TECHNO-ECONOMIC FEASIBILITY OF RENEWABLE BASED WATER PURIFICATION SYSTEM FOR ISOLATED AREAS

by

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DECLARATION

I, ETIENNE KABIPANGI KAYEMBE, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

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ABSTRACT

Potable water is an essential commodity for human beings. A typical individual requires at least 2 litres of potable water daily for drinking purposes. Yet, one of the most significant challenges facing the world today is currently confronted with is the shortage of potable water sources. Decreased rainfall, population growth, and industrial development are factors that have led to a rapid increase in the pressure on existing water supplies worldwide. In recent years, desalination systems have been used to produce high-quality fresh water from brackish water and seawater. The reverse osmosis process represents an emerging water treatment technology. At present, compared with the traditional distillation process, the recently developed technology is improving the competitiveness of the reverse osmosis process. This study deals with the techno-economic feasibility of a renewable-based water purification system to assess the system technical characteristics and the system costs for providing drinkable water to some portion of the population in a remote farming area of the Mbhashe municipality in the South African province of Eastern Cape.
Furthermore, the investigation aims to determine the size of components involved in the reverse osmosis process and the size of the renewable power system feeding the plant. The techno-economic assessment is carried out in two stages; the first step consists of designing the reverse osmosis water purification system based on the population water requirement. The next stage focuses on the feasibility of the renewable power system to meet the reverse osmosis process power requirement. The results obtained in both stages show that to meet the demand for water of 56000 inhabitants, the plant must be characterized by a design product flow rate of 250 m^3 per hour, an overall membrane area of 10417 m^2, a feed-in pressure of 19.14 bar, and a specific energy per volume of water produced of 1 kWh per m^3. In addition, the plant must receive its power from a 1250 kW photovoltaic system with a 2408 kWh battery bank.

Furthermore, the capital cost of the reverse osmosis water purification plant is approximately US$ 2626745.0265, while the photovoltaic plant capital cost is 2,6 million.

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DEDICATION

To my lord and saviors, Jesus Christ, for the many blessings undeservingly bestowed upon me.

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GLOSSARY

WHO : World Health Organization
UNICEF: : United Nations International Children’s Emergency Fund
MDG : Millenium Development Goal
US : United State
GDP : Gross Domestic Product
SADWAF : South African Department of Water Affairs and Forestry
PPPs : Public–private partnership
PWh : Penta watt hour
IRENA : International Renewable Energy Agency
LCOE : Levelized Cost of Energy
KWh : kilo watt hour
kW : kilowatt
W : watt
mg/L : milligram per liter
m^3 : cubic meter
ρ : volumic mass
g : gravitational acceleration
kg : kilogram
m per s^2 : meter per second square
DC : Direct Current
AC : Alternative Current
Mpa : Mega pascal
M : meter
mm : millimeter
V : Volt
UV : Ultraviolet
OH : Hydroxyl
PCA : Principal component analysis
UN : United Nation

FAO : Food and Agriculture Organization

WISA : Water Institute of Sourthern Africa

GVA : Gross Value Income

PV : Photovoltaic

CHAPTER ONE
INTRODUCTION

1.1 Introduction

Water is an essential commodity that living creatures, including plants, animals, and human beings, need to survive. It plays a crucial role in balancing the bond between all living organisms by contributing to plants' growth, photosynthesis, greenhouse effect, global wind patterns, etc. According to international geological surveys, around 71% of the earth's surface is covered by oceans, accounting for 96.54% of all water on the planet, which is entirely undrinkable due to salt. The rest of the 3.46% of earth's water is at icebergs, groundwater, lakes, soil water, atmosphere, etc. Among them, only 1.42% is drinkable water that could be used to survive the living beings. Only less than 1% of earth's water can be quickly accumulated as the primary source of freshwater for humans' survival. Because of the worldwide rapid population growth and industrialization, freshwater sources' availability reduces day by day. More than 3 billion people suffer from some form of water shortage; a quarter of people live in places where water is scarce. More than one billion people live in areas where water is economically scarce or usable, but the industry lacks treatment. Worldwide, 748 million people do not have access to water, and 842,000 people lose their lives every year. Of these, 82% live in rural areas of the world, and only 18% live in urban areas. For example, in Africa, 325 million people do not have access to clean water because most water sources contain large amounts of soil sediment, human excreta, and chemical pollutants (Wandiga, 2015). These water sources are from the continent's 63 shared water basins, six significant aquifers, and more than 160 inland lakes more massive than 27 km (WHO & Unicef, 2014), as depicted in Figure 1.1. Africa's water availability is not evenly distributed; for instance, the Central Africa tropical region has 50.66 % available water, while Northern Africa has only 2.99 %. Climate variability and climate change have contributed significantly to water scarcity and non-availability. Therefore, Africa relies heavily on its groundwater, representing only 15 % of total renewable water resources that supply about 75 % of its population with drinking water.

Drinking water originates either from the ground or on the surface; however, it contains sediments and some other particles no matter where it is extracted. A purification process is required to remove those sediments and particles into water.

Scientists and researchers have developed various water purification strategies for different purposes by examining untreated water's significant constituents and physical characteristics. Considering the treatment method, water's physical, chemical, and microbiological characteristics should be analyzed. After the analysis, the appropriate strategy of water purification can be developed. Water purification is generally carried out through filtration, coagulation, constituents, major inorganic flocculation, adsorption, and clarification. Compound processes such as aeration, sedimentation, and softening chlorination, oxidation, disinfection are also used.

Lack of clean drinking water and lack of basic sanitation facilities are the leading causes of many water-related diseases. There are many reasons for water-borne diseases due to the intake of non-drinking water from surface water sources. In these cases, renewable energy water treatment systems may benefit areas lacking power grids and sanitary drinking water centers and will be an excellent independent solution to this problem (Richards & Schäfer, 2010). The system also has the dual advantage that clean drinking water will improve the quality of life, while renewable energy will reduce fossil fuels (Phuangpornpitak & Katejanekarn, 2016).

There are a variety of technologies that can combine renewable technologies with water purification units. These technologies include photovoltaic-powered reverse osmosis, wind-powered reverse osmosis, photovoltaic-powered ultraviolet disinfection, and solar photocatalysis, which use sunlight and reusable reaction media and titanium dioxide to discharge groundwater pollutants (Park et al., 2011; Forstmeier et al., 2008). Another configuration might include photovoltaic-powered pumps with ultrafiltration membrane devices (Houcine et al., 2006; Vivar et al., 2012; Vivar et al., 2010). This type of system can be simple, compact, and easy to operate. Figure 1.1 shows the photovoltaic pump design and membrane-based water purification device. The system can include ultrafiltration membranes, photovoltaic panels, photovoltaic pumps, and water storage systems. This type of technology can be used where surface water is available; however, it is unsafe to drink.

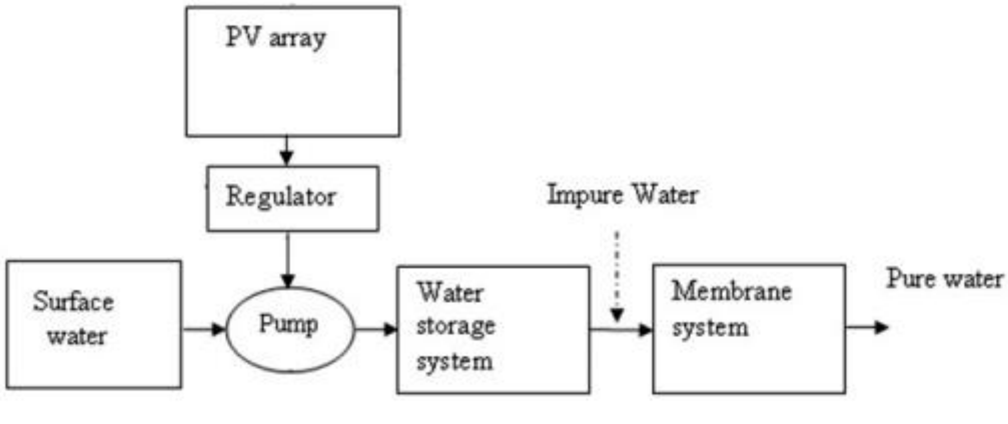


Figure 1. 1: Layout of photovoltaic-powered water purification unit (Phuangpornpitak & Katejanekarn, 2016)

When considering the provision of drinking water for non-water households and communities, administrative authorities must address the following issues:

- There is water available (not necessarily safe) near the town. This may require mapping homes and communities and understanding the source of the water, the way
- delivers this water to people, the locally available energy resources and technology needed,
- and the options available to purify the water and make it safe are consumption.

1.1.1 Africa's Current Water Situation

Surface water resources in Africa meet the daily water needs of 173 million people. However, the continent has large deserts, arid and semi-arid lands (Wandiga, 2015). It has 15% of the world's population and only 9% of its renewable water resources. In arid regions of Africa, water sources come mainly from groundwater, sandy beds of perennial rivers, spring water, and man-made dams and ponds (Wandiga, 2015). The source of drinking water is most wells (24%) in rural areas, which are increasingly unreachable (Wandiga, 2015). Tap water (39%) in urban areas mainly supplies the middle and upper classes. Approximately 37% of people use unpurified water for drinking, leading to diarrhea and other water-related illnesses (Wandiga, 2015). Figure 1.3 shows an example of water resources in Africa.

According to the World Bank, in 2012, except for sub-Saharan Africa, the rest of the African continent is expected to achieve water resources goals. In 2005, approximately 58% of the population in sub-Saharan Africa accessed safe and drinking water. Achieving Millennium Development Goal 7 (MDG7) will be a huge economic benefit, mainly due to time savings and health benefits. The "African Water Vision 2025", which aims to address water issues in Africa, summarizes the following important obstacles (African Studies Centre Leiden, 2012):

1. *High spatial and temporary changes in rainfall*

The annual average precipitation figures are the same as those of other continents, but the evaporation rate in Africa is much higher, and precipitation is unusually variable and inconsistent.

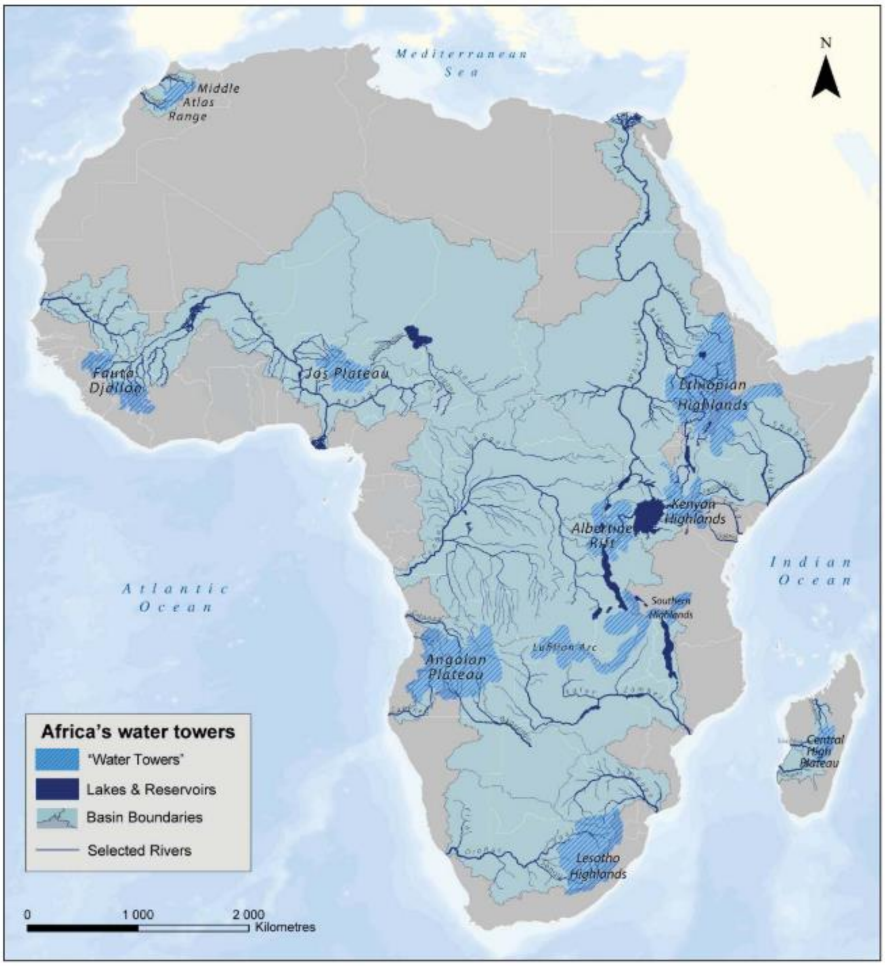


Figure 1. 2: Map of Africa's water resources (UNEP, 2006)**.**

Figure 1. 3: Africa water sources examples (Ahuja et al., 2015)**.**

2. *The developing water shortage*

   By 2025, 25 African countries will face water shortages, compared with 13 in 1995.

3. *Insufficient institutional and financial arrangements*

   There have been controversies about the management and commercialization of water as an economic product and decentralized community management and water as human beings.

4. *Insufficient data and staffing*

   The collection, evaluation, and dissemination of data on water resources are insufficient to formulate, plan, and implement complicated initiatives.

5. *Insufficient development of water resources*

   The scarcity of water resources in Africa is caused by natural phenomena and the low development and development of water resources. Only 3.8% of internal renewable resources are used for the three main water uses, including agriculture, community water supply, and industry.

6. *Water resources depletion caused by human activities*

   The factors leading to water shortage include:

   - stream pollutions caused by agricultural and industrial activities,
   - salinization caused by excessive pumping,
   - dry wetlands, eutrophication of lakes,
   - and the spread of invasive aquatic plants

   By 2025, at least 25 of the 48 countries expected to face water shortages are in Africa (Figure 1.4). This means that approximately 230 million Africans (16% of the estimated population) may live in water-scarce areas (less than 1,000 cubic meters of water per person per year), and another 460 million people (32%) live in water-scarce areas (1,000 to 1,700 cubic meters per capita per year) (African Studies Centre Leiden, 2012). In addition to population growth, agriculture also requires additional water supply requirements. Of the total water consumption, 85% is used for agriculture, 9% is used for community water supply, and 6% is used for industry. Political, economic, and institutional factors often lead to water scarcity, even in areas where resources are often quite abundant (African Studies Centre Leiden, 2012). Industrial exports to agriculture lead to the depletion of water resources. This represents another aspect of the coin of some of the latest stories of economic achievement in Africa, with virtual water flowing to other regions.

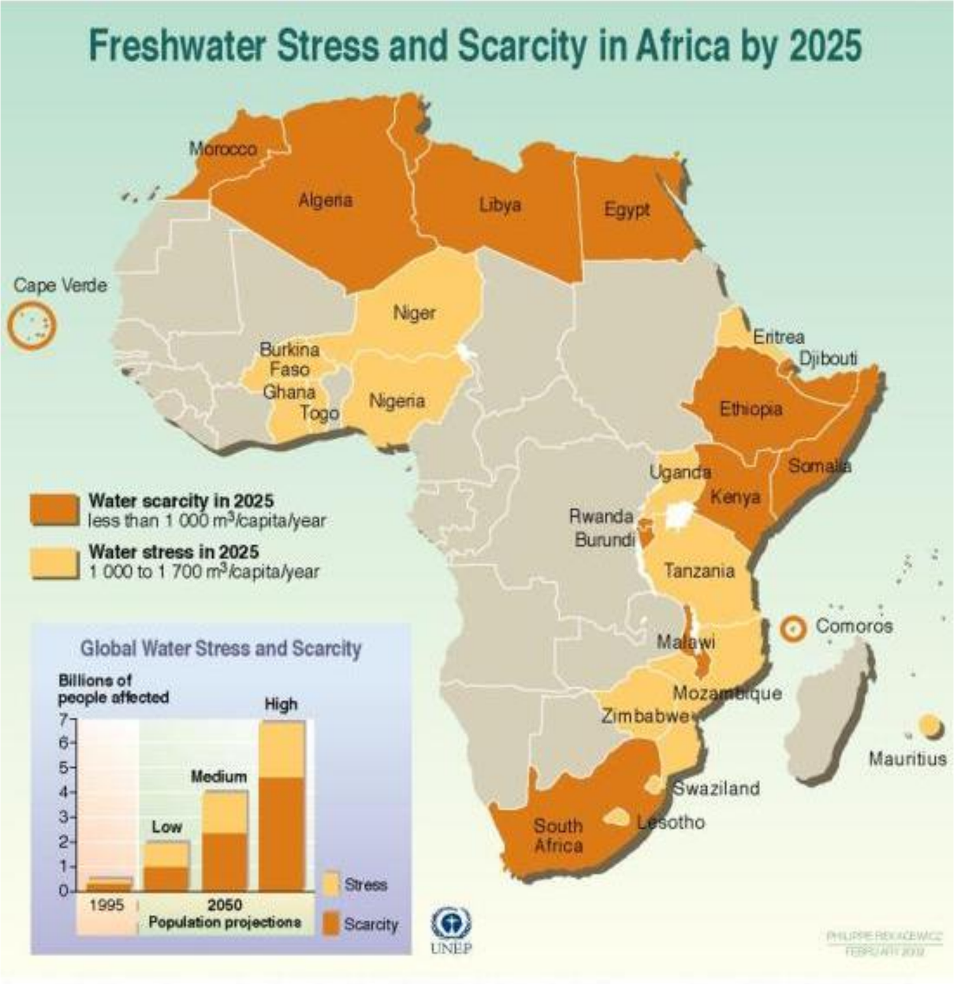


Figure 1. 4: Freshwater Stress and Scarcity in Africa by 2025 (GRID-Arendal, 2005)

Based on the continent, the annual rainfall in Africa is about 670 mm. This corresponds to Europe and North America. However, Africa's better evaporation rates have greatly reduced the chance that precipitation contributes to renewable water resources. The precipitation patterns in Africa also show significant changes in communities and weather. Temporary rainfall changes usually average 40°, which is much better than in temperate regions. The spatial distribution of rainfall also varies with the land of the Indian Ocean islands (1,700 mm per year) and the land of Central Africa (1,430 mm per year), and the low-level North African countries (71.4 mm) (African Studies Centre Leiden, 2012).

There are 17 rivers in Africa with a basin area of more than 100,000 square kilometers. It has more than 160 lakes over 27 square kilometers, most of which may be located in the sub-humid highlands of the Great Rift Valley and the equatorial region (African Studies Centre Leiden, 2012). Considering that countries share many river basins in Africa, cooperation between these countries is crucial. Some people claim that the possibility of war between coastal countries has increased in recent years and that as water shortages intensify, they may increase in the future.

Groundwater is vital in Africa. It is estimated that more than 40% of Africans use groundwater as their essential source of drinking water, especially in North Africa and South Africa. Piped water is the most important source of drinking water in metropolitan areas (39%), but water wells are becoming more and more important (24%). Subsequent studies evaluated the groundwater capacity of the sedimentary aquifers in North Africa, which was as high as 75 times that of 106 cubic meters per square kilometer. Sedimentary basins in other parts of Africa contained large amounts of excess groundwater on the continent (Figure 1.5). Due to rock types with low porosity and many thin effective aquifers, groundwater capacity is far from these basins (Figure 1.5). The Precambrian basement rocks contain the least accumulated aquifers, and the normal groundwater volume is estimated to be 0.5 times greater than 106 m^3 per km^2 (MacDonald et al., 2012).

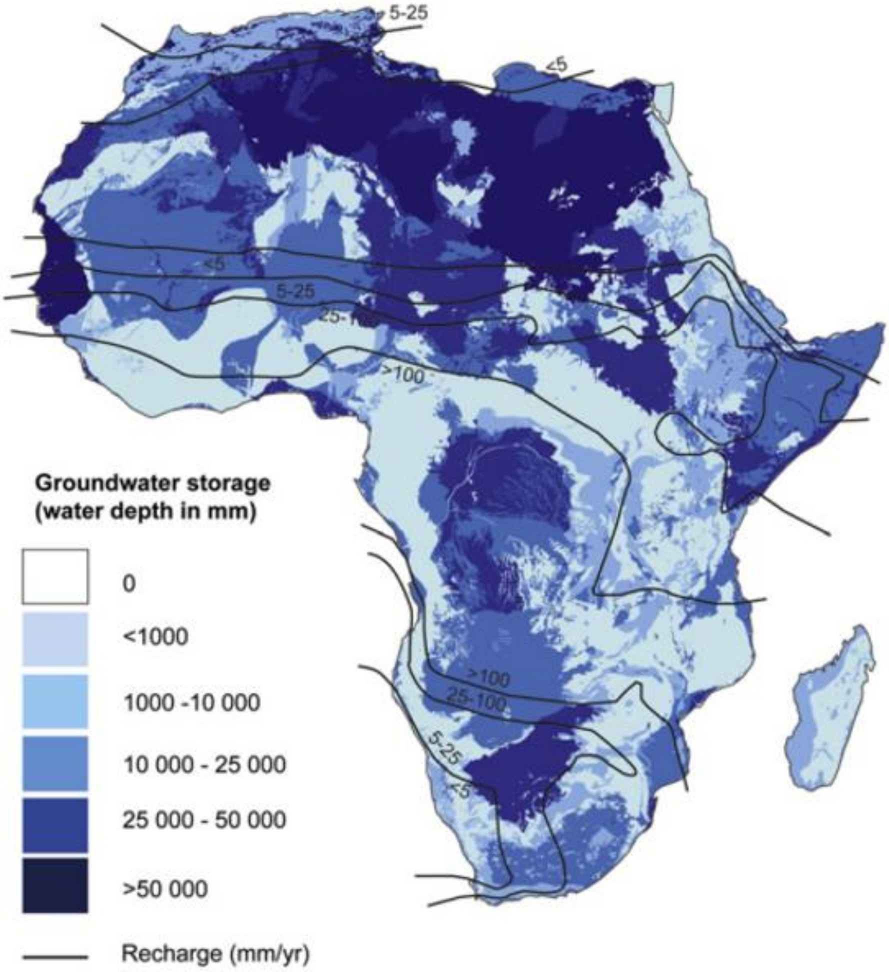


Figure 1. 5: Africa groundwater storage based on the effective porosity and saturated aquifer thickness (MacDonald et al., 2012)

Africa is losing 5% of its GDP due to inadequate water supply and sanitation, 2% due to power outages, 5% to 25% due to droughts and floods, and 5% due to the future impact of environmental changes. To cope with Africa's severe water resources situation, an annual investment of 50 billion U.S. dollars during 2010-2030 will be required, and an annual investment of 30 billion U.S. dollars will be required for the next 30 years. This figure fundamentally exceeds the 2025 African Water Vision originally estimated in 2000 of 20 billion U.S. dollars. The evaluation cost of water-related facilities has increased nearly tenfold to help financial development, food protection and energy, environmental change, transition, and risk executives (African Studies Centre Leiden, 2012).

1.1.2 South Africa's Current Water Situation

South Africa has a population of 58 million, of which 60% live in metropolitan areas, and 40% live in rural settlements. South Africa obtains surface water (77% of total use), groundwater (9% of total use), and reused water (14% of total use) (Hove et al., 2019). However, people's dependence on water is not evenly distributed. Due to the lack of water supply infrastructure in rural areas, 74% of the rural population depends on groundwater (Hove et al., 2019). Again, most of the water in urban areas with a general water dispersal framework comes from surface water sources, such as the Limpopo River and the Komati Canal (Hove et al., 2019). Due to population movement and population development, rural settlement development put pressure on South Africa's water supply. Currently, 19% of the rural population needs a reliable water supply system, while 33% do not have basic sterilization management (Hove et al., 2019). Although rural inhabitants suffer the most, considering that more than 26% (large cities or rural areas), 45% of the facilities do not have a water supply (Hove et al., 2019).

Although South Africa is short of water, most of South Africa's GDP is dependent on water. For example, more than 15% of its GDP comes from agriculture, and agriculture uses 60% of South Africa's water supply (Hove et al., 2019). Another efficient use of water in South Africa is energy production (which accounts for 2% of the national supply). South Africa is the fourth largest coal exporter in the world (Hove et al., 2019). Finally, South Africa's industrial sector accounts for around 29% of its total GDP and uses almost 11% of its water (Hove et al., 2019). However, since a large part of South Africa's industrial sector is mining, the impact of this sector on the water far exceeds 11% each year. The National Water Act was enacted in 1998 to prevent widespread pollution caused by mine runoff that seriously pollutes South Africa's water supply (Hove et al., 2019).

The 2017 mission identified two parts of the water supply problem that needed to be solved. The first part is finding a way to provide water for people who need water in their bodies. The second part is finding an available water source that can supply water.

1.1.2.1 Solve the problem of insufficient rural access

Currently, South Africa has a policy called free basic water. According to the South African Constitution, all citizens have the right to receive a certain amount of water, regardless of their payment capabilities. This policy defines the right to be 6000 liters per month per household (Hove et al., 2019). However, water distribution organizations, South African water problems (SADWAF), are not effective in determining water use per month in rural areas with the lack of surveillance equipment (Hove et al., 2019). SADWAF can not determine if the water cable is broken or when the water line is broken by not monitoring the amount of water used. Since South Africa loses a large amount of water supply available for communication errors, the broken cable can return to all the "stolen" or less than 20% of the lost water. (Hove et al., 2019).

Installing water meters across the country or equipment to measure the amount of water flowing into homes will help solve water scarcity. Then SADWAF can charge the house properly and begin charging for additional water. SADWAF in-house technicians will determine if the faucet line is broken when water consumption drops steadily. After realizing this, patrols will be dispatched to repair the disruption and ensure continued access to water in rural areas. Although the purchase and installation of meters will cost the South African government money, this money can be obtained from personal income tax (Hove et al., 2019). The source of the money is not important because the correct collection of water purchase fees can offset the cost. Therefore, proper water management will increase water availability in Africa because less waste will be wasted.

The next step is to build passages for people without water. It is estimated that 7 million people live in rural settlements without access to water (Hove et al., 2019). Although building the necessary faucet system (pipes and other infrastructure to provide a reliable source of water for the village) is a long-term goal, the short-term solution is to use tank trucks weekly (or, if necessary, daily) similar to the Ethiopian government's support for Melbena In the way of the village, six cubic meters of water are provided to the villagers at a time (Hove et al., 2019). To this end, SADWAF will establish a registration system where government officials determine and register the water supply schedule for each rural community based on the number of people living there. Since the standard is 6000 liters per month for a family of 4 (Hove et al., 2019), the truck will provide 375 liters of water per person per week to ensure that the quota is met. This will solve the problem of monitoring the amount of water available to everyone, but it will also provide the immediate water relief needed to save lives.

The long-term solution (20 years from now) is to build a public tap water system that can use groundwater (through wells) or rainwater. Each village will build a unique public tap system, but they can be as simple as a series of water storage tanks for domestic water or public taps located in the center of the village. This money is necessary to build a public system, but there are many ways to do it. Households can share costs in the community, or funding can come from public-private partnerships (PPPs), in which private companies work with local or national governments to provide funds to build public water systems.

1.1.2.2 Solving the problem of inefficient water use and management

South Africa currently uses water within its natural supply constraints (accounting for 98% of its total planned resources). Unfortunately, they did not use it effectively. In addition to lost or stolen water, South Africa also loses more than 1.5 billion cubic meters of water each year due to the failure of pipeline infrastructure that has exceeded its service life (Hove et al., 2019). Ideally, damaged pipes will be replaced and updated as needed. However, the funds may not be used for all of them immediately. Due to bureaucratic costs and inefficiency, Mission 2017 believes that if the private sector assists in maintenance (cost and workers) through PPP's, the time required to replace all necessary water pipes and infrastructure may be greatly reduced. In this strategy, the South African government will award several small contracts to local construction companies and replace pipelines in specific areas. To ensure that the pipeline returns quickly, incentives can be used. If the pipeline is completed within a specified time frame, the government can reduce the cost to the company. Since multiple teams are working on the project and the area is small, the pipe replacement speed will be faster.

If measures are not taken to improve water efficiency or distribute it to the people, South Africa will face serious water problems. Mission 2017 believes that the above solutions, including water meters and truck transportation routes, will significantly reduce wasted or lost water. Although this particular key combination may be unique to South Africa, several other countries worldwide are also facing similar or more serious similar or related problems. Mission 2017 believes that it can solve water problems in any country by applying the right combination and scale.

1.2 Statement of Research Problem

In the most remote areas of Africa, people not only have no access to electricity but also clean water. Drinking contaminated water may cause many diseases. In these cases, water treatment systems based on renewable energy can be a solution to overcome water purification problems in these areas. Therefore, the problem in this study is the feasibility of solar water purification systems to provide clean water to Mbashe's population.

1.3 Aim and Objectives of the research

This research aims to carry out a techno-economic feasibility assessment of a renewable water purification system for isolated areas. The project will use a solar photovoltaic system as the primary power source and integrating an intelligent configuration to monitor and control the entire system. Additional objectives include:

- A review of literature in the water treatment process and solar photovoltaic systems
- Propose a design of an intelligent water treatment control for the plant
- A collection of solar resources from the selected location and relevant components data to model and simulate the system for economic feasibility analysis
- Conduct an economic feasibility study of the system using HOMER PRO software
- Analyses of technical and economic results
- Making recommendations on possible design, simulation, and strategy improvements

1.6 Organization of the Thesis

Besides the introductive chapter, the rest of the thesis is organized as follows:

Chapter two provided a literature review of renewable energy resources for water techniques. A section on water quality norms is also considered. The last section of the chapter is dedicated to various existing water technologies.

The third chapter of this investigation discusses water delivery and sanitation in South Africa. Aspects such as water accessibility and resources, wastewater reuse, access to water and sanitation, water quality and continuity of supply, water treatment, and water and sanitation stakeholders in South Africa are presented.

The fourth chapter is dedicated to the site selection as well as its characteristics. This chapter covers the following topics: demography and economic growth of Mbhashe, gross value added, and water and solar resources of Mbhashe.

The fifth chapter deals with the techno-economic assessment of the plant. Topics such as the system description, design methodology of the reverse osmosis water treatment, and the design methodology of the solar-based power system are considered. Furthermore, the chapter presents the results obtained from conducting the techno-economic assessment.

Chapter six of this research gives the conclusion.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter deals with the review of the existing literature on water technologies

2.2 Renewable energy resources for water technologies

Renewable energy refers to electricity and heat generated from wind, solar, hydropower, biomass, ocean, biofuels, geothermal resources, and hydrogen produced from renewable resources. Currently, there are several reasons to power water purification plants using renewable resources. These reasons are:

- The global increase in water demand.
- The high cost of gas, oil, and coal to generate power and heat,
- The security of supply as gas, oil, and coal will be depleted in years to come.
- The cost decrease of desalination and renewable technologies.
- The need to operate small systems in remote areas without access to electricity from the grid.
- And climate change.

Renewable energy such as solar, wind, ocean, hydropower, and biomass derives from the sun, except tidal energy and geothermal energy.

2.2.1 Solar Energy

Renewable energy sources used primarily for power generation include biomass energy, geothermal energy, and solar energy. Among these sources, solar energy has the highest global potential because geothermal sources are only found in certain places, and the biomass supply is not everywhere in nature (Holm-Nielsen & Ehimen, 2016; Sampaio & González, 2017). Factors such as latitude, diurnal changes, climatic and geographical changes are significant in determining the intensity of the sun's intensity. The average solar energy received in the earth's atmosphere is about 342 watts per square meter, of which 30% is scattered or reflected space, and 70% (239 watts per square meter) can be used for collection (Kabir et al., 2018). The annual effective solar irradiance in the world ranges from 60 to 250 watts per square meter (Luqman et al., 2015). Figure 2.1 shows the yearly average solar radiation on the earth's surface. The sunniest region on the planet is Africa. Theoretically, the potential concentrated solar energy and photovoltaic energy in Africa are estimated to be about 470 and 660 petawatt hours (PWh), respectively (IRENA, 2014). However, in the southwestern United States, Central, and South America, North Africa and South Africa, the Middle East, India, Pakistan, Australia, and other desert plains, its power generation potential is limited to 125 gigawatt-hours (GWh) of the land area of 1 square kilometer (Adaramola, 2008).

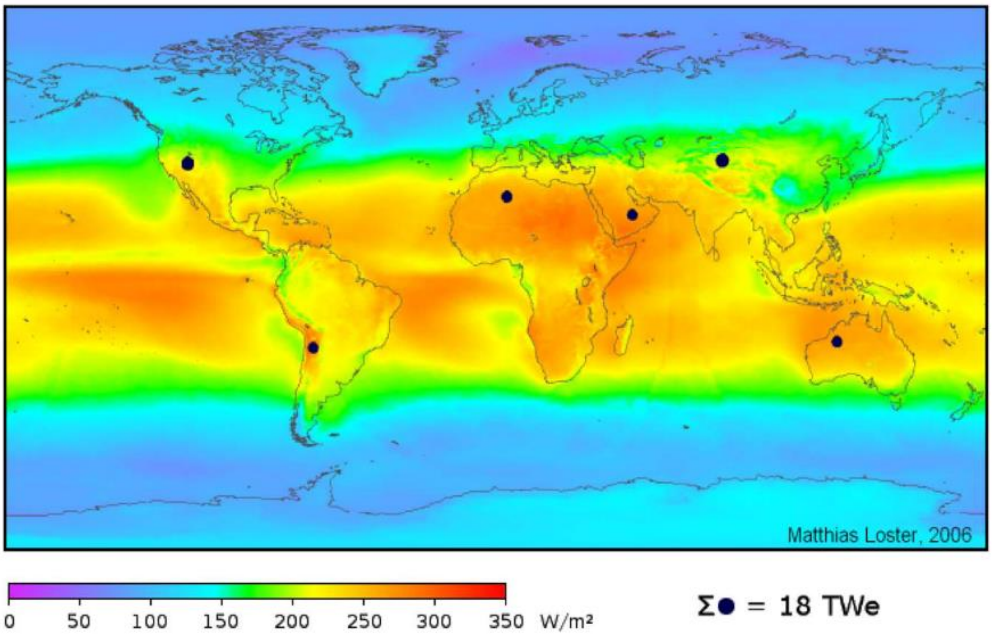


Figure 2. 1: Yearly average solar distribution over the surface of the earth. (Kabir et al., 2018)

The concept of solar energy refers to the harvesting and using light and heat energy generated by the sun. Technologies involved in such a concept are passive and active solar systems (Besarati et al., 2013). Passive technology involves accumulating solar energy without transforming thermal or light energy into any other form (Sun & Wang, 2016). Instead, solar energy is collected, stored, and then distributed in the form of heat. On the other hand, active solar technology collects solar radiation and uses mechanical and electrical equipment to convert solar energy into heat and electric power. Active solar energy technology includes photovoltaic technology and solar thermal technology (Herrando & Markides, 2016). Recently, photovoltaic technology has become an effective alternative for power generation (Mohanty et al., 2015). The intense research on solar energy has helped to improve photovoltaic technology efficiency (Jeon et al., 2013; Green et al., 2014).

In the solar thermal process, solar energy is converted into thermal energy for commercial and domestic applications such as cooling, heating, cooking, drying, etc. (Raisul Islam et al., 2013; Seddegh et al., 2015). However, concentrated solar thermal technology is utilized for industrial-grade heating demands, while concentrated solar power units serve to generate electricity. Concentrated solar power is a height magnifying mirror that gathers solar energy before converting it into heat to drive a steam turbine (Kabir et al., 2018). Four types of concentrating solar technologies can be found in the market, namely (Romero & González-Aguilar, 2014):

- Parabolic trough collectors which collect sunlight into a receiving tube filled with working fluid),
- Fresnel reflectors which use multiple flat reflectors to concentrate sunlight onto a receiving tube,
- Power towers consisting of a collection of thousands of reflective solar tracking mirrors placed in a field to concentrate solar radiation on one point, and the solar collectors focus that power on a single point on the reflector.

