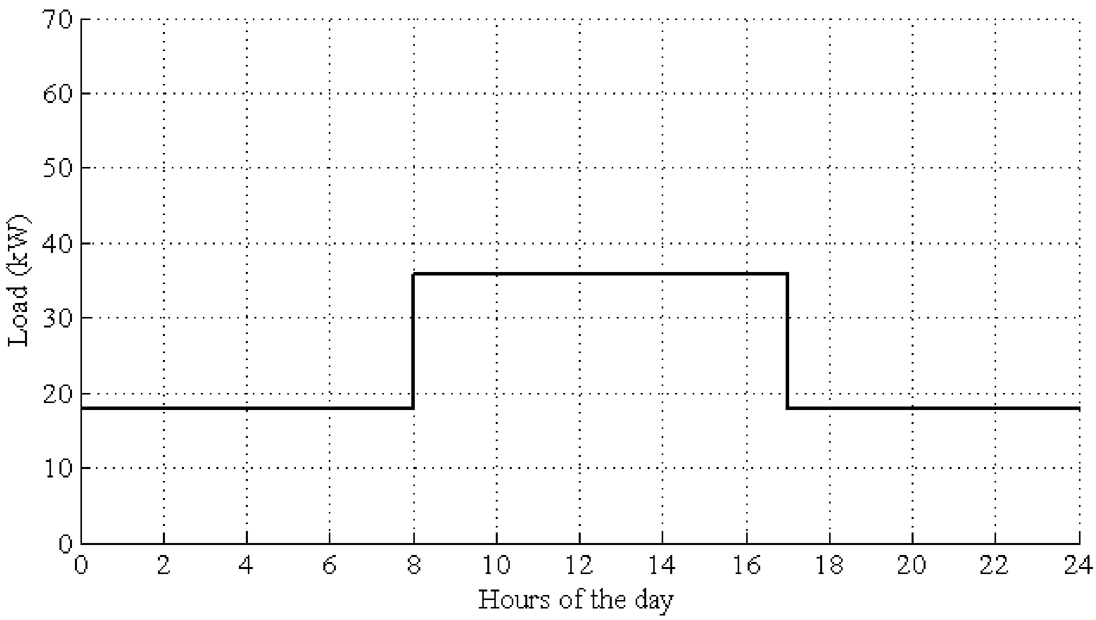

Figure 7.4 Load profile Scenario 2

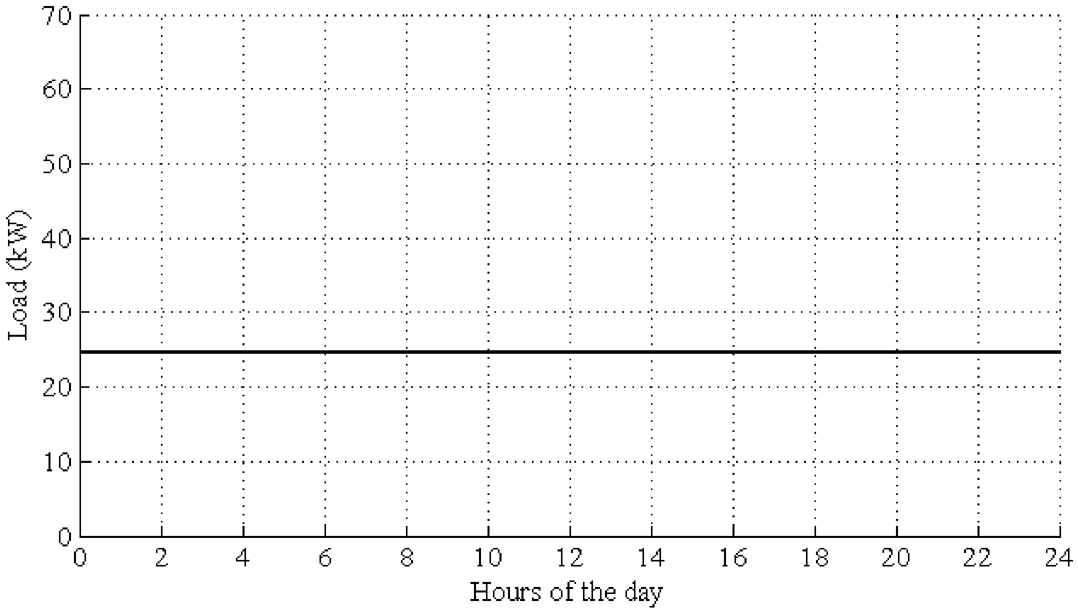

Figure 7.5 Load profile Scenario 3

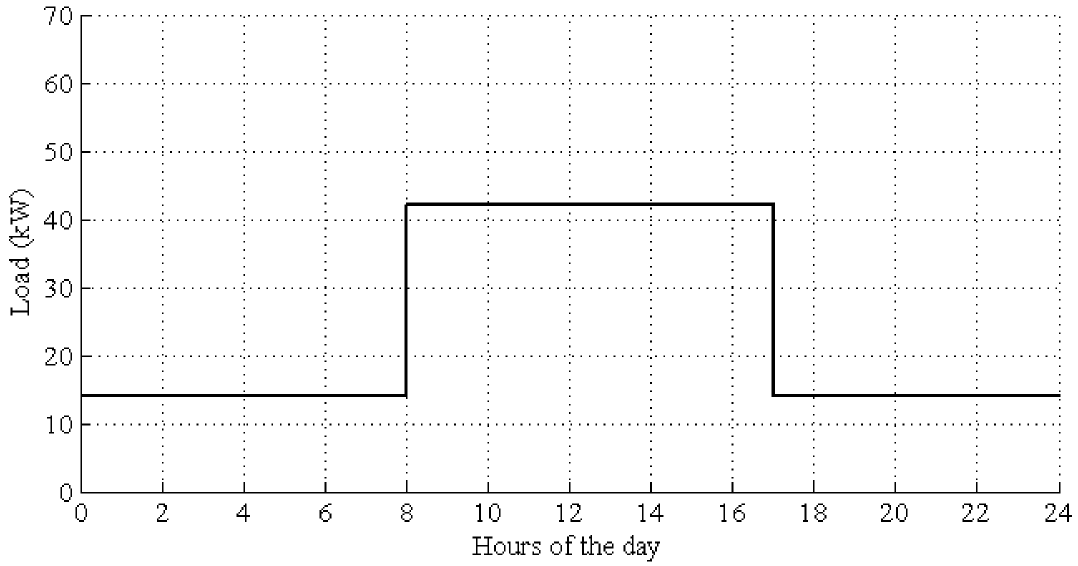

Figure 7.6 Load profile Scenario 4

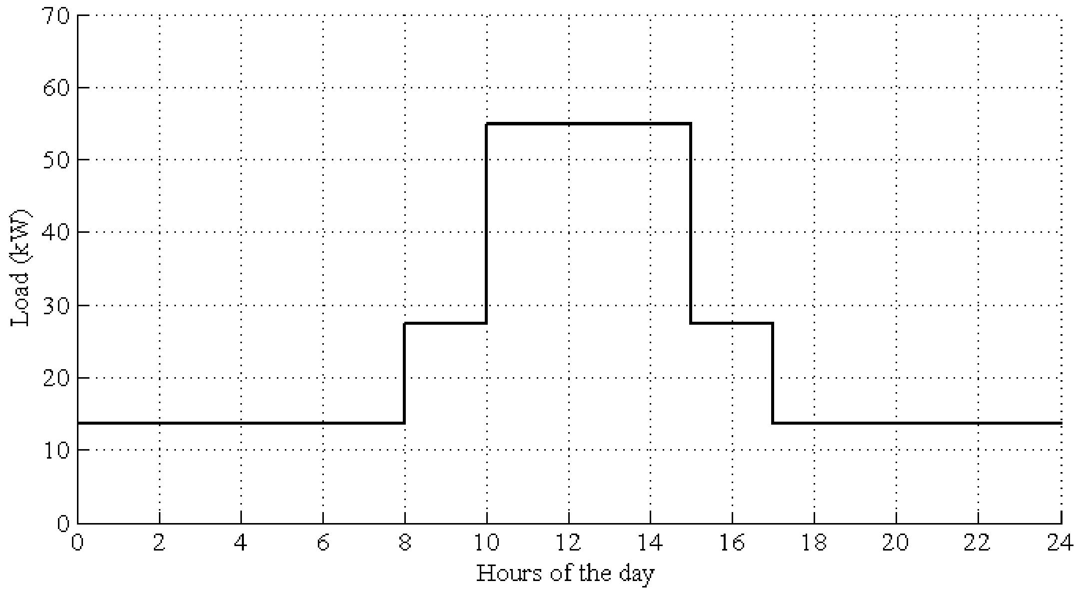

Figure 7.7 Load profile Scenario 5

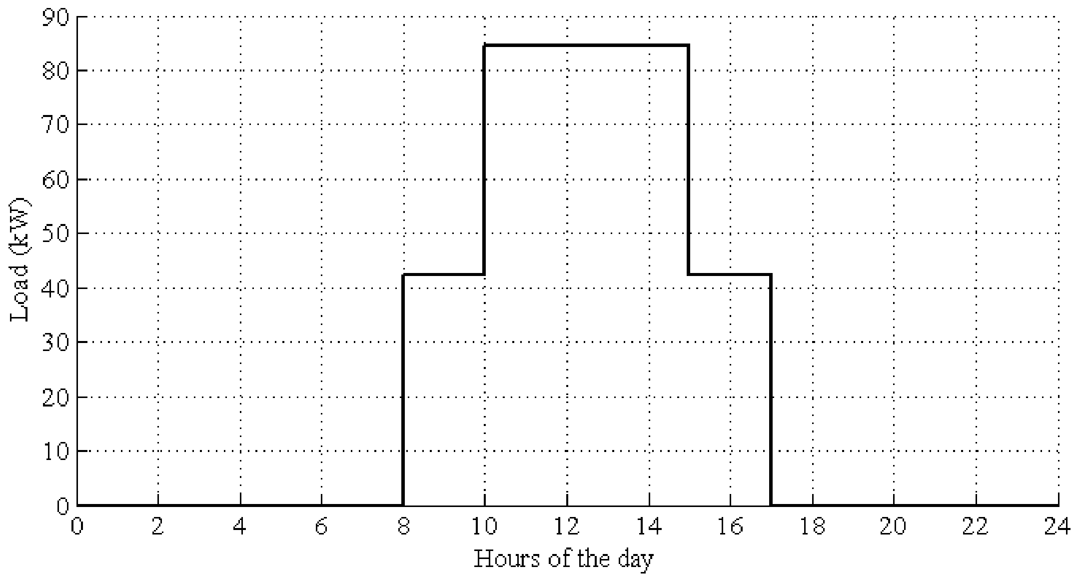

Figure 7.8 Load profile Scenario 6

In order to evaluate the energy balance for the six scenarios, a series of assumptions have to be made. A PV module efficiency of 15 % is estimated based on typical polycrystalline module efficiencies that were presented in section 2.7.2, which means that 15 % of the solar irradiation is converted to useful energy. The PV modules were sized according to the annual average irradiation values for Pozo Colorado in order to obtain PV production data. As a result, the system could be oversized for periods with high solar irradiation and undersized for the winter period when irradiation is lower. The PV sizing calculations are presented in Appendix F. It is assumed that the energy deficit that cannot be covered by excess electricity stored in a battery bank can be covered by a diesel generator to avoid plant shut-down. The MATLAB script that section 7.2 is based upon is enclosed electronically to this thesis, as described in Appendix G.

Figure 7.9 presents the energy deficit throughout the year for all six scenarios if no energy storage is included in the system. The colored lines represent the average amount of energy per day that has to be covered by battery storage and diesel generator to provide the desalination plant with sufficient energy. It can be observed from the figure that Scenario 3, with a constant load profile, has the highest energy deficit. For Scenario 6, where the load is zero during night-time and more closely related to the solar irradiation during the day, the energy deficit is considerably lower although it has high peak values for some days of the year. The deficit is also low for Scenario 1 that also has zero production during night-time. For Scenario 2, Scenario 4 and Scenario 5, which all have production during night-time, the energy deficit is in between the other three. As a result of the different energy deficits for the load profiles, the required battery storage will vary between the scenarios.

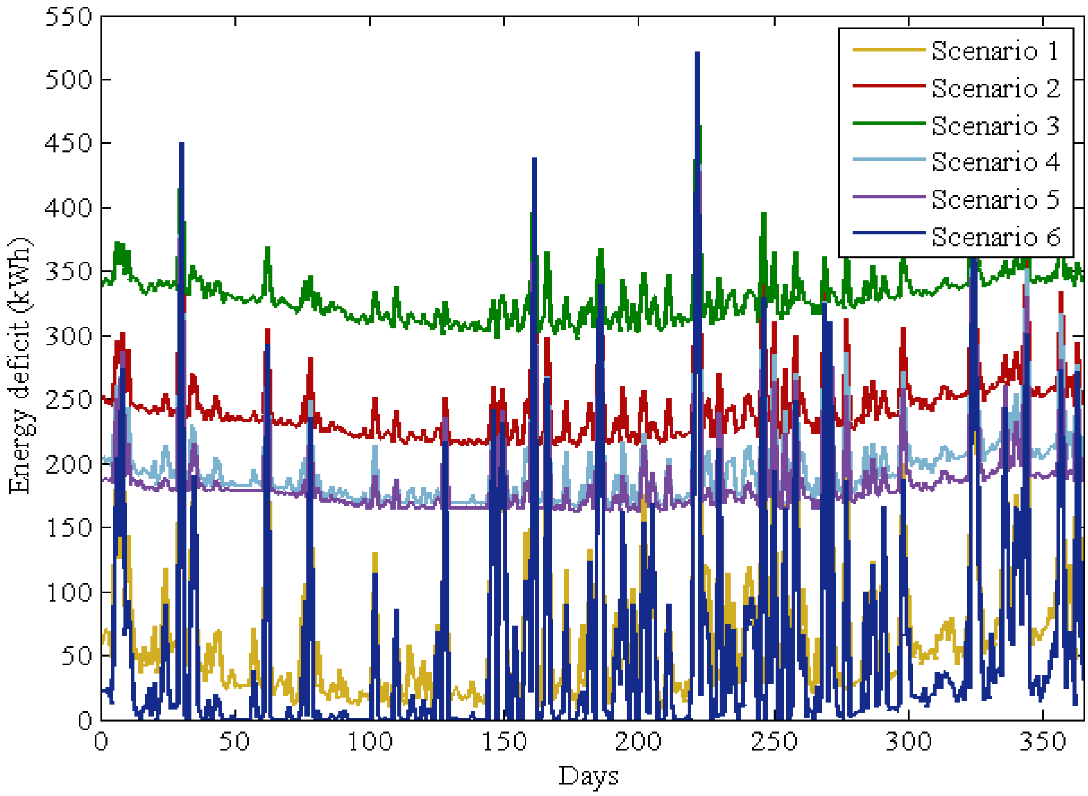

Figure 7.9 Mean daily energy deficit for Scenario 1-6 without energy storage

The usage pattern of membranes and batteries will also affect the lifetime of the components and thereby replacement costs. In addition, the production profile will determine the required rating of pumps and motors. All the scenarios have different maximum loads that will have an impact on the pump and motor capacities. The cost increase for larger pumps and motors is not very high [45], however, and will not be taken into consideration here due to the minor contribution to the total costs. Therefore, only issues of membranes and batteries for the respective scenarios will be studied in the following.