2.2.2 Wind Energy

The uneven solar heating of the earth causes the poles to receive less solar energy than the equator. In addition, the land can heat up and cool down faster than the ocean. This different heating leads to jets in the earth's upper atmosphere and characteristic winds: mid-latitude westerly winds, polar east winds, and trade winds. Wind energy is most collected through windmills to generate mechanical energy or using wind turbines to generate electricity. (Willis et al., 2018)

2.2.3 Wave Energy

Wave energy is a form of storage and concentration of solar energy because waves are produced by wind passing through them. When the propagation speed of the waves is slower than the wind speed (only above the waves), the energy is transferred from the wind to waves with the highest energy. (Zheng et al., 2017)

2.2.4 Tidal Energy

The tidal energy system uses the natural fluctuations of coastal tides produced by the interaction of the sun and the moon's gravitational fields. In some estuaries, the difference between high tide and low tide is more obvious, with a tidal range up to 11 m. Although several demonstration projects worldwide, especially the 240 MW barrage project in La Rance, France, which has been in operation since 1967, no major expansion of the technology is currently expected. (Khan et al., 2017)

2.2.5 Small-Scale Hydropower

Hydropower converts the energy available in running water (river, canal, or stream) into electricity. The technology is commercially and technologically mature, and small-scale hydropower is defined as an installed capacity of less than 10MW. Importantly, compared to the valley flooding required for large-scale hydropower generation, it also greatly reduces the environmental impact. Most of the world's small hydroelectric power system is located in China. (Balkhair & Rahman, 2017)

2.2.6 Geothermal Energy

Geothermal energy comes from the heat produced deep in the earth. Although 50 to 150°C natural water from aquifers can be used for district heating, power generation requires temperatures above 150°C. The main disadvantage of geothermal energy is the geological conditions that determine the quality of resources, such as the temperature and flow rate of formation fluids. Without a large amount of drilling and testing capital investment, it is difficult to predict. Therefore, compared with other forms of energy production, geothermal energy is considered a high-risk investment. (Shortall et al., 2015)

2.2.7 Renewable Energy Powering Water Technologies

The renewable energy technologies most commonly used to power water purification systems are photovoltaic energy, solar thermal energy, and wind energy. Figure 2.1 depicts the global distribution of renewable water desalination plants. As the cost of renewable energy technologies continues to decrease, the benefits of combining renewable energy technologies with desalination systems have become widely known. These energy sources have become very competitive in meeting future electricity demand. Driven by the 81% increase in the price of solar photovoltaic modules since the end of 2009, coupled with the reduction in the balance of power plant costs, the global weighted average energy cost (LCOE) of photovoltaic energy and the scale of public utilities fell by 73 % between 2010 and 2017, which is USD 0.10$ per kWh (Elfaqih & Belhaj, 2019).

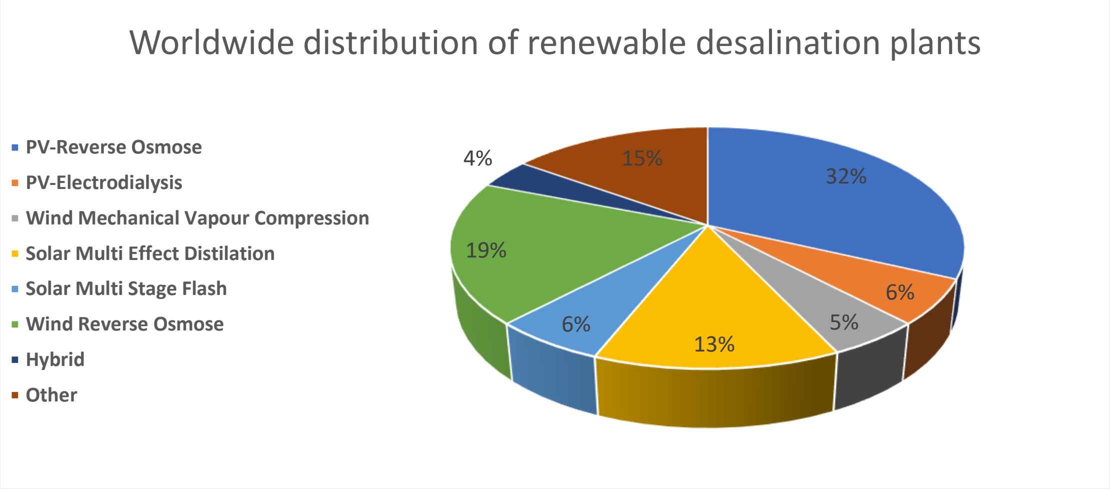


Figure 2. 2: Distribution of renewable desalination plants. (Elfaqih & Belhaj, 2019)

Compared to other water purification technologies, the reverse osmosis process has the advantage of lower energy consumption; for example, a Flash MultiStage plant requires approximately 3 to 5 kWh of electricity and approximately 60 to 80 kWh of heat energy per cubic meter of distillate, regardless of what is the salt content of the raw water. In contrast, for raw water with a salt content of 3,500 ppm (parts per million), a similar reverse osmosis device requires 2 to 5 kWh of total energy per cubic meter of distilled water. Seawater with a salt content of 35,000 ppm increases to about 15 kWh per cubic meter (Mahmoud, 2003). Therefore, reverse osmosis is becoming a leading technology, with continuous progress to reduce total energy consumption and reduce the cost of produced water.

Table 2.1 compares the energy consumption of different desalination processes using renewable energy and the shortcomings of each technology. For reverse osmosis and nanofiltration technologies, the main energy requirement is to pressurize the feed water, while the brackish water system operates at a 5 to 15 bar pressure. In contrast, the range of desalination is about 40 to 60 bar.

Table 2. 1: Comparison of renewable desalination systems. (Escobar & Schafer, 2010)

Technology	Operating Principle	Disadvantages
Solar Still	Solar heat evaporates the water, and the water condenses on the sloping surface of the glass and then drains into the collection tank.	• High specific energy consumption (639 kWh per cubic meter) • Low daily output • Considerable maintenance costs • Glass panels can easily be affected by storms and vandalism
Multi-Stage Flash	Saline water is held under pressure at about 120°C. It is then flashed" into vapour in a series of about 50 chambers, condensing and collecting.	• Both thermal and electric energy is required • High specific energy consumption of 20 to 64 kWh per cubic meter (electrical energy about 4 kWh per cubic meter)
Multiple Effect Distillation	In the thin-film evaporation process, the vapor formed in one chamber is condensed in the next chamber to provide a heat source for more evaporation.	• Electrical and thermal energy is required • High specific energy consumption (15 kWh per cubic meter)
Mechanical Vapor Compression	The vapor evaporated in the evaporator is mechanically compressed and reused as a heating medium in the evaporation system.	• Electrical and thermal energy is required • High specific energy consumption (11 to 16 kWh per cubic)
Freeze Separation	The ice crystals formed in the incoming water separate and then melt to form product water.	• High specific energy consumption (97 kW per cubic meter) • Ice crystals separate from the brine; operation in vacuum

		required due to lower freezing point of saline water
Reverse Osmosis	Pressure-driven separation of two solutions with different salt concentrations in a semi-permeable membrane	• Low energy consumption of 4 kWh per cubic meter of sea water • No special chemicals in remote areas • Chemicals required for scale control-increasing system complexity and cost and reducing system reliability • Membrane from 3 to 5 years
Nanofiltration	Pressure-driven separation of two solutions with different salt concentrations in a semi-permeable membrane	• Similar to reverse osmosis, but reduces the specific energy consumption of brackish water (2 kWh per cubic meter) • Not applicable to seawater
Electrodialysis	Electromigration of ions via cation and anion exchange membranes	• Low energy consumption of 2 kWh per cubic meter of brackish water • Chemical cleaning required • No pre-treatment is required to remove particles • Not applicable to seawater
Electrodialysis Reversal	Similar to electrodialysis; however, the polarity of the electrode is periodically reversed to promote cleanliness of the electrodialysis membrane	• Similar to electrodialysis, however, decreased chemical cleaning is needed.

2.3 Water Quality norms

The fundamental health issues related to drinking water contamination result from the lack of water for hygiene purposes and contaminated water utilisation. The Sphere Project defines two standards (The Sphere Project, 2011) for water supply norms. The main standard includes access to water, while the last standard controls water quality. The minimum quantity of water for protected and solid utilization is shown in Table 2.1. Water for hygiene use is a fundamental water need since it is significant in maintaining legitimate hygiene during disasters to decrease illness danger.

Alongside the 7.5 to 15 liters of water per individual every day, other water amount indicators that can be utilized to quantify the amount of water accessibility include:

- Distance from a family to a water point (500 m);
- Waiting time at a water source (no longer than 30 min).

These norms should not be followed aimlessly, as they do not ensure that water is similarly accessible to all.

As indicated by the Sphere Project (The Sphere Project, 2011), water quality is an auxiliary norm. When water quantity has been guaranteed, water quality should be improved to lessen the danger of diarrhoea and different sicknesses. The Sphere Project indicates the quality parameters given in Table 2.2 as the base norms met by water treatment technologies.

Table 2. 2 Individual daily water requirements. (The Sphere Project, 2011)

Water usage	**Daily minimum water requirement (liter per day)**	
Water for food and drinking	2.5 to 3	Depending on the climate and physiology
Water for hygiene	2 to 6	Depending on social and cultural habits
Water for cooking	3 to 6	Depending on food type, social and cultural habits
Total	7.5 to 15	

Table 2. 3 Water quality parameters. (The Sphere Project, 2011)

Water quality measure	**Minimum requirement**
Coliforms	**0/100 mL of water measured at the point of delivery**
Turbidity	**< 5 NTU for proper disinfection**
Chlorine Residual	**0.5 mg/L to reduce risk of post-treatment contamination**

2.4 Water Technologies

Generally, water systems require energy to operate. The entire model of pumping, transporting, treating, using, and collecting used water depends on energy. In this way, the local power supply is essential for obtaining clean water. In addition, energy is essential for wise use of water and reuse when necessary. Pumping is necessary for certain water and water transportation tasks. Various uses of water or groundwater require different water quality: the quality of irrigation water is usually lower than that of drinking water; the greywater produced by washing can be reused for various purposes. This section focuses on the pumping and treatment system.

2.4.1 Water Pumping

The extraction of clean or contaminated water is a key activity in decentralized and centralized water supply operations. The water must be treated at the source (streams, lakes, or drawn from the ground). Pumping water for the supply, reuse, and treatment of used water is the main electricity use in rural areas. Energy consumption is usually the largest expense in the life cycle cost of a pumping system, where the pump regularly runs for more than 2,000 hours per year. Providing electricity to pumps in rural areas of developing countries is not easy. However, fascinating products that rely on solar energy are presently accessible.

For a small-scale water supply, the distribution pressure of the water can be obtained through a pump or through an elevated reservoir, where the potential energy can provide sufficient pressure for the water. Whenever contaminated water is treated through desalination, pumping is urgently needed. Any used water treatment or water reuse will utilized pump energy.

Among the benefits of solar photovoltaic water pumps, four advantages are often highlighted: unattended operation, low maintenance costs, convenient installation, and long service life. Technical and economic feasibility is considered in a comprehensive review of the literature on solar pumping technology (Chandel et al., 2017). The authors identified the factors that affect the performance of solar photovoltaic water pumping systems and photovoltaic module degradation and efficiency improvement techniques. In rural, remote and urban areas, solar pumping systems have proven to be more economically viable than diesel-based irrigation and water supply systems (IRENA, 2016). Some solar photovoltaic pumping systems have a payback period of four to six years. Of course, this depends on local conditions, as shown below. System costs vary based on size, usage, and configuration. It may make more sense to calculate the cost of the energy service provided and compare it with the existing cost that users pay for off-grid energy services.

2.4.1.1 Characteristics of pumping

The best-known type of pump is the centrifugal pump depicted in Figure 2.3, where the motor's mechanical energy is converted into kinetic energy. This will create a pressure difference between the inlet and the outlet of the pump (Olsson, 2015). Pressure consists of static and dynamic pressure. The static pressure that occurs at zero flow depends on the amount of water the pump must lift. The dynamic pressure depends on the flow rate in the pipe. The higher the flow rate, the higher the dynamic pressure. If the pipeline is very wide, the friction loss of the pipeline is small, and the dynamic pressure will only increase slowly with the increase of the flow rate. Or, if the pipe is very narrow, as the flow rate increases, the speed of the water increases faster. Therefore, the dynamic pressure will increase faster as the flow rate increases.

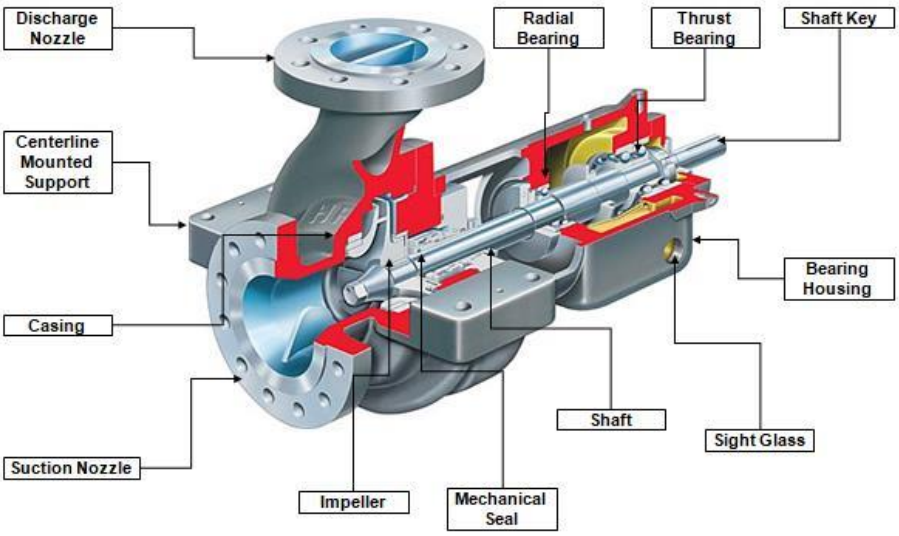


Figure 2. 3: Layout of a centrifugal pump (CCE, 2020)

Figure 2.4 shows the curve of the flow rate and a function of the head in a pump, also known as the QH curve or pump characteristics, which describes the pressure that the pump can produce based on the flow rate. Static and dynamic pressures are given in heads. The head is estimated in units of one meter of liquid column and is proportional to the pressure generated by the pump. Given a specific pressure, the head also indicates how high the pump can lift the water. The higher the flow, the lower the head the pump can produce.

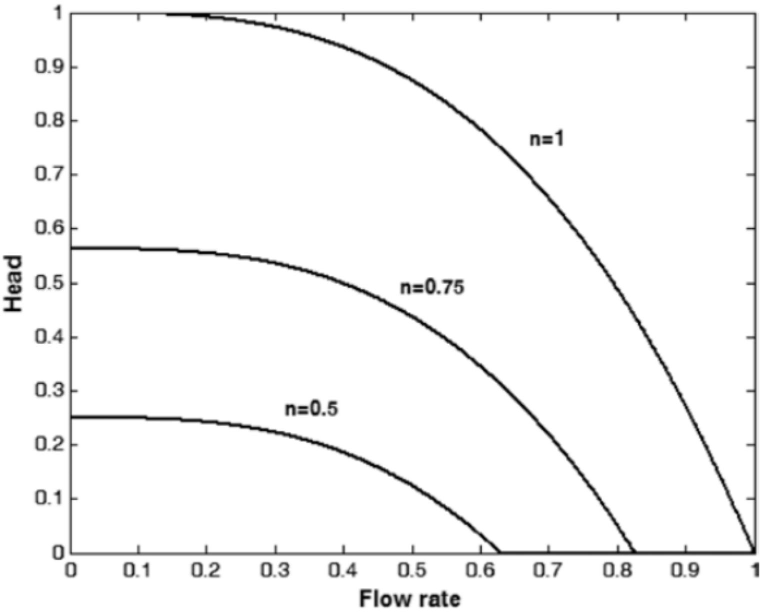


Figure 2. 4: Pump QU curve. (Olsson, 2019)

Equation 2.1 expresses the relationship of the head expressed in meter as a function of the pressure in pascal:

$$H = \frac{p}{\rho . g} \tag{2.1}$$

Where ρ represents the water density in kg per m^3, and g the acceleration of gravity m per s^2.

2.4.1.2 Pumping efficiency

The pump efficiency is dependent on the flow rate and the design of the pump. The power fed to the mechanical power transferred to the pump shaft is slightly less than the electrical power provided to the motor and considers the loss of power in the motor. Generally, the efficiency of the motor is above 90%. Therefore, the pump must be designed to achieve maximum efficiency at the most common flow rates. The efficiency of large pumps is usually around 89%, while the efficiency of small pumps can reach 85%.

2.4.1.3 Solar pumping system

The photovoltaic panels cost accounts for a larger portion of the cost of solar pumping systems, and pumps generally only account for a small portion of the cost. Generally, the size of panels depends on the required flow rate and solar irradiance.

2.4.1.3.1 Solar panels

The main benefit of photovoltaic panels is that they can generate economically interesting energy without tracking the sun's position. The need for maintenance due to the lack of moving parts is lower, reflecting overall better economic results. Generally, for most photovoltaic panels, the module is guaranteed to generate 90% of its rated power during the first ten years and 80% of its rated power for up to 25 years. This is a very long service life, longer than most other devices. The limited complexity of the assembly, the operation of photovoltaic systems and solar cells' safety, and manufacturing costs are factors in expanding photovoltaic energy. If the equipment is located in a remote area, the commercial value of the warranty may be quite limited. However, the fact that this warranty is still provided indicates the reliability of the system.

2.4.1.3.2 Power converters and pump controllers

The pump can operate using direct current (DC) or alternating current (AC). For AC pumps, the inverter converts the DC power of the photovoltaic panels into AC power. DC pumps are mainly utilized for small-scale applications, including single-family houses or small irrigation systems less than 3 kW. DC motors have various moving parts, and replacement of these parts is usually expensive. Generally speaking, it is easier to control the speed. However, the combination of AC motors and power electronic converters is economical and more reliable.

Inverters are mature technologies at various power levels and usually have very high efficiency (98% or higher). Inverters used in photovoltaic systems are usually affected by harsh conditions, such as operating under long sunshine hours and temperatures above 40 °C. Dust is another challenge. When a small inverter is directly coupled to the photovoltaic module and installed in the rear, the situation may be difficult. The temperature can reach 80°C. Under these conditions, electronic equipment must be ready to operate for a period of time comparable to the useful life of photovoltaic modules, at least 20 years. Therefore, it is important to have a design margin to ensure long-term reliability. Individual components must meet the most demanding conditions. If the design is good, the life of the inverter will exceed 20 years.

2.4.2 Water purification

The energy required for purifying water is dependent on the raw water source quality. Available water sources may be polluted, and a considerable amount of energy in terms of water volume may be needed to purify the water to an acceptable quality.

2.4.2.1 Underground water

Groundwater is the main source of water in many parts of the world. The serious problem is that the groundwater level is falling because pumping the groundwater in these areas is not sustainable. In many places, water has been drawn from aquifers for centuries. In these locations, the amount of water used now exceeds the amount of make-up water. Therefore, it may take generations or centuries to fill these aquifers with rainwater because this resource is not renewable.

2.4.2.2 Saline water

Due to population growth and climate change, seawater as a source of fresh water has greatly increased. Seawater provides an indispensable use possibility, especially in coastal areas. The salt concentration in seawater is usually 3.5% of the weight of the water. Many groundwater aquifers or other groundwater sources contain brackish water, which must be removed for drinking. Another increasingly serious water supply problem is the intrusion of seawater into groundwater. Sometimes groundwater resources have been depleted. In other cases, rising sea levels caused by climate change will exacerbate this problem. Table 2.4 shows the typical salinity of various water qualities.

Table 2. 4: The salinity of different types of waters. (Olsson, 2019)

Saline water type	**Salinity in mg/L**
Seawater	**35000**
Highly saline water	**10000 to 35000**
Brackish water	**1000 to 10000**
Freshwater	**< 1000**

2.4.2.3 Polluted water

Various surface or groundwater reservoirs in remote areas are heavily contaminated by contamination of organic carbon (COD), nutrients (ammonia and phosphorus), pathogens, viruses, protozoa, and worms. Additionally, many reservoirs are heavily polluted due to harmful metals, including fluoride and arsenic. On the other hand, surface reservoirs are repeatedly used as landfills, and there are often defecations at the edge of the water body, leading to bacterial contamination.

Biological treatment to remove pollutants requires some quantity of energy per kilogram of COD. Water purification can be accomplished through various techniques. One major technique is ultraviolet disinfection. Other techniques include the use of filters of different sizes. Both of the above technologies require electrical energy to generate ultraviolet light or generate pressure for the operation of the membrane filter.

2.4.2.4 Water purification technologies

A water purification system aims to eliminate pathogenic organisms to make water drinkable. Depending on the water quality, the purification can be done using membrane separation, disinfection and desalination.

2.4.2.4.1 Water purification through membrane separation

Using semipermeable membranes, substances are physically separated from water (Figure 2.3). The pressure drives the process across the membrane. The smallest particles contained in the water are pushed through the membrane, while the largest are retained. There are four different types of pressure-driven semi-permeable membranes:

- microfiltration can filter from 0.1 to 0.5 micron (10-6 m) particles;
- ultrafiltration can filter from 0.005 to 0.05 micron particles;
- nanofiltration filters particles from 0.5×10^{-3} to 1×10^{-3} microns;

- reverse osmosis with a molecular size up to about 1 angstrom (10^{-4} microns).

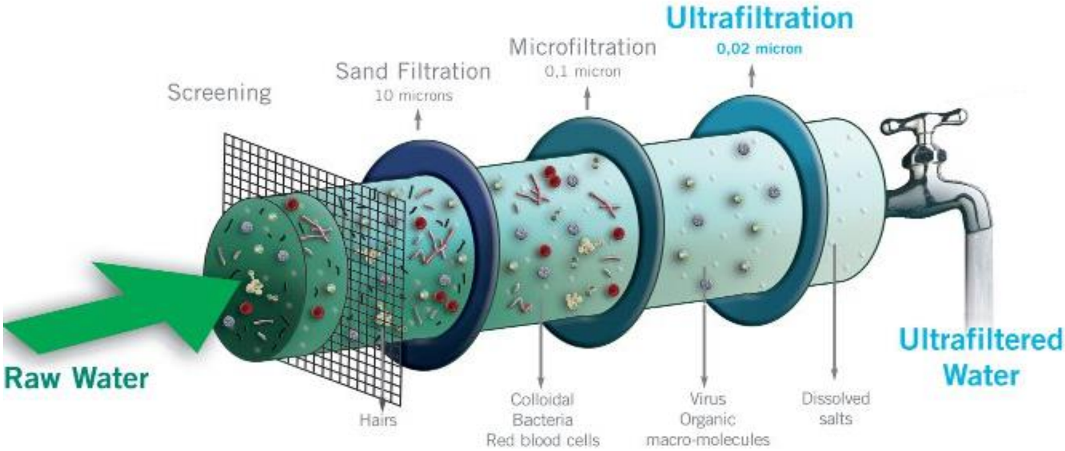


Figure 2. 5: Membrane filtration. (PureMedion, 2018)

These membranes can treat different types of polluted water, such as blackwater, and greywater, including urine. The parameters that differentiate the four membranes from each other are given in Table 2.5. In liters per square meter of membrane per hour, purified water's permeation capacity depends on the inlet water pressure.

Table 2. 5: Membrane filtration types

Filtration membrane	**Microfiltration**	**Ultrafiltration**	**Nanofiltration**	**Reverse osmose**
Molecular Weight Cut Off in kilodalton	**100-500**	**20-150**	**2-20**	**0.2-2**
Retained Diameters in µm	**10^{-1}-10**	**10^{-3}-1**	**10^{-3}-10^{-2}**	**10^{-4}-10^{-3}**
Pressure Required in bar	**1-3**	**2-5**	**5-15**	**15-75**
Membrane Type	**Porous, asymmetric or symmetric**	**Microporous, asymmetric**	**Tight porous, asymmetric, thin-film composite**	**Semi porous, asymmetric, thin-film composite**
Average Permeability in L/m^2 h bar	**500**	**150**	**10-20**	**5-10**
Solutes Retained	**Bacteria, fat, grease, colloids, organics, micro-particles**	**Proteins, pigments, oils, sugar, organics, microplastics**	**Pigments, sulfates, divalent cations, divalent anions, lactose, sucrose, sodium chloride**	**All contaminants, including monovalent ions**

2.4.2.4.1.1 Microfiltration

Microfiltration membranes can remove high molecular weight species, suspended solids, bacteria, pathogens like giardia and cryptosporidium in drinking water. This technique does not require any chemicals to inactivate microbes.

2.4.2.4.1.2 Ultrafiltration

Ultrafiltration membranes can remove macromolecules, colloids, viruses, proteins, and pectins. The technique does not require chemicals to inactivate microbes and cannot remove natural minerals, such as calcium (Ca^{2+}) or the salinity of seawater.

2.4.2.4.1.3 Nanofiltration

Nanofiltration membranes remove small molecules and polyvalent ions like magnesium (Mg^{2+}) and calcium (Ca^{2+}). The nanofiltration process would require pressure between 1 to 4 MPa (10 to 40 bar).

2.4.2.4.1.4 Reverse Osmosis

Reverse osmosis removes colors, smaller ions, soluble salts, and low molecular weight substances. Microfiltration and ultrafiltration require relatively low pressure, while nanofiltration and reserve osmosis require more. Generally, reverse osmosis requires 1.5 to 8 MPa (15 to 80 bar). Above optimal pressure, the "pores" will be blocked, and the membrane will compact.

2.4.2.4.2 Water purification through disinfection

Water purification through disinfection can be performed using chlorine gas, sodium hypochlorite solution, solid calcium hypochlorite, chloramines, and ozonation.

2.4.2.4.2.1 Chlorine Gas

Using chlorine for water disinfection is very effective in removing most pathogenic microorganisms. Chlorine is suitable for large-scale water treatment systems but not in a household system due to its dangerous features. It is cheaper than other disinfectants, it is highly effective against a wide variety of pathogens, and the dosing rate can be flexibly controlled. However, it may affect the taste and odor of the water and present health-related concerns.

Chlorine can be used in gaseous or liquid form, as both forms can accumulate and be used in pressurized gas cylinders (Figure 2.6). When chlorine mixes with water, hypochlorous acid and hypochlorite ions are formed. Hypochlorite ion is a better disinfectant than hypochlorite and has a higher concentration at low pH. When the pH is 7.3, the hypochlorite and hypochlorite ions can have the same concentration. The application of chlorine in water is always performed after treatment to avoid the formation of trihalomethanes and haloacetic acids (Lindsay, 2011).

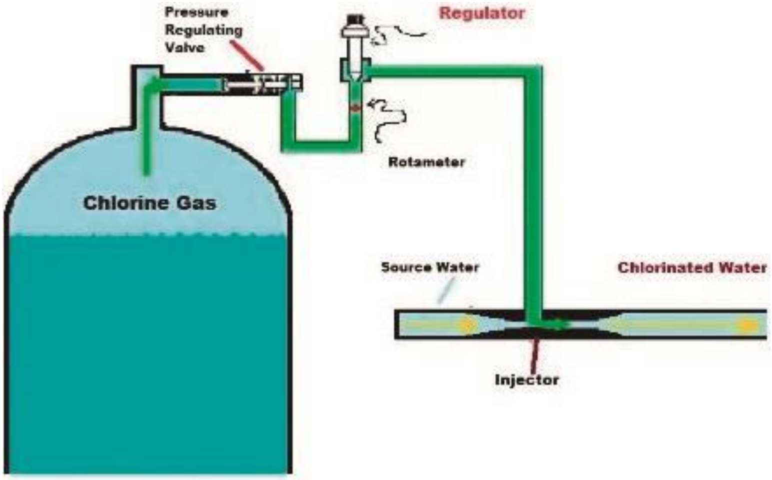


Figure 2. 6: Chlorine gas process (Saqib et al., 2018)

2.4.2.4.2.2 Sodium Hypochlorite Solution

Generally, sodium hypochlorite is used for bleaching purposes in textiles in papers. However, it can also be used as a disinfectant in solutions (including water). Compared with chlorine, sodium hypochlorite can reduce the hazards during storage and handling. It can be purchased or produced on-site; however, hydrogen is also be produced (Saqib et al., 2018).

Sodium hypochlorite is a solution with a chlorine concentration of 5% to 15%. Therefore, it is easier to produce and process than calcium hypochlorite or gas. However, it lacks stability and is corrosive. In addition, both salt and electricity need to be continuously available for on-site generation (Figure 2.7).

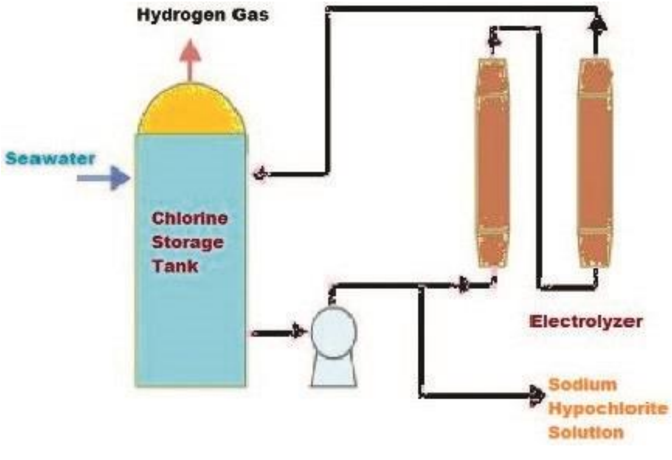


Figure 2. 7: Chlorination using chlorine liquid (Saqib et al., 2018)

2.4.2.4.2.3 Solid Calcium Hypochlorite

Solid calcium hypochlorite can substitute sodium hypochlorite solution as a disinfectant. It has the same characteristics and is safer to handle at the same time. It is suitable for wastewater and drinking water, and has very good stability when stored in dry areas (Saqib et al., 2018). However, contamination or improper use can cause explosions, fires, or the release of toxic gases. The solution must not come into contact with foreign objects, including other water treatment products. Even when exposed to a very small amount of water, it can produce toxic gases, heat, and splashes. Instead, it should be added to water rather than adding water. Heating will cause rapid decomposition, leading to an explosion, violent combustion, and the release of toxic gases. A dry, cool and well-ventilated area is required to store the product (Saqib et al., 2018).

A typical calcium hypochlorite system consists of a cylindrical PVC tank with a height of 0.6 to 1.2 m and a diameter of 230 to 610 mm. A sieve plate with holes is used to support calcium hypochlorite tablets with a diameter of 80mm. Each tablet usually provides 1 to 295 kg of chlorine per day.

Calcium hypochlorite can be added to the wastewater either by mixing calcium hypochlorite powder in a mixing unit and then injecting it into the wastewater stream or by immersing chlorine tablets in the wastewater using a calcium hypochlorite tablet (Figure 2.8) (Saqib et al., 2018).

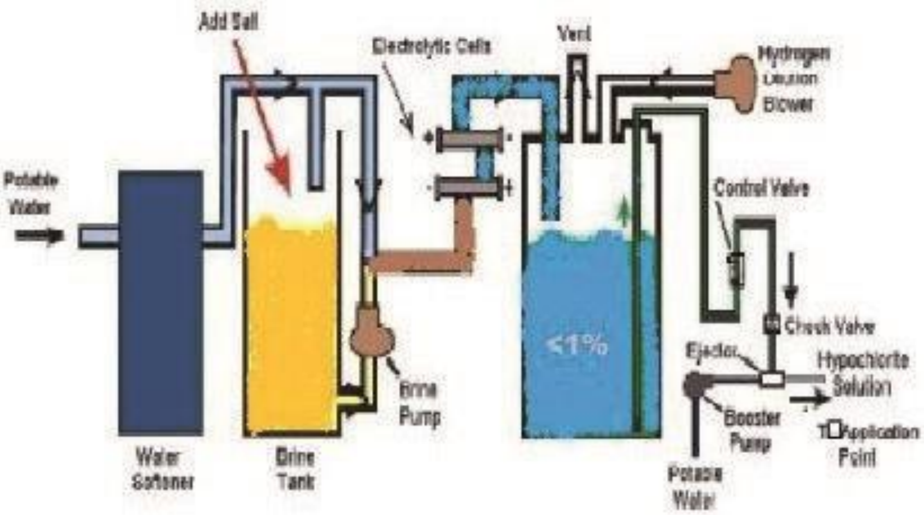


Figure 2. 8: Chlorination using calcium hypochlorite (Saqib et al., 2018)

2.3.2.4.2.4 Chloramines

Chloramine is obtained by reacting ammonia with free chlorine. They are more stable but are not strong disinfectants like chlorine and provide long-lasting residual disinfectants (Saqib et al., 2018). Chloramine chlorination does not produce any by-products.

The equipment required for chloramine production and the chlorination system is similar. Both chlorine and ammonia can be added in liquid or gaseous form. However, great care must be taken to avoid the use of concentrated chlorine and ammonia mixers because they will form nitrogen trichloride, a potentially explosive compound (Saqib et al., 2018).

2.3.2.4.2.5 Ozonation

Ozone is an unstable molecular formula of oxygen in which three molecules combine to form a new molecule. It quickly decomposes to produce active free radicals. The oxidation potential of ozone (-2.7 V) is greater than chlorine (-1.36 V) or hypochlorite ions (-1.49 V) or other substances widely used in wastewater treatment, except for hydroxyl radicals (•OH) and fluorides (Forero et al., 2001). Ozone has a strong oxidizing ability and requires a short reaction time to kill bacteria, including viruses. Ozone does not change color and produces a taste of water. It does not require chemicals, can destroy and remove algae, iron oxide, and manganese, and react and remove all organic matter (Saqib et al., 2018). However, since ozone is unstable under atmospheric pressure, it needs to be produced on-site. In addition, it is a greenhouse gas, which is toxic at high concentrations.

The ozone system consists of an ozone destroyer, an ozone contact chamber, and a generator (Figure 2.7). The ultraviolet or corona discharge process is used to generate ozone. Ozone is added to the water in the contact chamber, and the main function of the destroyer is to limit the amount of ozone removed into the air. After ozone is introduced into water, the ozone release process is decomposition, reaction with impurities in the water, and extraction into the atmosphere (Saqib et al., 2018).

Ozone is produced by ambient air and is processed to remove impurities, dry dust, or pure oxygen in the dust. Gas is converted to ozone through an electric field. Then, the ozone is supplied to the contact tank to be dissolved in water for the disinfection process (Saqib et al., 2018).

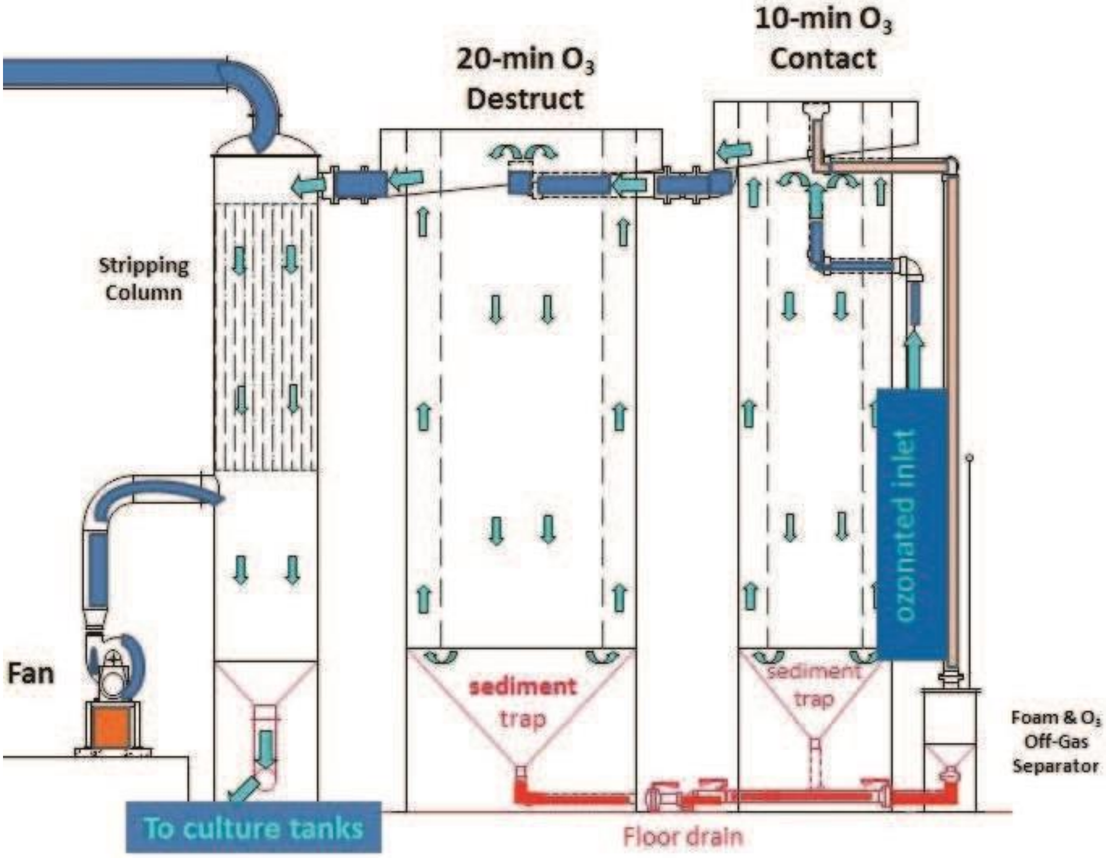


Figure 2. 9: Ozone plant (Saqib et al., 2018).

2.3.2.4.2.6 Ultraviolet light

Ultraviolet light can be utilized to treat drinking water, wastewater, and aquaculture. It transforms the biological elements of microorganisms by destroying the chemical bonds in DNA, RNA, and proteins, thereby achieving disinfection (Saqib et al., 2018). There are no by-products involved in water treatment using ultraviolet light. However, people are worried about the chemical composition and quality of microorganisms in the water because water containing many minerals will cause the lamp cover to form a coating, reducing the treatment effect. Phosphate syringes or water softeners can be used to prevent lamp coating.

The ultraviolet light water purification design consists of an ultraviolet light source encased in a transparent protective cover (Figure 2.8). The light source is installed to pass through the flow chamber to supply water to enter and absorb the light. The treatment does not change the taste or color of the water. Furthermore, the contact time is very short because these rays will quickly kill pathogens (AMA, 2000). UV lamps lose their effectiveness over time. Therefore, the bulb should be cleaned regularly and replaced once a year because a new bulb may lose 20% of its strength during the first 100 hours of operation.

One of the advantages of using ultraviolet in remote areas is that it does not require any consumable chemicals. Maintenance is simple, and there is no risk of excesses. Ultraviolet radiation does not leave any residue in the water. Ultraviolet rays have been used extensively to disinfect the water supply in small communities. It is one of the few small-scale water supply technologies that can effectively kill most harmful bacteria, viruses, and other microorganisms. Ultraviolet lamps will imitate sunlight. In nature, sunlight destroys some bacteria and purifies water naturally. The effectiveness of UV disinfection depends on the intensity and wavelength of the radiation. If the water is colored or turbid, the exposure to microorganisms will be reduced, and the disinfection efficiency will also be reduced.

During the first six months of equipment use, the water treated with ultraviolet rays should be regularly checked monthly for the presence of heterotrophic bacteria and coliforms (Saqib et al., 2018).

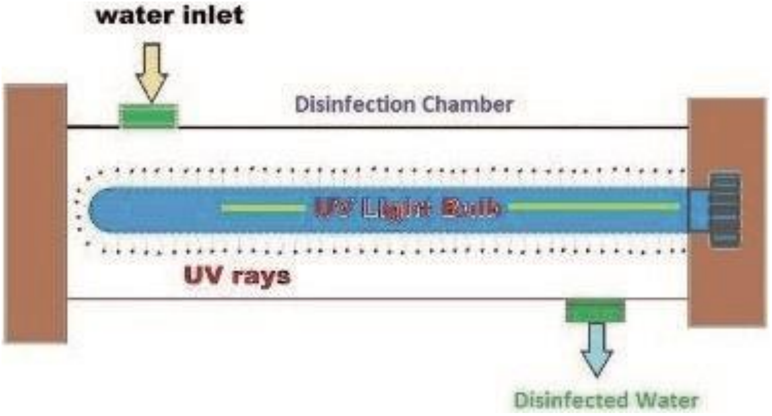


Figure 2. 10: Disinfection using ultraviolet light (Saqib et al., 2018)

2.3.2.4.2.7 Photocatalytic

Accelerating the photoreaction in the presence of a catalyst is called photocatalysis. In catalytic photolysis, the adsorbed substrate is used to absorb light. In photocatalysis, electron-hole pairs are generated by photocatalytic activity (PCA) to generate free radicals (hydroxyl radicals: • OH) for side reactions. By discovering the use of titanium dioxide to electrolyze water, its practical application becomes possible. The advantages of photocatalytic disinfection include (Saqib et al., 2018):

- The ability to use renewable and pollution-free solar energy; compared against traditional purification techniques,
- Photocatalytic leads to the formation of harmless compounds;
- The ability to destroy a wide range of these dangerous compounds in various wastewater streams.
- The process requires less chemical input, and the reaction time is moderate.
- Photocatalysis can be used to produce hydrogen, gaseous phase, and aqueous treatments for solid.

On the other hand, drawbacks of photocatalysis are that for titanium dioxide to be effectively used in water treatment, mass transfer restrictions must be minimized because photocatalytic degradation mainly occurs on the surface of titanium dioxide. TiO2 has a low affinity for organic pollutants (more specifically, hydrophobic organic pollutants), so the adsorption of organic contaminants on the TiO2 surface is low, resulting in slow photocatalytic degradation. Therefore, the pollutants around the TiO2 nanoparticles must be considered to improve photocatalytic efficiency. In addition, due to the instability of nanoparticles, TiO2 nanoparticles will aggregate, which will make it difficult for light to irradiate the active center, thereby reducing catalytic activity. However, it should be noted that small particles may exhibit greater scattering, which reduces their photocatalytic activity compared to larger particles. In addition, one of the main practical challenges of the grout system is the recovery of nano-sized TiO2 particles from the treated water, which involves economic and safety concerns (Saqib et al., 2018).

2.3.2.4.3 Water purification through desalination

Approximately 300 million people worldwide, especially in water scarcity areas, are provided with drinking water from desalination plants. It is reported that about 87 million m^3 of fresh water is treated daily through the desalination process (IWA, 2016). Additionally, desalination projects' increased water is expected to be around 12% every year from 2018 to 2022.

Most desalination plants use fossil fuels as the primary energy, and only less than 1% of plants use energy from renewable sources (IEA-ETSAP & IRENA, 2012). The primary issue with desalination plants based on fossil fuels is that coal and gas power plants require a huge quantity of water for cooling. Due to this issue, in 2010, an initiative for solar water desalination project was launched to increase water security and promote low-cost solar desalination systems development as the cost of the input energy is more than 50% of the plant cost (IEA-ETSAP & IRENA, 2012). In a desalination plant, the water source is not necessary. The seawater coming from other sources can as well be used, as shown in Table 2.6.

Table 2. 6: Characteristics of water sources (Olsson, 2015)

Water sources for desalination	(%)
Seawater	59
Brackish water	21
River water	9
Pure water for industrial processes	5
Used water for reuse	< 5

Solar desalination units can be divided into direct and indirect systems, as shown in Figure 2.11.

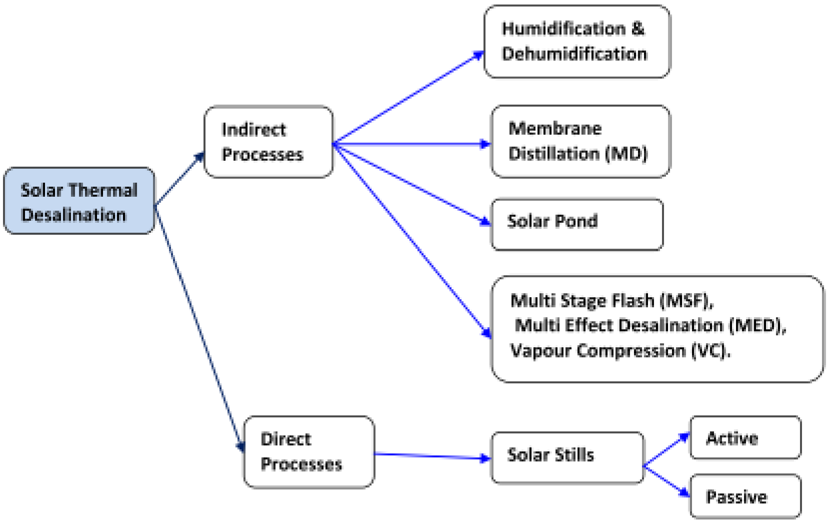


Figure 2. 11: Solar water desalination topologies (Shatat et al., 2013)

2.3.2.4.3.1 Indirect systems

By the indirect method, the solar desalination plant includes two main solar collectors and a desalination system. Different types of solar collectors, including flat plates, vacuum tubes, heat pipes, etc., can be used with thermal desalination processes such as membrane distillation, multi-stage distillation, vapor compression, and multi-effect evaporation (Shatat et al., 2013). Reverse osmosis is the most energy-efficient method for large-scale desalination systems, generating up to 1.8 kWh / m3 (M. & Yadav, 2017). Additionally, multi-stage, multi-effect flash evaporation reduces energy costs when coupled with solar concentrators and is suitable for small communities.

2.3.2.4.3.1.1. Solar desalination based on humidification and dehumidification

Through solar humidification and dehumidification processes, saltwater is heated to humidify the air, and freshwater is obtained by condensing the humid air generated at atmospheric pressure (Desware, 2002). Increasing air temperature can contain more water vapor (Desware, 2002). Its operating principle is based on water evaporation and the condensation of steam in the humid air. Convection guides the humid air between the evaporator and the condenser, and the humid air flows in a clockwise direction, as shown in Figure 2.12. Single tank heat preservation, consisting of condenser and evaporator. The brine evaporates through thermal energy and is slowly distributed. The air moves counter currently with the brine through the evaporator, and the air reaches saturation.

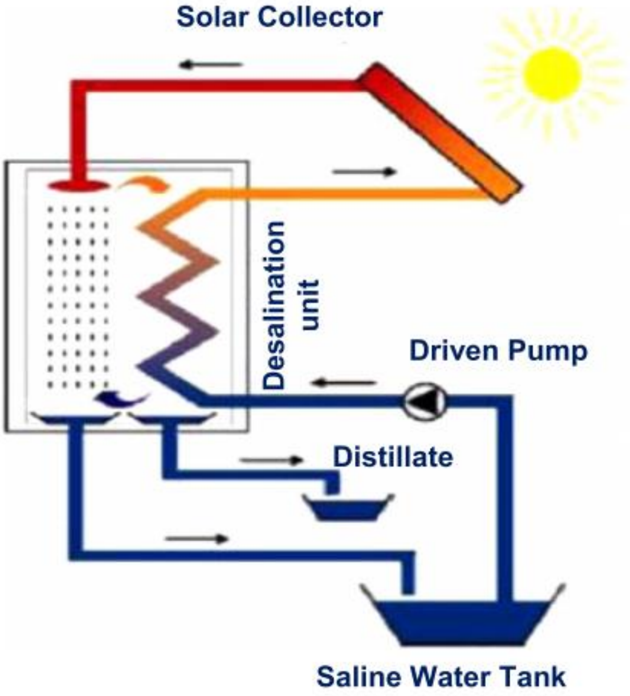


Figure 2. 12: Solar water desalination topologies (M. & Yadav, 2017)**.**

The new multi-effect air humidification and dehumidification unit can produce an average of 355 kg of freshwater per day per month and produce up to 516 liters of freshwater per day. However, the resulting costs are high (Narayan et al., 2010). Furthermore, freshwater is still very expensive due to the high cost of air collectors, humidifiers, and heat exchangers (Houcine et al., 2006).

2.3.2.4.3.1.2. Membrane distillation

In this process, the water is heated and then flows through the porous hydrophobic membrane. High pressure or electrical potential is applied to water vapor to produce freshwater (Sharon & Reddy, 2015). This process consumes a lot of energy (Ali et al., 2011). The difference in vapor pressure across the membrane allows the water vapor molecules to flow and condense on the other side of the membrane. The membrane distillation membrane has the following characteristics: high porosity, hydrophobicity, and low thermal conductivity.

2.3.2.4.3.1.3. Multistage flash

This desalination process involves raising the temperature of the brine feed above its saturation value in a brine heater and flashing it gradually with a decrease in pressure. Use a vacuum pump to maintain low pressure at each stage of the vessel. The brine discharged from each step can be flashed in successive stages, the steam formed in the successive stages is condensed in the condenser, and the incoming feed brine is preheated there. Many remote and coastal areas do not have the power to use traditional desalination technologies (such as multi-stage flash evaporation, reverse osmosis, and vapor compression) to produce drinking water (Eltawil et al., 2009; Bhardwaj et al., 2015; Kalogirou, 2005; Xiao et al., 2013). Conventional processes such as multi-stage flash evaporation and reverse osmosis require large amounts of thermal energy (multi-stage flash evaporation) or electrical energy (reverse osmosis) (Narayan et al., 2010). This process generally requires an external steam supply at a temperature of approximately 100 ° C. The maximum operating temperature is limited by fouling, so the thermodynamic performance of the process is also limited.

2.3.2.4.3.1.4. Vapor compression

Water desalination using vapor compression consists of using solar energy to heat the feed saline water. The vapor produced is then compressed through a mechanical vapor compressor or Thermo vapor compressor to increase the temperature and pressure of the vapor. Finally, the same pressurized fluid is utilized to preheat the same feed saline water in other sages. The schematic diagram of the mechanical vapor compression water desalination system is shown in Figure 2.13.

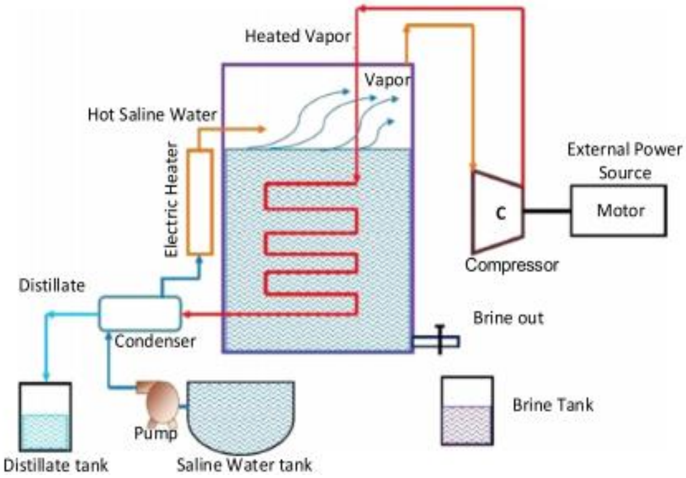


Figure 2. 13: Solar water desalination topologies (Chandel et al., 2017)**.**

2.3.2.4.3.1.5. Solar pond

The solar pond can be used as a heat storage device for the desalination process. In low sunshine or nighttime and seasonal cycles, you can obtain continuous and stable water production through thermal energy storage. Solar pools have a unique ability to capture and store the sun's heat for months, even in harsh and cloudy seasons. This is a clear advantage compared to other solar energy collection methods. In natural ponds, heat from the sun radiates to the pond's bottom and heats the water. The heated water layer is lighter than the top layer and rises to the pond's surface, where it then generates convective motion and heat loss to the atmosphere. This cycle of convection continues, and the pond temperature generally remains constant.

2.3.2.4.3.1.6. Multi-effect distillation

In a multi-effect distillation unit, heat from the condensation surface from the previous still is transferred to preheat the water in the next still. The thermal energy required for evaporation is supplied by solar energy. The latent heat of evaporation in the vapor is given up to the next stage. The distilled water obtained is three times more than the single effect, as shown in Figure 2.14.

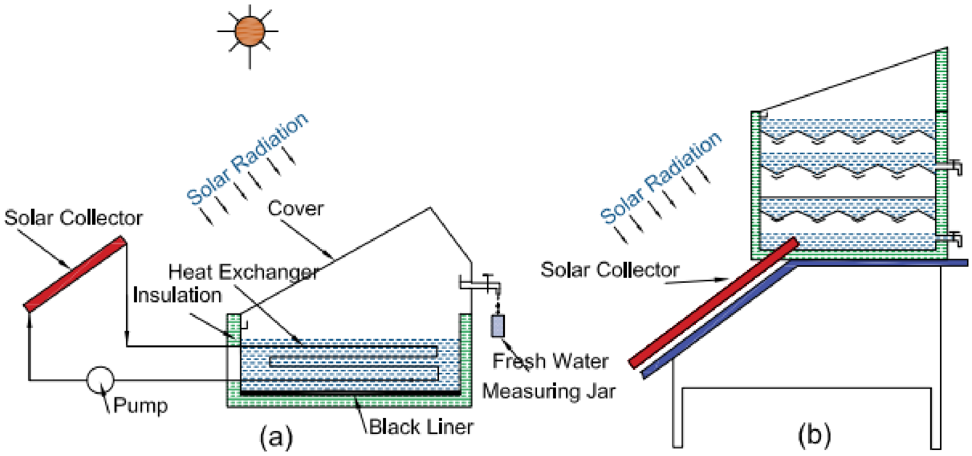


Figure 2. 14: Solar water desalination topologies (Chandel et al., 2017)**.**

2.3.2.4.3.2 Direct systems

In the direct system, the thermal desalination process takes place in the same unit. It is mainly suitable for small production systems, such as solar stills, where the daily demand for freshwater is less than 200 cubic meters (Ma & Lu, 2011). Solar distillation Distillation represents a small-scale natural hydrological cycle. The basic solar distiller is shown in Figure 2.13. The system operates to capture solar radiation passing through the transparent cover. It consists of a basin filled with saltwater and a pair of glass or plastic plates. These plates are inclined on the basin and meet at the top, forming a structure much like a greenhouse. The sinks are usually painted black to maximize the absorption of the longwave radiation that falls on the surface. Solar radiation falls on the inclined panel. The seawater desalination device of the internal solar still raises the temperature of the brine in the basin. The water on the surface evaporates, and the water vapor rises in the still and reaches the slanted panel, where it condenses into liquid water and flows down the sides of the panel. The solar still can produce 3 to 4 liters of freshwater per square meter per day. Due to low productivity, it is necessary to minimize capital costs by using inexpensive building materials. Efforts have been made to improve the efficiency of the solar still by changing the design, using additional effects such as using multi-stage vacuum stills, and adding absorbent materials. These improvements have increased the yield per unit area (Buros, 2000). In a basic solar still, the latent heat from condensation dissipates into the atmosphere. However, the latent heat from condensation can be used to preheat the feedwater and improve efficiency.

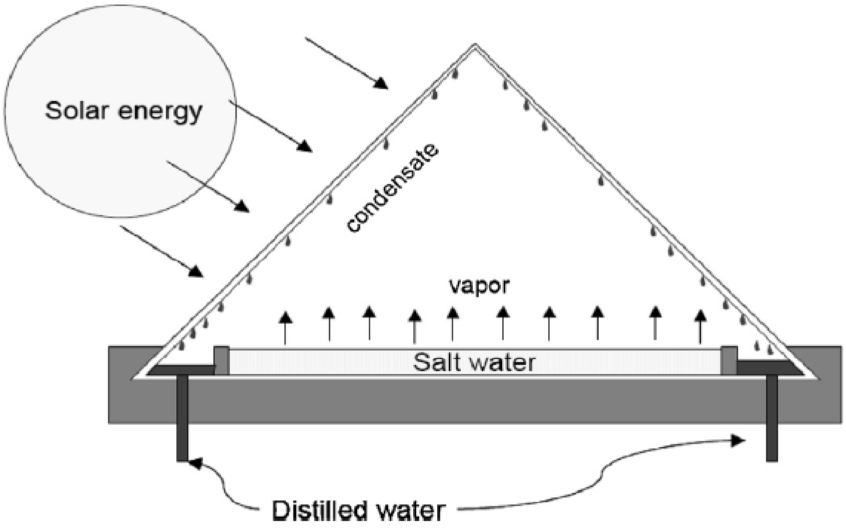


Figure 2. 15: Basic solar still (Chandel et al., 2017)**.**

The solar distiller shown in Figure 2.15 is cheap, simple to operate, does not require much energy, and does not produce harmful gases. They are easy to build and cheaper than other desalination systems. In addition, their design and manufacture are simple and can produce 4 to 6 liters per (m^2/day) (Al-Karaghouli et al., 2009). However, solar distillation technology requires a large area of solar energy collection. Therefore, they are not suitable for mass production, especially near cities where land is scarce and expensive.

Also, the relative installation cost is usually much higher than the installation cost of other systems. The solar Still is also vulnerable to weather damage. Labor costs are a bit high because regular maintenance is required to prevent scale formation and repair steam leaks and damaged glass panels (Buros, 2000). However, they are economically viable for small-scale production in homes and small communities, especially where solar energy and low-cost labor are available (Al-Karaghouli et al., 2009).

The solar still consists of a blackened basin filled with brackish water or saltwater and covered with tilted glass to transmit solar radiation and condensation. Solar radiation entering the basin heats the darkened lining, thus heating the water and causing evaporation. Due to the partial pressure difference and the temperature difference, the water vapor condenses with the sloping glass cover and accumulates at the bottom (Sharon & Reddy, 2015). The water obtained is pure, and a small amount of mineral sand can be added to improve it and reduce the corrosivity of the material (WHO, 2012).

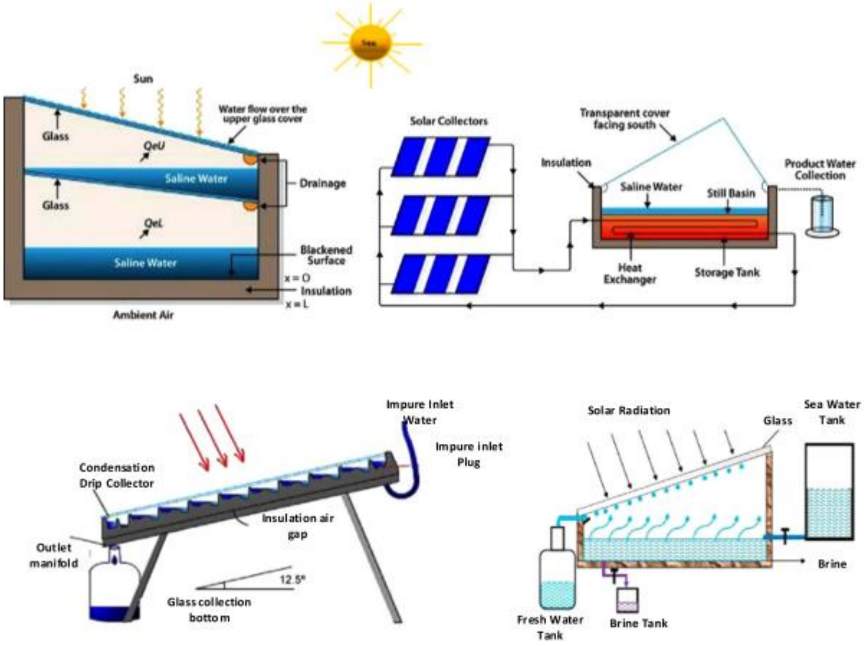


Figure 2. 16: Solar water desalination topologies (Shatat et al., 2013)**.**

CHAPTER THREE
SOUTH AFRICA WATER DELIVERY AND SANITATION

3.1 Introduction

Both achievements and challenges can describe South Africa's water supply and sanitation facilities. After apartheid, the newly elected government of South Africa fought against the accumulation of development services and the stagnation of water and sanitation. Therefore, the government is committed to achieving these standards with high standards of service and a high level of funding subsidies. Since then, the country has made some progress in improving the water supply. South Africa has achieved universal access to improved water sources in metropolitan areas and remote areas. From 1990 to 2010, the proportion of the population with access increased from 66% to 79%.

South Africa also has a reliable water industry and has a long history. However, improvements in hygiene have been much less. During the same period, the number of visits increased from 71% to 79%. There are still major issues related to the economic sustainability of service providers, leading to a lack of maintenance. Uncertainty about the ability of public authorities to continue to subsidize the level of the region is also worrying. The two main features of the South African water sector are the free basic water policy and the existence of the Water Commission, the bulk water supplier's office operating in the pipeline. They provide water to the area from the reservoir (WHO & UNICEF, 2017).

In May 2014, it was announced that the Durban Water Supply and Sanitation Department won the Stockholm Industrial Water Award “for its extraordinary and comprehensive approach”, calling it “one of the most innovative public utilities in the world (CISION PR NEWSWIRE, 2014). The city provided tap water for another 1.3 million people and provided toilets for 700,000 people in 14 years. It is also the first area in South Africa to test free basic water for the poor. In addition, it also has advanced water traps, smaller water and electricity than normal, and the urine is redirected to dry toilets.

On February 13, 2018, the country announced a public disaster in Cape Town, as it was gracefully expected that its water would run out before the end of June. Since the dam's capacity is only 24.9% of its capacity, each inhabitant must use less than 50 liters of water per day. Each of the country’s nine provinces is under the influence of public authorities and has been described as the “enormity and severity” of the three-year drought. As the forecasts supported by the United Nations indicate, Cape Town is one of the 11 largest cities in the world that may suffer from water shortages (BBC NEWS, 2018).

3.2 Water accessibility and resources in South Africa

The availability of water resources in South Africa has undergone tremendous changes in time and space. The western region is dry, with rainfall as low as 100 mm throughout the summer, while the average annual rainfall in the eastern and southeastern regions is as high as 1,000 mm. According to data sources (United Nations, 2002; FAO, 2016), the annual total surface runoff is estimated to be 43 to 48 square kilometers (UN, 2002; FAO, 2016).

Most of the runoff is lost due to flooding and the goal is to assess available surface water assets at 14 square kilometers per year. Although groundwater is restricted due to geological conditions, it is widely used in more arid areas. Available groundwater is estimated to be 1 square kilometer per year. Compared to the great rivers of the world, the major rivers of South Africa are insignificant. For example, the Nile River discharge alone is several times greater than the total surface water assets available from all the waterways in South Africa (Anon, 2019; Anon, 2020).

The main rivers are the Orange River, the Tugela River, the Incomati River, the Olifants River (Limpopo River), the Maputo River, and the Breed River that consumes the Limpopo River. The uMkhomazi, Maputo, Tukla and Limpopo rivers flow into the Indian Ocean. The most important river in South Africa is transboundary: the Orange River passes into Botswana, Namibia and Lesotho, the "water tower" of southern Africa. The Limpopo Olifants River Bowl gives into Botswana, Zimbabwe and Mozambique, which are the furthest downstream. A global committee of all coastal countries has been established to deal with these transboundary water resources (Anon, 2019; Anon, 2020). Possible future water assets are desalination or water exchange in the Zambezi.

Total annual water withdrawal in 2000 was estimated at 12.5 square kilometers, of which about 17% was used for urban water use (UN, 2002; FAO, 2016).

Almost all surface and groundwater resources have been developed and used in the northern part of South Africa. In the southeastern part of the country, where water resources are abundant, there are many scarce and little-used assets (FAO, 2016). The province of Gauteng around Johannesburg is very water short and draws water from different dams in the area. For example, the Val Dam and the Orange River lattice intake through the Lesotho Highlands Water Project, especially from the Katse Dam. (RAND WATER, 2010). Cape Town’s drinking water comes from various rivers and dams, including the Burg River Dam.

3.3 Wastewater reuse

In South Africa, the small town of Garden Route in George Town is facing water shortages. They decided to adopt the circulating water method (2009/2010). The final effluent from the Outeniqua Wastewater Treatment Plant undergoes ultrafiltration and disinfection treatment before returning to the main storage facility of the Garden Route Dam, where it merges with the raw water supply. This activity increases the current supply by 10,000 cubic meters per day, accounting for approximately 33% of drinking water demand. The circulation setting includes the following treatment measures: drum screen, ultrafiltration and chlorine disinfection.

In Beaufort West, due to severe water shortages (2,300 cubic meters per day), South Africa's direct wastewater recycling plant for drinking water production was completed at the end of 2010 (Burgess et al., 2015). Adjustments Processes include the following treatment measures: sand filtration, ultrafiltration, secondary reverse osmosis, and ultraviolet sterilized permeate.

Another example of direct drinking reuse is the reuse factory built-in Hermanus (Overberg), where 2,500 cubic meters are reused per day, and preliminary arrangements are made to increase it to 5,000 cubic meters per day. Treatment measures include ultrafiltration pretreatment, reverse osmosis desalination, advanced oxidation and carbon filtration. The water from the reuse plant is utilized directly in the drinking water system (Burgess et al., 2015).

3.4 Access to water and sanitation

South Africa is one of the few countries on the planet that values the fundamental right to adequate water in the Constitution. However, much work is still to be done to make this right a reality (Anon, 2007). After apartheid, in 1990 in South Africa, the democratically elected government obtained a huge management surplus in the provision of water and disinfection. by a source Approximately 15 million people do not have safe drinking water, and more than 20 million people do not have adequate disinfection management (Busari & Jackson, 2006).

In 2015, the number of people in South Africa without an improved water supply was 3.64 million (UNICEF & WHO, 2015). That year, 93% of the population was close to enhanced water sources (Schreiner, 2020). However, in May 2004, the then president had guaranteed that all households would have running water within five years (Schreiner, 2020). Although significant progress has been made, this goal has not been fully achieved. In some rural areas, women spend up to 33% of their time collecting water from streams and wells (Adam, 2021). They are also responsible for using it for cooking, washing clothes and washing children.

In 2015, the total number of people in South Africa without access to improved sanitation facilities was 18 million (UNICEF & WHO, 2015). This means that only 66% of the population received better sterilization that year.

According to a survey and census data of the Global Water Supply and Sanitation Joint Monitoring Program, the proportion of South Africans who received improved sterilization techniques gradually increased from 71% in 1990 to 75% in 2000 and 79% in 2010. In 2010, it was estimated that 11 million South Africans will not come close to improving disinfection levels (JMP, 2021).

As per the 2011 South Africa statistics, access to sanitation facilities increased from 83% in 2001 to 91% in 2011, including shared and separate pit toilets and chemical toilets (Kings, 2017). The proportion of households with access to flush toilets increased from 53% in 2001 to 60% in 2011. The impact of poor sanitation can be significant, as evidenced by the estimated 1.5 million cases of diarrhea in younger children five-year-olds and the cholera incident of 2001.

3.5 Water quality and continuity of supply

Water quality varies greatly, and the data is unclear. In 2003, 63% of cities could not prove whether they met drinking water quality standards. In 2003, 37% of households were without water for about one day (Itano, 2002). Consumers do not, and sometimes still do not believe that the quality of their drinking water is good enough. This led to the introduction of blue drip water quality control by the Ministry of Water Affairs in 2008. According to the plan, if urban service providers meet specific needs, they will receive a certificate with a blue mark. These include an agreement with water quality standards and water safety strategies, process control, and reliability of sample results. (Statistics South Africa, 2012)

This system is considered a unique feature in drinking water control globally and is widely accepted by the World Health Organization. However, private sector viewers said that the quality of water across the country is deteriorating, “and the government is trying to destroy the reputations of those who express those opinions. (DWA, 2001) In 2009, 23 water supply units received Blue Drop certification. In 2010, 9 companies withdrew from recognition, and 24 companies were recognized for the first time, bringing the total number of certified companies to 38 (less than 5 %). Eutrophication is an evolving problem (Development Bank of Southern Africa, 2006). Approximately 33% of the water volume is held in significant storage, no longer suitable due to the absence of large-scale and costly management involvement. Return flows out of mining zones, especially from gold mining plants, quickly worsen, with highly acidic water decanting from surrendered and abandoned mines (The New Humanitarian, 2008).

3.6 Wastewater treatment

Approximately 55% of sewage treatment facilities, especially small factories, do not meet the effluent standards, and some do not even quantify the effluent quality. The public sector initiated the municipal sewage treatment green drop certification regarding the drinking water blue drop certification system. As of 2011, 7 out of 159 water supply units and 32 out of 1,237 sewage treatment plants were recognized as green declines. (DWAF: Department of Water Affairs, 2011) In 2009, when 449 sewage treatment plants were evaluated, according to legal government information, 7% were classified as well-managed, 38% met the standard, and 55% met the standard. (Department of Water Affairs, 2010)

3.7 Water and sanitation stakeholders

South Africa's water and sanitation sector is divided into three unique stages:

- The national authority represented by the water and sanitation sector acts as a policy-making agency,
- Water Authority primarily provides bulk water and provides some retail services, and treats some Wastewater Treatment Plants while serving a water control function,
  and municipalities providing full services retailers even have some bulk supply infrastructure.

In addition, banks, WISA professional associations, water research committees and civil society are also important stakeholders in the sector.

3.7.1 Regulation and Policy

The water affairs department of the Ministry of Water and Environment is usually responsible for the formulation and implementation of water resources management and drinking water transportation policies. The independent investigation report indicated that authorities at all levels still lack oversight of sanitation facilities. Since 2010, health issues have shifted from the water sector to the human settlements sector, although some regulatory functions appear to remain the responsibility of the water sector, creating confusion between the roles and responsibilities of the agency. (Tissington, 2011)

3.7.2 Service provision

All entities share the obligation to provide services. The country’s 231 cities are responsible for delivering water and sanitation facilities through municipal companies or individual companies. The Government Water Authority is responsible for operating a large amount of water supply infrastructure and some wastewater systems. The price range of the TransCaledon Tunnel Authority and the development of a large number of water supply infrastructure and dams.

According to the Constitution, the Municipal Structure Act, and the 1997 Water Supply Act (Republic of South Africa, 1997), the water service authority bears the water supply and sanitation obligations. The Water Supply Act stipulates how municipal authorities perform their duties. The country comprises 278 municipalities, including 8 metropolitan areas, 44 districts and 266 municipalities (Republic of South Africa, 2019).

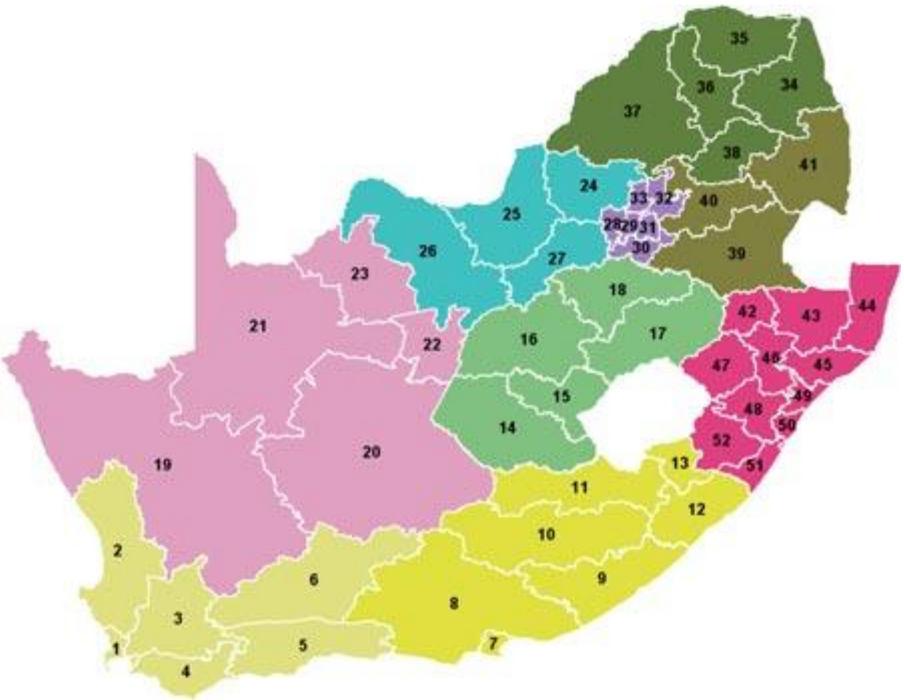


Figure 3. 1: South Africa map of districts (South Africa Explore, 2020)

In many cases, the district municipality is the water supply entity, but the national authority may assign service provision obligations to the local municipality. There are 169 water supply agencies, water offices, district municipalities, local municipalities and municipal companies in South Africa. Municipalities provide water and sanitation services immediately through municipal units or departments; for example, eThekwini in Durban provides these services through the eThekwini Water and Sanitation Unit. (eThekwini Municipality, 2011)

However, they can delegate this responsibility to the water service provider within a specified time. For example, in 2001, the city of Johannesburg established the Johannesburg Water Company, a legally and financially independent company wholly owned by the city. This is an integral part of the transformation plan initiated by the Johannesburg Municipality during this period. Johannesburg Water Company has agreed to comply with the King Report on Corporate Governance (Manual of Operational Guidelines and Corporate Governance Structure), which includes affirmative action, transparency, general performance evaluation and ethical threat management guidelines, and sustainability reports. The 1996 Constitution strengthened the autonomy of the municipalities so that rural water supply and sanitation facilities have been transferred from national to municipal authorities.