7.2.2 Membranes and batteries

Based on the average daily energy deficit presented in Figure 7.9, the battery storage capacity can be estimated for all six scenarios. Equation (2.7.2) in section 2.7.3 was applied using the average annual energy deficit for each scenario as W and 1 day of autonomy. By using the average annual energy deficit for sizing of the energy storage, the battery bank can only cover the energy demand for some days of the year. A diesel generator is therefore obligatory in the system to ensure the energy supply for the remaining days. The generator will supply more energy during days of low solar irradiation and less during days of higher solar intensity. For estimation of the battery capacity, equation (2.7.2) was modified to equation (7.2.1):

$$C_m = \frac{\text{Annual average energy deficit}}{0.7} \qquad , 1 <= m <= 6 \qquad (7.2.1)$$

where C_m is the battery capacity for Scenario m in kWh. The resulting battery storage capacities are presented by the y-axis in Figure 7.10. It can be observed that the scenario of constant production, Scenario 3, requires the highest battery bank capacity. In Scenario 6, where production follows solar irradiation more closely and there is no production during night-time, the battery storage capacity is considerably lower. The storage requirement is also low for Scenario 1.

The number of membranes required for each scenario was estimated based on the maximum production capacity per day that is specified for the membrane type. The very same membrane type as presented in section 3.3 was applied, with a maximum permeate flow rate of 1.025 m^3/h. For the scenarios where production varies throughout the day, the period with the highest production determines the number of membranes required. Equation (7.2.2) was applied to estimate the number of membranes:

$$M_m = \max\left\{\frac{Q_{mt}}{Q_{\max}}\right\} \forall t = 0,1,2,...,24 \qquad (7.2.2)$$

where M_m is the number of membranes in Scenario m, Q_{mt} is the permeate production rate in m^3/h for Scenario m in hour number t and Q_{max} is the maximum permeate production rate per membrane of 1.025 m^3/h.

The x-axis in Figure 7.10 presents the resulting number of membranes required for each scenario. It can be observed from the figure that the number of membranes and the battery storage have an inverse correlation. For Scenario 3 that requires the highest battery bank capacity, only 12 membranes are needed. Scenario 6, on the other hand, requires as much as 41 membranes.

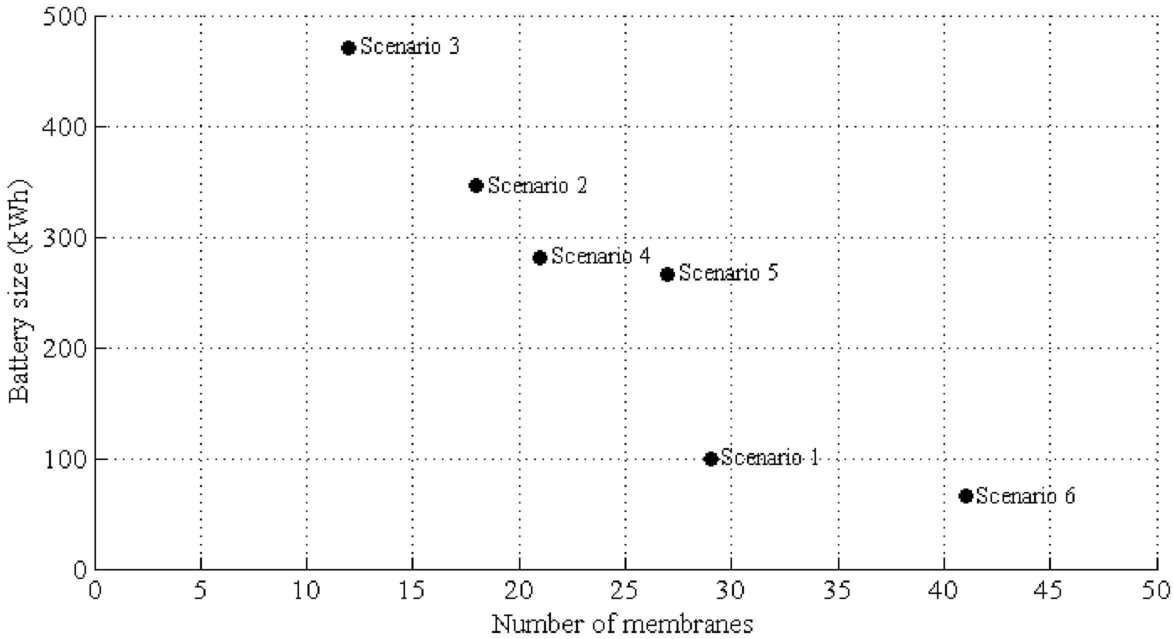

Figure 7.10 Number of membranes and battery bank size for Scenario 1-6

As described in section 2.7.3, the number of cycles that a battery can withstand decreases with the depth of discharge that the battery is subjected to. For the six load profiles, the lifetime of the battery bank will vary with charge level of the battery and energy demand of the plant. Naturally, for the scenarios where there is production during night-time, there will be more stress on the batteries. According to [61], 1 cycle with a depth of discharge of 100 % is roughly equivalent to 2 cycles with a depth of discharge of 50 %. It can also be observed from Figure 2.24 in section 2.7.3 that the relationship between number of cycles and discharge rate is close to linear. Data from Figure 2.24 was applied in the calculations, where the lead-acid battery can withstand 1,500 cycles at a 100 % discharge rate. Here, a 100 % discharge is equivalent to a 30 % state of charge (SOC), which is the limit for lead-acid batteries, as described in section 2.7.3. Due to the hot climate in Pozo Colorado, a factor of 0.7 was applied to the lifetimes to account for reduction in lifetime caused by high temperatures [50].

By adding the number of battery cycles for every scenario, the lifetime of the battery bank in years was estimated according to equation (7.2.3):

$$(\text{Battery lifetime})_m = \frac{f_{th} \cdot n_{100}}{\sum_{d=1}^{d=365} (1-(SOC)_t)} \quad \text{for } 0.3 < \text{SOC} < 1 \tag{7.2.3}$$

where m is the scenario number, f_{th} is the thermal loss factor of 0.7, n_{100} is the number of cycles at 100 % discharge rate (1,500) and $(SOC)_t$ is the state of charge at the end of day t starting with fully charged batteries 12am midnight. The minimum value of SOC is set to 30 % in order to avoid damage on the batteries. The resulting lifetimes for the battery bank for every scenario are presented in Figure 7.11. The numbers were rounded down to the closest integer for simplicity. For Scenario 6, the battery lifetime is 5 years, for Scenario 2-5 it is 3 years and for Scenario 1 it is 4 years, as can be seen from the graph. The lower graph in Figure 7.11 presents the size of the battery bank for every scenario. The largest battery banks, in Scenario 2-5, have the shortest lifetimes as these are the scenarios where there is production during night-time. In Scenario 1 and Scenario 6 there is no production during the night and this leads to longer lifetime for the battery bank.

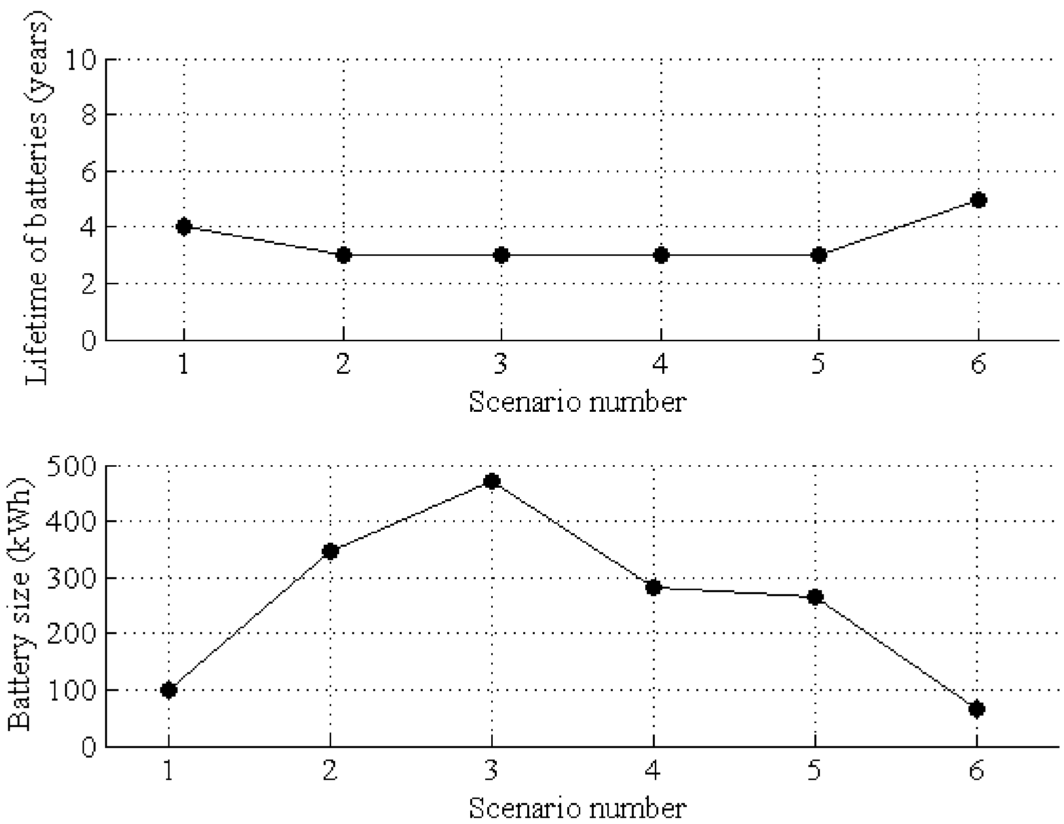

Figure 7.11 Lifetime and size of battery bank for Scenario 1-6

Next to the battery bank, the operational regime of the plant will affect the lifetimes of the desalination equipment. As described in section 2.6.3, RO membranes can tolerate start and stop and it is therefore assumed that a reduced usage time would increase the lifetime of the membranes. Start and stop in production requires flushing of the system for every shut-down, which is performed primarily to prevent fouling and clogging in the membrane structures. According to [21], fouling is mainly connected to the quality of the source water and the performance of the pretreatment facilities in the desalination plant. Based on this information and data from Table 2.4 in section 2.6.4 from Aguamin desalination plant, it is estimated that a lifetime of 1 year for the membranes is representable if the plant has a continuous operation. This is a rough estimation as the source water in Pozo Colorado is likely to differ from the groundwater in Filadelfia but yet it gives an indication of membrane lifetimes for different operational regimes. Based on a lifetime permeate production of 8,979 m^3/membrane, the lifetimes of the membranes in years were estimated for Scenario 1-6 according to equation (7.2.4):

$$(\text{Membrane lifetime})_m = \frac{q_{lifetime} \cdot M_m}{Q_{annual}} \tag{7.2.4}$$

where m is the scenario number, q_{lifetime} is the lifetime permeate production of 8,979 m^3/membrane, M_m is the number of membranes for Scenario m and Q_{annual} is the total permeate production of 96,980 m^3/year. It is assumed that frequent start and stop in production will have no negative effect on the membranes [28]. The results are presented in Figure 7.12, with the associated number of membranes in the lower graph. It can be observed that Scenario 1 and Scenario 6 are the load profiles with the highest membrane lifetimes of 2.4 and 3.4 years, respectively. For Scenario 3, which has the very same production profile as Aguamin, the lifetime is 1 year and for the remaining scenarios the membranes have lifetimes between 1.5 and 2.3 years. As can be observed from the graphs, the number of membranes is proportional to the lifetime. The combination of membrane and battery lifetimes will affect the costs of the system, which will be further studied in the following.

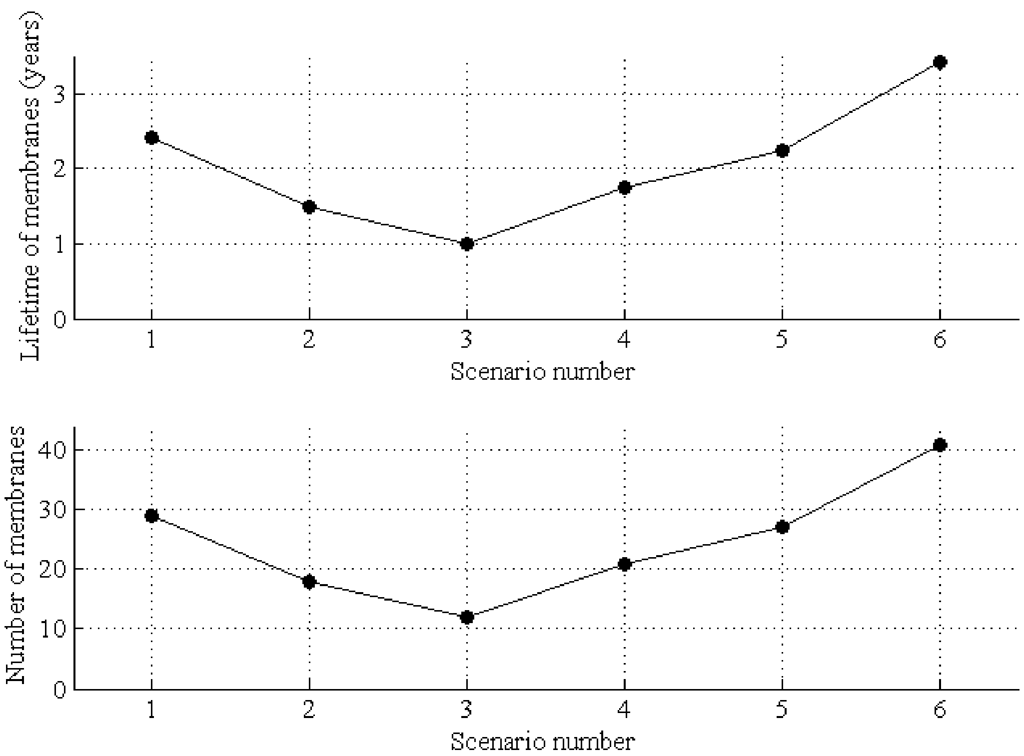

Figure 7.12 Lifetime and number of membranes for Scenario 1-6

7.2.3 Economic evaluations

In order to determine the most cost-effective load profile, the NPC of membranes and batteries was estimated according to the formulas in Appendix B. A cost of $150/kWh was applied for the batteries and $1,005/membrane as presented in section 4.2.1 and 5.1, respectively. For the battery bank, the salvage value at the end of the analysis period is included in the estimations for every scenario. This is not included in the evaluation of the membrane costs as the lifetimes are considerably shorter and this will not have a large effect on the total costs. An interest rate of 6 % was applied in the calculations.

For Scenario 1-6, the NPC of batteries and membranes are presented in Figure 7.13 and Figure 7.14, respectively. Not surprisingly Scenario 1 and Scenario 6, which have no production during night-time, have the lowest battery costs. Scenario 3 with constant production has the highest battery costs. The opposite trend can be observed from the NPC of membranes but here the differences in cost between the scenarios are minor compared to the battery costs.

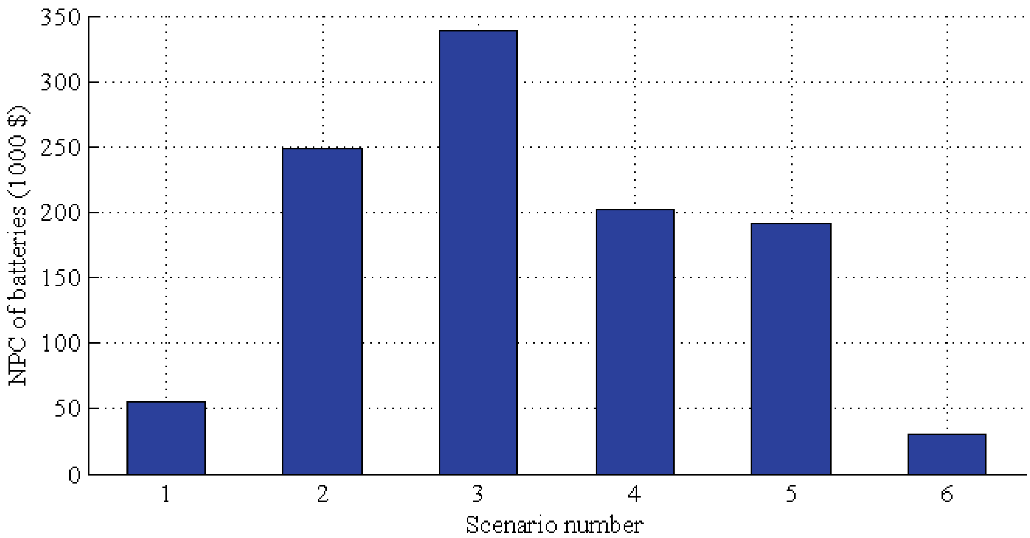

Figure 7.13 Net present cost of batteries for Scenario 1-6

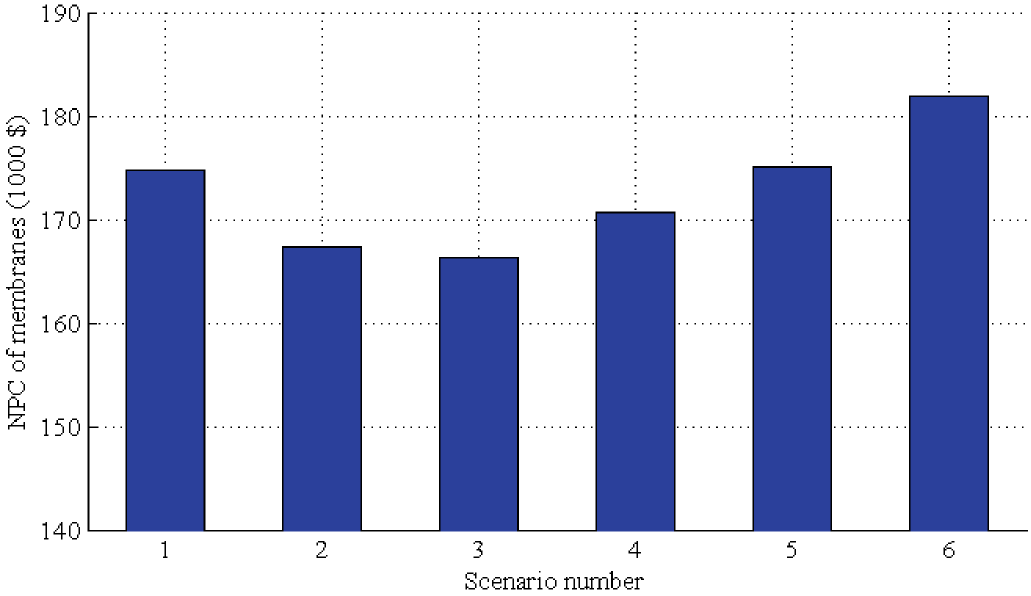

Figure 7.14 Net present cost of membranes for Scenario 1-6

The number of membranes and the battery storage for each scenario, next to the sum of the NPCs for batteries and membranes are presented in Figure 7.15. As can be observed from the bar chart, Scenario 6 is the most cost-effective load profile, followed by Scenario 1 that has 8 % higher NPC. Scenario 3 is by far the most expensive option. The NPC of Scenario 3 is more than double the NPC of Scenario 6. Hence, the scenario with the lowest battery storage and the highest number of membranes is the most cost-effective load profile. Based on this economic evaluation, Scenario 6 was simulated in HOMER.

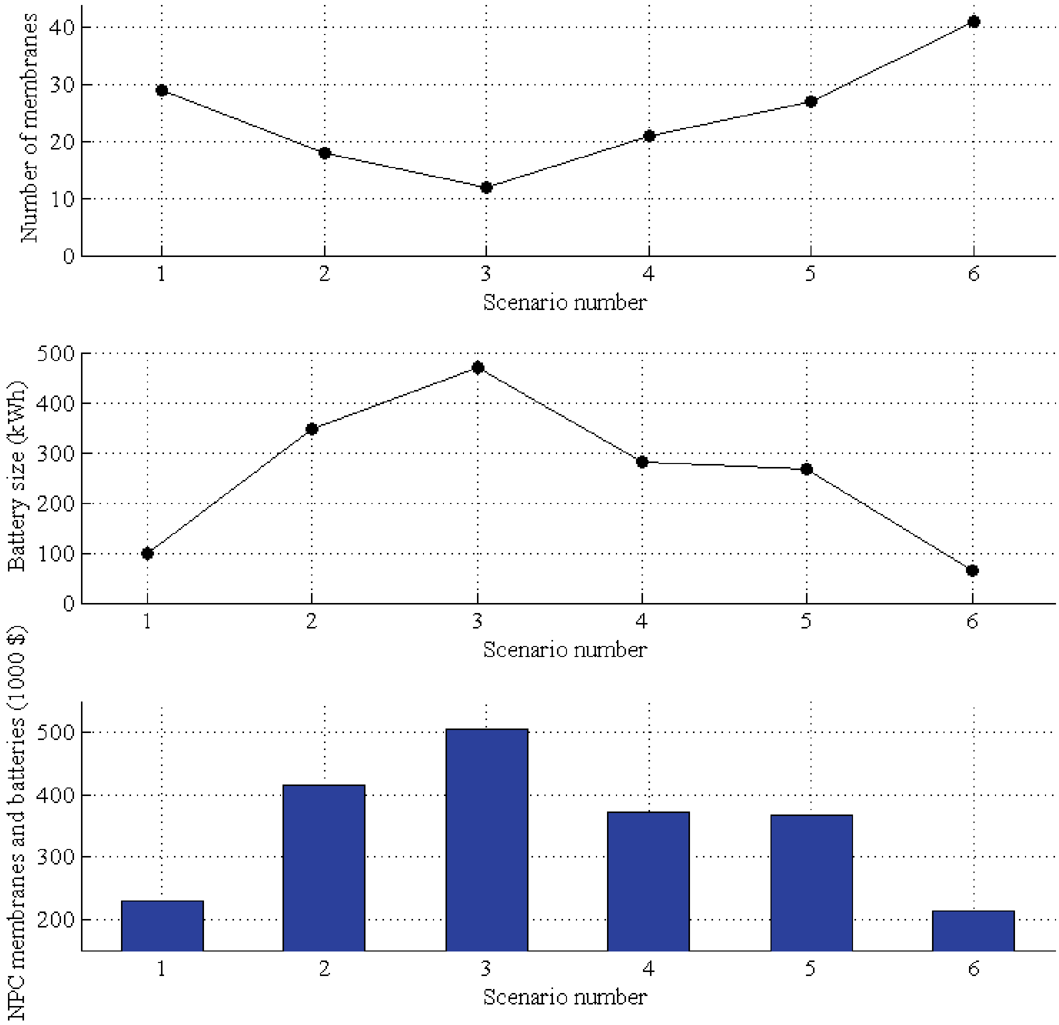

Figure 7.15 Number of membranes, battery size and NPC of membranes and batteries for Scenario 1-6

7.3 Energy balance considerations

7.3.1 Input parameters

Prior to simulation in HOMER, input parameters had to be defined for Scenario 6. The load profile presented in Figure 7.8 was implemented. For the four time periods the load requirements are presented in Table 7.1. As described in section 7.2.2, it is necessary to include a back-up diesel generator in the system to obtain a reliable electricity supply for the plant. Therefore, costs of fuel and generators had to be implemented in HOMER, next to lifetime of the diesel generators. These values are presented in Table 7.2. The components of the power system were implemented in HOMER as presented in Figure 7.16. The peak load is 84 kW and the daily energy demand is 590 kWh.

Table 7.1 Load profile data for Scenario 6 to be simulated in HOMER

Time period	**Load (kW)**
8am – 10am	42.18
10am – 3pm	84.34
3pm – 5pm	42.18
5pm – 8am	0

Table 7.2 Diesel, generator costs and generator lifetime

Parameter	**Value**		**Reference**
Diesel cost	1.3	$/l	[44, 62]
Generator cost 1	3,375	$/5 kW	[63]
Generator cost 2	5,475	$/10 kW	[63]
Generator cost 3	8,799	$/30 kW	[63]
Lifetime diesel generator	15,000	operating hours	Default in HOMER

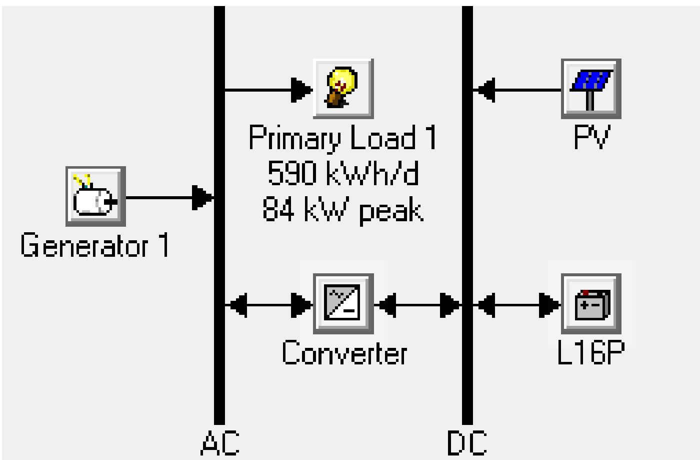

Figure 7.16 HOMER system configuration

7.3.2 Simulation results

The simulation in HOMER yielded capacities for the PV system, diesel generator, battery storage and converter. The results are presented in Table 7.3. This combination of energy system components is able to cover the whole energy demand of the desalination plant. The PV system has a capacity of 165.7 kW in total. For energy storage, the battery bank has a rating of 86.4 kWh, not far from the value estimated for Scenario 6 in section 7.2.2. The security of supply is ensured by a dispatchable diesel generator of 69 kW. To enable DC/AC and AC/DC conversion, a converter of 93 kW is necessary in the system. In total, the system has a production of 391,955 kWh. This is distributed on 88 % from the PV array and 12 % from the diesel generator, as presented in Table 7.3. Excess production from the PV system is higher in summer than in winter and is in total 138,332 kWh/year or 42 % of the total PV production. A full simulation report is included in Appendix F.

Table 7.3 Capacity of the energy system components, production rates and excess production, Scenario 6

Component	**Capacity**		**Production (kWh/year)**	**Fraction (%)**	**Excess production (kWh/year)**
PV system	165.7	kW	326,469	88	138,332
Generator	69	kW	46,318	12	0
Battery bank	86.4	kWh	-	-	-
Converter	93	kW	-	-	-
Total			**391,955**	**100**	**138,332**

In Figure 7.17, the monthly energy production from the diesel generator and PV system is presented. It can be observed that the PV production is higher in months of high solar intensity. During the winter months, PV production is lower and hence production from the diesel generator increases in this period.

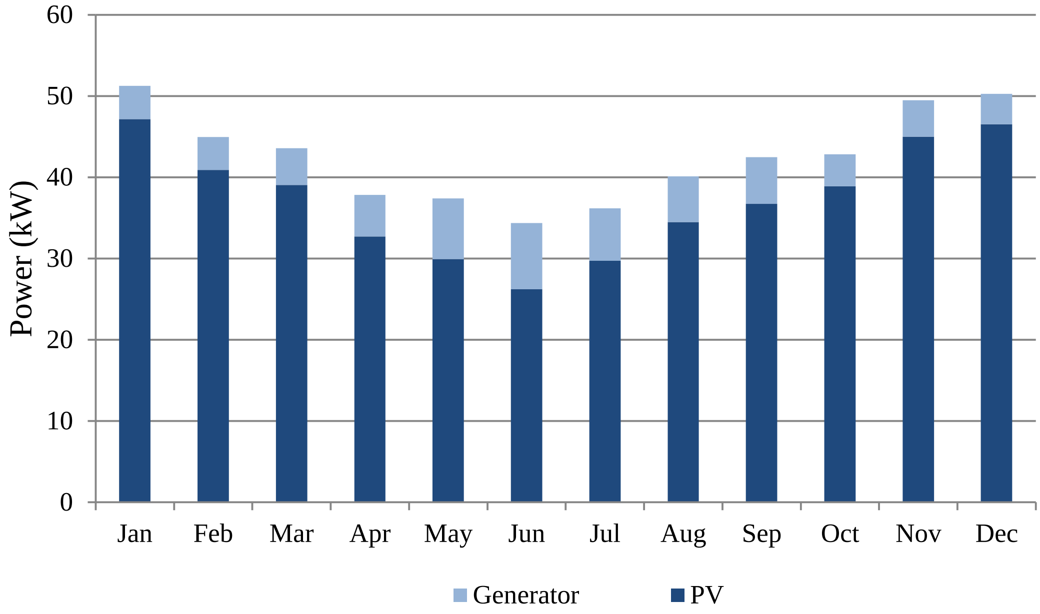

Figure 7.17 Monthly energy production from diesel generator and PV system

Compared to Case 3 investigated in Chapter 5, investment costs will be considerably higher for Scenario 6 due to the stand-alone PV system. Costs of investment, operation and replacement are presented in Table 7.4, next to salvage value at the end of the 25 year period and NPCs. Investment costs are around $450,000 for the energy system and the NPC is about $800,000. Costs of diesel represent the operational costs of the system, which is around $24,000 per year. Replacement costs involve the generator and battery bank and these costs total about $4,000 per year if distributed annually.

Table 7.4 Energy system costs for a 25 year period, Scenario 6

Component	**Investment ($)**	**Fuel ($/year)**	**Replacement ($/year)**	**Salvage ($)**	**NPC ($)**
PV modules	364,540	-	-	-	364,450
Generator	15,281	23,901	878	-3,365	328,678
Batteries	45,600	-	3,104	-5,312	79,969
Converter	27,900	-	-	-	27,900
Total	**453,321**	**23,901**	**3,982**	**-8,677**	**801,087**

The nominal costs over a 25 year period are presented graphically in Figure 7.18. It can be observed from the graph that the PV system cost is highly dominant in year 0. During operation it is primarily diesel costs and in addition some replacement costs for the battery bank and the diesel generator. The diesel generator and the battery bank have a salvage value that is indicated by a negative cost in year 25.