Some municipalities link the private sector to contracts for specific services in various ways to provide services, such as wastewater treatment, temporary management contracts, and long-term concessions (Chirwa, 2004).

The 15 government water offices have played an important role; they operate dams, bulk water supply systems, retail infrastructure, and wastewater treatment plants. In addition, some provide technical assistance to municipalities (Republic of South Africa, 2020).

The Trans-Caledon Tunnel Authority is a state-owned entity whose mission is to fund and influence bulk raw water infrastructure. It was established in 1986 to augment the Lesotho Highlands Water Mission in the Lesotho-South Africa cooperation project. Since 2012, the agency has been developing another six dams and bulk water supply projects. It sells water in bulk to the state, represented by the water authority, because it is the owner of the water authority, responsible for treating the water and selling it directly to municipalities and mines. The Trans-Caledon Tunnel Authority used the sale to pay off the debt it incurred for infrastructure financing, labor costs and royalties paid to the Lesotho government (TCTA, 2020).

South Africa has a fairly strong research and education infrastructure in the water sector. The Water Research Council funds water research and development and establishes sustainable water research capacities in the country, and assumes the role of the national water knowledge entity in the creation, dissemination and application of knowledge of water resources in the management of water resources, water ecosystems, water use and waste management and water use for agriculture (WATER RESEARCH COMMISSION, 2018).

The Southern African Water Research Institute is a professional subsidiary organization that keeps participants informed of modern developments in water technology and research through its national and global contacts, contacts and associations. (WISA, 2020)

The Southern African Development Bank is a major player in the water and sanitation sector, a financier, consultant and project sponsor. From 2005 to 2006, approximately 29% of approved initiatives were used for water supply and sanitation. Other financial institutions in the industry include Infrastructure Finance Corporation Limited, the world's only 100% private infrastructure debt fund.

CHAPTER FOUR
SITE SELECTION AND CHARACTERISTICS

A feasibility study of an isolated solar water purification requires a site with adequate resources. South Africa has a wealth of solar resources with readily available topographic and geographic resource information. The study considers a farming community of fifty households in The Mbhashe Local Municipality in the Eastern Cape province of South Africa.

4.1 Background of the selected site

4.1.1 Demography of Mbhashe

The local municipality of Mbhashe has an area of 3169 km^2 and is located within the Amasole area of the southeast part of the Eastern Cape. It includes Idutywa, Elliotdale, and Willowvale towns, and many cities and rural settlements. The municipality is limited by the Quora River and the Mincwasa River along the Indian Ocean. The northeast is the city of Sabata King Darindibo, the south is the city of Mkuma, the southwest is the city of Ntikayetu, and the west is the city of Nkobo. Its name comes from the river called Mbhashe, which flows from the banks of the eNgcobo river. The main towns in Mbhashe are Dutywa, Elliotdale, and Willowvale (Malusi, 2017).

Figure 4.1 shows the location of the city of Mbhashe, including the areas where Elliotdale, Willowvale, and Dutywa TLCs and TRCs were formerly formed. The farming sector of Mbhashe is mainly used for subsistence, and the subsistence agricultural sector is the most critical contributor to the municipality's economy. Several households rely heavily on agriculture for their livelihoods. The area of a municipality is mainly public land use rights. Agriculture is based primarily on small-scale agriculture and animal husbandry with open pastures (Malusi, 2017).

Mbhashe has 269,000 residents, and in 2016 it was home to 0.5% of South Africa's population. Based on the current age and gender structure and current fertility, mortality, and migration rates, the population of Mbhashe is estimated to grow at an average annual rate of 0.7%, from 269,000 in 2016 to 280,000 in 2021.

Figure 4. 1 Map of Mbhashe Local Municipality (Google, 2021)

Table 4. 1: Mbhashe population, unemployment rate, education levels, number of households, and dwelling (Municipality, 2016)**.**

Population 254909	**Unemployment rate 42.4%**	**Education levels**	**Households 60124**	**Formal dwellings 30.9%**
Young (0 – 14) 38 %	Youth unemployment rate 50.7%	No schooling aged 20^+ 21.2%	Agricultural households 36377	Housing owned/paying off 73,6%
Working-age (15 – 64) 53.9%	-	Higher education aged 20^+ 5.1%	Average household size 4.1	Flush toilet connected to sewerage 3,8%
Elder (65^+) 8.1%	-	Matric aged 20^+ 10.2 %	Female-headed households 58.3 %	Weekly refuse removal 3,1%
Dependency ratio 85.5	-	-	-	Piped water inside dwelling 3,5%
Sex ratio 85.1	-	-	-	and Electricity for lighting 49,7%
The population growth rate of 0.35%	-	-	-	
Population density of 80 individuals per km^2	-	-	-	

Compared to other regions, the Mbhashe Local Municipality population represents 31.6% of the Amatole District Municipality population in 2021 (Table 4.2).

Table 4. 2 Population of Mbhashe Municipality from 2016 to 2021 (Municipality, 2016)**.**

Year	Mbhashe	Amatole	Eastern Cape	National Total	Mbhashe as % of the district municipality	Mbhashse as % of the province	Mbhashse as % of national
2016	269000	862000	7010000	55700000	31.2	3.8	0.48
2017	271000	866000	7080000	56500000	31.3	3.8	0.48
2018	273000	870000	7160000	57400000	31.4	3.8	0.48
2019	275000	875000	7240000	58100000	31.5	3.8	0.47
2020	277000	880000	7310000	58900000	31.5	3.8	0.47
2021	280000	886000	7380000	59600000	31.6	3.8	0.47

Figure 4.2 compares the population structure of Mbhashe from 2016 to 2021. The feature of 2016 is that the proportion of young workers aged 20 to 34 (24.2%) is higher than that in 2021 (22, 5%). The population of this age group will decrease over time. The fertility rate in 2021 is expected to be significantly higher than in 2016. Compared with 2016 (36.2%), the proportion of children aged 0-14 in 2021 is expected to drop significantly (34.6%).

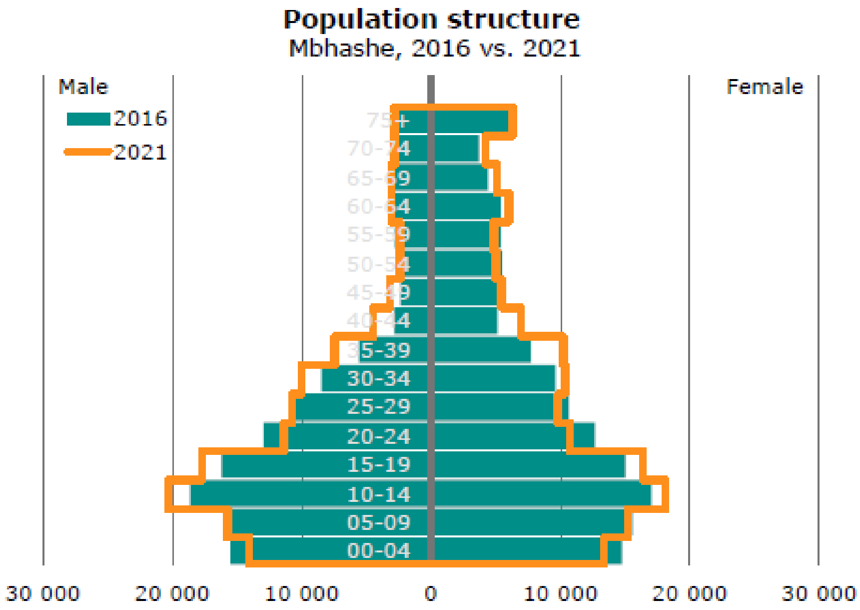


Figure 4. 2 Comparison of Mbhashe Population from 2016 to 2021 (Statistics South Africa, 2012)**.**

In 2016, the female population in the 20-34 age group accounted for approximately 12.2% of the total female population, while the male population accounted for almost 12.0% of the entire male population. In 2021, 11.5% of the male working-age population is still higher than 11.0% of the female working-age population, but both are lower than 2016.

4.1.1.2 Population of Mbhashe Municipality by group, gender, and age

The total population is defined as the total number of residents quantified in a given area in the middle of the year. The total population can be grouped according to population groups and subcategories of age and gender. The population groups include Africans, whites, people of color, and Asians, and the Asian group includes all people from Asia. The age subcategory divides the population into 5-year-old cohorts.

Table 4. 3 Mbhashe population based on gender (Statistics South Africa, 2012)**.**

	Male	**Female**	**Total**
Mbhashe	126000	143000	269000
Mnquma	117000	128000	244000
Great Kei	14900	15500	30400
Amahlathi	47900	51600	99500
Ngqushwa	29700	33000	62700
Raymond	75700	80100	156000
Amatole	411000	451000	862000

The latest data on the population group, gender and age of Mbhashe dates back to 2016. The male/female population of Mbhashe can be divided into 87.9 males per 100 females. Compared with a typical stable population, the local municipality of Mbhashe has significantly more women (53.22%) than men. This is likely to be an area where men have moved to other places to find work. In total, there are 143,000 (53.22%) women and 126,000 (46.78%) men (Table 4.3). This is different from the general situation in the Amatole district, where the female population is 451,000, representing 52.35% of the total population of 862,000.

In 2016, the population of the local municipality of Mbhashe included 99.49% of blacks (268,000), 0.20% of whites (532), 0.17% of color people (448), and 0.14% of Asian (381) (Municipality, 2016).

The most important part of the population is the child age group (0-14 years old). The total number is 97,500, accounting for 36.2%. The second most populous age group is the youth working-age group (2544 years old), accounting for 22.5% of the total share, followed by the adolescent and youth age group (1524 years old), with 56800 people.

The age group with the least number of people in the retirement/senior-age group (65 years and over), with only 22,300 people (Municipality, 2016).

Table 4. 4 Mbhashe population in 2016 based on gender and age (Municipality, 2016).

Population	**African**		**White**	
Age	Male	Female	Male	Female
0-4	15500	14700	9	14
5-9	16100	15500	8	11
10-14	18600	17000	9	7
15-19	16100	14900	41	32
20-24	12800	12600	40	34
25-29	10700	10600	21	27
30-34	8400	9560	26	26
35-39	5510	7670	33	14
40-44	2800	5080	11	13
45-49	2340	5000	15	19
50-54	2600	5490	7	3
55-59	2780	5360	11	7
60-64	2910	5360	13	14
65-69	2980	4350	7	24
70-74	2560	3690	8	11
75+	2670	5900	7	10
Total	125000	143000	268	265

4.1.1.3 Mbhashe household by population group

A household is a group of people who live together and provide food and other necessities together or a person who lives independently. If a person spends at least four nights at home a week, they are considered part of the family. To classify households according to population groups, the group to which the user belongs.

If the number of households is growing faster than the population is growing, the average household size is shrinking, and vice versa. In 2016, the local municipality of Mbhashe consisted of 63,800 households. This represents an average annual growth rate of 0.86% in households from 2006 to 2016. The average annual growth rate of the total population is 0.05%, and the average family size in the municipality of Mbhashe has diminished. The data confirm that the average family size in 2006 decreased from approximately 4.6 persons per household to 4.2 persons per household in 2016 (Municipality, 2016).

Table 4. 5 Mbhashe households from 2006 to 2016 (Municipality, 2016).

Year	Mbhashe	Amatole	Eastern Cape	National Total	Mbhashe as % of the district	Mbhashe as % of the province	Mbhashe as % of national
2006	58600	218000	1570000	13000000	26.8%	3.7%	0.45%
2007	59100	219000	1590000	13100000	27.0%	3.7%	0.45%
2008	60300	223000	1620000	13400000	27.1%	3.7%	0.45%
2009	62000	227000	1670000	13700000	27.3%	3.7%	0.45%
2010	62300	227000	1680000	13900000	27.5%	3.7%	0.45%
2011	62500	226000	1700000	14200000	27.6%	3.7%	0.44%
2012	62800	227000	1720000	14500000	27.7%	3.7%	0.43%
2013	62900	226000	1730000	14700000	27.8%	3.6%	0.43%
2014	62800	225000	1740000	15000000	27.9%	3.6%	0.42%
2015	63200	226000	1770000	15400000	28.0%	3.6%	0.41%
2016	63800	227000	1790000	15800000	28.0%	3.6%	0.40%
Average annual growth							
2006-2016	**0.86%**	**0.40%**	**1.32%**	**1.97%**			

Compared to district municipalities, Mbhashe has a higher average annual growth rate from 2006 to 2016, which is 0.86%. In contrast, the province's average annual growth rate as of 2006 was 1.32%. A total of 15.8 million households in South Africa have a growth rate of 1.97%, so the growth rate is higher than that of Mbhashe (Municipality, 2016).

The composition of households by population category represents 99.5%, which belongs to the African population category with the highest number of households by population. The total Asian population is 0.2%, while the entire composition of the white population accounts for 0.2% of all households. The smallest population group by family is people of color, accounting for only 0.1% in 2016.

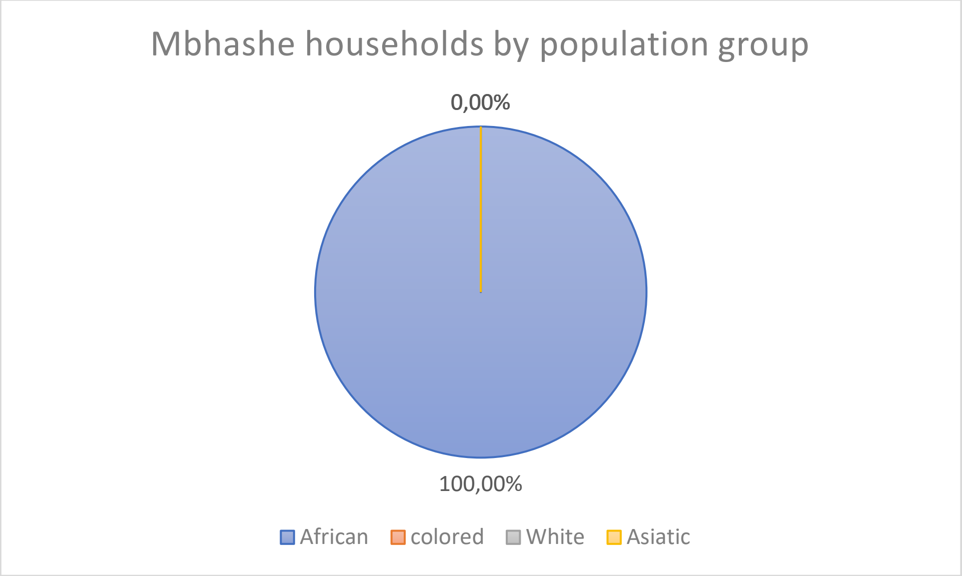


Figure 4. 3: Mbhshe households by population groups (Municipality, 2016).

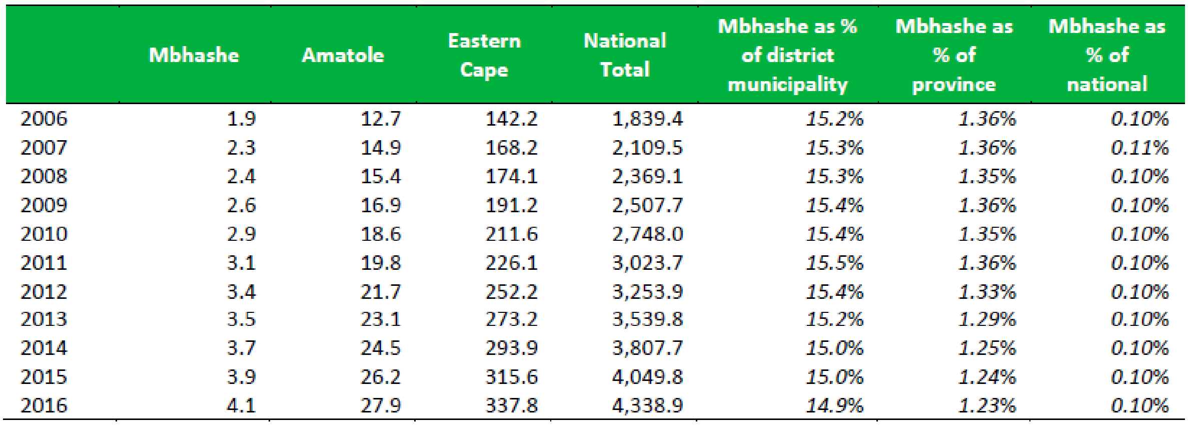
Between 2006 and 2016, the number of African-headed households increased by 0.84% per year, implying that the families increased by 5,080. Although the Asian population group is not the largest, it was the fastest-growing population group between 2006 and 2016, reaching 18.33%. The average annual growth rate of households in all other population groups increased by 0.84% (Municipality, 2016).

4.1.2 Economic growth of Mbhashe Municipality

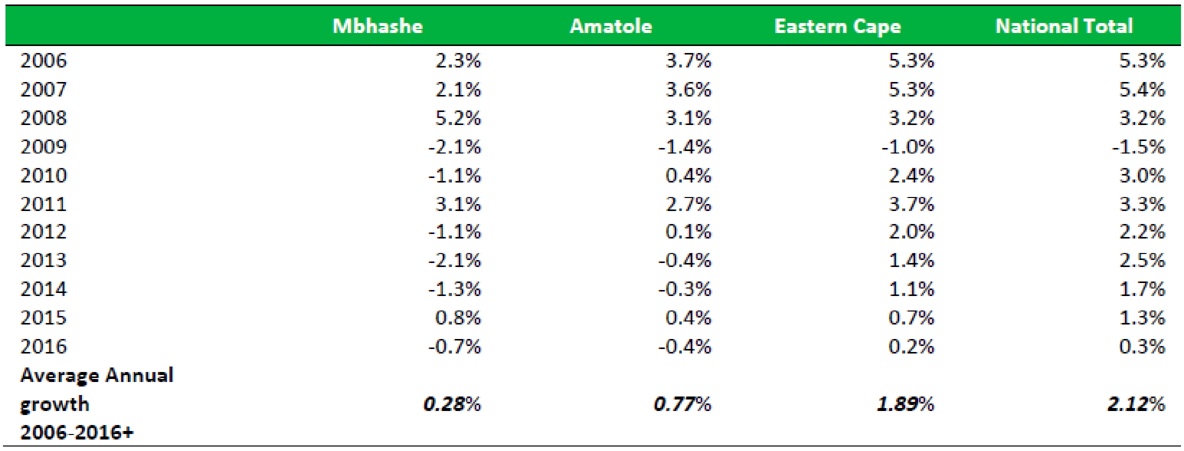
Gross domestic product (GDP) is an essential indicator of economic performance used to compare economies and economic conditions. It describes the value of all goods and services produced in a region in one year, including taxes and fewer subsidies. You can use current prices or constant prices to evaluate GDP, where current prices are measured in real rands, while constant prices measure the economy by removing the effects of inflation. Therefore, the real growth in quantity is captured as if the price were at a particular value. The situation is the same as the fixed base year.

GDP in 2016 was R4.15 billion (compared to R1.93 billion in 2006). The local municipality of Mbhashe contributed 14.86% to the GDP of the Amatole district and city. In 2016, it was R9 billion, which increased Amatole's GDP. The share is 15.22 % in the year 2006. The local municipality of Mbash contributed 1.23% of the GDP of the Eastern Cape and 0.10% of the GDP of South Africa. The total GDP in 2016 was 4.34 trillion rands (measured in nominal or current prices) (Municipality, 2016). Since its contribution to South Africa was 0.10% in 2006, the importance of its contribution to the national economy has remained similar, but it is lower than the 2007 peak of 0.11% (Municipality, 2016).

Table 4. 6: Mbhashe population from 2006 to 2016 (Municipality, 2016).



	Mbhashe	Amatole	Eastern Cape	National Total	Mbhashe as % of district municipality	Mbhashe as % of province	Mbhashe as % of national
2006	1.9	12.7	142.2	1,839.4	*15.2%*	*1.36%*	*0.10%*
2007	2.3	14.9	168.2	2,109.5	*15.3%*	*1.36%*	*0.11%*
2008	2.4	15.4	174.1	2,369.1	*15.3%*	*1.35%*	*0.10%*
2009	2.6	16.9	191.2	2,507.7	*15.4%*	*1.36%*	*0.10%*
2010	2.9	18.6	211.6	2,748.0	*15.4%*	*1.35%*	*0.10%*
2011	3.1	19.8	226.1	3,023.7	*15.5%*	*1.36%*	*0.10%*
2012	3.4	21.7	252.2	3,253.9	*15.4%*	*1.33%*	*0.10%*
2013	3.5	23.1	273.2	3,539.8	*15.2%*	*1.29%*	*0.10%*
2014	3.7	24.5	293.9	3,807.7	*15.0%*	*1.25%*	*0.10%*
2015	3.9	26.2	315.6	4,049.8	*15.0%*	*1.24%*	*0.10%*
2016	4.1	27.9	337.8	4,338.9	*14.9%*	*1.23%*	*0.10%*



	Mbhashe	Amatole	Eastern Cape	National Total
2006	2.3%	3.7%	5.3%	5.3%
2007	2.1%	3.6%	5.3%	5.4%
2008	5.2%	3.1%	3.2%	3.2%
2009	-2.1%	-1.4%	-1.0%	-1.5%
2010	-1.1%	0.4%	2.4%	3.0%
2011	3.1%	2.7%	3.7%	3.3%
2012	-1.1%	0.1%	2.0%	2.2%
2013	-2.1%	-0.4%	1.4%	2.5%
2014	-1.3%	-0.3%	1.1%	1.7%
2015	0.8%	0.4%	0.7%	1.3%
2016	-0.7%	-0.4%	0.2%	0.3%
Average Annual growth 2006-2016+	***0.28%***	***0.77%***	***1.89%***	***2.12%***

In 2016, Mbashe achieved an annual growth rate of - 0.69%, which was significantly lower than the Eastern Cape GDP growth rate of 0.25%, but lower than South Africa, which had a GDP growth rate of 0.28% in 2016. Like the short-term growth rate in 2016, the long-term average growth rate of Mbhashe (0.28%) is also significantly lower than that of South Africa (2.12%) (Municipality, 2016). Mbhashe's economic growth peaked in the year 2008 at 5.18%.

The total GDP of Mbhashe Municipality is 4.15 billion rands. In terms of total contribution to the district municipality of Amatole, the municipality of Mbhashe ranks third in the total GDP of the district municipality of Amatole among all regional economies. Compared to other regions of Mbhashe, this scale ranking has remained unchanged since 2006. In terms of its share, 2016 (14.9%) was slightly lower than 2006 (15.2%). From 2006 to 2016, in terms of constant price growth in 2010, Mbhashe's average annual growth rate was 0.3%, which was the lowest relative to its peers (Municipality, 2016).

From 2016 to 2021, the municipality's economy of Mbhashe has grown at an average annual rate of 1.23%. The average annual GDP growth rates of Amatole District and Eastern Cape Province were 1.39% and 1.62%. South Africa is expected to grow at an average annual growth rate of 1.61%, which is higher than the local municipality of Mbhashe.

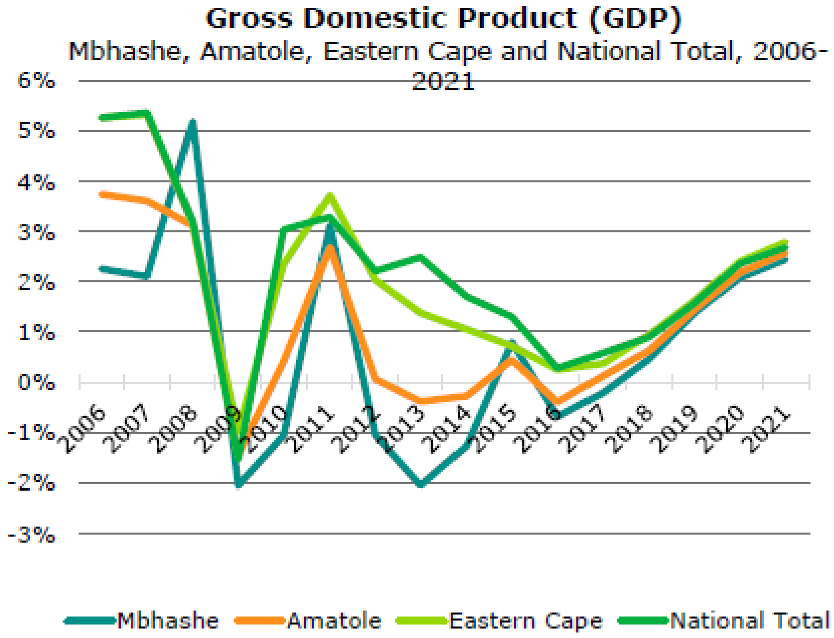


Figure 4. 4 Gross Domestic Product of Mbhashe Municipality (Municipality, 2016).

In 2021, Mbhashe's projected GDP is estimated to be R3.01 billion (constant prices in 2010), accounting for 14.8% of the total GDP of the Amatole district. From 2016 to 2021, the Mbhashe municipality's scale ranking remained unchanged. In 2021, its contribution to the Amatole district municipality's GDP was 14.8%, compared with 15.0% in 2016. With an average annual GDP growth rate of 1.23 between 2016 and 2021, Mbhashe ranked fourth compared to other regional economies (Municipality, 2016).

4.1.3 Gross Value Added

The economy of the local municipality of Mbhashe consists of several industries. The GVA variables provide fault of the sector. Here, each sector is measured from the perspective of its valuables produced in the regional economy.

Definition: Gross Valued Added (GVA) measures the region's output (total production) from the point of view of the value created in that area. GVA can be classified into several production departments.

The following summary table is expanding the GVA of all areas of the local municipality of Mbhashe.

Table 4. 7: Gross value added (Municipality, 2016).

	Mbhashe	Amatole	Eastern Cape	National Total	Mbhashe as % of district municipality	Mbhashe as % of province	Mbhashe as % of national
Agriculture	0.0	0.7	5.9	94.4	*7.0%*	*0.82%*	*0.05%*
Mining	0.0	0.0	0.5	306.2	*33.6%*	*3.47%*	*0.01%*
Manufacturing	0.1	2.0	36.3	517.4	*5.8%*	*0.32%*	*0.02%*
Electricity	0.1	0.5	6.2	144.1	*18.2%*	*1.41%*	*0.06%*
Construction	0.1	0.9	13.2	154.3	*15.1%*	*1.04%*	*0.09%*
Trade	1.2	5.5	61.5	589.7	*21.4%*	*1.93%*	*0.20%*
Transport	0.2	1.7	27.5	389.2	*11.5%*	*0.70%*	*0.05%*
Finance	0.5	4.7	60.5	781.7	*10.1%*	*0.79%*	*0.06%*
Community services	1.5	9.1	89.7	894.1	*16.3%*	*1.66%*	*0.17%*
Total Industries	**3.7**	**25.1**	**301.2**	**3,871.2**	***14.9%***	***1.24%***	***0.10%***

In 2016, the community service department was the largest local department in Mbhashe, accounting for R1.48 billion or 39.6% of the local economy. The industry that contributes the most to the GVA of the local municipality of Mbhashe is the commercial sector, accounting for 31.7%, followed by the financial sector, accounting for 12.7%. The industry that contributes the least to the local economy of Mbhashe City is the mining industry, which has 15.8 million rands or 0.42% of the total GVA (Municipality, 2016).

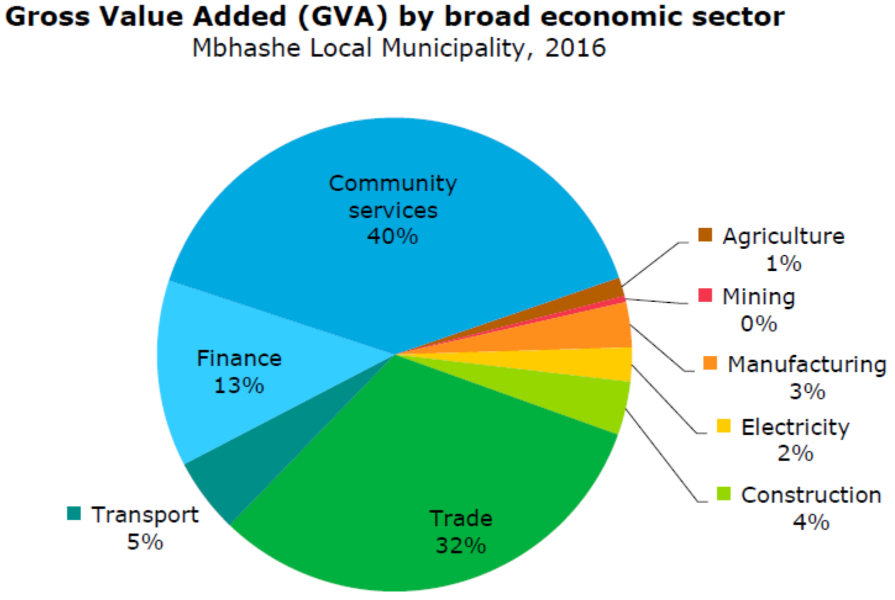
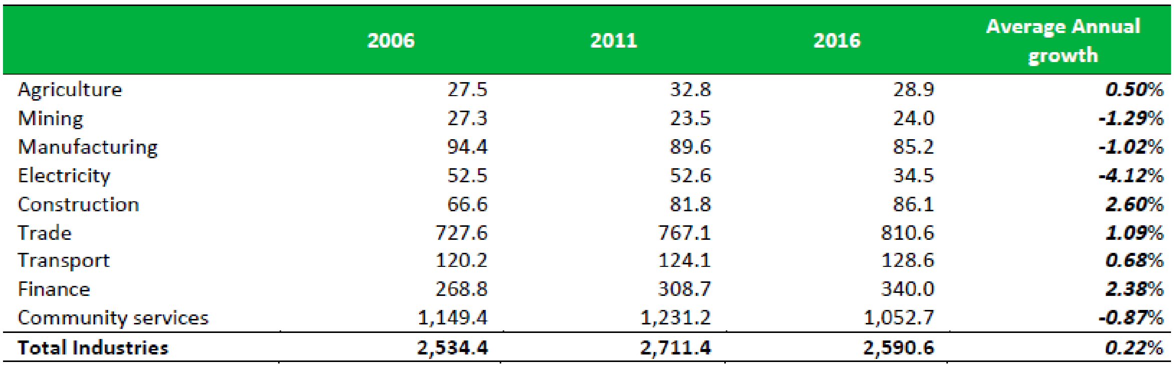


Figure 4. 5: GVA by broad economic sector (Municipality, 2016).

The community sector, including government services, is often the most significant contributor to GVA. If all areas of the Amatole district are analyzed, it is evident that Mkuma has contributed most of the community services to its own GVA, accounting for 27.37%, compared to other areas of the Amatole district. Mnquma contributed R7.61 billion or 30.30% to the GVA of the Amatole district. The area in the Amatole district that contributed the most to the GVA is Ngqushwa, with a total of R2.49 billion or 9.90% (Municipality, 2016).

In 2016 and 2006, the GVA of the construction industry had the highest average annual growth rate in Mbhashe, at 2.60%. The industry with the second-highest average annual growth rate in the financial industry, with an average annual growth rate of 2.38%. On the other hand, the mining industry has an average annual growth rate of 1.29%, while the energy sector has the lowest average annual growth rate of 4.12%. In 2016, all industries showed negative growth, with an average annual growth rate of 0.67% since 2015 (Municipality, 2016).

Table 4. 8: Historical GVA (Municipality, 2016).



	2006	2011	2016	Average Annual growth
Agriculture	27.5	32.8	28.9	***0.50%***
Mining	27.3	23.5	24.0	***-1.29%***
Manufacturing	94.4	89.6	85.2	***-1.02%***
Electricity	52.5	52.6	34.5	***-4.12%***
Construction	66.6	81.8	86.1	***2.60%***
Trade	727.6	767.1	810.6	***1.09%***
Transport	120.2	124.1	128.6	***0.68%***
Finance	268.8	308.7	340.0	***2.38%***
Community services	1,149.4	1,231.2	1,052.7	***-0.87%***
Total Industries	**2,534.4**	**2,711.4**	**2,590.6**	***0.22%***

The tertiary industry provides the most to the GVA within Mbhashe at 89.2%. This is significantly higher than the country's economy (68.6%). The secondary industry contributed 9.1% (ranked second), while the primary sector contributed the least at 1.7%.

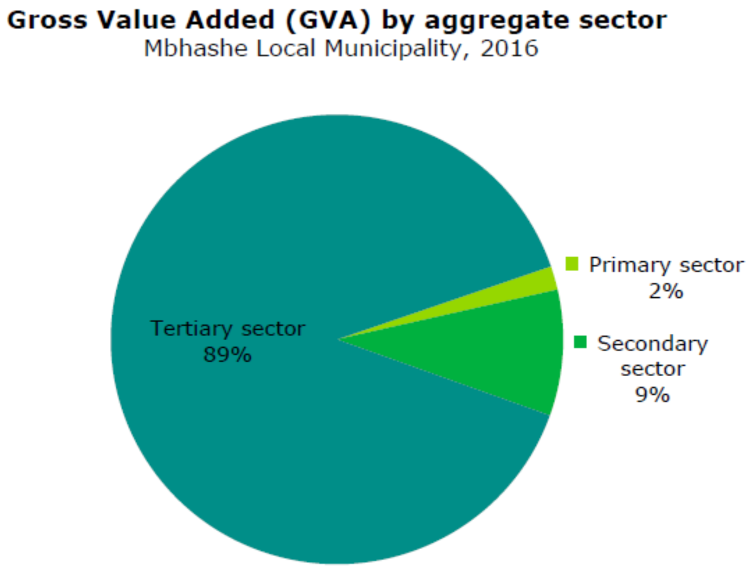


Figure 4. 6: Breakdown of the GVA (Municipality, 2016).

The following is a breakdown of the Gross Value Added (GVA) by aggregated sector (Municipality, 2016):

4.1.3.1 Primary Sector

The primary sector includes two main economic sectors, namely the mining industry and the agricultural sector. From 2006 to 2016, the agricultural sector experienced the highest positive growth in 2008, with an average growth rate of 16.9%, while the mining industry reached the highest growth point of 6.5% in 2014 (Municipality, 2016). The agricultural sector experienced the slowest growth in 2016 with -9.8%, while the mining industry reached the growth point lower with -8.4% in 2007 (Municipality, 2016). During this period, the development of agriculture and mining, in general, has fluctuated.

4.1.3.2 Secondary Sector

The secondary industry includes three major economic sectors: manufacturing, power, and construction. From 2006 to 2016, the manufacturing industry experienced the highest positive growth 2006, with a growth rate of 4.0% (Municipality, 2016). The construction industry achieved its highest growth in 2008, at 10.1% (Municipality, 2016). The manufacturing industry had the lowest growth rate in 2010 at -11.0%, while the construction industry reached its lowest point in 2010, with a growth rate of -5.1% (Municipality, 2016). The energy sector had the highest growth rate in 2007, at 4.7%, and the lowest growth rate in 2014, at -14.9%.