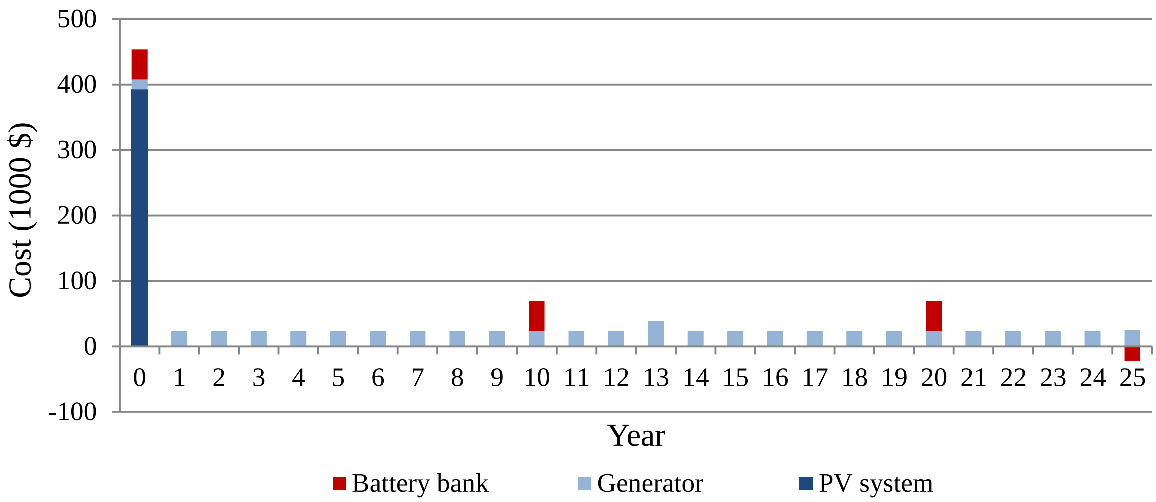

Figure 7.18 Nominal costs over 25 years for the energy system, Scenario 6

Chapter 8

Discussion

8.1 Desalination plant configuration

The preliminary system design presented in section 3.2 was based on state-of-the art RO plants and particularly Aguamin desalination plant in Filadelfia. This is not necessarily a suitable design for Pozo Colorado, although the optimal configuration probably will be similar. In order to develop a more appropriate design, drilling a well for investigation of the groundwater conditions is obligatory. Flow rates of the groundwater would determine the number of wells and the required distance between them. Feed water composition is also central when membrane types are considered. Groundwater conditions could be very different in Pozo Colorado and Filadelfia; therefore another membrane type could be necessary in Pozo Colorado than the type presented in section 3.3. A higher system pressure and thereby larger HP pump capacity could be required as well, depending on the salinity of the feed water.

Different pre- and post-treatment of the water could also be necessary in Pozo Colorado compared to Aguamin, depending on feed water quality and the preferred product water quality. This could affect operational costs of the desalination system. Due to lack of knowledge about the groundwater, a series of assumptions had to be made in order to suggest a plant design. In the economic evaluations, costs of drilling were not included as it is unknown to which depth it would have to be drilled. Since little is known about the existing water distribution system, costs for upgrading the pipes were not included either.

As described in section 2.6.1, feed water salinity has a large impact on the energy required for desalination. Lower salinity would reduce the system pressure and thereby the electricity demand for driving the HP pumps. With both groundwater and surface water available, blending the two water sources could possibly be a solution to reduce salinity prior to entering the membrane modules, as depicted in Figure 8.1. This depends on the availability of surface water, which could be drastically reduced in dry periods. In addition, the surface water quality is a central factor. An experienced RO system supplier should be consulted for development of a suitable system configuration for Pozo Colorado.

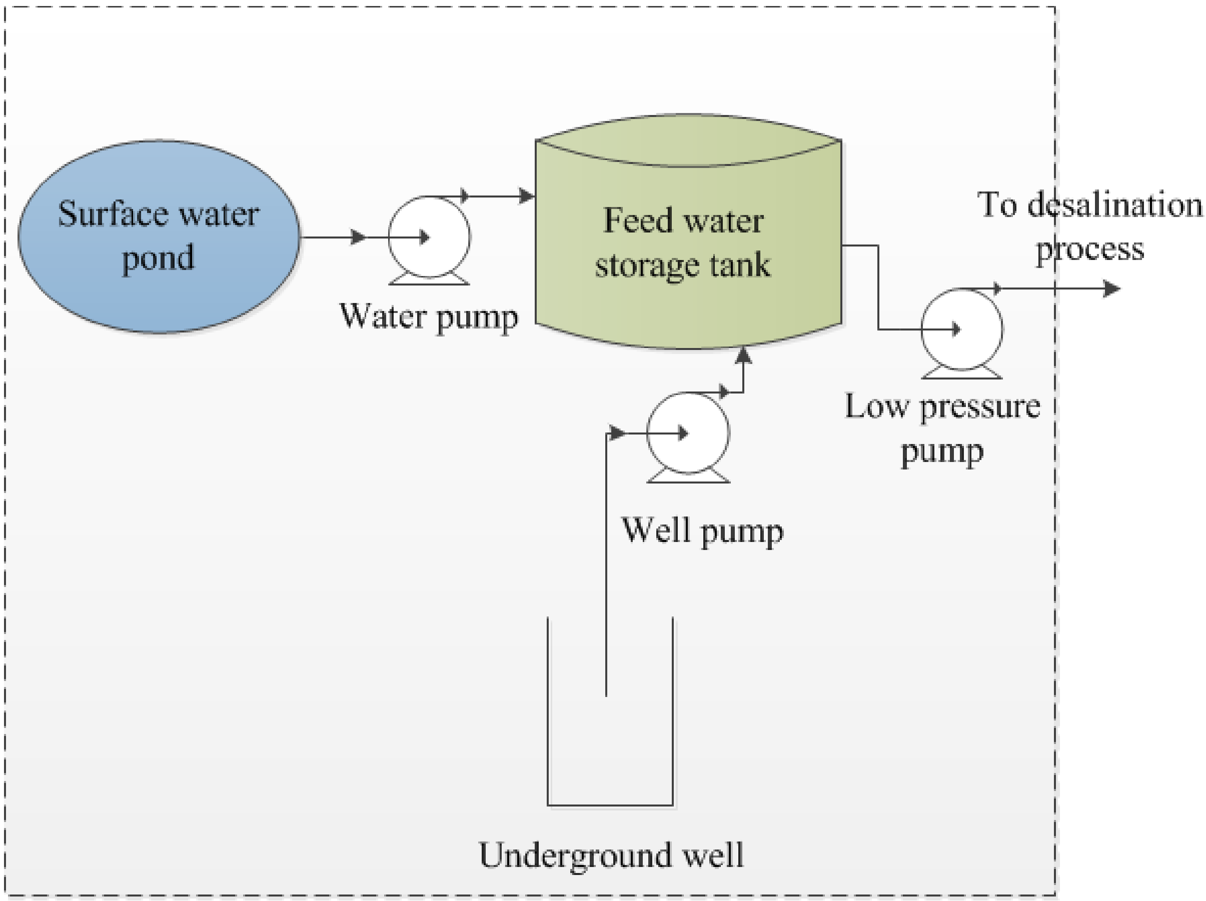

Figure 8.1 Blending of surface water and groundwater in feed water storage tank prior to desalination

The stages of construction presented in section 3.3 could be a good solution if the system is to be tested on a small scale in the beginning. However, if clean water is more readily available for the inhabitants in Pozo Colorado at a reasonable price, water consumption is likely to increase. Therefore, surface water should possibly be a back-up supply at the initial stage. This would also be a gradual transition from the current water supply and the system that the inhabitants of Pozo Colorado are accustomed to using.

8.2 Energy supply for the desalination plant

From Figure 5.16 in section 5.7 it was clear that the saving potential by installing a PV system increases with energy demand. This is natural as more energy can be substituted by solar energy that is free of charge. However, investment costs are still high for a PV system, which could be an obstacle for installation in Pozo Colorado due to the available grid. Table 8.1 presents cost figures of the three cases that have a production of 266 m^3/d. Case 3 grid only clearly has the lowest energy investment costs and a 100 % renewable share if grid electricity is considered to be only from hydro power. Case 3 and Scenario 6, which both include PV modules in the energy system, have considerably higher investment costs. Reliability will be higher in Case 3 and Scenario 6, however, since the PV modules ensure the energy supply in case of power outage (Case 3 and Scenario 6) and the diesel generator serve as a reliable energy supply in periods of low solar irradiation (Scenario 6). The NPC of the energy system in Case 3 is only 11 % higher than Case 3 grid only since solar energy is free of charge and will reduce operational costs in Case 3. For the stand-alone supply in Scenario 6, the energy mix will only be about 88 % renewable due to the diesel generator. This could have been increased if a limitation to generator use was implemented in HOMER, although this would have caused a higher NPC.

Table 8.1 NPC for a 25 year period and renewable share of Case 3, Case 3 grid only and Scenario 6

Case/scenario of study	Energy investment ($)	NPC energy system ($)	PV share (%)	Renewable share (%)
Case 3	57,905	255,200	20	100
Case 3 grid only	9,105	230,187	0	100
Scenario 6	453,321	801,087	88	88

The cost figures presented in Chapter 5 and Chapter 7 are only approximations that might deviate from real costs. No maintenance costs were included for diesel generator, battery storage and PV modules. For the generator, it is mainly oil change and tune-up of the engine that is required. Deep-discharge batteries normally requires addition of water for maintenance and for the PV modules it is mainly regular cleaning for dirt on the surface that is necessary [32]. Although these costs are not very dominant, they will increase project costs slightly. For neither of the cases the cost of a boost converter is included, which would further increase energy investment costs. Next, the battery lifetime applied for the back-up PV supply system might be a little short for Case 1, 2 and 3. Compared to the battery lifetimes in Scenario 1-6 presented in section 7.2.2, which are batteries used daily, it is likely that the back-up battery will have a longer lifetime. Uncertainties like risk level of power outage and depth of discharge make it difficult to estimate the battery lifetime, but a longer lifespan would reduce the project costs. Transport costs are also gross estimations and might be significantly different.

As described in section 2.1.4, there is an inverse correlation between wind and solar resources in Pozo Colorado. For a stand-alone energy supply, it could therefore be evaluated if wind turbines should be included in the system. Installing wind turbines would yield a lower PV capacity, which would also result in less excess energy production during summer. However, this would increase the complexity of the system and it has to be evaluated if introduction of another energy source will be beneficial in terms of economic and operational feasibility.

8.3 Future electricity prices

In the process of creating a synthetic electricity market model there are of course a series of uncertainties involved. First, for creation of the hourly variations, the usage of electricity in California and Paraguay will differ due to level of wealth and lifestyle. Second, the introduction of an electricity market is likely to have a different effect if it was introduced in Paraguay today, compared to Brazil, which was used as a basis for developing monthly variations. Moreover, it is certain that Brazil, and also Chile and Colombia, have experienced large fluctuations in the power price after deregulation, as described in section 6.1. Prices have been seen to increase in dry periods and in general vary between the seasons. With large hydro power dependency, this could also occur in Paraguay in a free electricity market. In addition, there is economic development and the country experiences an increase in electricity consumption per capita, as presented in section 2.1.3. Between 2011 and 2013, the average electricity price increased by as much as 16 %, as presented in the same section. Therefore, a 21 % increase in the overall price is not unlikely to occur if the market was deregulated, which was the minimum increase for PV feasibility in section 6.3. If the public monopoly on electricity persists, on the other hand, the power price would have to increase by as much as 75 % to make PV economically feasible, as described in section 5.2. This is a large increase and is not very likely to occur in the near future when the historical price development is studied.

8.4 Operational regime

It is crucial to carefully consider the operational regime when designing a RO plant supplied by a stand-alone PV system. Continuous operation will require a large ESS and hence increased costs of investment and operation. On the other hand, a variable production necessitates oversizing of the desalination system. As mentioned in section 2.6.3, RO membranes should preferably operate within their design conditions to prevent fouling and reduction in lifetime. According to [28], however, there is dissenting information in literature about how load variations affect membrane performance. Although it seems that it is widely assumed among membrane producers that frequent start and stop has a negative effect on the membranes [64], research in this field is limited. Therefore, it was assumed that start and stop in production has no effect on membrane lifetime. This was also assumed by [28] in an attempt to optimally operate a RO plant according to fluctuating electricity costs and is therefore considered to be a reasonable assumption at this stage of the project.

If a membrane fouling factor was introduced for frequent start and stop, all scenarios but number 3 would be affected. Scenario 5 and Scenario 6 would be particularly penalized due to the 3-step load profile and thereby four starts and stops per day. Yet the difference in NPC between the scenarios, particularly Scenario 1 and Scenario 6 relative to the other four, is relatively large and a fouling factor would probably not affect which scenario that is the most economical.

Determining the most optimal operational regime for the desalination plant is a multidisciplinary task and the study conducted in this thesis is only a first step to solve the problem. The impact of variable production on RO membranes would require knowledge from people with insight in membrane technology. Tests during operation would have to be performed on the membranes in order to evaluate the effect of start and stop in production. Also, electrical engineers should be involved to assess the battery storage requirements and hence the optimal energy system configuration according to the production pattern. When these results are ready, the optimal operational regime could be found from economic evaluations.

8.5 Accuracy of results

When evaluating the accuracy of the results from this project it is essential to distinguish between the results that were based on a number of assumptions and the simulation results from HOMER. Calculations for developing load profiles, battery and membrane properties and economic figures are very accurate. The assumptions that the calculations were based on, on the other hand, make the results more imprecise. This is necessary at this stage of the project, however, since there are a number of variables that are not identified. In addition it is difficult to develop exact cost estimations without consulting suppliers directly.

The simulations in HOMER were also based on a number of assumptions that became input parameters to the program. First of all, the hourly solar irradiation data that was created synthetically in the program from monthly values can lead to some inaccuracies. Tests show, however, that there are small differences between simulation results using synthetic and real data in HOMER. For key performance output variables like PV production, generator run time and battery throughput the difference is typically less than 5 %. For key economic output variables like NPC the difference is normally less than 2 % [38].

Second, the load profiles implemented in HOMER were assumed to have no random variability. This could lead to some inaccuracies in the simulation results, as there will be natural fluctuations in feed water salinity and temperature, which will change the required feed pressure in the plant [21]. Hence, the motor load could vary to some extent. A percentage variability could have been introduced, which would have caused more fluctuations in the load. Since this was omitted, it is possible that the energy system size and hence the energy system costs presented were slightly too low.