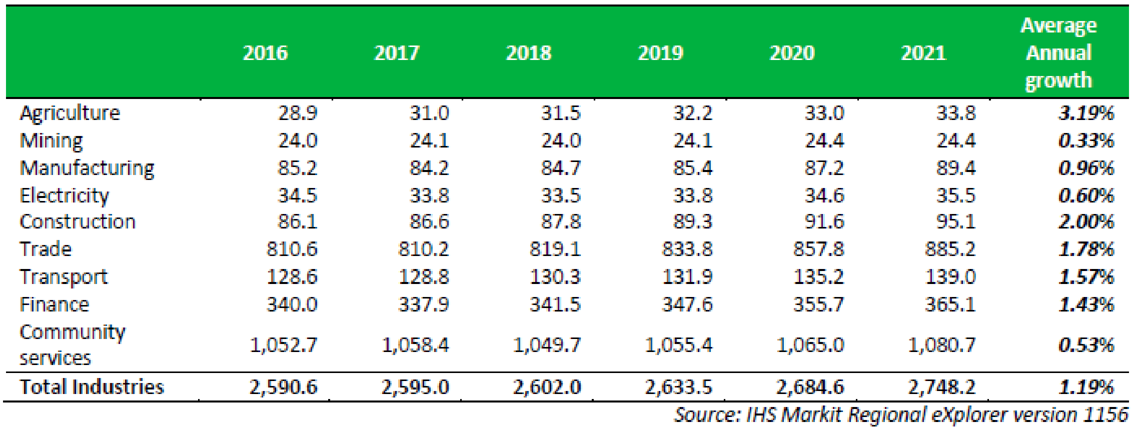
4.1.3.3 Tertiary Sector

The tertiary industry includes four main economic sectors: commerce, transportation, finance, and community service. The commerce sector experienced the highest positive growth in 2008, with a growth rate of 5.6%. The transport sector also experienced the highest positive growth rate, which was 3.8% in 2008, lower than that of the manufacturing industry. The financial industry had the highest growth rate in 2008, at 7.7%, and the lowest growth rate in 2009, at 1.6% (Municipality, 2016). The commercial sector also had the lowest growth rate in 2009, at -4.0% (Municipality, 2016). The community service sector, mainly composed of the government, had the highest positive growth in 2008, at 5.2%, and the lowest growth rate in 2013, at 5.9% (Municipality, 2016).

4.1.3.4 Sector growth forecast

GVA predictions are based on forecasted growth rates derived from historical growth rate estimates and national industry forecasts. Therefore, these forecasts are based in part on the view that regions that have performed well in the short term may continue to perform well (and vice versa), and in part on the idea that areas that have prominent industries are expected to grow excessively across the country. The economy can work well (and vice versa). As the target year moves away from the base year (2010), the focus shifts from historical growth rates to industry growth rates nationwide.

Table 4. 9: GVA by broad economic sector (Municipality, 2016).



	2016	2017	2018	2019	2020	2021	Average Annual growth
Agriculture	28.9	31.0	31.5	32.2	33.0	33.8	***3.19%***
Mining	24.0	24.1	24.0	24.1	24.4	24.4	***0.33%***
Manufacturing	85.2	84.2	84.7	85.4	87.2	89.4	***0.96%***
Electricity	34.5	33.8	33.5	33.8	34.6	35.5	***0.60%***
Construction	86.1	86.6	87.8	89.3	91.6	95.1	***2.00%***
Trade	810.6	810.2	819.1	833.8	857.8	885.2	***1.78%***
Transport	128.6	128.8	130.3	131.9	135.2	139.0	***1.57%***
Finance	340.0	337.9	341.5	347.6	355.7	365.1	***1.43%***
Community services	1,052.7	1,058.4	1,049.7	1,055.4	1,065.0	1,080.7	***0.53%***
Total Industries	**2,590.6**	**2,595.0**	**2,602.0**	**2,633.5**	**2,684.6**	**2,748.2**	***1.19%***

Source: IHS Markit Regional eXplorer version 1156

The agricultural sector is expected to grow at an average annual rate of 3.19%, from R28.9 million in the local municipality of Mbhashe to R33.8 million in 2021 (Table 4.9). The community service department is estimated to be the biggest department in the local municipal government. In 2021, Mbhashe accounts for 39.3% of the total GVA (at current prices), with an average annual growth rate of 0.5% (Figure 4.7). The industry with the slowest growth rate is expected to be the mining industry, with an average yearly growth rate of 0.33% (Municipality, 2016).

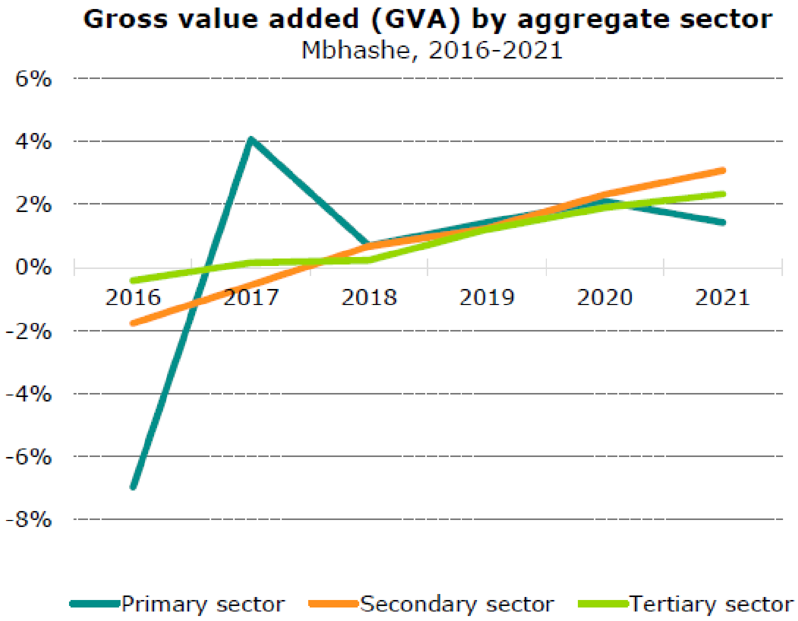


Figure 4. 7: Gross value added by aggregate sector (Municipality, 2016)**.**

It is estimated that the average annual growth rate of the primary industry from 2016 to 2021 will be 1.94%, and the annual growth rate of the secondary industry will be 1.34%. The tertiary industry is expected to grow at an average annual rate of 1.16% during the same period (Municipality, 2016).

4.2 Water resources of Mbhashe Municipality

Generally speaking, most communities in the rural areas of the Eastern Cape depend on raw, untreated water from rivers, springs or wells. A survey conducted in the province revealed that the water supply for several communities came from groundwater; from more than 2,000 wells. However, due to the lack of proper land management and source protection, many of these sources are contaminated and cause health problems. Monitoring data from selected rural wells in the Eastern Cape shows that the degree and extent of severe contamination of groundwater by microbial contaminants is mainly due to insufficient land use management practices. In the city of Mbhashe, the main sources of water are the Quora River and the Mncwasa River (Lehohla, 2016).

The amount of groundwater in South Africa is generally similar to surface water (about 7.5 billion cubic meters per year). Groundwater accounts for 12.5% to 20% of total water consumption in South Africa. In the past three years, the country's groundwater use has increased by 0.6% annually on average. Nevertheless, only about 40% (3 billion cubic meters per year) of available groundwater is used. 66% of the country's land relies entirely or mainly on groundwater to meet household needs. Groundwater is commonly used in more than 420 cities, and many areas use groundwater as the only inlet for irrigation purposes. Groundwater is vital to the water supply of many cities in the driest part of South Africa (Lehohla, 2016).

Approximately 59% of irrigation water and 6% of livestock water come from groundwater. The remainder is used for mining (13%), domestic water supply services (13%), industry (3%), and Schedule 1 (6%). The attached Table 1 allows the use of relatively small amounts of groundwater, primarily for domestic use (including non-commercial gardening) and in crisis, as well as for specific sporting purposes (Lehohla, 2016).

4.3 Solar resources of Mbhashe Municipality

Mbhashe local municipality has enough solar resources for solar power generation. Figure 4.8 displays the monthly average solar global horizontal irradiance data for Mbhashe (Anon, n.d.) within one year. The highest irradiance occurs in January and December, and the lowest occurs in May, June and July. The annual mean global horizontal irradiance of the sun is 4.48 kWh per square meter per day.

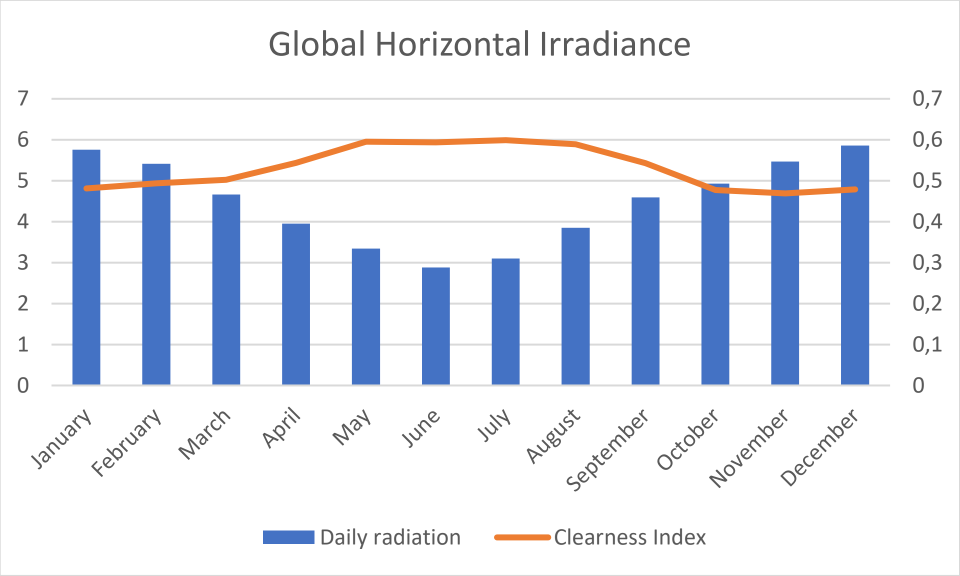


Figure 4. 8: Solar radiation of Mbhashe

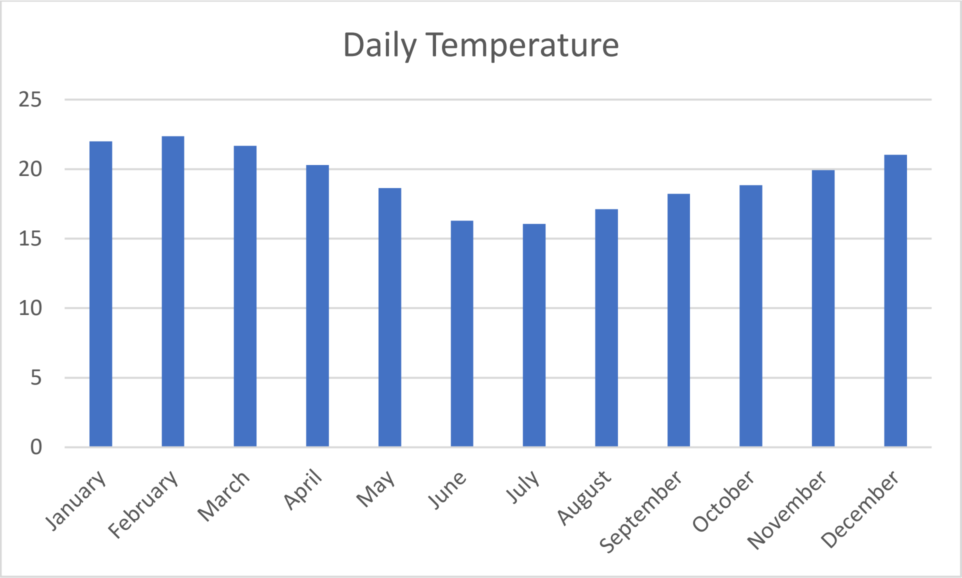


Figure 4. 9: Average daily temperature of Mbhashe

The average daily temperature for each month is shown in Figure 4.9. The highest temperatures occur in January, February, March, and December, while the lowest temperatures occur in May, June, and July.

CHAPTER FIVE
TECHNO-ECONOMIC ASSESSMENT

5.1 Introduction

This chapter is dedicated to the technical and economic evaluation of the photovoltaic energy water purification system, which can provide drinking water to 50 households in rural areas of Mbasi city. The photovoltaic water purification technology used in this study is based on a reverse osmosis process. The evaluation is carried out in two stages. The first stage of the assessment involves evaluating the technical and economic feasibility of the water purification system by determining the size of the components and the system's total cost. In the second stage, the Homer Pro software is used to realize the power system's technical and economic feasibility and meet the electrical load demand of the reverse osmosis process at the lowest possible cost. The dimensions of solar panels, inverters, battery packs, the net current costs and the resulting energy balance costs should be evaluated.

5.2 System description

The system consists of photovoltaic (PV) panels, inverters, batteries, and reverse osmosis water treatment systems. Reverse osmosis is a method from organic pollution and inorganic pollution (such as toxic metals, salts, toxic substances (including nitrates, metal salts, and cyanides) and various particles, asbestos, PCBs, pesticides, herbicides, drugs, Metabolites, drugs in drinking water and even microorganisms. UV disinfection is constantly being recommended, mainly due to potential organisms.

In the presence of inorganic pollutants, carbon filtration alone cannot effectively remove pollutants, while reverse osmosis is good. On the other hand, reverse osmosis is a more "manual" technology than carbon filtration, requiring you to carefully observe the chemical composition of the water to see if any water quality issues will contaminate the reverse osmosis membrane. Reverse osmosis also requires a certain amount of water pressure to function.

5.3 Methodology of designing the reverse osmosis water treatment plant

The design of a reverse osmosis water purification plant is generally based on the method shown in Figure 5.1.

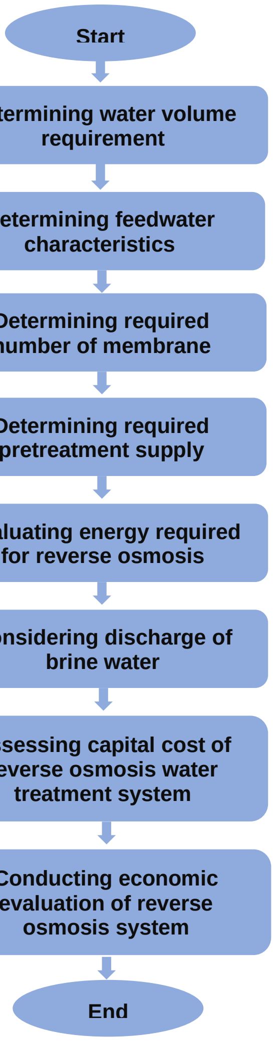


Figure 5. 1: Design methodology of reverse osmosis water purification system

5.3.1 Determining water volume requirement

A fair assessment needs to be conducted to estimate water demand as some consumers may experience water usage increase due to economic growth. Additionally, plant downtime should also be considered. The following equation gives the actual water production rate in a reverse osmosis plant:

$$Q_{Total} = \frac{Q_{Requirement}}{v} \tag{5.1}$$

Where Q_{Total}, $Q_{Requirement}$, and v are the total quantity of cubic metre of water to be produced by the membranes daily, consumers' water requirement in cubic meter per day, and availability fraction, respectively.

5.3.2 Determining feedwater characteristics

The feed water quality estimates the maximum recovery rate that can be achieved by reverse osmosis equipment. Due to fouling, membrane fouling is the limiting factor for the recovery rate. For seawater, the formation of crystals in the brine stream will occur at a critical recovery rate due to the saturation point of the salt. The operation of reverse osmosis equipment should not exceed this critical recovery rate. The following estimates guide the relationship between seawater and groundwater restoration.

- Seawater: 30 % < recovery ratio > 50 %
- Groundwater: 60 % < recovery ratio > 90 %

5.3.2.1 Estimating the maximum recovery ratio

As reported by the South African Ministry of Water, the following calculation estimates the maximum recovery rate with suitable antifouling media. There are many anti-fouling products on the market. Professionals should also be consulted to conduct a comprehensive study and propose the best anti-fouling medium for reverse osmosis systems.

5.3.2.2 Calcium Salts

If it is not removed by softening, the presence of calcium salt will greatly limit the recovery rate. Three types of calcium salts are considered, and an equation is established to determine the single maximum recovery rate before membrane fouling accumulates.

- Calcium Carbonate ($CaCO_3$)

CaCO3 is among the most easily available salts in the feed water. In the presence of anti-fouling media, the possibility of fouling can be controlled by lowering the pH of the influent water. Equation (5.2) determines the estimated recovery rate in the presence of calcium carbonate:

$$RR_{CaCO_3} \approx 1 - \frac{\sqrt{Alk.C_{Ca}}}{2000} \tag{5.2}$$

Where RR_{CaCO_3} is the maximum allowed recovery ratio, Alk is the feed alkalinity $CaCO_3$ in milligram per liter and C_{Ca} is the feedwater concentration of Ca in milligram per liter.

- Calcium Sulphate ($CaCO_4$)

Changing the pH of the feed water will not affect the possibility of calcium sulfate scaling. Employing a softener, limiting the concentration factor, and controlling the feedwater temperature will decrease the possibility of membrane fouling. Equation (5.3) gives the estimated recovery rate:

$$RR_{CaCO_4} \approx 1 - \frac{\sqrt{C_{SO_4}.C_{Ca}}}{2500} \tag{5.3}$$

Where RR_{CaCO_4} and C_{SO_4} are the maximum allowed recovery ratio and the feedwater concentration of $S0_4$ in milligram per liter.

- Calcium Fluoride (CaF_2)

By limiting the concentration factor or using softeners to remove calcium, the maximum recovery rate can be achieved before the membrane becomes dirty. Equation (5.4) expresses the maximum recovery rate that can be achieved in the presence of an antifouling medium.

$$RR_{CaF_2} \approx 1 - \frac{\left[(C_F)^2.(C_{Ca})\right]^{0.33}}{40} \tag{5.4}$$

Where RR_{CaF_2} is the maximum allowed recovery ratio, and C_F the Ca feedwater concentration in milligram per liter.

- Silicates (SiO_2)

In the combination of calcium and magnesium, silica can polymerize or precipitate. Equation (5.5) expresses the maximum recovery rate of SiO_2 in the antifouling medium:

$$RR_{SiO_2} \approx 1 - \frac{C_{SiO_2}}{200} \tag{5.5}$$

Where RR_{SiO_2}, and C_{SiO_2} are the SiO_2 maximum allowed recovery ratio and feedwater concentration, respectively.

- Oxides and hydroxides of iron, manganese, and aluminum (Fe, Mn, Al)

Fe, Mn, and Al must be kept at a specific concentration in the brine stream to avoid fouling of the membrane. Manufacturers and experts should be contacted. Equation (5.6) gives the maximum recovery rate of SiO_2 in the scale inhibition medium.

$$RR_{Fe} \approx 1 - \frac{C_{Fe}}{3} \tag{5.6}$$

Where RR_{Fe} is the maximum allowed recovery ratio and C_{Fe} is the Fe feedwater concentration in milligram per liter.

- Salts with barium and strontium (Ba, Sr)

The dissolving capability of barium is very low, and the maximum recovery rate of $BaSO_4$ in the scale inhibition medium is expressed by Equation (5.7).

$$RR_{BaSO_4} \approx 1 - \frac{\sqrt{C_{SO_4}.C_{Ba}}}{30} \tag{5.7}$$

Where RR_{BaSO_4} is the maximum allowed recovery ratio, C_{SO_4} is the feedwater concentration of SO_4 in milligram per liter, and C_{Ba} is the feedwater concentration of Ba in milligram per liter.

Equation (5.8) determines the $SrSO_4$ maximum recovery rate in an anti-scaling medium.

$$RR_{SrSO_4} \approx 1 - \frac{\sqrt{C_{SO_4}.C_{Sr}}}{400} \tag{5.8}$$

RR_{SrSO_4} is the maximum allowed recovery ratio, and C_{Sr} is the feedwater concentration of Sr in milligram per liter.

5.3.3 Determining required membrane size

At this stage, the designer must determine the reverse osmosis supplier to acquire information about membrane performance. Nowadays, many excellent reverse osmosis experts worldwide can provide detailed information upon request, and designers can use this data to make preliminary designs. Some companies have developed their design software programs to allow designers to simulate reverse osmosis systems using different membranes. These software tools can simulate complex reverse osmosis designs that require iteration in solving reverse osmosis equations.

This stage includes estimating the total area of the membrane. Equation (5.9) calculates the number of membrane modules required.

5.3.3.1 Estimating the required total membrane area

The entire membrane area can be determined using the flux rate of a membrane according to Equation (5.10). The flux rate is subjective to parameters, including the supply pressure, water quality, feedwater temperature, etc. Additionally, the membrane area is utilized as a guideline to evaluate a reverse osmosis plant's physical size, which is also a guideline to the capital cost.

$$Area_{Total} \approx \left(\frac{1000Q_{Total}}{\varphi_1}\right) + Z\left(\frac{1000Q_{Total}}{\varphi_2}\right) \tag{5.10}$$

Where $Area_{Total}$ is the total required membrane area in meter square, Q_{Total} is the total quantity of water produced using Equation (5.1) in cubic meters per day, φ_1 is the first pass membrane flux in liter per meter square day, φ_2 is the second pass membrane flux in liter per meter square day, and Z is the passes' number (Z=0 for one pass and one for two passes).

5.3.3.2 Estimating the required total membrane area

The applicable membrane must be known to determine the required number of membrane components. Addressing Equation (5.11) and gathering together the highest integer will provide an expected number of membranes required.

$$Number_{Elements} \approx \frac{Area_{Total}}{Area_{Membrane}} \tag{5.11}$$

Where $Number_{Elements}$ is the total required membrane components, $Area_{Total}$ the total required membrane area in meter square, and $Area_{Membrane}$ the membrane area of a component in meter square.

5.3.4 Determining the required feed pressure

The membrane will be permanently damaged due to overpressure. Normally, the supply pressure is limited to around 78.9539 atm. However, to increase protection, some manufacturers reduce the pressure to 69.0846 atm. Equation (5.12) is used to determine the feed pressure required for a specific permeate flow rate. Higher inlet water temperature will reduce the required inlet water pressure.

Contrarily, a higher recovery and flow rate will increase the feed pressure. It should be noted that for the second pass, the variable must be changed to the characteristics of the second feedwater flow. For example, the second step TDS value can be 1% of the first stream.

$$P_{f(T)} \approx \frac{\pi(TDS)_F}{1-RR} + \left(\frac{\varphi}{\psi} + 5\right).1.034^{(25-T)} \tag{5.12}$$

Where $\pi(TDS)_F$ is the osmotic pressure multiply by the TDS of feedwater, RR is the maximum allowed recovery, φ is the membrane flux in liter per meter square per hour, ψ is the membrane flux per driving pressure in liter per meter square per hour per bar, and T is the feedwater temperature in degree Celcius.

5.3.5 Determining required pretreatment supply

A pretreatment setup requires extra water due to maintenance, including CIP, backwash, etc. Hence, the feed pumps should provide a supplementary water volume for the pretreatment unit beside the reverse osmosis membranes. Equation (5.13) gives the required daily to be provided by the feed pumps.

$$Q_{Total(Feed)} \approx \frac{Q_{Total}}{RR.(1-\xi)} \tag{5.13}$$

Where $Q_{Total(Feed)}$ is the total quantity of water to be supplied in cubic meters per day, Q_{Total} is the total quantity of product water in a cubic meter, RR is the maximum required recovery ratio, and ξ is the water fraction required at pretreatment (generally between 3 to 15 %).

5.3.6 Estimating the required energy

Generally, high-pressure pumps are employed to realize a supply pressure of 70 bar. However, this leads to high energy requirements for the reverse osmosis process. The estimated energy consumption of a reverse osmosis system is expressed in Equation (5.14) (du Plessis et al., 2006):

$$E \approx \left[\frac{Q_{Total}.P_{f(T)}}{36.RR.\eta_{Pump}}\right] - S\left[\frac{Q_{Total}\left(P_{f(T)}-5\right).(1-RR)}{36.RR.\eta_{Recovery}}\right] \tag{5.14}$$

Where E is the estimated required energy, Q_{Total} is the total quantity of product water in a cubic meter, $P_{f(T)}$ is the feed pressure, RR is the maximum allowed recovery ratio, η_{Pump} is the pump efficiency, S is zero if the installation does not include a pressure recovery unit and one if the pressure recovery is included, and $\eta_{Recovery}$ is the efficiency of the pressure recovery (the efficiency of new positive exchangers can get up to 96 %).

5.3.7 Supplementary energy requirements

In addition to power, the reverse osmosis plant also requires additional power supply for auxiliary systems, lighting, etc. By design, using slightly overestimated pre and post-processing pressures ($P_{Pre/Post}$), Equation (5.15) will give an estimate of the energy needs of these systems (du Plessis et al., 2006):

$$E_{Extra} \approx \left[\frac{Q_{Total\,(Feed)}.P_{Pre/Post}}{36.\eta_{Pump}}\right] \tag{5.15}$$

Where E_{Extra} is the extra required energy in kilowatt, $Q_{Total\,(Feed)}$ is the total quantity of water to be supplied in a cubic meter per day, $P_{Pre/Post}$ is the estimated required pressure for the pre and post-treatment expressed in bar, and η_{Pump} is the pump efficiency.

Therefore, the total reverse osmosis system energy consumption (E_{Total}) is given as follows (du Plessis et al., 2006):

$$E_{Total} = E + E_{Extra} \tag{5.16}$$

The specific energy consumed for the water production (E_{Spec}) is evaluated using Equation (5.17) as follows (du Plessis et al., 2006):

$$E_{Spec} = \frac{E_{Total}}{Q_{Total}} \tag{5.17}$$

5.3.8 Considering brine water discharge

The designer of a reverse osmosis water treatment plant must consider that the liberation of high saltwater into the environment will significantly negatively impact flora and fauna. Experts must address the issue and evaluate strategies for the discharge. There are two options for the discharge process: use an evaporation pond or discharge the brine back to the water source (sea). Evaporation tanks are only employed for small reverse osmosis plants; however, additional costs will be incurred. If saltwater is discharged back to the water source, ocean currents, marine life, the inflow of large rivers, etc., they must be verified at the design stage. At the micro-level, measurements including colloidal, organic, and biomass are essential and must be evaluated by experts. Another option is to extract ingredients from saltwater.

5.3.9 Estimating the reverse osmosis capital cost

5.3.9.1 Cost of desalination installation

The desalination cost refers to civil, electrical, and mechanical systems and the cost of the reverse osmosis membrane. The membrane area directly influences all of the above facilities. Therefore, according to the relevant calculation of the required membrane area, the installation cost of the desalination department can be obtained. Figure 5.3 to Figure 5.5 provides the relationship between installation cost and installation membrane area.

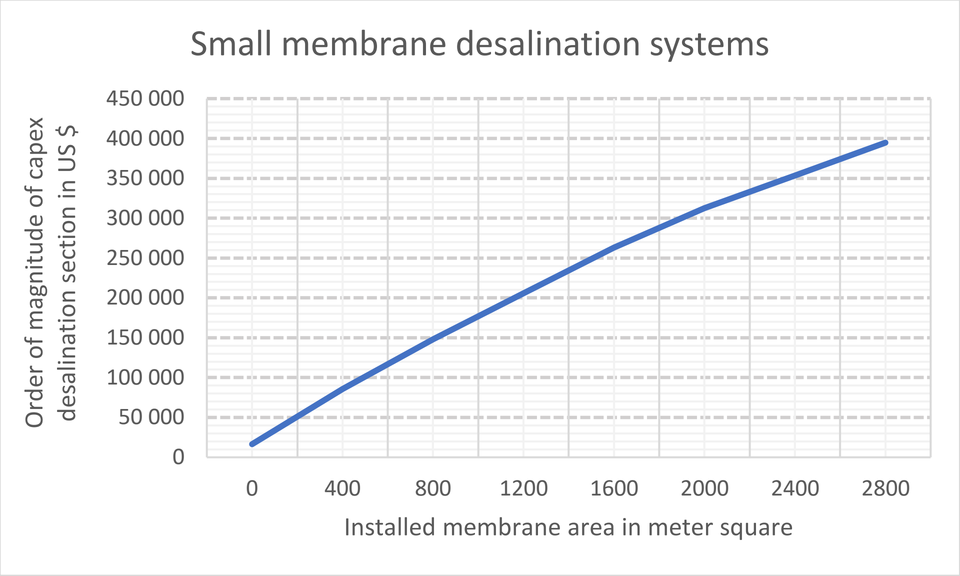


Figure 5. 2: Estimated installation cost of small desalination sections (du Plessis et al., 2006).

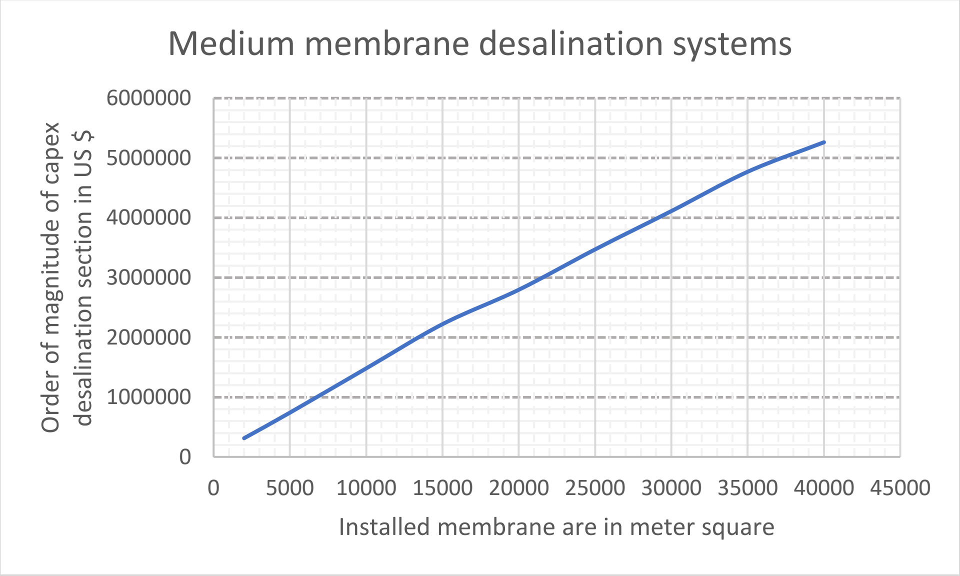


Figure 5. 3: Estimated installation cost of medium desalination sections (du Plessis et al., 2006).

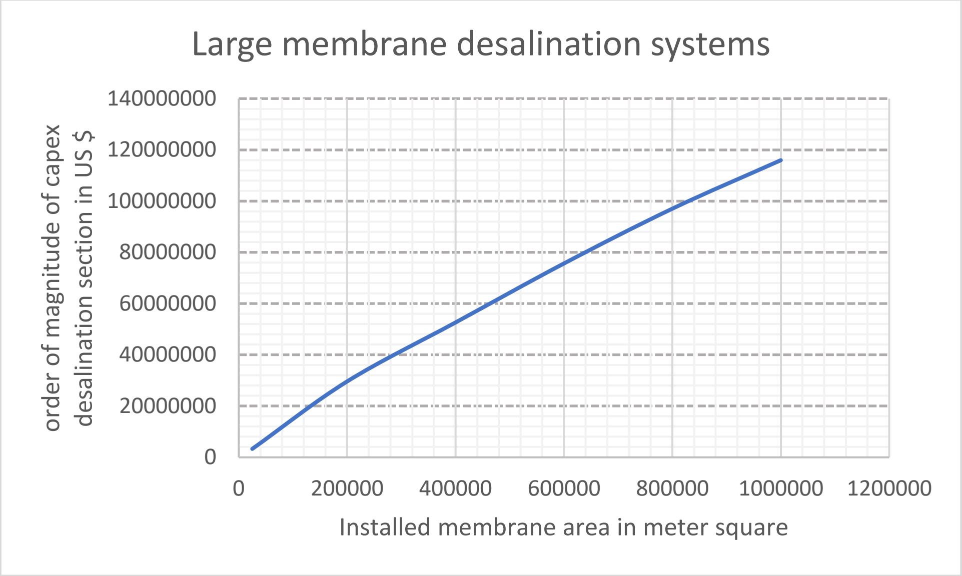


Figure 5. 4: Estimated installation cost of large desalination sections (du Plessis et al., 2006).

5.3.9.2 Cost of pretreatment installation

The pretreatment system is a critical and complex process. If the system design is invalid, the lifetime of the membrane can be shortened significantly because of scaling and increasing the plant's running cost. Therefore, experts must carry out a detailed investigation and design to choose the most effective pretreatment system for the used feedwater. The pretreatment installation cost can be determined using Equation 5.18 as follows (du Plessis et al., 2006):

$$C_{Pre} \approx CC_{Pre}.K \tag{5.18}$$

Where C_{Pre} is the pretreatment installation cost, CC_{Pre} is the cost obtained from Figures 5.6 or 5.7, and K is the pretreatment complexity correlation factor.

The estimated correlations between the pretreatment installation cost and the total feedwater are provided in Figures 5.6 and 5.7.

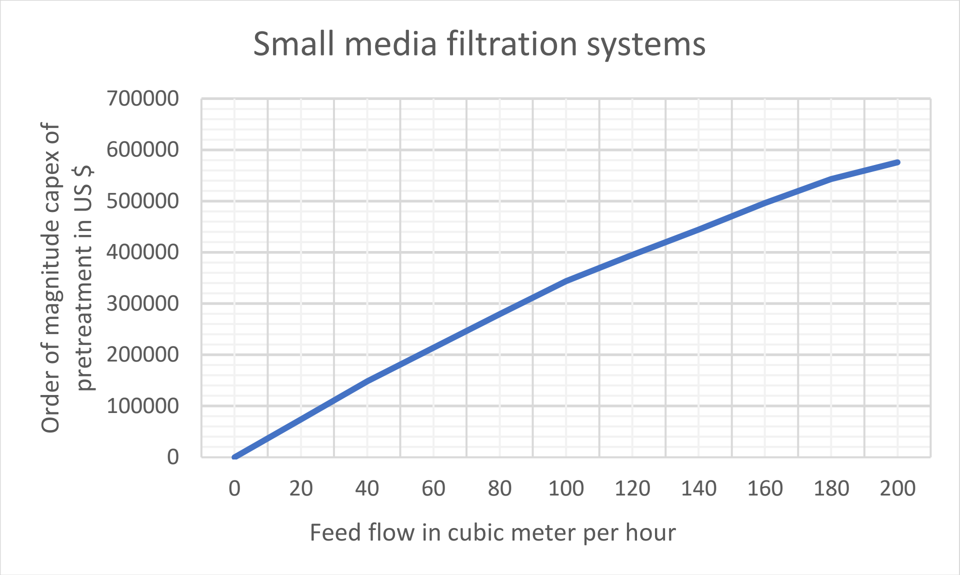


Figure 5. 5: Estimated cost of pretreatment installations of small reverse osmosis systems

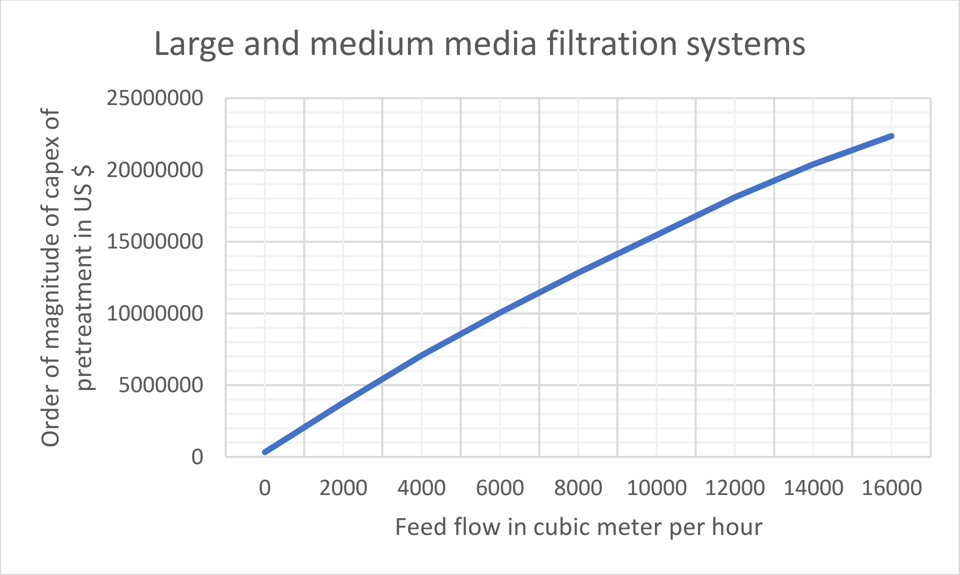


Figure 5. 6: Estimated cost of pretreatment installations of large and medium reverse osmosis systems

5.3.9.3 Estimating the intake, outfall, and post-treatment cost

Such charge consists of the costs of pipe lengths, intake systems, etc. Equation 5.19 evaluates the intake, outfall, post-treatment systems of seawater, and inland brackish water desalination costs (du Plessis et al., 2006):

$$C_{Pipe/Post} \approx C_{Desal\,\&\,pre}.P \qquad (5.19)$$

Where $C_{Pipe/Post}$ is the intake, outfall, and post-treatment system installation cost, $C_{Desal\,\&\,pre}$ is the total cost of pretreatment and desalination system, and P is the complexity factor estimated between 15 to 30 % for seawater and between 2% and 10% for inland brackish water desalination systems.

5.3.9.4 Estimating the environmental assessment and contract costs

The designer must keep in mind that the environment is a crucial issue during the design stage. Specialists should be consulted to assess the feedwater and seawater desalination, including the marine life, sea currents, inflow of large rivers, etc. Measurements on the microscopic level, including the colloidal, organic, and biological amounts, are essential. In addition, licensing and mitigation costs must be accounted for. Equation 5.20 expresses the estimated cost (du Plessis et al., 2006):

$$C_{Enviro} \approx C_{Contract}.P \tag{5.20}$$

Where C_{Enviro} is the estimated installation cost of the environmental assessment and liable fees, $C_{Contract}$ is the total contract cost, and P is the complexity factor estimated between 0.05 and 5 %.

5.3.10 Evaporation ponds costs

Several factors affect the evaporation ponds' costs to process the brine from the water purification facility. Rain, evaporation, suitable materials for dam construction, geology location, and topography can have a role to play. The basic design principles used to compile the cost curve consists of the following (du Plessis et al., 2006):

- The critical area to evaporate the received brine is the net evaporation, using yearly average precipitation and evaporation data. The evaporation coefficient of the tray is not used.
- Calculations are based on cut and fill exercises.
- The calculation of winter rainfall provides the most crucial retention period to permit saltwater storage from wet winter with little evaporation to drier summer. A pond of about one meter deep can provide enough storage space. As the net evaporation decreases, the depth of the pond will also decrease to reduce storage. However, from a practical point of view, the excavation depth of the pond cannot be less than 400 mm, although this gives a retention time of nearly twelve months in places with low net evaporation.
- All evaporation tanks are lined to prevent leakage.
- Each pond is considered square and includes two ponds for cleaning and maintenance.

- The cost of the lining is US$ 7.5 per square meter, while the cutting and filling price is US$ 5.75 per cubic meter.

Figure 5.7 provides a guideline as a preliminary estimate of the possible cost of a well-designed evaporation pond based on the annual net evaporation loss and the expected daily brine flow rate. These costs are considered conservative and can be reduced based on specific locations and local weather conditions.

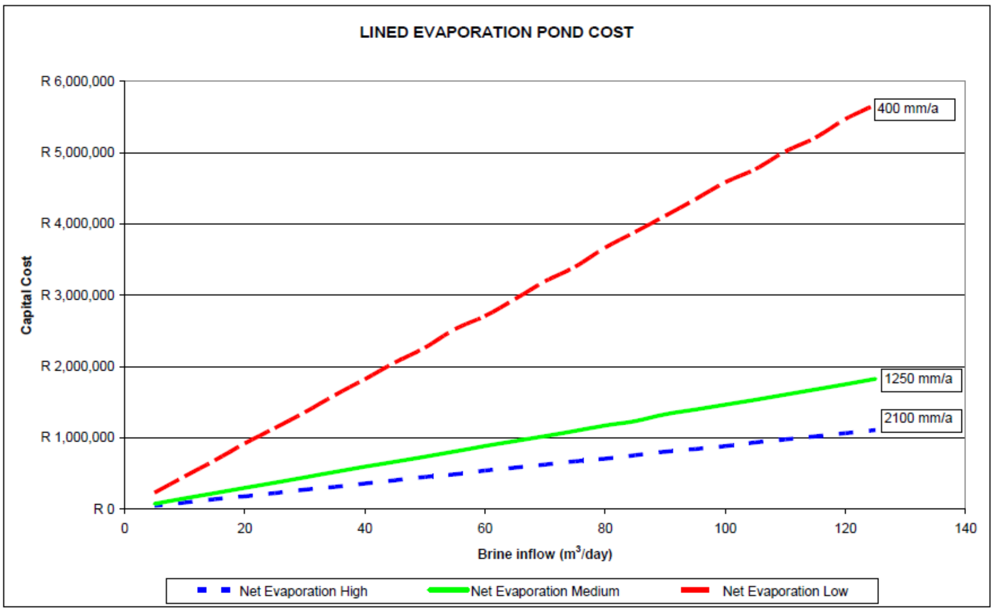


Figure 5. 7: Lined evaporation pond cost (du Plessis et al., 2006).

5.3.11 Economic assessment of a reverse osmosis plant

An economic evaluation consists of calculating the specific cost of one cubic meter of product water. Each expense before and during the operation of the unit is considered.

5.3.11.1 Capital repayment cost

The capital repayment cost is determined using the following equation (du Plessis et al., 2006):

$$CR = \frac{C.r.(1+r)^n}{(1+r)^n-1} \tag{5.21}$$

Where CR is the capital cost repayment in US $ per month, C is the capital cost, r is the monthly interest rate, and n the redemption period.

5.3.11.2 Specific cost of capital redemption

The specific cost of the capital redemption is determined using Equation (5.22) as follows (du Plessis et al., 2006):

$$SC_{Cap} \approx \frac{CR}{30.Q_{Total}} \tag{5.22}$$

Where SC_{Cap} is the specific cost of redemption in US $ per cubic meter, CR is the capital repayment cost, and Q_{Total} the total quantity of water

5.3.11.3 Specific cost of energy

The specific cost of energy is determined using Equation (5.23) as follows (du Plessis et al., 2006):

$$SC_{Energy} \approx D_{Electric}.E_{Specific} \tag{5.23}$$

Where SC_{Energy} is the specific energy cost per product water volume in US $ per cubic meter, $D_{Electric}$ is the cost of electricity in US $ per kWh, and $E_{Specific}$ is the specific energy consumption per product water volume in kWh per cubic meter

5.3.11.4 Membrane replacements specific cost

The membrane replacement specific cost is expressed as follows (du Plessis et al., 2006):

$$SC_{Mem} \approx \frac{Z.Cost_{Mem}.\delta}{Q_{Total}} \tag{5.24}$$

Where SC_{Mem} is the specific membrane replacement cost per water product volume in US $ per cubic meter, Z is the number of membranes, $Cost_{Mem}$ is the cost of a membrane element, δ is the membrane depreciation per year, and Q_{Total} is the total quantity of product water in cubic meter per day.

5.3.11.5 Cost of chemicals and consumable

This is a difficult cost forecast and must be calculated carefully during the RO design stage. Its characteristics may vary greatly for each water supply source, so various chemicals and consumables must be used to protect the reverse osmosis membrane. The equations in (5.25) and (5.27) give the specific costs of chemicals and consumables for reverse osmosis equipment, depending on the influent source. For brackish water feedwater with pH adjustment system, disinfectant and antifouling system, and sensitive post-treatment system, the cost estimate is as follows (du Plessis et al., 2006):

$$SC_{Chemicals} \approx 0.05\ US\ \$/m^3 \tag{5.25}$$

On the other hand, seawater is treated with the necessary acid, chlorine, coagulant, and scale inhibitor. In addition, the cost of using a dechlorination system and a reasonable aftercare system is approximately (du Plessis et al., 2006):

$$SC_{Chemicals} \approx 0.08\ US\ \$/m^3 \tag{5.26}$$

Finally, for the supply of brackish water with a complete system of lime, acid, chlorine, dichloride system and scale inhibitor, and a reasonable after-treatment device, the cost is approximately (du Plessis et al., 2006):

$$SC_{Chemicals} \approx 0.26\ US\ \$/m^3 \tag{5.27}$$

5.3.11.6 Labour and maintenance costs

The maintenance and labor cost of reverse osmosis plants larger than 2000 cubic meters per day is estimated to be 5% of the capital cost (du Plessis et al., 2006). Equation (5.28) estimates the labor and maintenance cost for smaller reverse osmosis systems.

$$SC_{Main/Labor} \approx \frac{Z.Cap}{366.Q_{Total}} \tag{5.28}$$

$SC_{Main/Labor}$ is the specific replacement cost of the membrane for a cubic meter of water in US $ per cubic meter, Z is the number of membranes, Cap is the capital cost, and Q_{Total} is the total quantity of product water in cubic meters per day.

5.3.11.7 Total cost

The overall cost of a cubic meter of product water is estimated to (du Plessis et al., 2006):

$$SC_{Total} = SC_{Cap} + SC_{Energy} + SC_{Membranes} + SC_{Main/Labor} + SC_{Chemicals} \tag{5.29}$$

It can be seen that this study did not consider the cost of product water storage facilities, the cost of distribution systems including pumps, pipes, etc., the cost of buildings, roads, and infrastructure, and the cost of exploration cost of onshore evaporation ponds.

5.4 Design methodology of the renewable power system driving the RO

HOMER Pro is utilized to design and implement renewable energy sources for reverse osmosis water treatment plants. This tool simplifies the evaluation of grid-connected and off-grid power system designs. Sensitivity analysis and optimization algorithms facilitate the assessment of various system architectures. HOMER Pro's work rules include adjusting the energy generated and consumed at each step of the year. The simulation process involves selecting a technically feasible system configuration within the defined system constraints. This also estimates the cost of installing and operating the potential system during the project life cycle. The optimization process uses input data, including load curves, solar resources at the selected site, and technical and economic data of the system.

5.4.1 Optimization criteria

The optimal system setup is chosen considering the Levelized cost of energy, the Net Present Cost, and the reliable system configuration to select the best structure to meet the load demand.

5.4.1.1 Net Present Cost

The Net Present Cost (NPC) represents the sum of all costs included in the life of the project. These costs include capital, operation, and maintenance (O&M), replacement, and fuel costs minus the fee of damage, which is the expected value of the system at the end of the project’s useful life. Homer Pro calculates NPC according to Equation 5.30 as follows (Kalinci et al., 2015):

$$NPC = \sum_{N=1}^{N=t} f_{d,N} \left(C_{cap} + C_{rep} + C_{main} - C_s\right) \tag{5.30}$$

Where C_{cap}, C_{rep}, C_{main} and C_s are the capital cost, replacement cost, O&M and salvage costs respectively, t is the lifetime of the project and $f_{d,N}$ is expressed in Equation 5.31 as (Kalinci et al., 2015):

$$f_{d,N} = \frac{1}{(1+i)^N} \tag{5.31}$$

Where i and N are the yearly interest rate and the year considered in the calculation, respectively.

5.4.1.2 Cost of Energy (COE)

The system COE is calculated using Equation (5.32) as follows (Kalinci et al., 2015):

$$COE = \frac{AC_T}{E_{served}} \tag{5.32}$$

Where E_{served} is the system primary load and AC_T is the total cost of the component per year of the project lifetime and expressed in Equation (5.33) as (Kalinci et al., 2015):

$$AC_T = \sum C_{cap} + C_{rep} + C_{main} - C_s \tag{5.33}$$

5.4.2 Technical reliability

The technical reliability standard of the system involves selecting the optimal size of system components to maintain a balance between supply and demand, taking into account the lack of system capacity.

5.4.2.1 Inputs data

According to the system configuration, the tool requires input data, including load profile, meteorological resources of the research site, technical characteristics, component cost data, and restrictions, such as the actual discount rate and the inflation rate of the project, and annual capacity. The shortage and service life of the project.

Equation (5.34) gives the project real discount rate 'i' (Per.gov.ie, n.d.):

$$i = \frac{i' - f}{1 + f} \tag{5.34}$$

Where i' is the discount rate, and f is the projected inflation rate over the lifetime of the project.

5.4.2.2 Optimization methodology

The optimization method follows the algorithm depicted in Figure 5.8.

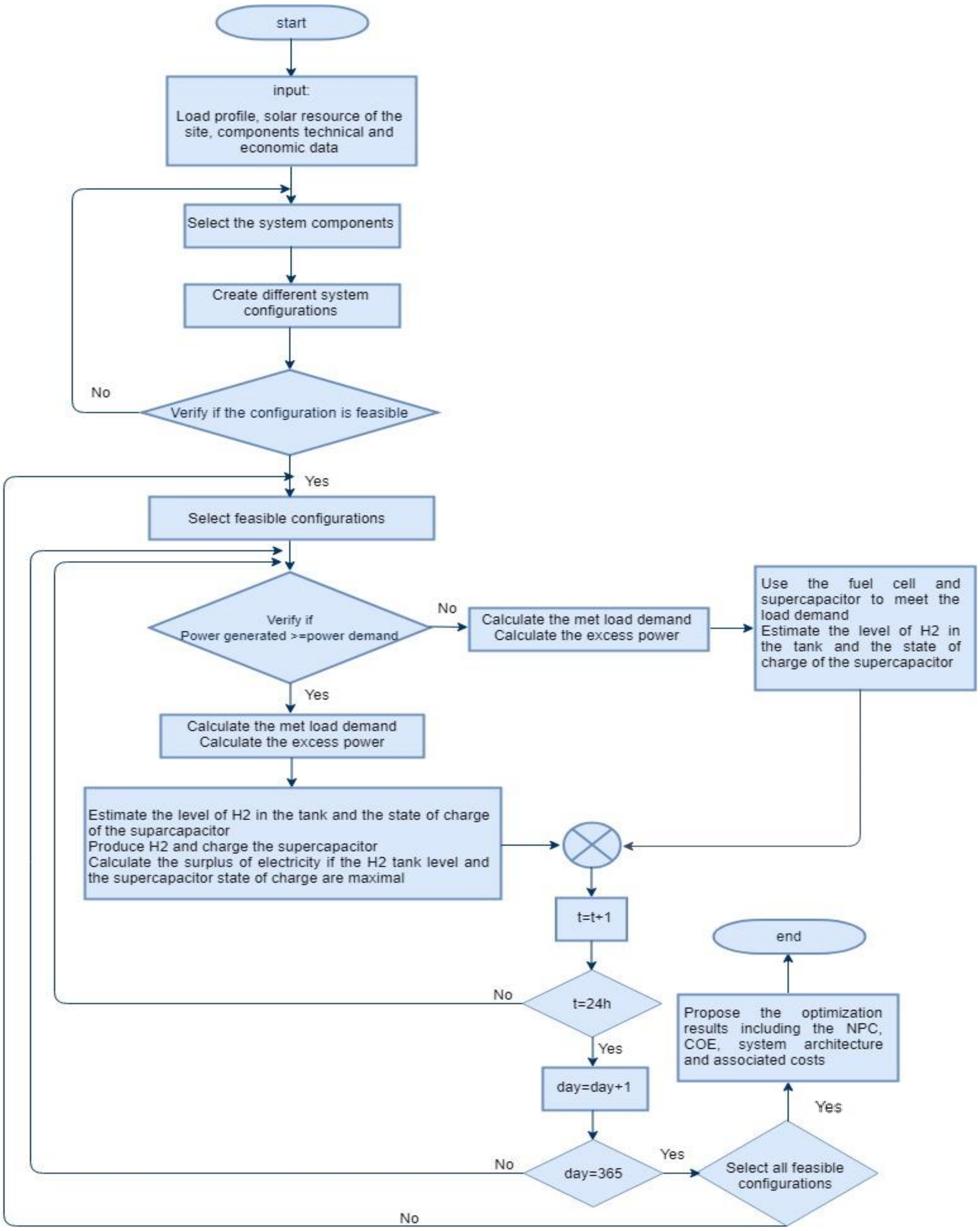


Figure 5. 8: Optimization methodology

5.5 Results and discussions

Following the methodology depicted in Figure 5.2, the design of a water treatment plant based on the reverse osmosis process was carried out. This design provides potable water to approximately 56000 inhabitants, representing one-fifth of the Mbashe population. It is assumed that the daily water requirement per person for drinking and sanitation purposes is 52 litres, as the World Health Organization defines the limit between 50 and 100 litres (WHO, 2011). Hence, the water flow rate to meet the population needs is about 3000 cubic metres per day. The plant is considered to operate for 12 hours a day, and a photovoltaic plant powers it.

The techno-economic feasibility is conducted in two stages; in the first stage, the reverse osmosis water purification design is achieved using the Matlab software, whereas the second stage focuses on designing the photovoltaic system using Homer Pro software.

5.5.1 Reverse osmosis water treatment results

The Matlab code in Appendix 1 was developed to evaluate the system's components sizing and cost. The following costs are not considered in this investigation:

- The storage unit for the product water.
- The distribution network including pumps, pipes, etc.
- The buildings, roads, and infrastructure
- The exploration of land evaporation ponds, as it is considered that the brine is discharged back to the water source (ocean)
- The chemicals

Table 5.1 gives the input parameters used in the design process of the plant, based on the daily water flow rate. The availability fraction depends on the plant's operating hours, and based on the design robustness, if the plant operates 24 hours daily, the availability fraction (a) is between 0.90 and 0.95. On the other hand, if the plant runs for 12 hours, this fraction is equal to or less than 0.5. The average fluxes through the first and second membranes are considered 24 liters per square metre.

Generally, the factor (Z) is 1 for a double pass configuration and 0 for a single pass system; in this investigation, a single pass system is adopted. Hence Z is equal to zero. The membrane-specific flux (e) is dependent on the membrane manufacturer and may vary between 1 and 5 liters per m2.h.bar.The value adopted in this study is 4.5 litres/m2.h.bar. The total dissolved solids (TDS) refer to the sum of all dissolved solids, volatile and no volatile in the water that requires treatment. In South Africa, the TDS levels of groundwater are ordinarily lower than the TDS levels of seawater, usually below 15 000 mg per liter. In this study, the TDS level is assumed to be 2000 mg per liter. The water temperature is considered to be 18^{o}C, whereas the efficiency of pumps is 78 %. It is also assumed that the facility does not include an energy recovery unit; hence, the energy recovery factor and the energy recovery efficiency are equal to zero.

The fraction of feedwater lost at the pretreatment process and the feedwater pressure are considered to be 0.05 and 3 bar, respectively.

Table 5. 1: Input Parameters

Input parameters of reverse osmosis water purification	
Quantity	**Value**
Daily flow rate (Q_d)	3000 m^3 per day
Availability fraction (a)	0.5
Average flux of first membrane (U_1)	24 liters per m^2
Average flux of first membrane (U_2)	24 liters per m^2
Selection factor (Z)	0
Membrane specific flux per driving pressure (e)	4.5 litres per m^2.h.bar
Total Dissolved Solids (TDS)	2000 milligram per liter
Temperature (T)	18^oC
Efficiency of pumps (np)	0.78
Energy recovery selection factor (s)	0
Efficiency of the energy recovery unit	0
Fraction feedwater lost at pre-treatment (B)	0.05
Feedwater pressure	3 bar

The output technical features of the reverse osmosis water purification plant are shown in Table 5.2. These characteristics include the hourly design flow rate, membrane area, number of membranes, and plant feed-in pressure.

Table 5. 2: Technical characteristics of the reverse osmosis water purification plant

Technical characteristics on the plant	
Quantity	**Value**
Design product flow rate	250 m^3 per hour
Total membrane area	10417 m^2
Number of membranes	86
Feed-in pressure	19.14 bar
Design feed flow rate	350.8772 m^3/h
Total power demand	249.9939 kW
Specific energy per volume of water produced	1 kWh/m^3

5.5.1.1. Design product flow rate

The hourly product flow rate of the plant is evaluated to 250 cubic metres per hour since the plant is operating only for 12 hours and the daily flow rate is 3000 cubic metres per day.

5.5.1.2. Total membrane area

The total membrane area is evaluated to 10417 m^2; when two membrane arrays, several ratios (3:1, 5:2, 1:1, etc.) are employed between membrane arrays depending on the application. In this investigation, the single-array flow setup is used. Table 5.3

provides the characteristics of the selected type of membrane. The total number of membranes needed is 86, as the area of each membrane in the first array is 120.8 m^2.

Table 5. 3: Membranes characteristics (Hoffman, 2008)

Membranes characteristics	
Membranes in array 1	
Model	Hydranautics SWC3-16X40
Permeate flow rate	80 m^3 per day
Stabilized salt rejection	99.5 %
Effective area	120.8 m^2
Flux rate	19 litre per hm^2
Membranes in array 2	
Model	CSM RE 1640-BLR
Permeate flow rate	136.8 m^3 per day
Stabilized salt rejection	99.5 %
Effective area	116.2 m^2
Flux rate	34 litre per hm^2

5.5.1.3. Feed-in pressure

Since the membrane-specific flow rate for each driving pressure is 4.5, the supply pressure provided by the high-pressure pump is 19.14 bar.

5.5.1.4. Design feed flow rate

In evaluating the designed feed rate, it is assumed that a well-designed and complete media filtration system exists, and the stoichiometric system is used as a pretreatment. Since 5% of the effluent water is considered for backwash and purge in this investigation, the designed effluent flow rate is 350.8772 cubic meters per hour.

5.5.1.5. Plant specific energy demand

Since the plant is considered to operate with no energy recovery unit and the high-pressure pump runs at the efficiency of 78%, the power requirement of the purification process is 227.1869 kW. Furthermore, since it is assumed a single pretreatment stage, the total feed pressure is considered to be approximately 3 bar (Table 5.1). The estimated total additional power demand of the facility is 22.8070 kW. Therefore, the overall power requirement of the designed reverse osmosis water purification plant is 249.9939 kW. Hence, the produced water's specific energy demand per volume is approximately 1 kWh per cubic meter.

5.5.1.6. Volume to be evaporated

Consider the various environmental problems associated with handling concentrates. If the brine discharge through an evaporation pond or the sea is not considered, constructing an adequately lined pond can account for a large part of the total cost of installation. The estimated influent to be evaporated is 100.8772 cubic meters per hour.

5.5.1.7. Cost of the plant

The designed reverse osmosis treatment plant cost is given in Table 5.4. this cost includes the total cost of membranes, the pre-treatment and post-treatment costs, and environmental evaluation and contractual items costs. The cost of the evaporation pond is not considered in this investigation.

Table 5. 4: Reverse osmosis water purification plant costs

Cost of the plant	
Quantity	**Value**
Membranes	US$ 1541990
Pre-treatment	US$ 934903
Post-treatment	US$ 2600737.65
Total cost without evaporation pond cost	US$ 2626745.0265

5.5.1.7.1. Cost of membranes

With a total membrane area of 10417 m^2, the desalination section estimated cost is provided in Table 5.4, and it is approximated to US$ 1541990.

5.5.1.7.2. Cost of pre-treatment

From Figure 5.6, the price of a common pre-treatment infrastructure is about US$ 934903 since the feed flow rate obtained is 350.8772 cubic metres per hour. Because the pre-treatment section comprises a typical media filtration system in this study, the cost factor of the pre-treatment is 1, and the pre-treatment infrastructure installed cost is still US$ 934903.

5.5.1.7.3. Total cost

The additional cost of 5% is considered for the water inlet and outlet system and the after-treatment (post-treatment) infrastructure. Hence, the total installed cost, without environmental evaluations and contractual items, is US$ 2600737.65. This price is not inclusive of the evaporation ponds facility costs. Assuming that the environmental evaluation and contractual items cost is 1% of US$ 2600737.65, the overall installed cost of the facility (without evaporation ponds) is approximately US$ 2626745.0265.

5.5.1.8. Unit cost of water production

Evaluating the produced water unit cost implies determining the cost of capital redemption, energy cost (cubic meter of water), membrane replacement cost, the cost of chemical and consumables, and labor and maintenance costs. The input parameters considered to evaluate these costs are provided in Table 5.5.

Table 5. 5: Input parameters

Input parameters	
Parameter	**Value**
Capital cost	US$ 2626745.0265
Monthly interest rate	13 %
Period of full capital redemption	25 years
Cost of electricity	US$ 0.503
Cost of membrane area	US$ 16..5/m^2
Membrane frequency of replacement	4 years
Z_1	0.05 %

5.5.1.8.1. Cost of capital redemption

The specific cost of redemption expressed in US $ per cubic meter is evaluated based on the monthly capital repayment using Equation 5.22. As a result, its value is determined as US $ 30.733.

5.5.1.8.2. Specific cost of energy

The specific cost of energy depends on the specific energy requirement per volume of water produced and the cost of electricity. It is evaluated to US $ 0.498 per cubic metre.

5.5.1.8.3. Cost of membranes replacement

The cost of the membrane generally depends on the manufacturer, each element area, the rejection rate, the pressure level, and so on. This price also depends on the number of parts ordered; thus, any specific cost indication may be misleading. In this investigation, the cost of the membrane is considered as US$ 16.5. Generally, complete replacement usually occurs after three to six years, considering the nature of the fouling and degradation experienced in the plant. This study considers the frequency of replacement to be four years.

The specific cost of membrane replacement is estimated at US$ 0.0392 per cubic using Equation 5.24.

5.5.2 Design of the solar power system driving the reverse osmosis

The solar power system model is shown in Figure 5.9 and consists of photovoltaic panels, power converters, a battery bank, and the load. The reverse osmosis load is connected to the AC bus. Its daily profile is depicted in Figure 5.10, and its peak value is 250 kW, while the average daily energy consumption is 16665 kWh per day. The plant operates for 12 hours, from 6 in the morning to 6 in the evening. The PV panels and the battery bank are connected to a 48 V DC bus, and the converter (inverter) connects the two buses.

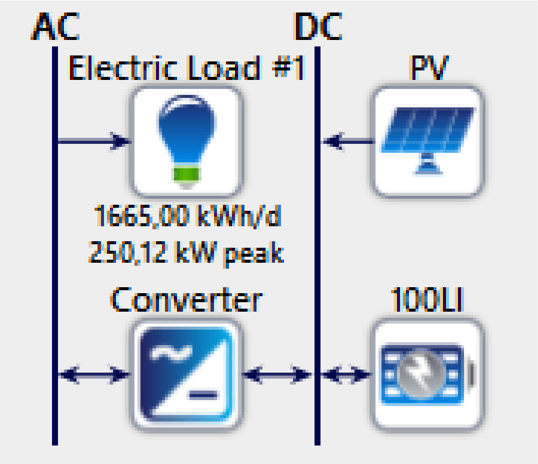


Figure 5. 9: Homer Pro layout of the PV plant

Figure 5.11 shows Mbhashe's annual average daily solar global level irradiance data. The highest solar irradiance occurs in January, February, November, and December, while the lowest occurs in May, June, and July. The yearly mean global solar horizontal irradiance is 4.48 kilowatts-hour per meter square per day.

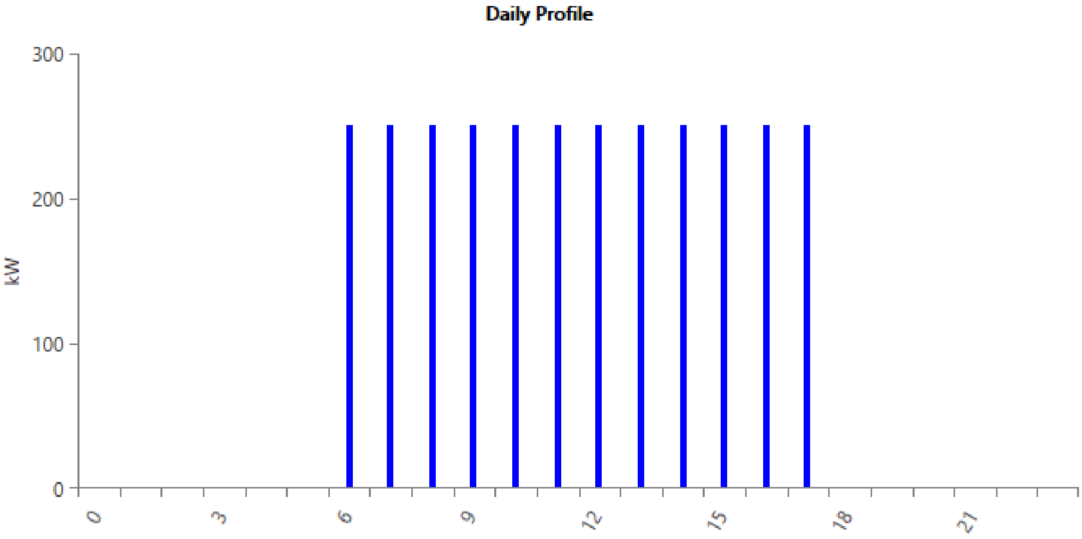


Figure 5. 10: Daily load profile

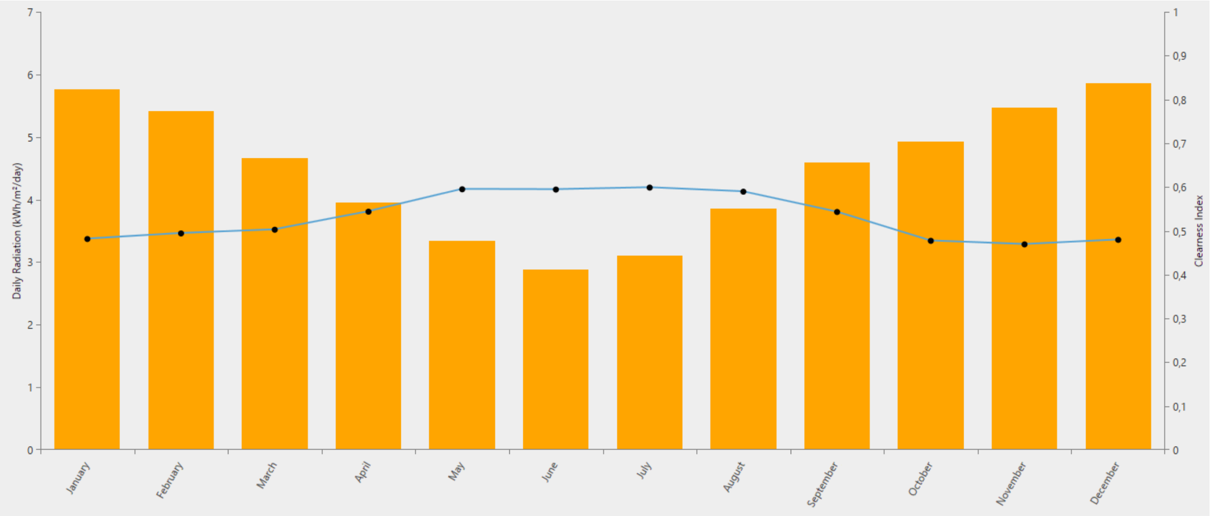


Figure 5. 11: Solar resources of Mbhashe

5.5.2.1. Component costs

The costs of components are given in Table 5.6; Luta and Raji (Luta & Raji, 2018) provide the capital cost, O&M, and replacement costs of the PV panels and the inverter, whereas Kabede et al. (Kebede et al., 2021) give the capital, operation and maintenance, and replacement costs of the lithium-ion battery. The PV capital cost is estimated to US$ 1000 per kW, while the O&M costs and the replacement cost are 55 per year and US $ 750, respectively.

The inverter capital cost is approximately US $ 400 per kW, while the replacement cost is US $ 300 per year, and the operation and maintenance is nil since such component does not require consistent maintenance, and its operation does not involve any additional expenses.

On the other hand, the capital cost of the lithium-ion battery is estimated to US $ 549.58 per kWh, while the operation and maintenance costs and the replacement cost are US $ 0 per year and US $ 489.62, respectively.

Table 5. 6: Components costs

Components costs			
Component	**Capital costs**	**Replacements**	**O&M costs**
PV	US$ 1000 per kW	US$ 750	US$ 55 a year
Inverter	US$ 400 per kW	US$ 300	US$ 0
Battery bank	US$ 549,58 per kWh	US$ 489,62	US$ 0

5.5.2.2. Simulation constraint

The assumptions considered limit the system to an annual capacity shortage of 0% and assume inflation and discount rates of 2% and 8%. The optimal configuration must meet the above minimum NPC restrictions within a 25-year life cycle. Finding this configuration involves deciding what combination of components your system should contain, including the size of each component. The HOMER Pro search space data used to determine the component size is given in Table 5.7. All parts, including PV generators, battery packs, and inverters, are optimized through Homer Pro's optimization system, meant to reduce design techniques to determine the lowest-cost components and even the system.

Table 5. 7: Search space configuration and components characteristics

System search space data			
Component	**Sizing option**	**Lifetime**	**Characteristics**
PV	Homer Optimizer	25 years	Derating factor (%): 80
Inverter	Homer Optimizer	15 years	Efficiency (%): 95
Battery bank	Homer Optimizer	15 years	Throughput (kWh): 3000

5.5.2.3. Technical optimization results

The simulation will select the dispatch strategy to provide the best results between the cycle-charging and load-following approaches. To meet the load demand of the reverse osmosis water treatment plant, the solar-based power system must comprise 1250 kW photovoltaic panels, 2408 kWh battery bank, and a converter of 248 kW (Table 5.8). More system results are provided in Appendix 2. The results consider the cycle charging approach as the suitable technique to acquire the optimal configuration. The system COE is approximately US$ 0.503 per kWh, and the NPC is US$ 3949750, while the system operating cost is US$ 100750.2 (Table 5.9).

The energy production of the PV system serves to meet the reverse osmosis energy requirement, and the excess is utilized to charge the battery bank (Table 5.10). Figure 5.10 shows the daily power produced by the PV system over the course of a year. The PV system operates for about 4376 hours every year. The power generated varies from one day to another, depending on the available solar radiation. The peak power production is about 1171 kW and occurs in September (Figure 5.10). The photovoltaic system generates a total of 1800046 kWh each year to satisfy the load requirements. 63.9% of this production is stored in the battery bank, and 33.7% of the energy produced is directly used to meet the water treatment plant load.

Table 5. 8: Optimal component sizes

Optimization results under cycle charge strategy	
Component	**Size**
PV panels	1250 kW
Battery bank	2408 kWh
Inverter	248 kW
Control strategy	
Dispatch	Cycle charging
Cost of energy	
US $ 0.503	

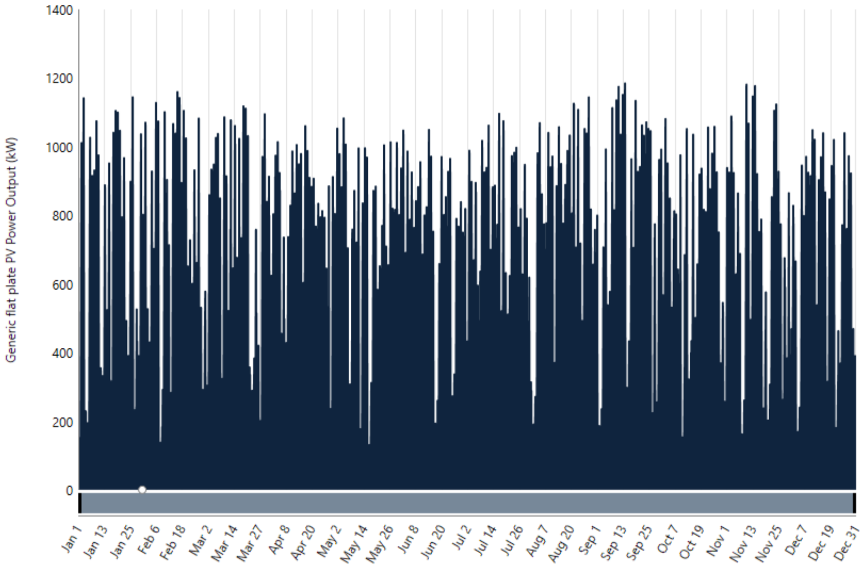


Figure 5. 12: Power generated by the PV system per annum

Table 5. 9: System costs

Power generation		
Component	**kWh per annum**	**%**
PV system	1800046	100
Battery bank		
Energy in	106391 kWh per year	
Energy out	95777 kWh per year	
Storage depletion	26 kWh per year	
Losses	10640 kWh per year	
Power consumption		
Load	607509	100
Inverter		
Hours of operation	4380 hours	
Energy-in	639483 kWh	
Energy-out	607509 kWh	
Losses	31974 kWh	

On the other hand, the battery bank has an autonomy of about 27.8 hours. It stores approximately 106391 kWh per annum to complement the photovoltaic system in meeting the load requirement if the latter does not produce sufficient energy or does not produce any energy to provide power to the load. The energy stored per annum in the battery bank is depicted in Figure 5.11. The battery's peak power charging is observed around the 27th of March, the 14th of May, and the 6th of August (Figure 5.12). The peak power required from the battery bank to feed the load occurs around the 27th of March, the 26th of May, and the 12th of September (Figure 5.13).