8.6 Social effects

Building a desalination plant in Pozo Colorado could lead to a series of positive social effects. First of all, a safe and clean water supply means that there will be less diseases and thereby a healthier population. Compared to the system of today, where many people cannot afford chemicals for water treatment, clean fresh water will be readily available for everyone. Second, with a stable source of water the town will be a more attractive place to live, which can lead to more development in the area. Utilization of the groundwater resources could also serve as an example for other places in the region where underground water has never been exploited.

Finally, a pilot plant in Pozo Colorado could be a source of knowledge about water cleaning technologies and renewable energy sources. Students from schools and universities could possibly gain experience in natural sciences by visiting the plant, learning how technology could be used to improve people's living conditions. The already established contacts at UNA and UCSA in Asunción could perhaps lead to research programs related to the desalination plant, which could be beneficial for further development of the project.

Conclusion

Three possible stages of construction have been presented for a BWRO desalination plant in Pozo Colorado, with associated energy supply. At the initial stage, the system was supplied by electricity from the utility grid only, in addition to a small PV system with battery storage to serve as a security of supply for the distribution pump. For the two following stages, the energy system could be expanded by introducing solar PV modules, and this has been simulated in HOMER. Investment costs will be higher with PV modules in the energy system but introduction of PV was considered in order to make the system more suitable in areas without grid-connection, in addition to reliability concerns. Moreover, it was found for all stages that the cost of water will be lower than the current water cost in Pozo Colorado, if production over a period of 25 years is considered. As the cost figures are only estimates, it is likely that they will be higher in a real system.

The cost of electricity in Paraguay is currently very low. With simulations in HOMER it was shown that the power price would have to increase by 75 % in order to make it economically feasible to start installing PV modules in Pozo Colorado. Hence, introduction of PV in the energy system would not be economically viable without subsidies. If the electricity sector is deregulated in Paraguay in the future, it is more likely that installation of PV modules will be economically feasible for the plant in Pozo Colorado. By creation of a synthetic electricity market with seasonal variations and higher prices during daytime, it was found from simulations in HOMER that the average price has to increase by only 21 % in order to make it economically feasible to start installing PV modules.

For areas in the Chaco that lack grid-connection, a configuration of a stand-alone PV system with diesel generator was suggested. Six different load profiles were studied; one with continuous production and five scenarios where production is adjusted to available solar irradiation at different levels. It was shown that required membrane area and battery storage capacity vary largely between the six scenarios. In order to find the most cost-effective load profile, the scenarios were evaluated on the basis of net present costs of membrane and batteries. It was found that a two-step adjustment in load during the day with no production during night-time was the most cost-effective scenario. Hence, using water as storage for solar energy rather than batteries would be optimal from an economic perspective. From simulations in the software HOMER, the optimal ratings of PV modules, battery storage and diesel generator have been estimated for this scenario: 165.7 kWp of PV modules, a battery storage capacity of 86.4 kWh and a diesel generator with a rating of 69 kW. Investment costs for this scenario are particularly high due to the PV supply and there will also be operational costs related to fuel for the generator.

For further work, the main task will be to perform test drilling in order to analyze the groundwater conditions in Pozo Colorado. Thereafter a more suitable plant design can be developed and more accurate cost valuations can be made. This process has to be conducted in cooperation with an experienced RO supplier and hydrologists should possibly also be involved. An important task would be to determine whether the leftover brine should be pumped back into the soil or if other methods should be used. An engineer should be consulted for evaluation of the energy supply system and it should be assessed whether wind turbines could be a supplement to the PV system. When more information is available about the system design, a detailed business plan should be developed. For proper distribution of the water it is crucial that the existing piping system is upgraded.

Hopefully, Ren-PEACE will be capable of collecting sufficient funds to initiate the project in Pozo Colorado. In April 2014, the organization applied for funding from the National Council of Science and Technology (CONACYT) in Paraguay for developing a research project about the desalination plant. Contacts already established at two of the universities in Asunción could be important for project implementation. Another essential factor is the willingness of the population in Pozo Colorado to introduce a new water supply system, which was high during the time of visit in January 2014. With this project, along with the work of Johannes Waatevik, the village is hopefully a step closer to project implementation and a safe and clean water supply. If all goes well in Pozo Colorado, the solution could be replicated in other areas. Hence, it could ensure the delivery of potable water to people living in rural parts of the Chaco and stimulate development and settlement in the region.

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Appendix A Pozo Colorado Data

About the district

Citizens: 17,727 in the district of Pozo Colorado (1,700 in the town Centre) [2]

Altitude: 97 m.

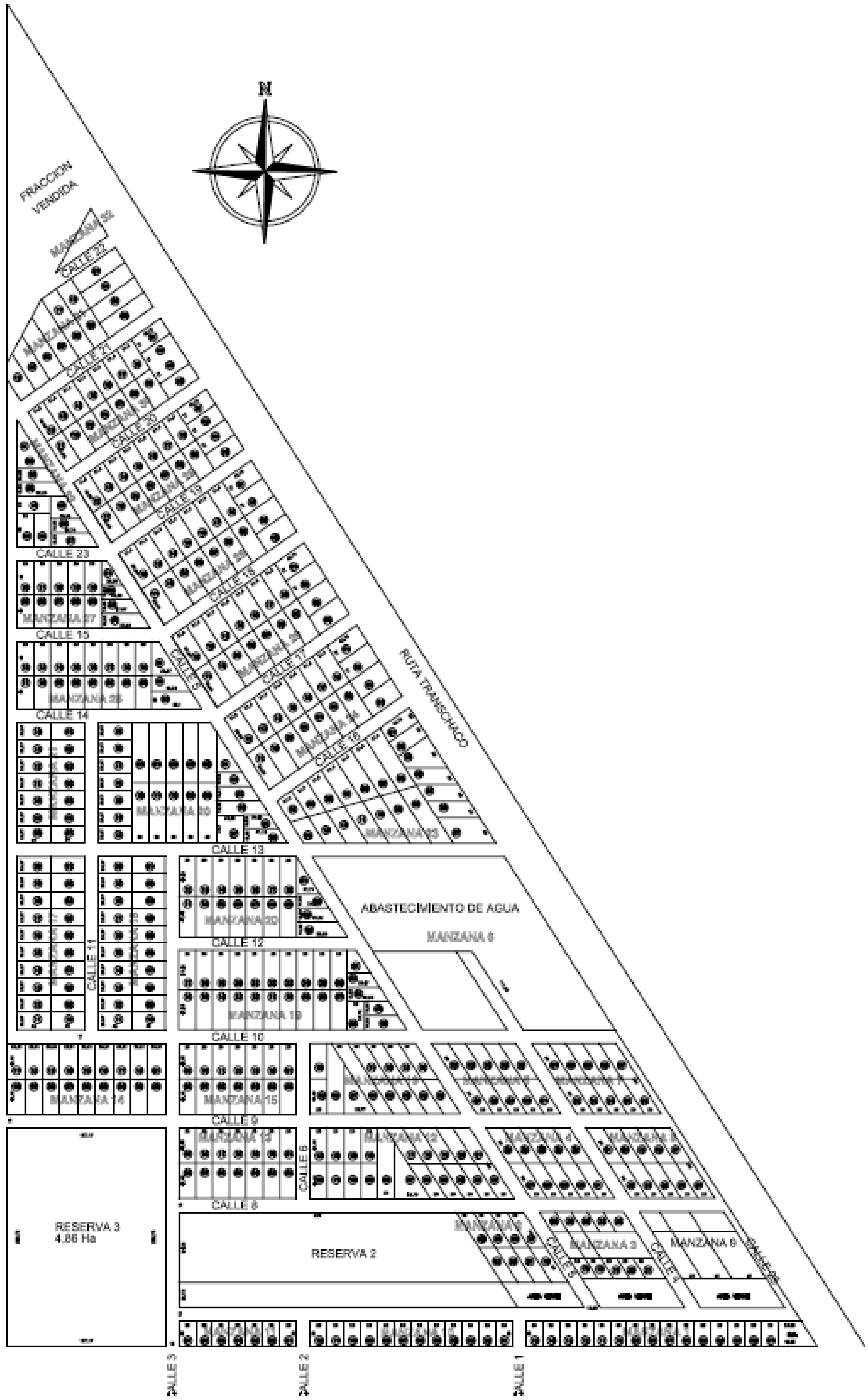
Latitude: -23.5

Longitude: -58.8 [16]

Irradiation data [16]

Month	**kWh/m^2/day**	**W/m^2**
January	6.62	275.8
February	5.94	247.5
March	5.38	224.2
April	4.31	179.6
May	3.51	146.3
June	3.06	127.5
July	3.46	144.2
August	4.17	173.7
September	4.84	201.7
October	5.58	232.5
November	6.25	260.4
December	6.57	273.8
Average	**4.97**	**207.1**

Town plan


N
FRACCION VENDIDA
RUTA TRANSCHACO
CALLE 23
MANZANA 27
CALLE 15
CALLE 14
CALLE 13
ABASTECIMIENTO DE AGUA
MANZANA 6
CALLE 12
CALLE 11
CALLE 10
CALLE 9
CALLE 6
CALLE 8
RESERVA 3
4,86 Ha
RESERVA 2
MANZANA 3
MANZANA 9
CALLE 3
CALLE 2
CALLE 1

Surface water properties and constituents (surface water collected in Pozo Colorado in January 2014 and analyzed at NTNU in February/March 2014)

Due to the state of the water sample at the time of analysis, only a few analyses could be conducted.

Dissolved organic carbon (DOC): 12.4235 mg/l

Total organic carbon (TOC): 14.8964 mg/l

Conductivity: 392 µS/cm at 21.8°C

Isotope	µg/l	Isotope	µg/l
Li7	*10.485*	Th232	*0.0135*
Be9	*0.031*	U238	*0.6617*
B11	*180.86*	Na23	*48,293*
Se82	*0.05*	Mg25	*7,700*
Y89	*0.326*	Al27	*171.15*
Zr90	*0.036*	Si29	*7,261*
Cd114	*0.01*	P31	*74*
Mo98	*0.991*	S34	*11,026*
Sn118	*0.005*	K39	*4 002*
Cs133	*0.0466*	Ca44	*20,076*
Ce140	*0.420*	Sc45	*0.008*
Pr141	*0.0489*	Ti49	*2.42*
Nd146	*0.2620*	V51	*6.821*
Sm147	*0.0755*	Cr52	*0.16*
Tb159	*0.0159*	Mn55	*98.707*
Dy163	*0.0738*	Fe56	*191.39*
Ho165	*0.0133*	Co59	*0.489*
Er166	*0.0356*	Ni60	*0.65*
Tm169	*0.0042*	Cu63	*1.26*
Yb172	*0.0229*	Zn66	*1.18*
Lu175	*0.0037*	Ga69	*0.083*
Ta181	*0.0002*	Rb85	*0.803*
Hf178	*0.0274*	Sr88	*199.35*
Ir193	*0*	Ag109	*0.003*
Pt195	*0*	Sb121	*0.394*
Au197	*0.0113*	Ba137	*30.34*
W182	*0.0308*	La139	*0.167*
Hg202	*0.008*	Ge72	*0.030*
Tl205	*0.0024*	As75	*11,713*
Pb208	*0.429*	Nb93	*0.006*
Bi209	*0.0082*		

Appendix B Economic Formulas

All formulas from [65]. In all formulas, n is year number and i is the interest rate.

If a cost is expected in the future, the net present worth of this cost can be calculated by multiplication with the present worth factor (PWF):

$$Present\ worth\ factor, PWF = \frac{1}{(1+i)^n}$$

If there are equal annual payments, the annual payment has to be multiplied by the compound amount factor to obtain the present value:

$$Compound\ amount\ factor, CF = \frac{1-(1+i)^{-n}}{i}$$

If the net present value of an investment is known, the equivalent annuity formula could be applied to show the investment as a series of equal cash flows for the length of the investment:

$$Equivalent\ annuity\ factor, AF = \frac{i}{1-(1+i)^{-n}}$$

Appendix C   Membrane Specifications

Data from [47]

Membrane: Hydranautics SWC4 +

Size (mm): 8.0 x 40

Flow Rate (gpd): 6,500

Rejection Rate: 99.8%

Pressure rating (PSI): 800

Appendix D PV System Sizing for Back-up Supply

Capacity of distribution pump: 2.2 kW

Estimated hours of operation: 9 h/d

Energy requirement: 19.8 kWh/d

Battery bank: Assume 1 day of autonomy. Applying equation (2.7.2) to find the capacity, C:

$$C\ [Ah] = \frac{19.8\ kWh \cdot 1}{0.7\ \cdot 12\ V} \cdot 1000 = 2{,}357\ Ah\ or\ 28.2\ kWh$$

To serve as a security of supply, it is assumed that the probability for an electricity outage is every 10 days. Hence, the battery bank can be charged from the PV system for 10 days (if it cannot be charged from the grid). This yields the daily energy requirement from the PV modules:

$$W_{daily} = \frac{28.2\ kWh}{10\ d} = 2.82\ kWh/d$$

The average peak sunshine hours for Pozo Colorado (6.18 h) were calculated by applying MATLAB to integrate the irradiation over a year from hourly irradiation data created synthetically in the software PVsyst, from “globirr2.txt”. This data was applied in [1] and is enclosed electronically to this thesis (MATLAB script presented below):

```
file=load('globirr2.txt');    % loading irradiation file
time = file(:,1);
irr = file(:,2);

y = trapz(time,irr);          % area below graph in Wh/m2

averageperday = y/365;    % average daily irradiation

hoursof1000Wm2 = averageperday/1000;    % hours of 100 W/m2 per day on average
```

With the peak sunshine hours calculated, applying equation (2.7.1) yields the PV module capacity:

$$\mathrm{P_{peak}} = \frac{2.82\ \mathrm{kWh/d}}{6.18\ \mathrm{h} \cdot 0.68} = 670\ \mathrm{W_p}$$

Appendix E HOMER Simulation Results Case 3

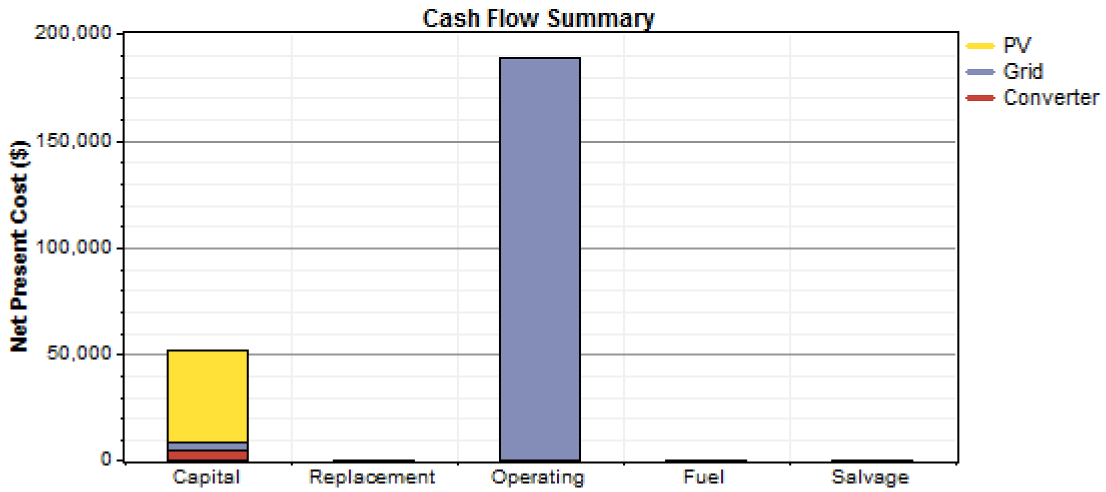
System Report - stage3_220414.hmr

System architecture

PV Array	20 kW
Grid	1,000 kW
Inverter	16 kW
Rectifier	16 kW

Cost summary

Total net present cost	$ 240,488
Levelized cost of energy	$ 0.097/kWh
Operating cost	$ 14,745/yr

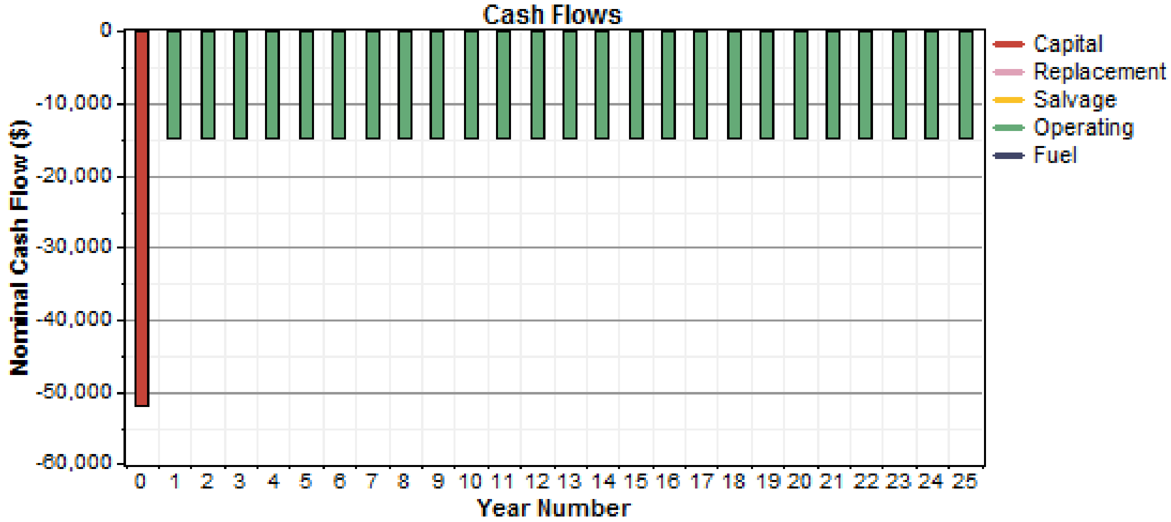


Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
PV	44,000	0	0	0	0	44,000
Grid	3,200	0	188,488	0	0	191,688
Converter	4,800	0	0	0	0	4,800
System	52,000	0	188,488	0	0	240,488

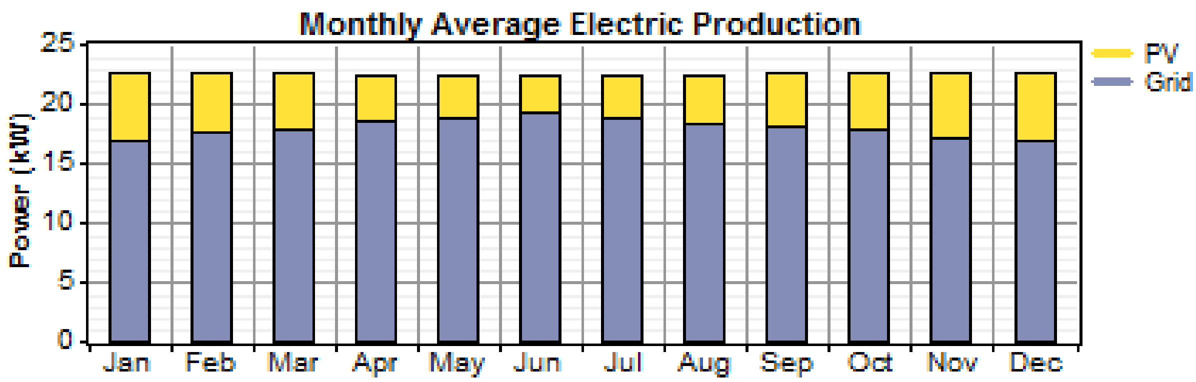
Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
PV	3,442	0	0	0	0	3,442
Grid	250	0	14,745	0	0	14,995
Converter	375	0	0	0	0	375
System	4,068	0	14,745	0	0	18,813



Electrical

Component	Production	Fraction
	(kWh/yr)	
PV array	39,405	20%
Grid purchases	157,858	80%
Total	197,263	100%



PV

Quantity	Value	Units
Rated capacity	20.0	kW
Mean output	4.50	kW
Mean output	108	kWh/d
Capacity factor	22.5	%
Total production	39,405	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	20.6	kW
PV penetration	20.4	%
Hours of operation	4,385	hr/yr
Levelized cost	0.0873	$/kWh

Converter

Quantity	Inverter	Rectifier	Units
Capacity	16.0	16.0	kW
Mean output	4.0	0.0	kW
Minimum output	0.0	0.0	kW
Maximum output	16.0	0.0	kW
Capacity factor	25.1	0.0	%

Quantity	Inverter	Rectifier	Units
Hours of operation	4,385	0	hrs/yr
Energy in	39,160	0	kWh/yr
Energy out	35,244	0	kWh/yr
Losses	3,916	0	kWh/yr

Grid

Rate: Rate 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	12,662	0	12,662	22	1,013	176
Feb	11,844	0	11,844	22	948	176
Mar	13,253	0	13,253	22	1,060	176
Apr	13,313	0	13,313	22	1,065	176
May	13,986	0	13,986	22	1,119	176
Jun	13,823	0	13,823	22	1,106	176
Jul	14,008	0	14,008	22	1,121	176
Aug	13,627	0	13,627	22	1,090	176
Sep	13,009	0	13,009	22	1,041	176
Oct	13,257	0	13,257	22	1,061	176
Nov	12,417	0	12,417	22	993	176
Dec	12,658	0	12,658	22	1,013	176
Annual	157,858	0	157,858	22	12,629	2,116

Appendix F PV Production and HOMER Simulation Results

Scenario 6

Assumptions:

- Average annual irradiation: 4.97 kWh/m^2/d [16]
- Energy demand: 2 kWh/m^3 of permeate produced, based on the energy consumption in Case 3 presented in section 5.5.1. This yields a demand of 590 kWh/d for a production of 295.2 m^3/d. With 90 % availability the production will be 266 m^3/d but the plant is designed according to 100 % availability.
- PV module efficiency : 15 % [33]

$$PV\ area = \frac{590\ kWh/d}{\frac{4.97\frac{kWh}{m^2}}{d} \cdot 0.15} = 791\ m^2$$

Simulation results from HOMER: Scenario 6

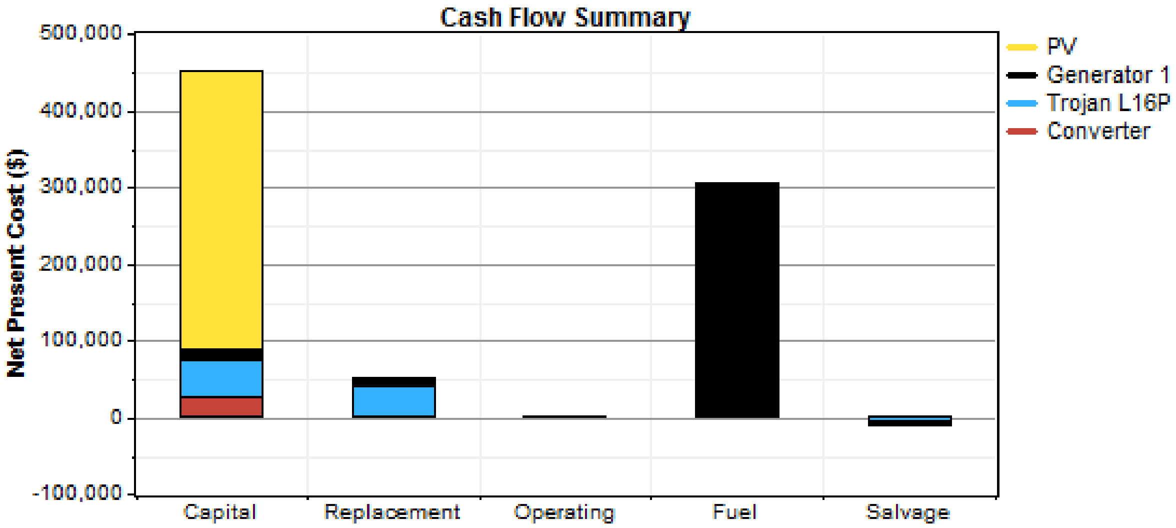
System Report - Case6_060514.hmr

System architecture

PV Array	166 kW
Generator 1	69 kW
Battery	40 Trojan L16P
Inverter	93 kW
Rectifier	93 kW
Dispatch strategy	Cycle Charging

Cost summary

Total net present cost	$ 801,087
Levelized cost of energy	$ 0.291/kWh
Operating cost	$ 27,205/yr

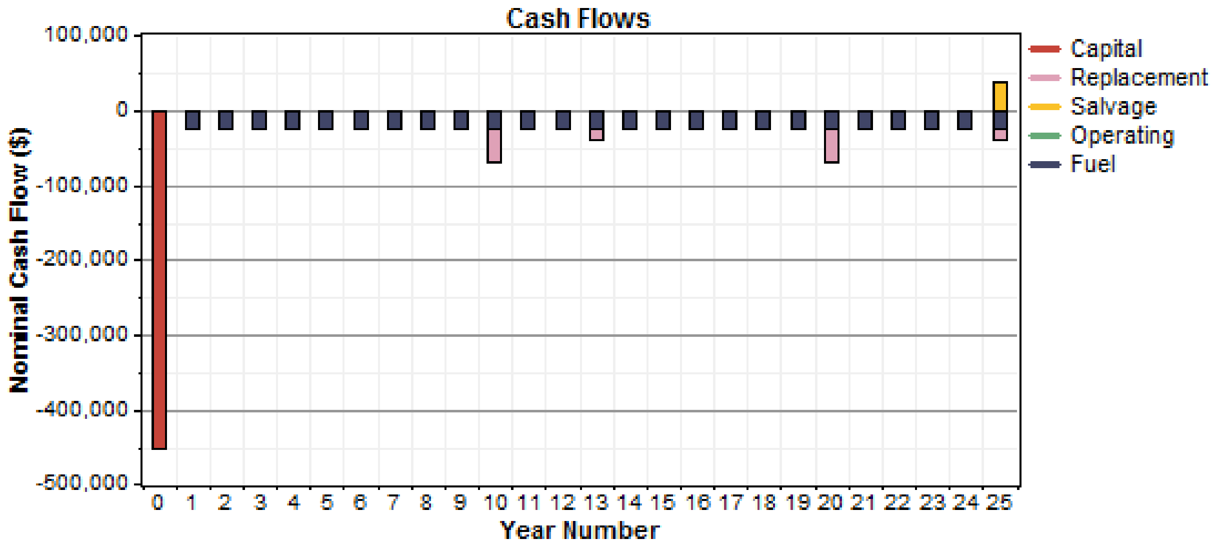


Net Present Costs

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	364,540	0	0	0	0	364,540
Generator 1	15,281	11,223	0	305,539	-3,365	328,678
Trojan L16P	45,600	39,681	0	0	-5,312	79,969
Converter	27,900	0	0	0	0	27,900
System	453,321	50,904	0	305,539	-8,677	801,087

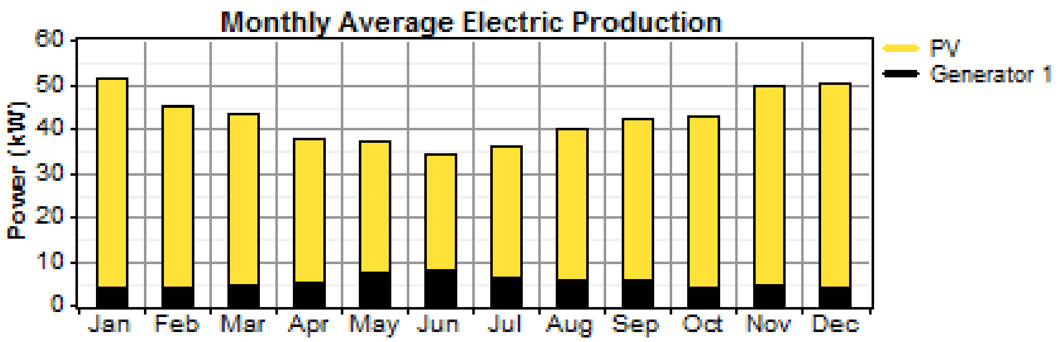
Annualized Costs

Component	Capital ($/yr)	Replacement ($/yr)	O&M ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	28,517	0	0	0	0	28,517
Generator 1	1,195	878	0	23,901	-263	25,711
Trojan L16P	3,567	3,104	0	0	-416	6,256
Converter	2,183	0	0	0	0	2,183
System	35,462	3,982	0	23,901	-679	62,666



Electrical

Component	Production (kWh/yr)	Fraction
PV array	326,469	88%
Generator 1	46,318	12%
Total	372,787	100%



Load	Consumption (kWh/yr)	Fraction
AC primary load	215,339	100%
Total	215,339	100%

Quantity	Value	Units
Excess electricity	138,332	kWh/yr
Unmet load	0.000114	kWh/yr
Capacity shortage	3.40	kWh/yr
Renewable fraction	0.785	

PV

Quantity	Value	Units
Rated capacity	166	kW
Mean output	37.3	kW
Mean output	894	kWh/d
Capacity factor	22.5	%
Total production	326,469	kWh/yr

Quantity	Value	Units
Minimum output	0.00	kW
Maximum output	171	kW
PV penetration	152	%
Hours of operation	4,385	hr/yr
Levelized cost	0.0873	$/kWh

Generator 1

Quantity	Value	Units
Hours of operation	1,233	hr/yr
Number of starts	384	starts/yr
Operational life	12.2	yr
Capacity factor	7.66	%
Fixed generation cost	8.19	$/hr
Marginal generation cost	0.325	$/kWhyr

Quantity	Value	Units
Electrical production	46,318	kWh/yr
Mean electrical output	37.6	kW
Min. electrical output	20.7	kW
Max. electrical output	69.0	kW

Quantity	Value	Units
Fuel consumption	18,386	L/yr
Specific fuel consumption	0.397	L/kWh
Fuel energy input	180,914	kWh/yr
Mean electrical efficiency	25.6	%

Battery

Quantity	Value
String size	2
Strings in parallel	20
Batteries	40
Bus voltage (V)	12

Quantity	Value	Units
Nominal capacity	86.4	kWh
Usable nominal capacity	60.5	kWh
Autonomy	2.46	hr
Lifetime throughput	43,000	kWh
Battery wear cost	1.150	$/kWh
Average energy cost	0.151	$/kWh