About 95777 kWh per year of the stored energy is used to meet the load requirement, while 10640 kWh per year is lost, and 26 kWh per annum represents storage depletion.

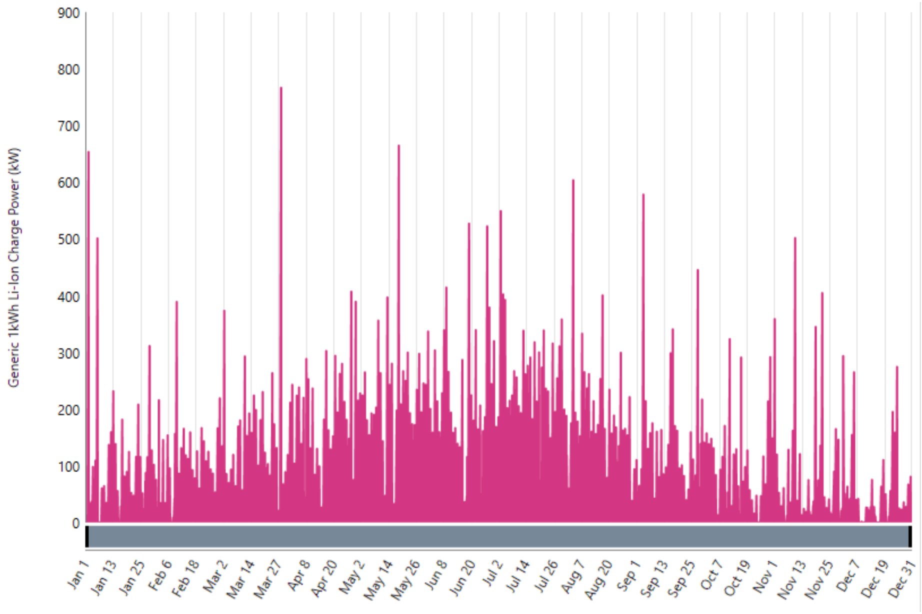


Figure 5. 13: Yearly energy stored into the battery bank

In the same vein, the inverter operates for about 4380 hours while receiving a total energy of 639483 kWh, supplying the load with 607509 kWh, and lossing approximately 31974 kWh (Table 5.9).

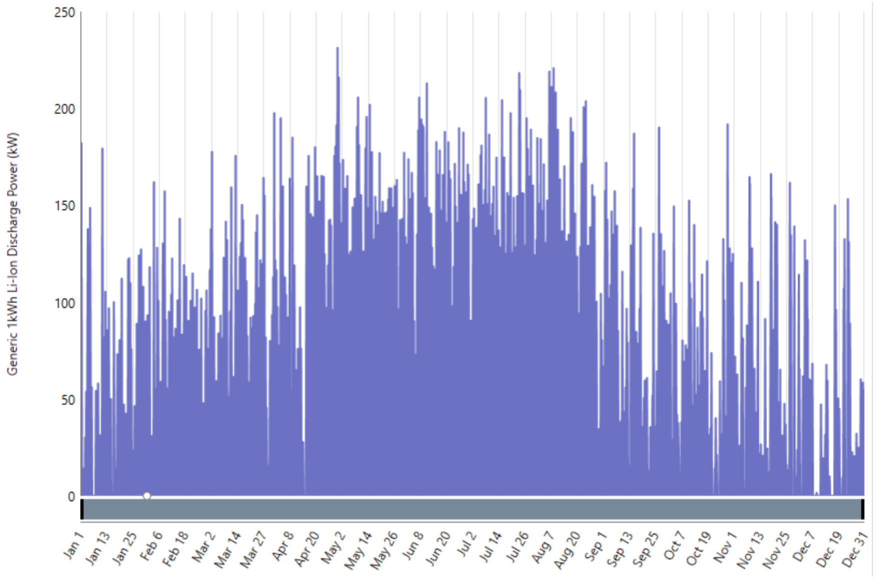


Figure 5. 14: Yearly discharged power from the battery bank

5.3.2.4. Economic characteristics of the PV plant

The capital cost of the optimal PV configuration is US$ 2.6 million, the NPC is US$ 3.9 million, with the Levelized Cost of Energy (COE) of US$ 0.503 per kWh. In addition, this configuration's operation and maintenance cost throughout the project lifetime is US$ 0.87 million (Table 5.10). Combining the capital costs, O&M costs, replacement costs, replacement costs, the total cost of the PV plant is the highest cost impact on the total system cost. The second contributor to the total cost is the battery bank, with an overall cost of approximately 1.7 million. However, the battery bank has the highest salvage cost of all the components at about US $ 94,147.

Table 5. 10: System costs

Solar-based power system costs					
Component	**Capital (US $)**	**Replacement (US $)**	**O&M (US $)**	**Salvage (US $)**	**Total (US $)**
PV panels	1,224,631.82	0.00	870,729.6	0.00	2,095,361.47
Battery bank	1,323,388.64	500,220.95	0.00	-94,146.63	1,729,462.96
Inverter	99,280.13	31,591.47	0.00	-5,945.83	124,925.76
System	2,647,300.59	531,812.42	870,729.6	-100,092.46	3,949750.19

5.3.2.5. Summary of the result of the techno-economic feasibility of the solar-based water purification system

The summary of the techno-economic feasibility of the solar-based water treatment system is shown in table 5.11.

Table 5. 11: Summary of the results

<table>
<tr><th colspan="6">Technical characteristics on the reverse osmosis water treatment plant</th></tr>
<tr><th colspan="3">Quantity</th><th colspan="3">Value</th></tr>
<tr><td colspan="3">Design product flow rate</td><td colspan="3">250 m^3 per hour</td></tr>
<tr><td colspan="3">Total membrane area</td><td colspan="3">10417 m^2</td></tr>
<tr><td colspan="3">Number of membranes</td><td colspan="3">86</td></tr>
<tr><td colspan="3">Feed-in pressure</td><td colspan="3">19.14 bar</td></tr>
<tr><td colspan="3">Design feed flow rate</td><td colspan="3">350.8772 m^3/h</td></tr>
<tr><td colspan="3">Total power demand</td><td colspan="3">249.9939 kW</td></tr>
<tr><td colspan="3">Specific energy per volume of water produced</td><td colspan="3">1 kWh/m^3</td></tr>
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</table>

CHAPTER SIX
CONCLUSION AND RECOMMENDATIONS FOR FURTHER STUDIES

6.1 Conclusion

Several people worldwide do not have access to potable or sanitary water. Studies reveal that many children die due to the lack of potable drinking water. Furthermore, research shows that this situation will not improve over time. By 2025, countries around the world may experience water shortages. In many countries, policies are implemented to maintain the future supply of potable water and increase the quantity and quality of healthy human lifestyles while protecting the ecosystem. One option to relieve pressure on water demand is to use desalination systems. Among these technologies, literature research recognizes that reverse osmosis technology competes with traditional distillation processes regarding product cost.

Furthermore, it is shown that the reverse osmosis process is gaining a larger market share than the conventional distillation process. The reverse osmosis process continually improves its efficiency through innovations and technologies. The process represents one of the emerging techniques for water treatment. Presently, recently developed technologies are improving the competitiveness of the reverse osmosis process against the traditional distillation processes. This study dealt with the techno-economic feasibility of a renewable-based water purification system to assess the system technical characteristics and the system costs for providing drinkable water to some portion of the population in a remote farming area of the Mbhashe municipality in the South African province of Eastern Cape. Furthermore, the investigation aimed to determine the size of components involved in the reverse osmosis process and the size of the renewable power system feeding the plant.

Therefore, the techno-economic assessment was carried out in two stages; the first step consisted of designing the reverse osmosis water purification system based on the population water requirement. The next stage focused on the feasibility of the renewable power system to meet the reverse osmosis process power requirement. The results obtained in both stages showed that to meet the water demand of 56000 inhabitants, the plant must be characterized by a design product flow rate of 250 m^3 per hour, a total membrane area of 10417 m^2, a feed-in pressure of 19.14 bar, and a specific energy per volume of water produced of 1 kWh per m^3. In addition, the plant must receive its power from a 1250 kW photovoltaic system with a 2408 kWh battery bank.

Furthermore, the capital cost of the reverse osmosis water purification plant was approximately US$ 2626745.0265, while the photovoltaic plant capital cost is 2,6 million.

6.2 Recommendations for further studies

Further investigations should focus on conducting techno-economic assessments using the solar thermal process for water purification. In addition, research should also be carried out to compare various existing water purification processes regarding their efficiency and capital costs.

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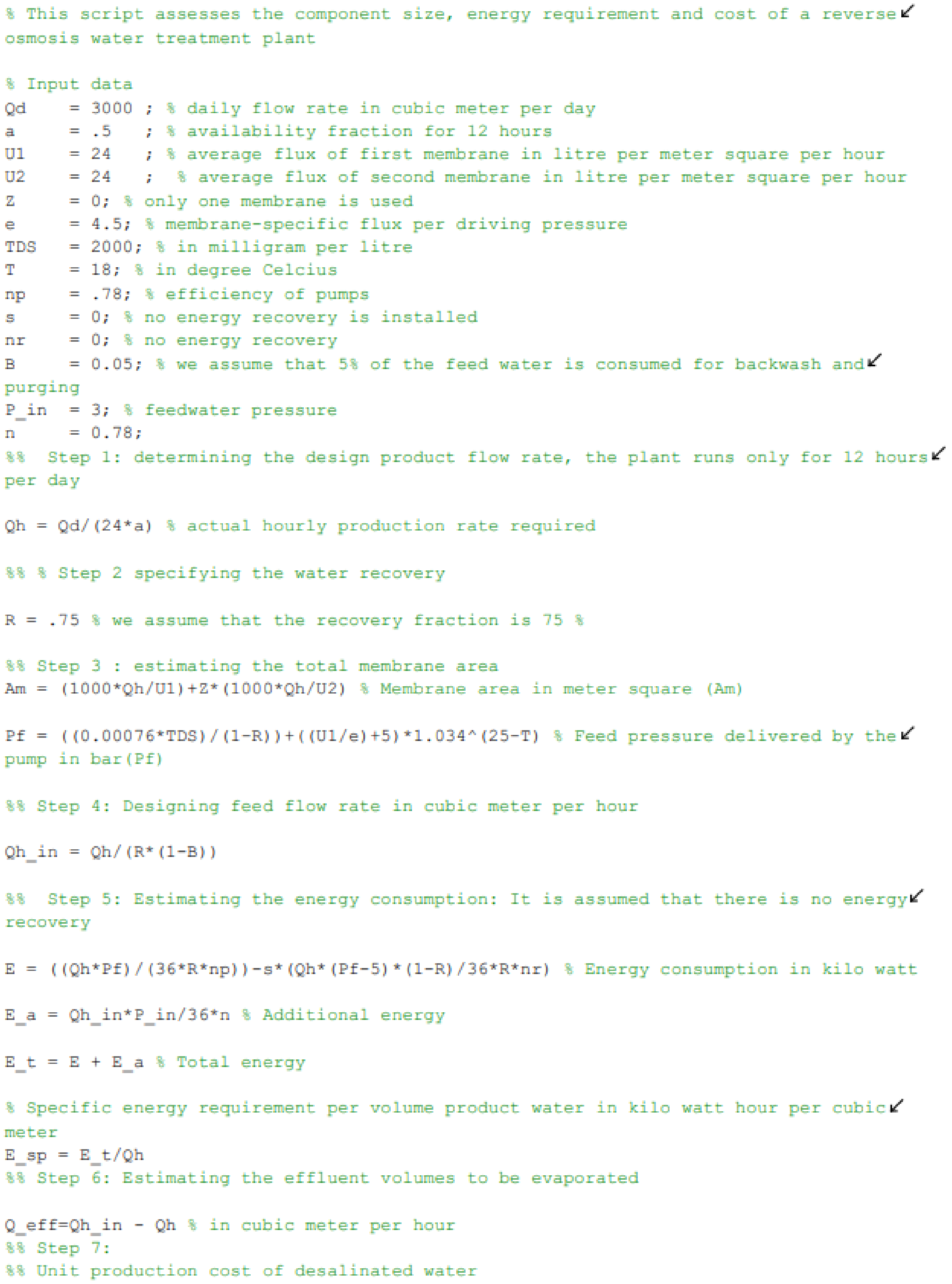
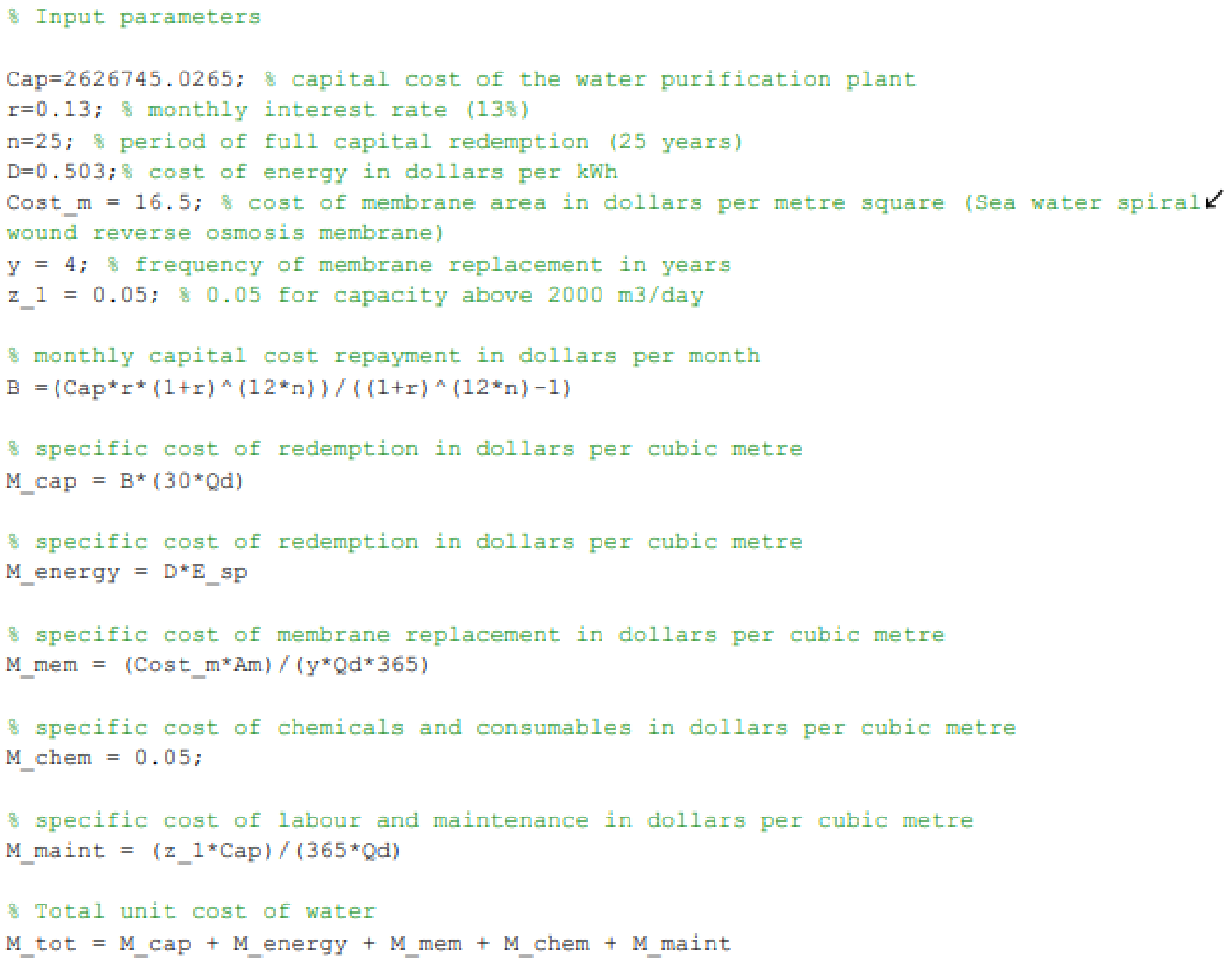
APPENDICES

Appendix 1

Matlab programming code



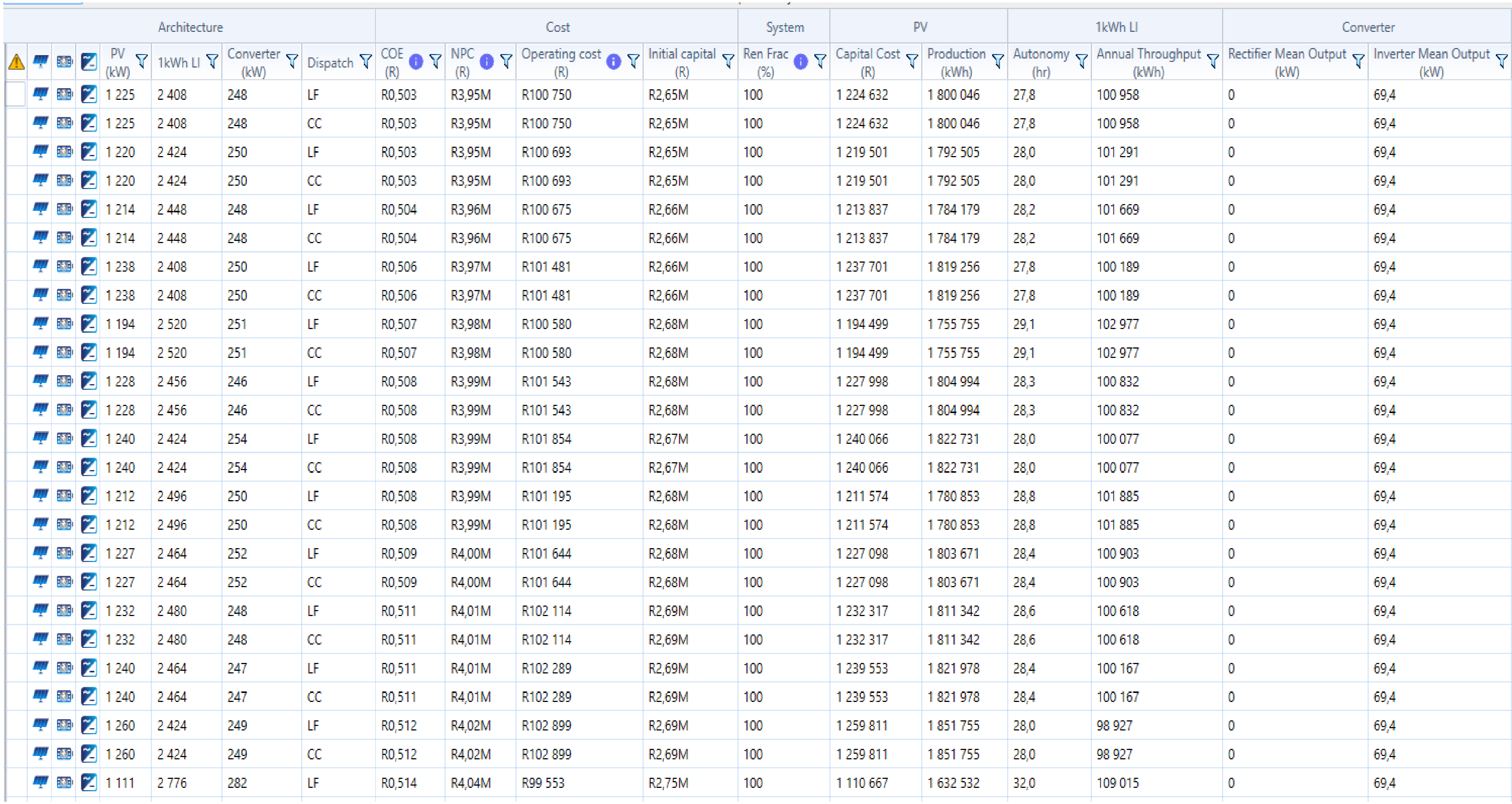
```
% This script assesses the component size, energy requirement and cost of a reverse↙
osmosis water treatment plant

% Input data
Qd     = 3000 ; % daily flow rate in cubic meter per day
a      = .5   ; % availability fraction for 12 hours
U1     = 24   ; % average flux of first membrane in litre per meter square per hour
U2     = 24   ;  % average flux of second membrane in litre per meter square per hour
Z      = 0; % only one membrane is used
e      = 4.5; % membrane-specific flux per driving pressure
TDS    = 2000; % in milligram per litre
T      = 18; % in degree Celcius
np     = .78; % efficiency of pumps
s      = 0; % no energy recovery is installed
nr     = 0; % no energy recovery
B      = 0.05; % we assume that 5% of the feed water is consumed for backwash and↙
purging
P_in   = 3; % feedwater pressure
n      = 0.78;
%%  Step 1: determining the design product flow rate, the plant runs only for 12 hours↙
per day

Qh = Qd/(24*a) % actual hourly production rate required

%% % Step 2 specifying the water recovery

R = .75 % we assume that the recovery fraction is 75 %

%% Step 3 : estimating the total membrane area
Am = (1000*Qh/U1)+Z*(1000*Qh/U2) % Membrane area in meter square (Am)

Pf = ((0.00076*TDS)/(1-R))+((U1/e)+5)*1.034^(25-T) % Feed pressure delivered by the↙
pump in bar(Pf)

%% Step 4: Designing feed flow rate in cubic meter per hour

Qh_in = Qh/(R*(1-B))

%%  Step 5: Estimating the energy consumption: It is assumed that there is no energy↙
recovery

E = ((Qh*Pf)/(36*R*np))-s*(Qh*(Pf-5)*(1-R)/36*R*nr) % Energy consumption in kilo watt

E_a = Qh_in*P_in/36*n % Additional energy

E_t = E + E_a % Total energy

% Specific energy requirement per volume product water in kilo watt hour per cubic↙
meter
E_sp = E_t/Qh
%% Step 6: Estimating the effluent volumes to be evaporated

Q_eff=Qh_in - Qh % in cubic meter per hour
%% Step 7:
%% Unit production cost of desalinated water
```



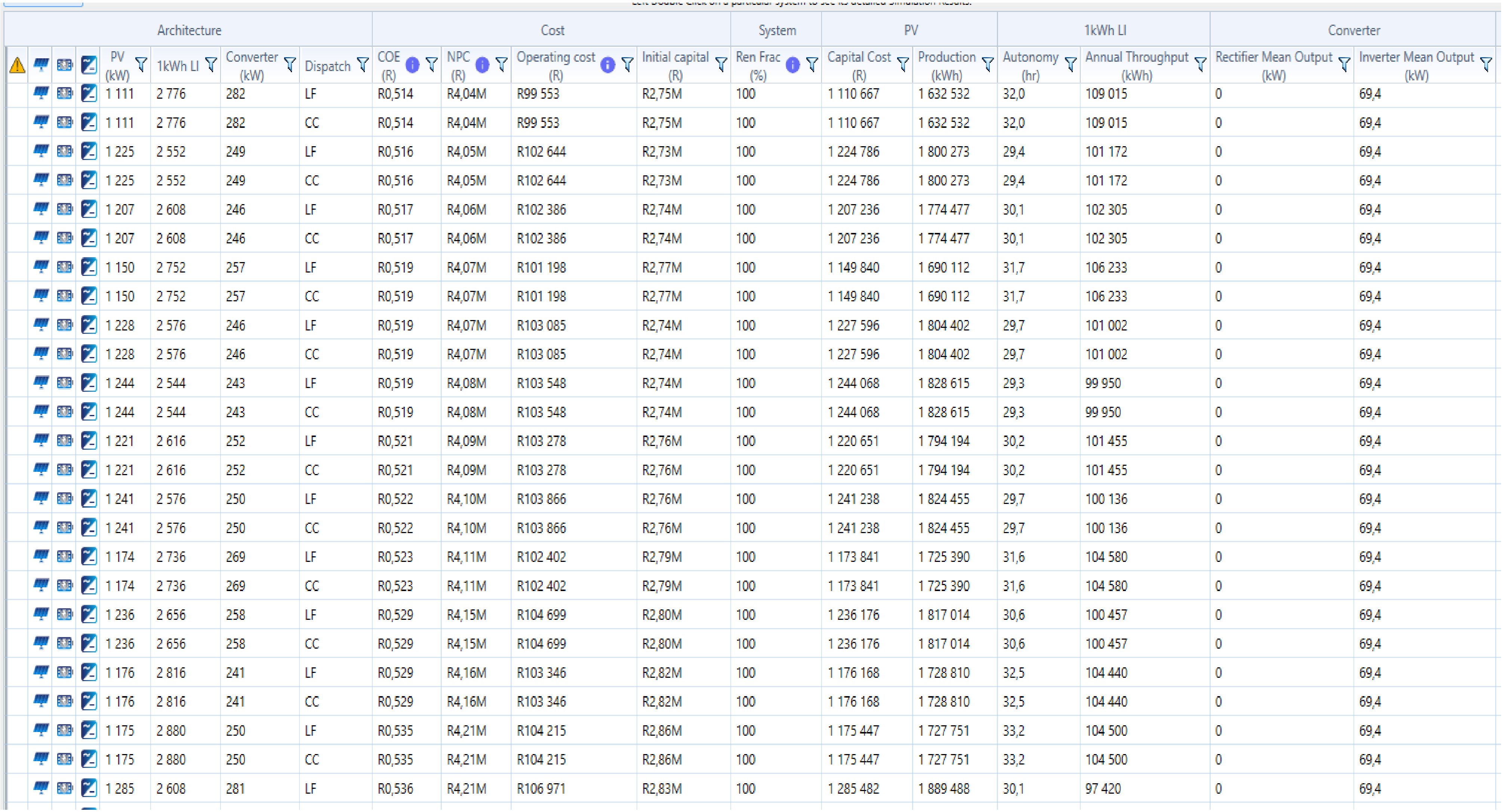
```
% Input parameters

Cap=2626745.0265; % capital cost of the water purification plant
r=0.13; % monthly interest rate (13%)
n=25; % period of full capital redemption (25 years)
D=0.503;% cost of energy in dollars per kWh
Cost_m = 16.5; % cost of membrane area in dollars per metre square (Sea water spiral↙
wound reverse osmosis membrane)
y = 4; % frequency of membrane replacement in years
z_1 = 0.05; % 0.05 for capacity above 2000 m3/day

% monthly capital cost repayment in dollars per month
B =(Cap*r*(1+r)^(12*n))/((1+r)^(12*n)-1)

% specific cost of redemption in dollars per cubic metre
M_cap = B*(30*Qd)

% specific cost of redemption in dollars per cubic metre
M_energy = D*E_sp

% specific cost of membrane replacement in dollars per cubic metre
M_mem = (Cost_m*Am)/(y*Qd*365)

% specific cost of chemicals and consumables in dollars per cubic metre
M_chem = 0.05;

% specific cost of labour and maintenance in dollars per cubic metre
M_maint = (z_1*Cap)/(365*Qd)

% Total unit cost of water
M_tot = M_cap + M_energy + M_mem + M_chem + M_maint
```

Appendix 2

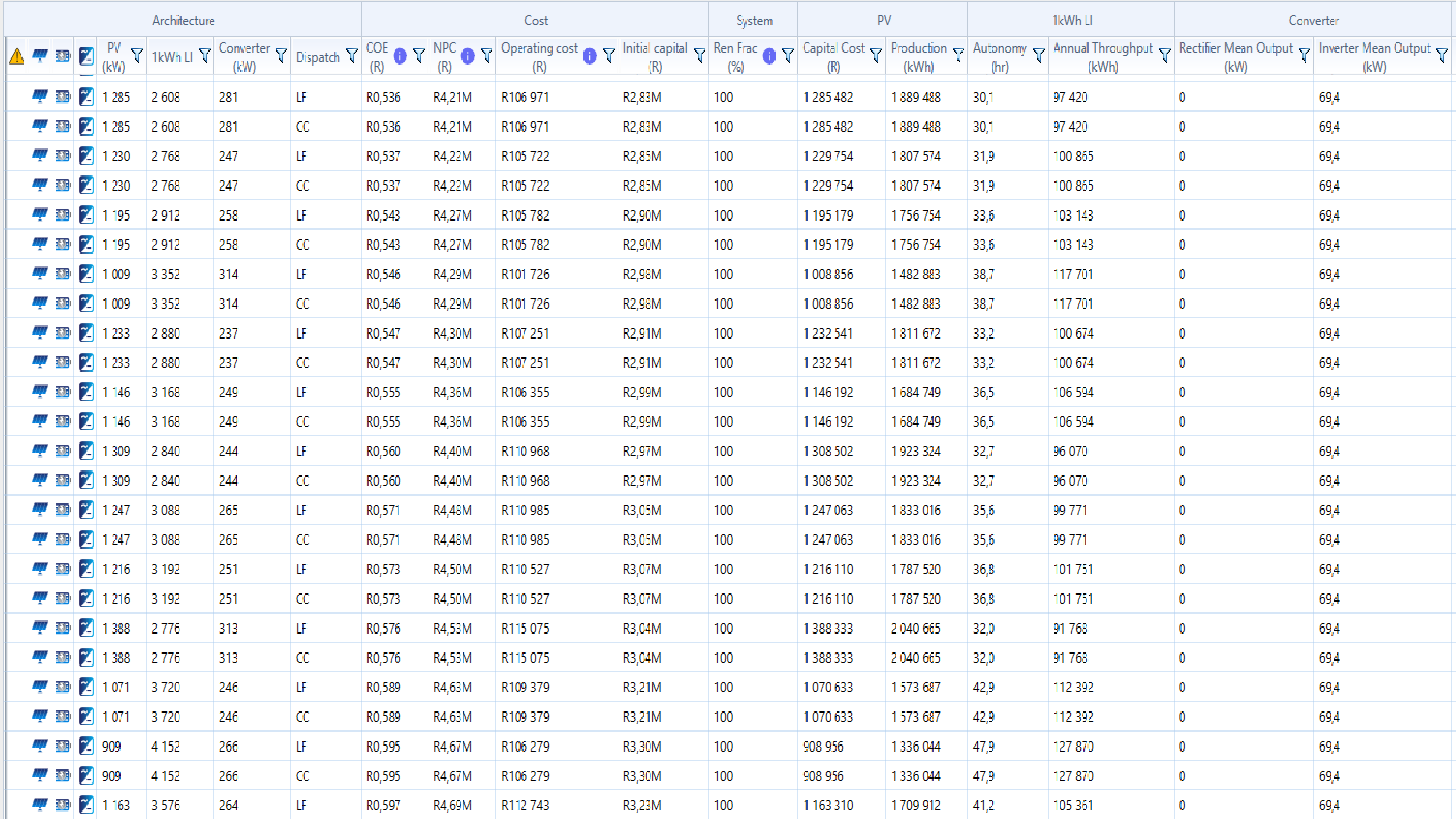
1. Overall optimization results



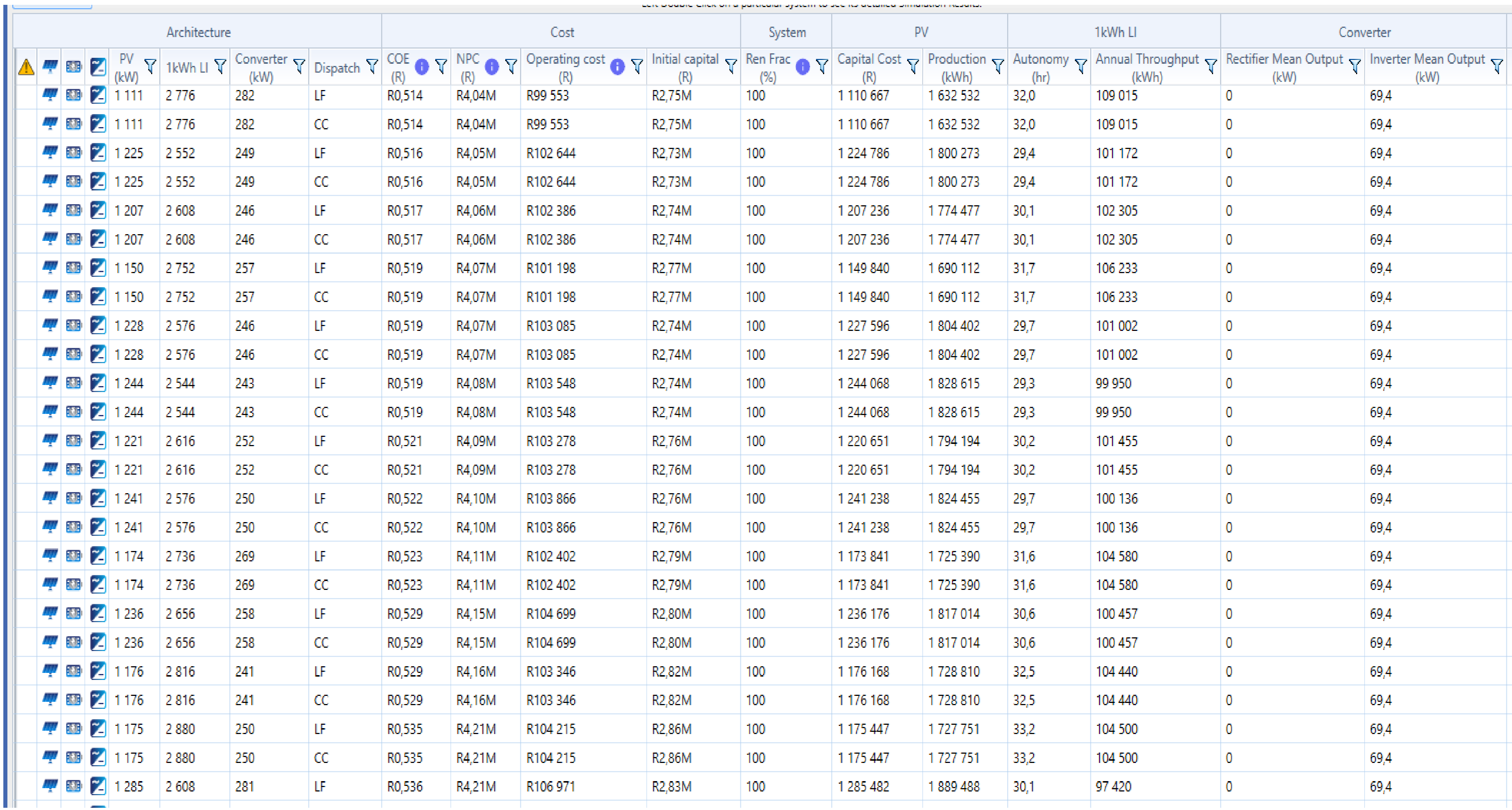
Architecture				Cost				System	PV		1kWh LI		Converter	
PV (kW)	1kWh LI	Converter (kW)	Dispatch	COE (R)	NPC (R)	Operating cost (R)	Initial capital (R)	Ren Frac (%)	Capital Cost (R)	Production (kWh)	Autonomy (hr)	Annual Throughput (kWh)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)
1 225	2 408	248	LF	R0,503	R3,95M	R100 750	R2,65M	100	1 224 632	1 800 046	27,8	100 958	0	69,4
1 225	2 408	248	CC	R0,503	R3,95M	R100 750	R2,65M	100	1 224 632	1 800 046	27,8	100 958	0	69,4
1 220	2 424	250	LF	R0,503	R3,95M	R100 693	R2,65M	100	1 219 501	1 792 505	28,0	101 291	0	69,4
1 220	2 424	250	CC	R0,503	R3,95M	R100 693	R2,65M	100	1 219 501	1 792 505	28,0	101 291	0	69,4
1 214	2 448	248	LF	R0,504	R3,96M	R100 675	R2,66M	100	1 213 837	1 784 179	28,2	101 669	0	69,4
1 214	2 448	248	CC	R0,504	R3,96M	R100 675	R2,66M	100	1 213 837	1 784 179	28,2	101 669	0	69,4
1 238	2 408	250	LF	R0,506	R3,97M	R101 481	R2,66M	100	1 237 701	1 819 256	27,8	100 189	0	69,4
1 238	2 408	250	CC	R0,506	R3,97M	R101 481	R2,66M	100	1 237 701	1 819 256	27,8	100 189	0	69,4
1 194	2 520	251	LF	R0,507	R3,98M	R100 580	R2,68M	100	1 194 499	1 755 755	29,1	102 977	0	69,4
1 194	2 520	251	CC	R0,507	R3,98M	R100 580	R2,68M	100	1 194 499	1 755 755	29,1	102 977	0	69,4
1 228	2 456	246	LF	R0,508	R3,99M	R101 543	R2,68M	100	1 227 998	1 804 994	28,3	100 832	0	69,4
1 228	2 456	246	CC	R0,508	R3,99M	R101 543	R2,68M	100	1 227 998	1 804 994	28,3	100 832	0	69,4
1 240	2 424	254	LF	R0,508	R3,99M	R101 854	R2,67M	100	1 240 066	1 822 731	28,0	100 077	0	69,4
1 240	2 424	254	CC	R0,508	R3,99M	R101 854	R2,67M	100	1 240 066	1 822 731	28,0	100 077	0	69,4
1 212	2 496	250	LF	R0,508	R3,99M	R101 195	R2,68M	100	1 211 574	1 780 853	28,8	101 885	0	69,4
1 212	2 496	250	CC	R0,508	R3,99M	R101 195	R2,68M	100	1 211 574	1 780 853	28,8	101 885	0	69,4
1 227	2 464	252	LF	R0,509	R4,00M	R101 644	R2,68M	100	1 227 098	1 803 671	28,4	100 903	0	69,4
1 227	2 464	252	CC	R0,509	R4,00M	R101 644	R2,68M	100	1 227 098	1 803 671	28,4	100 903	0	69,4
1 232	2 480	248	LF	R0,511	R4,01M	R102 114	R2,69M	100	1 232 317	1 811 342	28,6	100 618	0	69,4
1 232	2 480	248	CC	R0,511	R4,01M	R102 114	R2,69M	100	1 232 317	1 811 342	28,6	100 618	0	69,4
1 240	2 464	247	LF	R0,511	R4,01M	R102 289	R2,69M	100	1 239 553	1 821 978	28,4	100 167	0	69,4
1 240	2 464	247	CC	R0,511	R4,01M	R102 289	R2,69M	100	1 239 553	1 821 978	28,4	100 167	0	69,4
1 260	2 424	249	LF	R0,512	R4,02M	R102 899	R2,69M	100	1 259 811	1 851 755	28,0	98 927	0	69,4
1 260	2 424	249	CC	R0,512	R4,02M	R102 899	R2,69M	100	1 259 811	1 851 755	28,0	98 927	0	69,4
1 111	2 776	282	LF	R0,514	R4,04M	R99 553	R2,75M	100	1 110 667	1 632 532	32,0	109 015	0	69,4