Quantity	Value	Units
Energy in	1,736	kWh/yr
Energy out	1,476	kWh/yr
Storage depletion	-7.18	kWh/yr
Losses	268	kWh/yr
Annual throughput	1,601	kWh/yr
Expected life	10.0	yr

Converter

Quantity	Inverter	Rectifier	Units
Capacity	93.0	93.0	kW
Mean output	19.3	0.0	kW
Minimum output	0.0	0.0	kW
Maximum output	84.3	4.7	kW
Capacity factor	20.8	0.0	%

Quantity	Inverter	Rectifier	Units
Hours of operation	3,267	37	hrs/yr
Energy in	188,305	140	kWh/yr
Energy out	169,475	119	kWh/yr
Losses	18,830	21	kWh/yr

Appendix G List of Files Enclosed Electronically in DAIM

File name	Type	Content
Costestimations	Excel file	Cost estimations of desalination system and energy systems
Electricitymarket	Excel file	Generation of synthetic hourly electricity costs data for 1 year for Paraguay
Loadprofiles	MATLAB script	Evaluation of optimal load profile
globirr2	Text file	Global irradiation values for Pozo Colorado, applied in MATLAB script
Hourlyprices_paraguay	Text file	Synthetic hourly prices imported in HOMER
Hourlyprices_paraguay_1.21multiplier	Text file	Syntethic hourly prices 21 % increase imported in HOMER

Appendix H Paper Presented at EVER Conference 2014

Title: “System Design and Load Profile Shaping for a Reverse Osmosis Desalination Plant Powered by a Stand-Alone PV system in Pozo Colorado, Paraguay”

Presented at the Ninth International Conference on Ecological Vehicles and Renewable Energies in Monte-Carlo, Monaco , 26th March 2014

2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER)

System Design and Load Profile Shaping for a Reverse Osmosis Desalination Plant Powered by a Stand-Alone PV System in Pozo Colorado, Paraguay

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***Abstract*— Groundwater is a common source of drinking water all over the world. In some places the groundwater resources are brackish, which means that it is of high salinity and undrinkable unless it is desalinated. Brackish Water Reverse Osmosis (BWRO) desalination is a method that can be applied to produce potable water from saline groundwater resources. This requires electricity to drive the high pressure pumps that enable reverse osmosis. In this article, a preliminary BWRO plant design for a village in Paraguay is presented, supplied by a stand-alone PV system with battery storage. The energy requirement of the desalination plant is estimated for sizing the power supply and storage systems. Two different load profiles are evaluated by simulations in PVsyst; the first scenario is based on constant load for maximum utilization of the membrane capacity, while the second scenario is based on partly adapting the load to the solar irradiation. The second scenario implies an increase of the plant size, since parts of the plant are stopped during nighttime, but allows for reducing the battery capacity since more of the energy for desalination is used when it is directly available from the PV system. The presented results demonstrate how system designs that allow for operation schemes with reduced freshwater production during the night will be economically beneficial due to a larger reduction in investment cost for battery storage than the cost increase due to larger membrane installation.**

Keywords*— *Brackish Water Reverse Osmosis, Stand-alone PV System, Load Profile, System Design

I. Introduction

Water is crucial for life and a basic need for all living creatures on Earth. However, with increased urbanization, population growth and climate change, water scarcity is a growing challenge in the world today. Lack of freshwater is also a problem in the Chaco, a region in the northern part of Paraguay in South America. This region occupies almost two thirds of the country's territory, but is only home to 2 percent of the population. This can partly be explained by an extreme subtropical climate and the lack of modern infrastructure, but above all it is the scarcity of potable water that impedes activities the area [1]. Pozo Colorado is a village in the Chaco, with 1,700 inhabitants. The village has groundwater resources, but the water is saline and undrinkable unless it is treated. The amount of total dissolved solids (TDS) in the water is around 15,000 mg/l [2], a very high level for brackish water, which by definition has a TDS between 1,000 and 15,000 mg/l [3]. According to World Health Organization [4], drinking water should have a TDS content below 500 mg/l. To obtain this, the brackish water has to go through a desalination process. Among the available desalination technologies, membrane processes are the most prevalent, and Reverse Osmosis (RO) is today the most common process. This is also the most energy-effective technique compared to other desalination processes [5], [6].

As the name implies, RO is when the natural process of osmosis occurs in the reverse direction. Desalination by RO is thus obtained by applying a pressure higher than the osmotic pressure to the water with the highest concentration of dissolved solids. A semi-permeable membrane is placed between the two compartments containing the solutions, which will let water and some ions flow through it, while it is impermeable to most dissolved substances. As a result of the pressure increase, water will flow from the solution with higher concentration of dissolved solids to the solution with lower concentration. As a consequence, there will be purified water on one side and there will be a concentrated solution in the other compartment [7]. However, not all of the fresh water can be recovered in the process due to risk of fouling in the membranes. Depending on the system configuration and the feed water salinity, between 65 and 85 % fresh water can be recovered in a RO process [8].

A brackish water reverse osmosis (BWRO) plant could be a solution for Pozo Colorado, to supply potable water to

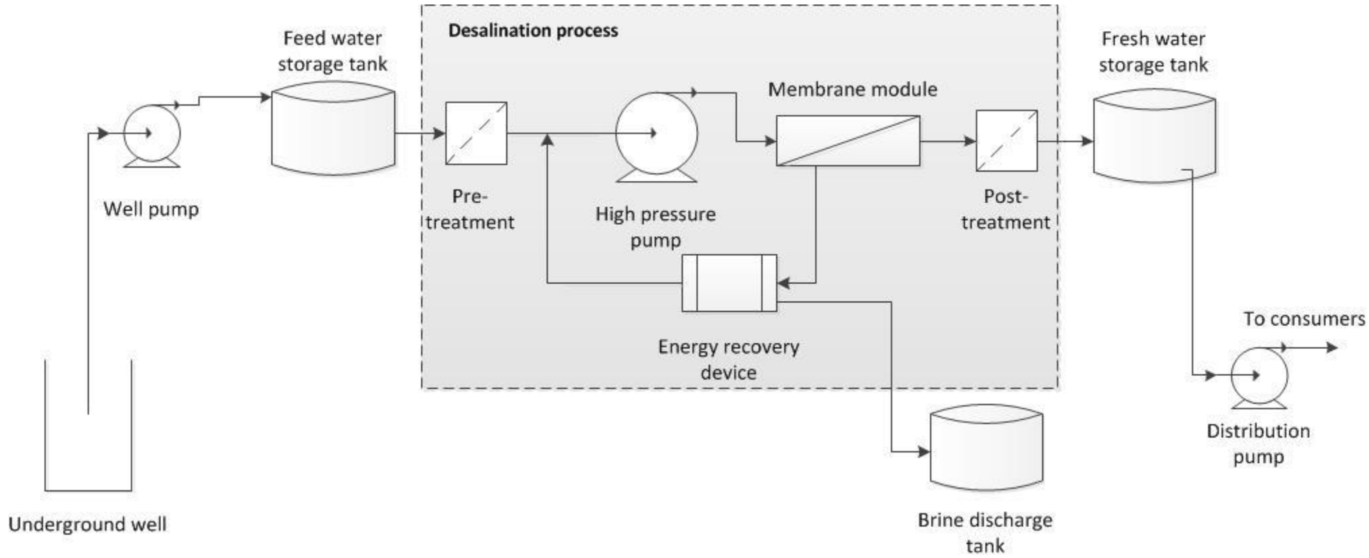

Fig. 1. Flow diagram for the BWRO plant in Pozo Colorado

the village. However, the process requires electricity, in particular to drive the high pressure pump that enables RO. Considering the limitations of the existing power distribution grid and the high levels of solar irradiation in the region, a stand-alone PV system could be a possible energy supply to the BWRO plant. There are already several existing BWRO plants supplied by PV worldwide [3], [9], [10]. In this article, the energy requirement for a BWRO desalination plant is evaluated for the fresh water demand in Pozo Colorado. A preliminary plant design is chosen and a stand-alone PV system is designed to supply the plant with energy. Next, two production scenarios are evaluated with respect to the amount of PV panels and batteries that are required for each case. The simulation tool PVsyst is used to consider the size of PV panels and batteries. Based on the simulation results, it is evaluated which scenario that is optimal when it comes to battery storage requirements, and a simple analysis of the investment costs is conducted to find the most cost-effective mode of operation.

II. Plant Configuration and power supply

For proposing a PV-based power supply system, a preliminary system design of the desalination plant, and an estimation of the energy requirements are needed, as will be outlined in the following.

A. *System configuration of the Desalination Plant*

The chosen design for the RO plant in Pozo Colorado is based on the system layouts presented in [3] and information provided by [11]. The flow diagram of the system is presented in Fig. 1, where the dashed line indicates the components that are part of the desalination process. The diagram shows that there are three pumping stages in the system; the well pump, the high-pressure pump for the RO process and a distribution pump. For the practical construction of the system, these pumping stages will most likely be based on several parallel pumps for improving system reliability, and the plant might also have several wells at some distance from each other. In the following, this will however not be considered in detail. As seen from Fig. 1, the system includes an energy recovery device to extract energy from the brine discharge stream, to reduce the overall energy requirement. A system without an energy recovery device would normally use two to three times more energy and this will increase for larger systems [3].

There are three storage tanks in the system; for feed water, fresh water and brine discharge. The size of the tanks is not considered here but there should be some extra available space for feed water and fresh water to allow for a varying production and consumption.

B. *Energy requirement*

For appropriate sizing of the desalination plant, the fresh water demand has to be estimated. Based on general information about average water consumption for rural villages, a fresh water demand of 150 l/person/day is estimated for Pozo Colorado [2], [12], [13]. This consumption is for purposes of drinking, cooking, personal hygiene and some watering. With 1,700 inhabitants the total demand is 255,000 l/day. Due to the high salinity of the feed water, a recovery rate of 70 % is assumed based on information from [8]. This requires 365,000 liters to be pumped from the underground well every day.

The high pressure pump for the RO process is the most energy intensive part of the system and dominates the energy requirement of the desalination plant. The energy that is needed depends on the salinity of the feed water, the temperature and the required quality of the produced fresh water. To be able to accurately determine the energy requirement for the RO process, a detailed water analysis

TABLE 1 FRESH WATER DEMAND AND ENERGY REQUIREMENT FOR THE RO PROCESS

Energy requirement for the RO process	3 kWh/m^3
Fresh water demand	255 m^3/day
Total energy demand, RO process	765 kWh/day

is necessary. Since such results have not yet been available for the particular site, assumptions are made on basis of information available from literature and from existing BWRO plants. In general, RO-based desalination of high salinity brackish water on a larger scale has energy consumption in the range between 2.2-2.6 kWh/m^3 [8]. Thus, a conservative energy requirement of 3 kWh/m^3 is assumed, considering the water salinity in Pozo Colorado is at a very high level for brackish water. This yields a total energy requirement of 765 kWh/day for a fresh water demand of 255 m^3/day. The rating of the desalination plant and its high pressure pump depends on the operational regime and will be further discussed in section III. The fresh water demand and energy requirement for the RO process are summarized in Table 1.

In addition to the high pressure pump, the system will include one or several well pumps that can supply the plant with feed water. A pump for distribution of the water will also be needed. The pump loads are estimated according to (1), where P is power in W, ρ is the density of water in kg/m^3, g is the gravitational constant in m/s^2, Q is the water flow in m^3/s and η_p is the pump efficiency [14]. H is the total dynamic head in meters, which is a sum of the static head H_s and the friction losses H_f in the pipes.

$$P = \frac{\rho g Q H}{\eta_p} \tag{1}$$

Head loss due to friction in the pipes is calculated from the Darcy-Weisbach equation[1]. For the well pump, a constant water flow of 365 m^3/day and a static head of 18.3 m [2] is assumed, while the tank is considered to be 2 m above ground level, resulting in a static head of 20.3 m. With an average pump efficiency of 75 % [14], and considering some additional losses of inlet filters in the pipes, the well pump is estimated to require 1.2 kW. For the distribution pump, only friction losses according to the Darcy-Weisbach equation[1] are assumed, considering an average pipe length of 400 m and a flow of 255 m^3/day. With the same assumptions regarding efficiency and additional losses as for the well pump, this results in a load of approximately 1 kW.

[1] Darcy-Weisbach equation for friction losses: $H_f = f\frac{L}{d}\frac{v^2}{2g}$, where f is Darcy's friction factor depending on the flow and the roughness of the pipe, L is the length of the pipe in m, V is the fluid velocity in m/s, d is the pipe diameter in m and g is the gravitational constant in m/s^2. In the calculations it is assumed a diameter of 0.15 m, a water velocity of 0.238 m/s from a constant water demand for the well pump, and a water velocity of 0.17 m/s for the distribution pump. It is assumed that there are smooth pipes. The pipe length is assumed to be 30 m for sizing of the well pump and 400 m for sizing of the distribution pump.

TABLE 2 OTHER ENERGY CONSUMING UNITS AND ASSOCIATED LOAD

Well pump	1.2 kW
Distribution pump	1 kW
Technical office	2 kW
Total	**4.2 kW**

A technical office is also necessary to house the desalination units and equipment for control and monitoring of the process. Based on adjustment of the feasibility study of a BWRO plant for Pozo Colorado, in [2], a constant load of 2 kW is assumed for the technical office. The energy consuming units are summarized in Table 2.

C. Power Supply

A possible layout of the stand-alone solar PV system that could supply the BWRO plant with energy is illustrated in Fig. 2. The system has a common DC-bus at 600 V, feeding dedicated Voltage Source Converter (VSC) variable speed drives for the main pump loads and for supplying AC power to the technical office and the distribution pumps. The main pumps are assumed to be rated for 3-phase 400 V RMS voltage, while the technical office and the distribution pumps are supplied by single-phase 230 V RMS. A battery bank is included in the system for storage, to supply the system with energy when there is not sufficient production from the PV panels, or to be charged when production is higher than consumption. The charge controller prevents the batteries from being overcharged or too heavily discharged. The PV array is connected to the DC-bus through a DC-DC converter with a maximum power point tracking (MPPT) algorithm. A diesel-generator for back-up power could be connected to the system, or there could be a connection to the local distribution system for the same purpose, but details on back-up power supply is not further considered.

III. LOAD SHAPING FOR THE DESALINATION PLANT

One of the most important issues to consider when designing an isolated micro-grid is the load profile. For a PV-based system, the power rating of the solar panels and the battery storage capacity are dependent on the energy demand and the variation throughout the day. To minimize the storage requirements, the load should therefore preferably operate only when irradiance is available from the sun. This might, however, not be compatible with the load requirements. Thus, it is essential to consider if the system components are capable of adapting to a variable production when determining a load profile.

A. General considerations on the BWRO load profile

For the high pressure pumps of the RO desalination, a variable speed drive can be used to adjust the pressure and

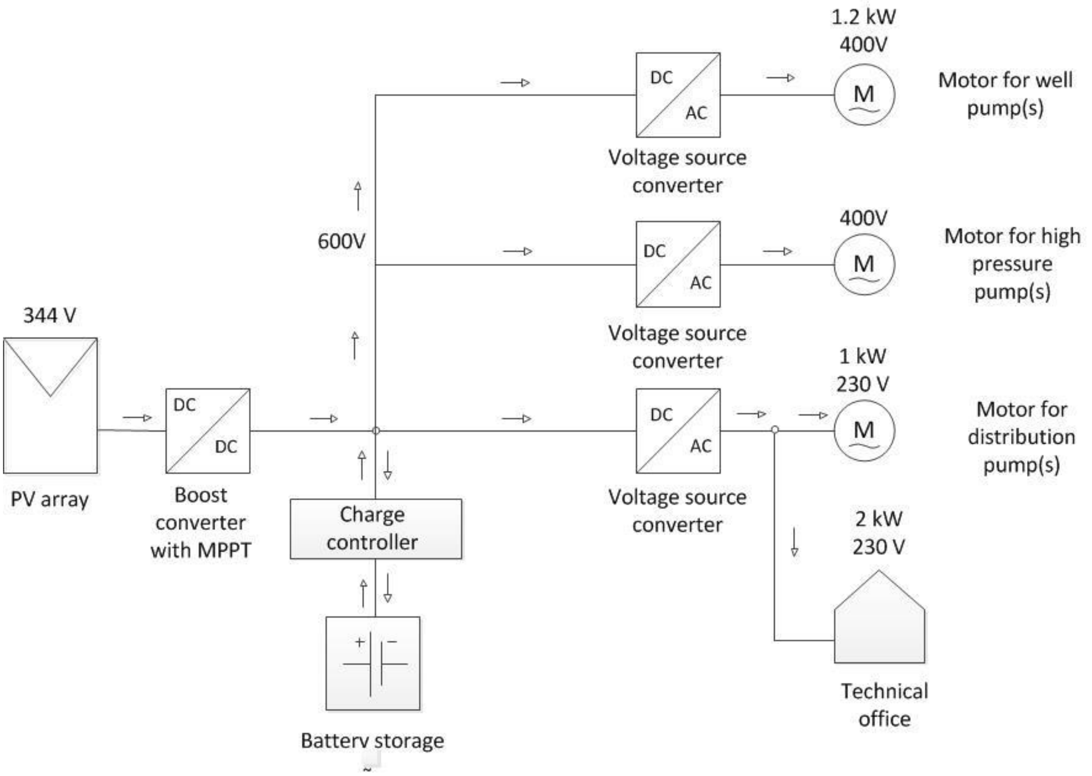

Fig. 2. Configuration of stand-alone solar PV system as energy supply for the BWRO plant in Pozo Colorado

flow of the system, and by that allow for a variable production [15]. For the membranes, it is however not desirable to have a varying flux outside the operation point they are designed for. Thus, significant variations in load can cause lower water quality and reduce the lifetime of the membranes [11]. Rather than reducing the production rate of each membrane during the night and when fresh water demand is low, it would therefore be preferable to shut down parts of the plant. If the plant consists of two or more trains of membranes with one high pressure pump each, one or more membrane trains could be shut down while others are kept in operation. It is then necessary to flush the membranes with fresh water from the production train in operation within the first five to ten minutes after shutdown [11]. Considering a design with two equal membrane trains and reduced production during nighttime, each part of the plant could then be shut down interchangeably every second night, or when demand is lower. This procedure would enable a variable production rate without significantly compromising the membrane lifetime.

The distribution of the solar irradiation has to be considered when determining the most suitable load profiles for the system. Between 8 am and 5 pm the solar irradiation is at its highest at the investigated site [16], and considering a varying load profile, the freshwater production should be at maximum during this timeframe.

In the following, two different scenarios are evaluated; one where production is constant throughout the day and one where production is reduced to half during the hours with little or no solar irradiation.

B. Case 1

In the first case, the desalination plant operates continuously and produces fresh water at a constant rate for 24 hours per day. Hence, this case allows for maximum utilization of the membranes. With a specific energy consumption of 3 kWh/m^3 and a freshwater demand of 255 m^3/day, this requires a rating of the high pressure pumps of P_{pump} = 32 kW. Assuming 2 equal high pressure pumps for improved reliability, each of them must be rated at 16 kW. For this case, the well pump and the distribution pump are also assumed to operate continuously with loads of P_{well} and P_{dist} respectively. However, the distribution pumps would probably operate with a variable load depending on the freshwater demand throughout the day, but considering its low contribution to the total energy demand, a constant load is assumed as a conservative assumption with respect to the energy storage requirements. The technical office is in full operation all the time with a load of P_{tech}, due to the constant need for surveillance and control of the desalination plant. The total constant load for this scenario as expressed by (2) adds up to 36.2 kW and the daily energy requirement is 869 kWh/day.

$$P_{Case1} = P_{well} + P_{pump} + P_{dist} + P_{tech},\ \forall\ 0 < t \leq 24 \tag{2}$$

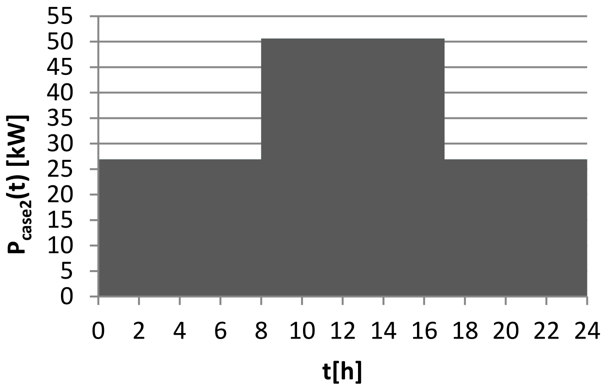

Fig. 3. Load profile for Case 2

C. Case 2

In the second investigated case, fresh water production is reduced to half during the hours of little or no solar irradiation. This implies that only 50 % of the membranes are operating during these hours and are not fully utilized at all times. Compared to Case 1, the two high pressure pumps have to be of a larger size to enable this production scenario. To produce 255 m^3/day, each high pressure pump will require 23.2 kW. As mentioned in section III.A, the period of the day with the highest solar irradiation is between 8 am and 5 pm, and the total load will be 50.6 kW during these 9 hours when solar energy is most available. The load will then be reduced to 26.8 kW during the remaining 15 hours, when one of the membrane trains is out of operation. As for Case 1, the well pump and the technical office operate continuously. The distribution pump is for simplicity assumed to operate at half of the load between 5pm and 8am, due to the reduced water demand during nighttime. In total the energy requirement for this scenario is 859 kWh/day. The load profile for Case 2 can be expressed by (3) and is illustrated in Fig. 3.

$$P_{Case2} = \begin{cases} P_{well} + \dfrac{P_{pump}}{2} + \dfrac{P_{dist}}{2} + P_{tech}, \forall\ 0 < t \le 8 \,\&\, 17 < t \le 24 \\ P_{well} + P_{pump} + P_{dist} + P_{tech}, \forall\ 8 < t \le 17 \end{cases} \quad (3)$$

IV. Simulation Results

The simulation software PVsyst was applied to appropriately size the PV array and the battery storage according to the energy needs [17]. Incorporated in the program are a series of algorithms that leads to a PV system design. The peak power, *P*, of the PV array is in general sized according to (4), although additional loss factors are included in the simulation program. In (4), *W* is the average daily energy consumption in kWh, *PSSH* is the average peak sunshine hours per day, F_{th} is the thermal efficiency of the PV array and η_{inv} is the efficiency of the inverter. For the simulations it is assumed that there is no shading of the PV panels.

$$P = \frac{W}{PSSH \cdot F_{th} \cdot \eta_{inv}} \quad (4)$$

The capacity of the battery bank, *C*, is in PVsyst estimated according to (5), where *W* is still the daily energy consumption, A is the number of autonomous days, SOC_{min} is the minimum allowable State of Charge (SOC) relative to the total storage capacity of the battery, *U* is the nominal voltage of the battery, and η_b is the battery efficiency:

$$C = \frac{W \cdot A}{SOC_{\min} \cdot U \cdot \eta_b} \quad (5)$$

TABLE 3 PARAMETERS USED FOR SIMULATIONS IN PVSYST

Parameter/component	Chosen value/type
Azimuth angle	0°
Panel tilt	4° for summer, 40° for winter
Autonomy time	1 day
Loss of load probability	5 %
Battery	Lead-acid, vented, 12 V
PV module	Polycrystalline, 580 Wp
Converter	MPPT

A. Simulation parameters

The two cases explained in the previous section have been simulated in PVsyst to be able to evaluate the required combination of PV panels and batteries for the different load profiles. Monthly solar irradiation data for Pozo Colorado was obtained by PVsyst from the NASA webpage [16], and hourly data was created synthetically in the program. A default value of 5% for the loss of load probability was used for the simulations. The panel tilt, the autonomy time of the system, the battery type, the PV cell type and the type of converter also had to be defined. The chosen parameters and components are summarized in Table 3.

In both investigated scenarios, the sizing of the stand-alone system is performed so that the load is fully covered, or close to fully covered, during the summer months when irradiation levels are high. This is to avoid oversizing the system, and it is assumed that the remaining energy can be supplied by another source when irradiation is low during the winter months.

B. Case 1

When production is constant throughout the day, a large battery bank will be necessary to supply energy to the plant for hours of little or no solar irradiation. The total energy requirement is approximately equal for both scenarios, which indicates that the power rating of the solar panels will be almost identical. The simulation results from Case 1 are summarized in Table 4. A total of

TABLE 4 SIMULATION RESULTS, CASE 1

	Simulation result
PV modules	**5 in series x 110 in parallel = 319 kWp**
Batteries	**28 in series x 11 in parallel = 3,256 Ah or 1,094 kWh**
Loss of load time fraction	**4.4 %**
Missing energy	**4.8 %**
Direct use	**33.7 %**
$E_{supplied}/E_{load}$ average	**95.4 %**

TABLE 5 SIMULATION RESULTS, CASE 2

	Simulation result
PV modules	**5 in series x 110 in parallel = 319 kWp**
Batteries	**28 in series x 9 in parallel = 2,664 Ah or 895 kWh**
Loss of load time fraction	**4.9 %**
Missing energy	**4.6 %**
Direct use	**43.9 %**
$E_{supplied}/E_{load}$ average	**95.6 %**

319 kW peak of solar PV modules and 1,094 kWh of battery storage is found to be necessary. This covers the load fully in September and November, and the load is close to being fully covered in January-April and in October. In May-August, the energy shortage is higher due to lower solar irradiation, and also December has a low rate of coverage. The loss of load time fraction is 4.4 %, which indicates that the demand is not met for 4.4 % of the time. 4.8 % of the energy is missing and only 33.7 % of the energy is used directly, which implies that 66.3 % of the utilized energy is stored in the battery before it is used. Overall 95.4 % of the demand is met by the combination of the PV panels and the battery storage on average per year.

C. *Case 2*

When production is lowered during nighttime, the battery requirement will naturally be lower because there is more direct use of the energy from the sun. In this scenario, the simulation yields the same power rating for the PV modules as in Case 1, however only 895 kWh of battery storage is required. The relationship between supply and demand is approximately the same as for Case 1. The loss of load time fraction is 4.9 % and the missing energy is 4.6 %. Compared to Case 1, the direct use of solar energy is higher, being 43.9 %. This is due to the higher production during the hours of higher solar irradiation. Overall 95.6 % of the demand is met on average per year. The simulation results from Case 2 are summarized in Table 5.

V. DISCUSSION

The load profiles that are used in this article indicate the approximate energy requirement for producing 255 m^3 of fresh water per day in Pozo Colorado by applying BWRO desalination. From the simulation results it is confirmed how less battery storage is required when fresh water production is lowered during nighttime. Thus, for the specified Case 2, more of the solar energy is used directly to operate the desalination plant without being stored in the batteries, compared to Case 1 with constant load. This is beneficial since some of the conversion losses from charging and discharging the batteries are omitted, and since the required investment in battery storage is reduced. The required PV array capacity is however equivalent for the two scenarios, due to the very similar energy demand. Thus, the load profile will have little influence on the size and the investment cost for the PV system, but significant influence on the cost of the battery storage.

TABLE 6 NET PRESENT COST (NPC) OF MEMBRANES AND BATTERY STORAGE IN CASE 1 AND CASE 2 (15 YEARS PERIOD OF ANALYSIS)

	NPC Case 1 (US$)	NPC Case 2 (US$)
Filmtec BW30-400 membranes	12,008	17,154
Lead-acid battery storage	664,772	543,808
Total NPC (US$)	**676,730**	**560,962**

From the presented case descriptions, it should be clear that the required area of the RO membranes will highly depend on the operational regime of the plant. If there is a high production rate during a short period of the day, a larger membrane area will be necessary for the same daily production than if production is lower and more evenly distributed over each 24 hour period. Hence, a larger membrane area is necessary in Case 2 than in Case 1. It is evident that there will be a difference in system costs in the two cases and a cost comparison of the two production scenarios is therefore relevant when determining the most optimal mode of plant operation. In addition to membrane area, the size of system components like pumps and motors will be affected by the operational regime. This is however considered to represent a minor contribution to the total costs compared to the PV, battery and RO membrane installations. Since the rating of the PV panels are almost identical in the two investigated cases, it can therefore be sufficient to consider the size and cost of the RO membranes and the battery storage for identifying the most cost-effective system design. Thus, the net present cost (NPC) of membranes and battery storage for the two production scenarios is presented in Table 6, considering a period of analysis of 15 years. It is assumed a price of $150/kWh for lead-acid batteries [18], [19], and the chosen membrane units has a price of $629.99/unit and a permeate flow of 1.67 m^3/h [20]. A lifetime of 5 years is assumed for the membranes [8] and it is estimated that the batteries can withstand 1,100 cycles which yields a lifetime of approximately 3 years. For the calculations, a rate of return of 6 % is applied. Installation and maintenance costs are not considered and neither are costs of other system components, as they are expected to have limited influence on the total system cost.

As can be seen from Table 6, the NPC for Case 2 is significantly lower than for Case 1. This clearly shows that it is beneficial from an economic perspective to shape the load profile to correspond more closely to the solar irradiation. Thus, further investigations on how the RO process can be operated with variable load without compromising the lifetime of the membranes will be relevant for studies on how the total cost of the system can be minimized. The sizes of motors, pumps and other system components will also be affected by the production rates, and have to be included if a full financial analysis is to be conducted.

VI. Conclusion

A possible system design for a BWRO desalination plant powered by a stand-alone PV system with battery storage has been studied for Pozo Colorado in Paraguay. The investigation has been based on estimates for the total fresh water demand, which has been used to determine the total energy requirement of the plant. Two different production scenarios for the desalination plant have been evaluated; one scenario where production is constant throughout the day and another scenario where production is reduced during nighttime. From simulations in the software PVsyst the required rating of PV panels and batteries have been estimated for both cases. It was shown how the size of the battery bank can be considerably reduced if there is higher production during hours with available solar irradiation. A simple cost analysis has also shown that this can lead to significant reductions in investment costs for the overall system, even if larger rating of the RO membranes is required.

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