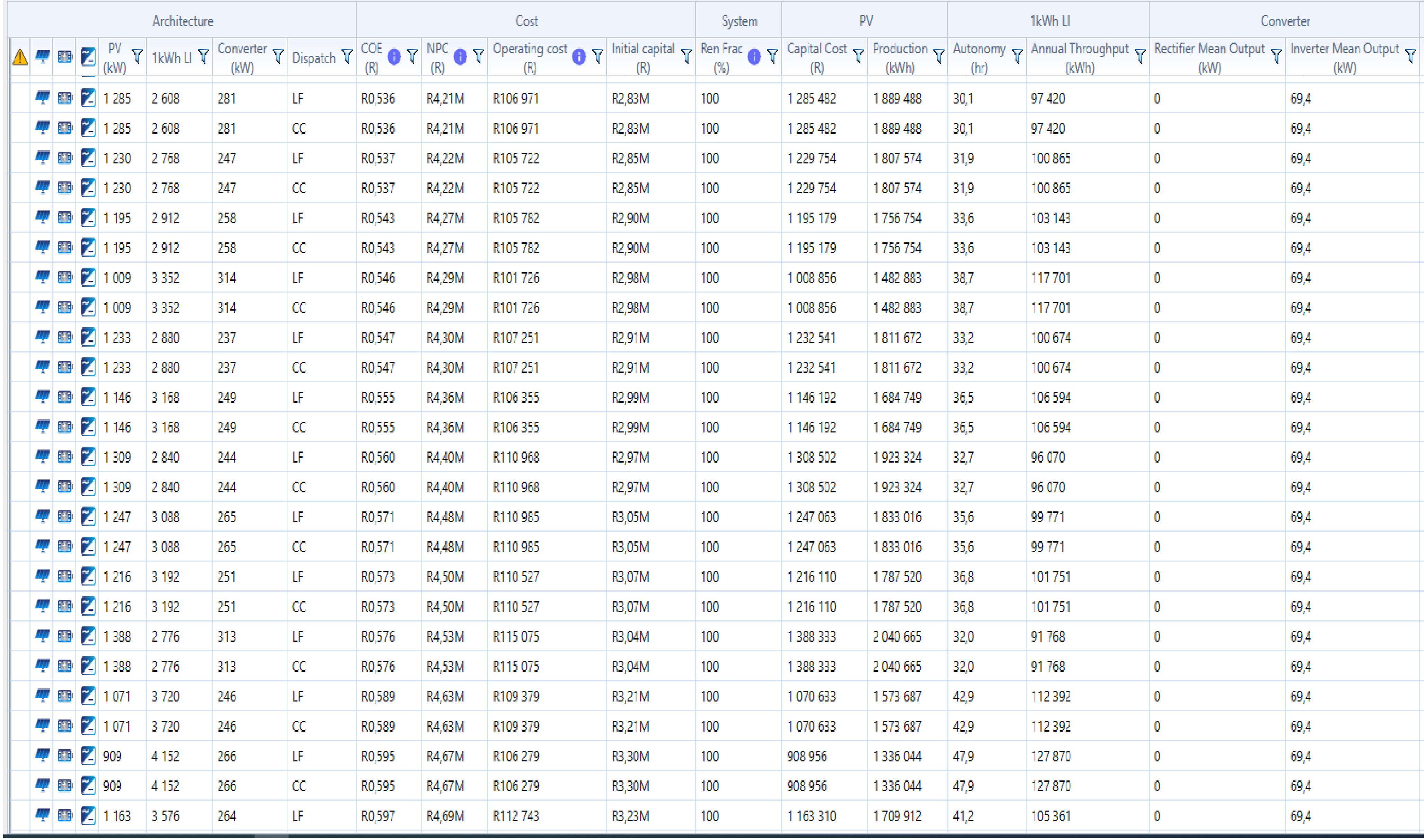
Architecture				Cost				System	PV		1kWh LI		Converter	
PV (kW)	1kWh LI	Converter (kW)	Dispatch	COE (R)	NPC (R)	Operating cost (R)	Initial capital (R)	Ren Frac (%)	Capital Cost (R)	Production (kWh)	Autonomy (hr)	Annual Throughput (kWh)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)
1 111	2 776	282	LF	R0,514	R4,04M	R99 553	R2,75M	100	1 110 667	1 632 532	32,0	109 015	0	69,4
1 111	2 776	282	CC	R0,514	R4,04M	R99 553	R2,75M	100	1 110 667	1 632 532	32,0	109 015	0	69,4
1 225	2 552	249	LF	R0,516	R4,05M	R102 644	R2,73M	100	1 224 786	1 800 273	29,4	101 172	0	69,4
1 225	2 552	249	CC	R0,516	R4,05M	R102 644	R2,73M	100	1 224 786	1 800 273	29,4	101 172	0	69,4
1 207	2 608	246	LF	R0,517	R4,06M	R102 386	R2,74M	100	1 207 236	1 774 477	30,1	102 305	0	69,4
1 207	2 608	246	CC	R0,517	R4,06M	R102 386	R2,74M	100	1 207 236	1 774 477	30,1	102 305	0	69,4
1 150	2 752	257	LF	R0,519	R4,07M	R101 198	R2,77M	100	1 149 840	1 690 112	31,7	106 233	0	69,4
1 150	2 752	257	CC	R0,519	R4,07M	R101 198	R2,77M	100	1 149 840	1 690 112	31,7	106 233	0	69,4
1 228	2 576	246	LF	R0,519	R4,07M	R103 085	R2,74M	100	1 227 596	1 804 402	29,7	101 002	0	69,4
1 228	2 576	246	CC	R0,519	R4,07M	R103 085	R2,74M	100	1 227 596	1 804 402	29,7	101 002	0	69,4
1 244	2 544	243	LF	R0,519	R4,08M	R103 548	R2,74M	100	1 244 068	1 828 615	29,3	99 950	0	69,4
1 244	2 544	243	CC	R0,519	R4,08M	R103 548	R2,74M	100	1 244 068	1 828 615	29,3	99 950	0	69,4
1 221	2 616	252	LF	R0,521	R4,09M	R103 278	R2,76M	100	1 220 651	1 794 194	30,2	101 455	0	69,4
1 221	2 616	252	CC	R0,521	R4,09M	R103 278	R2,76M	100	1 220 651	1 794 194	30,2	101 455	0	69,4
1 241	2 576	250	LF	R0,522	R4,10M	R103 866	R2,76M	100	1 241 238	1 824 455	29,7	100 136	0	69,4
1 241	2 576	250	CC	R0,522	R4,10M	R103 866	R2,76M	100	1 241 238	1 824 455	29,7	100 136	0	69,4
1 174	2 736	269	LF	R0,523	R4,11M	R102 402	R2,79M	100	1 173 841	1 725 390	31,6	104 580	0	69,4
1 174	2 736	269	CC	R0,523	R4,11M	R102 402	R2,79M	100	1 173 841	1 725 390	31,6	104 580	0	69,4
1 236	2 656	258	LF	R0,529	R4,15M	R104 699	R2,80M	100	1 236 176	1 817 014	30,6	100 457	0	69,4
1 236	2 656	258	CC	R0,529	R4,15M	R104 699	R2,80M	100	1 236 176	1 817 014	30,6	100 457	0	69,4
1 176	2 816	241	LF	R0,529	R4,16M	R103 346	R2,82M	100	1 176 168	1 728 810	32,5	104 440	0	69,4
1 176	2 816	241	CC	R0,529	R4,16M	R103 346	R2,82M	100	1 176 168	1 728 810	32,5	104 440	0	69,4
1 175	2 880	250	LF	R0,535	R4,21M	R104 215	R2,86M	100	1 175 447	1 727 751	33,2	104 500	0	69,4
1 175	2 880	250	CC	R0,535	R4,21M	R104 215	R2,86M	100	1 175 447	1 727 751	33,2	104 500	0	69,4
1 285	2 608	281	LF	R0,536	R4,21M	R106 971	R2,83M	100	1 285 482	1 889 488	30,1	97 420	0	69,4



Architecture				Cost				System	PV		1kWh LI		Converter	
PV (kW)	1kWh LI	Converter (kW)	Dispatch	COE (R)	NPC (R)	Operating cost (R)	Initial capital (R)	Ren Frac (%)	Capital Cost (R)	Production (kWh)	Autonomy (hr)	Annual Throughput (kWh)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)
1 285	2 608	281	LF	R0,536	R4,21M	R106 971	R2,83M	100	1 285 482	1 889 488	30,1	97 420	0	69,4
1 285	2 608	281	CC	R0,536	R4,21M	R106 971	R2,83M	100	1 285 482	1 889 488	30,1	97 420	0	69,4
1 230	2 768	247	LF	R0,537	R4,22M	R105 722	R2,85M	100	1 229 754	1 807 574	31,9	100 865	0	69,4
1 230	2 768	247	CC	R0,537	R4,22M	R105 722	R2,85M	100	1 229 754	1 807 574	31,9	100 865	0	69,4
1 195	2 912	258	LF	R0,543	R4,27M	R105 782	R2,90M	100	1 195 179	1 756 754	33,6	103 143	0	69,4
1 195	2 912	258	CC	R0,543	R4,27M	R105 782	R2,90M	100	1 195 179	1 756 754	33,6	103 143	0	69,4
1 009	3 352	314	LF	R0,546	R4,29M	R101 726	R2,98M	100	1 008 856	1 482 883	38,7	117 701	0	69,4
1 009	3 352	314	CC	R0,546	R4,29M	R101 726	R2,98M	100	1 008 856	1 482 883	38,7	117 701	0	69,4
1 233	2 880	237	LF	R0,547	R4,30M	R107 251	R2,91M	100	1 232 541	1 811 672	33,2	100 674	0	69,4
1 233	2 880	237	CC	R0,547	R4,30M	R107 251	R2,91M	100	1 232 541	1 811 672	33,2	100 674	0	69,4
1 146	3 168	249	LF	R0,555	R4,36M	R106 355	R2,99M	100	1 146 192	1 684 749	36,5	106 594	0	69,4
1 146	3 168	249	CC	R0,555	R4,36M	R106 355	R2,99M	100	1 146 192	1 684 749	36,5	106 594	0	69,4
1 309	2 840	244	LF	R0,560	R4,40M	R110 968	R2,97M	100	1 308 502	1 923 324	32,7	96 070	0	69,4
1 309	2 840	244	CC	R0,560	R4,40M	R110 968	R2,97M	100	1 308 502	1 923 324	32,7	96 070	0	69,4
1 247	3 088	265	LF	R0,571	R4,48M	R110 985	R3,05M	100	1 247 063	1 833 016	35,6	99 771	0	69,4
1 247	3 088	265	CC	R0,571	R4,48M	R110 985	R3,05M	100	1 247 063	1 833 016	35,6	99 771	0	69,4
1 216	3 192	251	LF	R0,573	R4,50M	R110 527	R3,07M	100	1 216 110	1 787 520	36,8	101 751	0	69,4
1 216	3 192	251	CC	R0,573	R4,50M	R110 527	R3,07M	100	1 216 110	1 787 520	36,8	101 751	0	69,4
1 388	2 776	313	LF	R0,576	R4,53M	R115 075	R3,04M	100	1 388 333	2 040 665	32,0	91 768	0	69,4
1 388	2 776	313	CC	R0,576	R4,53M	R115 075	R3,04M	100	1 388 333	2 040 665	32,0	91 768	0	69,4
1 071	3 720	246	LF	R0,589	R4,63M	R109 379	R3,21M	100	1 070 633	1 573 687	42,9	112 392	0	69,4
1 071	3 720	246	CC	R0,589	R4,63M	R109 379	R3,21M	100	1 070 633	1 573 687	42,9	112 392	0	69,4
909	4 152	266	LF	R0,595	R4,67M	R106 279	R3,30M	100	908 956	1 336 044	47,9	127 870	0	69,4
909	4 152	266	CC	R0,595	R4,67M	R106 279	R3,30M	100	908 956	1 336 044	47,9	127 870	0	69,4
1 163	3 576	264	LF	R0,597	R4,69M	R112 743	R3,23M	100	1 163 310	1 709 912	41,2	105 361	0	69,4

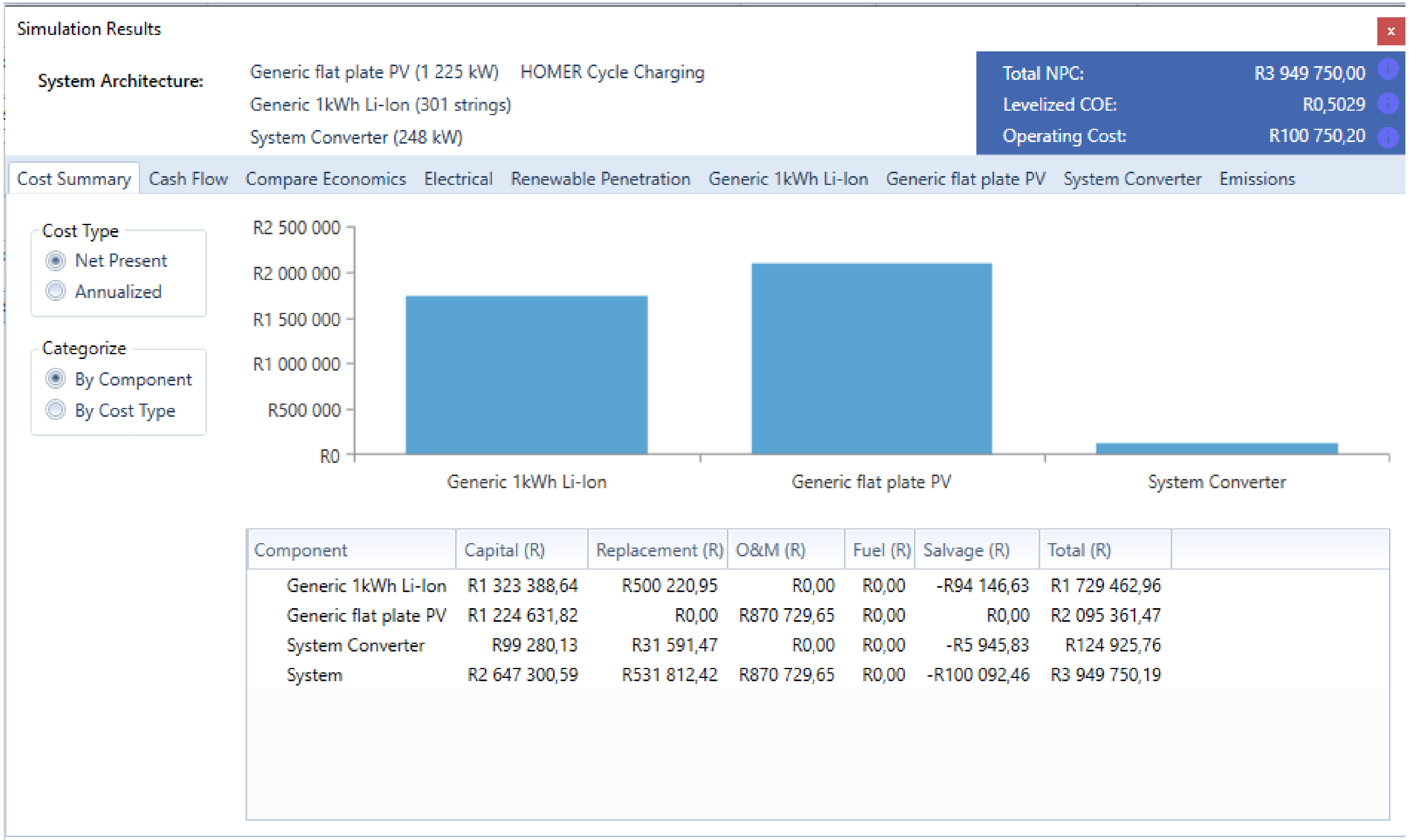


Architecture				Cost				System	PV		1kWh LI		Converter	
PV (kW)	1kWh LI	Converter (kW)	Dispatch	COE (R)	NPC (R)	Operating cost (R)	Initial capital (R)	Ren Frac (%)	Capital Cost (R)	Production (kWh)	Autonomy (hr)	Annual Throughput (kWh)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)
1 111	2 776	282	LF	R0,514	R4,04M	R99 553	R2,75M	100	1 110 667	1 632 532	32,0	109 015	0	69,4
1 111	2 776	282	CC	R0,514	R4,04M	R99 553	R2,75M	100	1 110 667	1 632 532	32,0	109 015	0	69,4
1 225	2 552	249	LF	R0,516	R4,05M	R102 644	R2,73M	100	1 224 786	1 800 273	29,4	101 172	0	69,4
1 225	2 552	249	CC	R0,516	R4,05M	R102 644	R2,73M	100	1 224 786	1 800 273	29,4	101 172	0	69,4
1 207	2 608	246	LF	R0,517	R4,06M	R102 386	R2,74M	100	1 207 236	1 774 477	30,1	102 305	0	69,4
1 207	2 608	246	CC	R0,517	R4,06M	R102 386	R2,74M	100	1 207 236	1 774 477	30,1	102 305	0	69,4
1 150	2 752	257	LF	R0,519	R4,07M	R101 198	R2,77M	100	1 149 840	1 690 112	31,7	106 233	0	69,4
1 150	2 752	257	CC	R0,519	R4,07M	R101 198	R2,77M	100	1 149 840	1 690 112	31,7	106 233	0	69,4
1 228	2 576	246	LF	R0,519	R4,07M	R103 085	R2,74M	100	1 227 596	1 804 402	29,7	101 002	0	69,4
1 228	2 576	246	CC	R0,519	R4,07M	R103 085	R2,74M	100	1 227 596	1 804 402	29,7	101 002	0	69,4
1 244	2 544	243	LF	R0,519	R4,08M	R103 548	R2,74M	100	1 244 068	1 828 615	29,3	99 950	0	69,4
1 244	2 544	243	CC	R0,519	R4,08M	R103 548	R2,74M	100	1 244 068	1 828 615	29,3	99 950	0	69,4
1 221	2 616	252	LF	R0,521	R4,09M	R103 278	R2,76M	100	1 220 651	1 794 194	30,2	101 455	0	69,4
1 221	2 616	252	CC	R0,521	R4,09M	R103 278	R2,76M	100	1 220 651	1 794 194	30,2	101 455	0	69,4
1 241	2 576	250	LF	R0,522	R4,10M	R103 866	R2,76M	100	1 241 238	1 824 455	29,7	100 136	0	69,4
1 241	2 576	250	CC	R0,522	R4,10M	R103 866	R2,76M	100	1 241 238	1 824 455	29,7	100 136	0	69,4
1 174	2 736	269	LF	R0,523	R4,11M	R102 402	R2,79M	100	1 173 841	1 725 390	31,6	104 580	0	69,4
1 174	2 736	269	CC	R0,523	R4,11M	R102 402	R2,79M	100	1 173 841	1 725 390	31,6	104 580	0	69,4
1 236	2 656	258	LF	R0,529	R4,15M	R104 699	R2,80M	100	1 236 176	1 817 014	30,6	100 457	0	69,4
1 236	2 656	258	CC	R0,529	R4,15M	R104 699	R2,80M	100	1 236 176	1 817 014	30,6	100 457	0	69,4
1 176	2 816	241	LF	R0,529	R4,16M	R103 346	R2,82M	100	1 176 168	1 728 810	32,5	104 440	0	69,4
1 176	2 816	241	CC	R0,529	R4,16M	R103 346	R2,82M	100	1 176 168	1 728 810	32,5	104 440	0	69,4
1 175	2 880	250	LF	R0,535	R4,21M	R104 215	R2,86M	100	1 175 447	1 727 751	33,2	104 500	0	69,4
1 175	2 880	250	CC	R0,535	R4,21M	R104 215	R2,86M	100	1 175 447	1 727 751	33,2	104 500	0	69,4
1 285	2 608	281	LF	R0,536	R4,21M	R106 971	R2,83M	100	1 285 482	1 889 488	30,1	97 420	0	69,4



Architecture				Cost				System	PV		1kWh LI		Converter	
PV (kW)	1kWh LI	Converter (kW)	Dispatch	COE (R)	NPC (R)	Operating cost (R)	Initial capital (R)	Ren Frac (%)	Capital Cost (R)	Production (kWh)	Autonomy (hr)	Annual Throughput (kWh)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)
1 285	2 608	281	LF	R0,536	R4,21M	R106 971	R2,83M	100	1 285 482	1 889 488	30,1	97 420	0	69,4
1 285	2 608	281	CC	R0,536	R4,21M	R106 971	R2,83M	100	1 285 482	1 889 488	30,1	97 420	0	69,4
1 230	2 768	247	LF	R0,537	R4,22M	R105 722	R2,85M	100	1 229 754	1 807 574	31,9	100 865	0	69,4
1 230	2 768	247	CC	R0,537	R4,22M	R105 722	R2,85M	100	1 229 754	1 807 574	31,9	100 865	0	69,4
1 195	2 912	258	LF	R0,543	R4,27M	R105 782	R2,90M	100	1 195 179	1 756 754	33,6	103 143	0	69,4
1 195	2 912	258	CC	R0,543	R4,27M	R105 782	R2,90M	100	1 195 179	1 756 754	33,6	103 143	0	69,4
1 009	3 352	314	LF	R0,546	R4,29M	R101 726	R2,98M	100	1 008 856	1 482 883	38,7	117 701	0	69,4
1 009	3 352	314	CC	R0,546	R4,29M	R101 726	R2,98M	100	1 008 856	1 482 883	38,7	117 701	0	69,4
1 233	2 880	237	LF	R0,547	R4,30M	R107 251	R2,91M	100	1 232 541	1 811 672	33,2	100 674	0	69,4
1 233	2 880	237	CC	R0,547	R4,30M	R107 251	R2,91M	100	1 232 541	1 811 672	33,2	100 674	0	69,4
1 146	3 168	249	LF	R0,555	R4,36M	R106 355	R2,99M	100	1 146 192	1 684 749	36,5	106 594	0	69,4
1 146	3 168	249	CC	R0,555	R4,36M	R106 355	R2,99M	100	1 146 192	1 684 749	36,5	106 594	0	69,4
1 309	2 840	244	LF	R0,560	R4,40M	R110 968	R2,97M	100	1 308 502	1 923 324	32,7	96 070	0	69,4
1 309	2 840	244	CC	R0,560	R4,40M	R110 968	R2,97M	100	1 308 502	1 923 324	32,7	96 070	0	69,4
1 247	3 088	265	LF	R0,571	R4,48M	R110 985	R3,05M	100	1 247 063	1 833 016	35,6	99 771	0	69,4
1 247	3 088	265	CC	R0,571	R4,48M	R110 985	R3,05M	100	1 247 063	1 833 016	35,6	99 771	0	69,4
1 216	3 192	251	LF	R0,573	R4,50M	R110 527	R3,07M	100	1 216 110	1 787 520	36,8	101 751	0	69,4
1 216	3 192	251	CC	R0,573	R4,50M	R110 527	R3,07M	100	1 216 110	1 787 520	36,8	101 751	0	69,4
1 388	2 776	313	LF	R0,576	R4,53M	R115 075	R3,04M	100	1 388 333	2 040 665	32,0	91 768	0	69,4
1 388	2 776	313	CC	R0,576	R4,53M	R115 075	R3,04M	100	1 388 333	2 040 665	32,0	91 768	0	69,4
1 071	3 720	246	LF	R0,589	R4,63M	R109 379	R3,21M	100	1 070 633	1 573 687	42,9	112 392	0	69,4
1 071	3 720	246	CC	R0,589	R4,63M	R109 379	R3,21M	100	1 070 633	1 573 687	42,9	112 392	0	69,4
909	4 152	266	LF	R0,595	R4,67M	R106 279	R3,30M	100	908 956	1 336 044	47,9	127 870	0	69,4
909	4 152	266	CC	R0,595	R4,67M	R106 279	R3,30M	100	908 956	1 336 044	47,9	127 870	0	69,4
1 163	3 576	264	LF	R0,597	R4,69M	R112 743	R3,23M	100	1 163 310	1 709 912	41,2	105 361	0	69,4

2. Cost summary results



Simulation Results

System Architecture:

Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

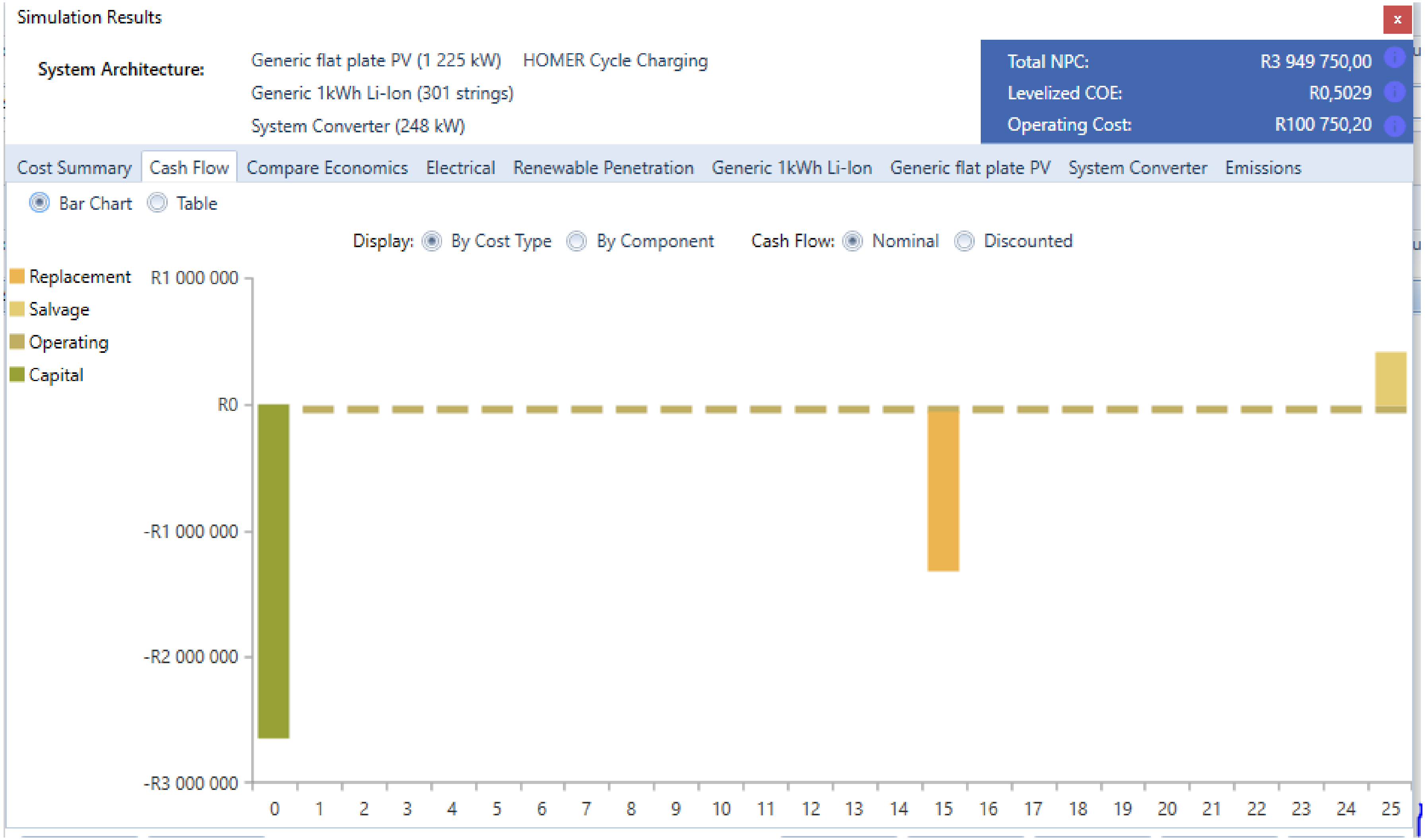
Total NPC:	R3 949 750,00
Levelized COE:	R0,5029
Operating Cost:	R100 750,20

Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital (R)	Replacement (R)	O&M (R)	Fuel (R)	Salvage (R)	Total (R)
Generic 1kWh Li-Ion	R1 323 388,64	R500 220,95	R0,00	R0,00	-R94 146,63	R1 729 462,96
Generic flat plate PV	R1 224 631,82	R0,00	R870 729,65	R0,00	R0,00	R2 095 361,47
System Converter	R99 280,13	R31 591,47	R0,00	R0,00	-R5 945,83	R124 925,76
System	R2 647 300,59	R531 812,42	R870 729,65	R0,00	-R100 092,46	R3 949 750,19

3. Cash flow results



Simulation Results

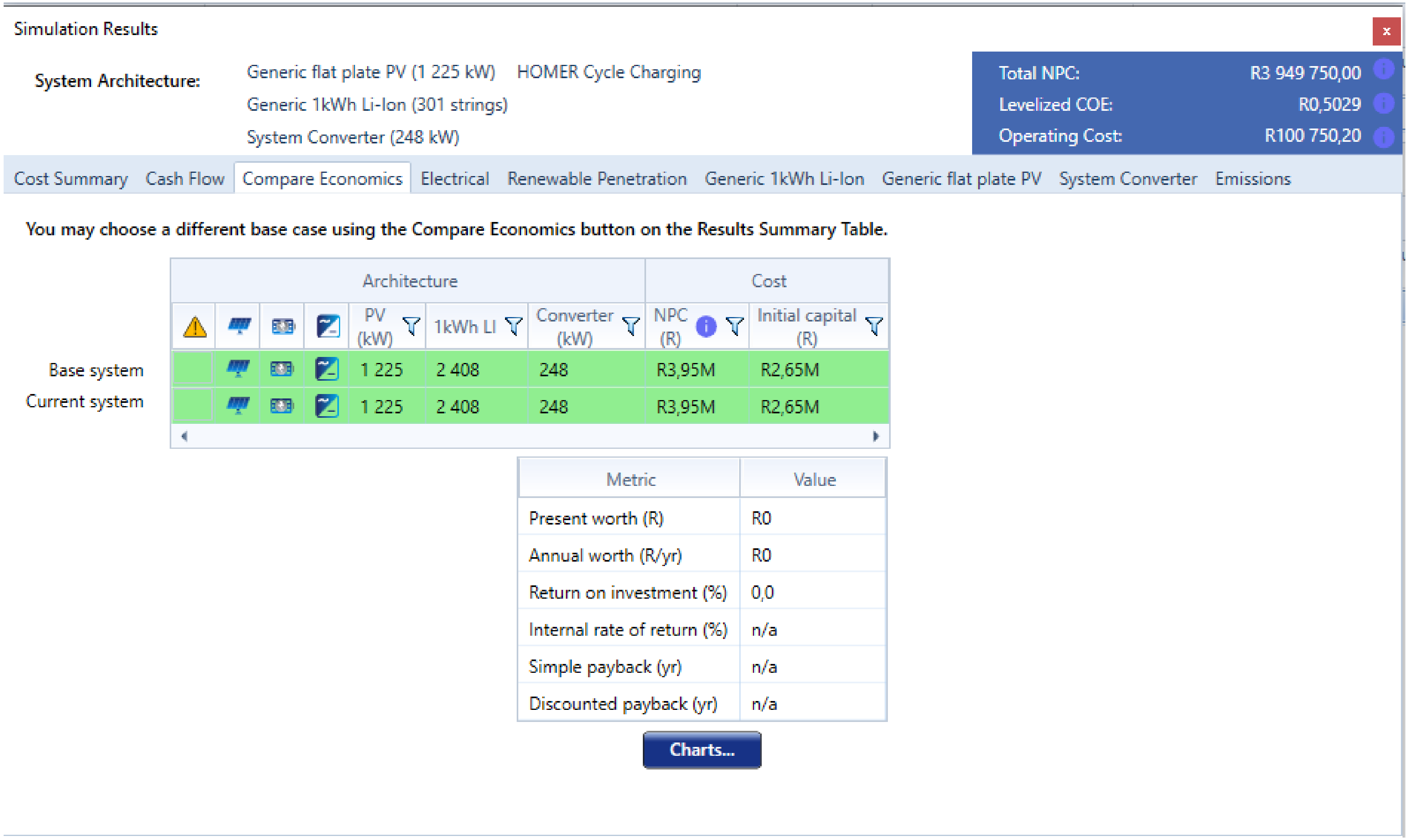
System Architecture: Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

Total NPC: R3 949 750,00
Levelized COE: R0,5029
Operating Cost: R100 750,20

● Bar Chart ○ Table

Display: ● By Cost Type ○ By Component Cash Flow: ● Nominal ○ Discounted

4. Economical comparaison



System Architecture:
Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

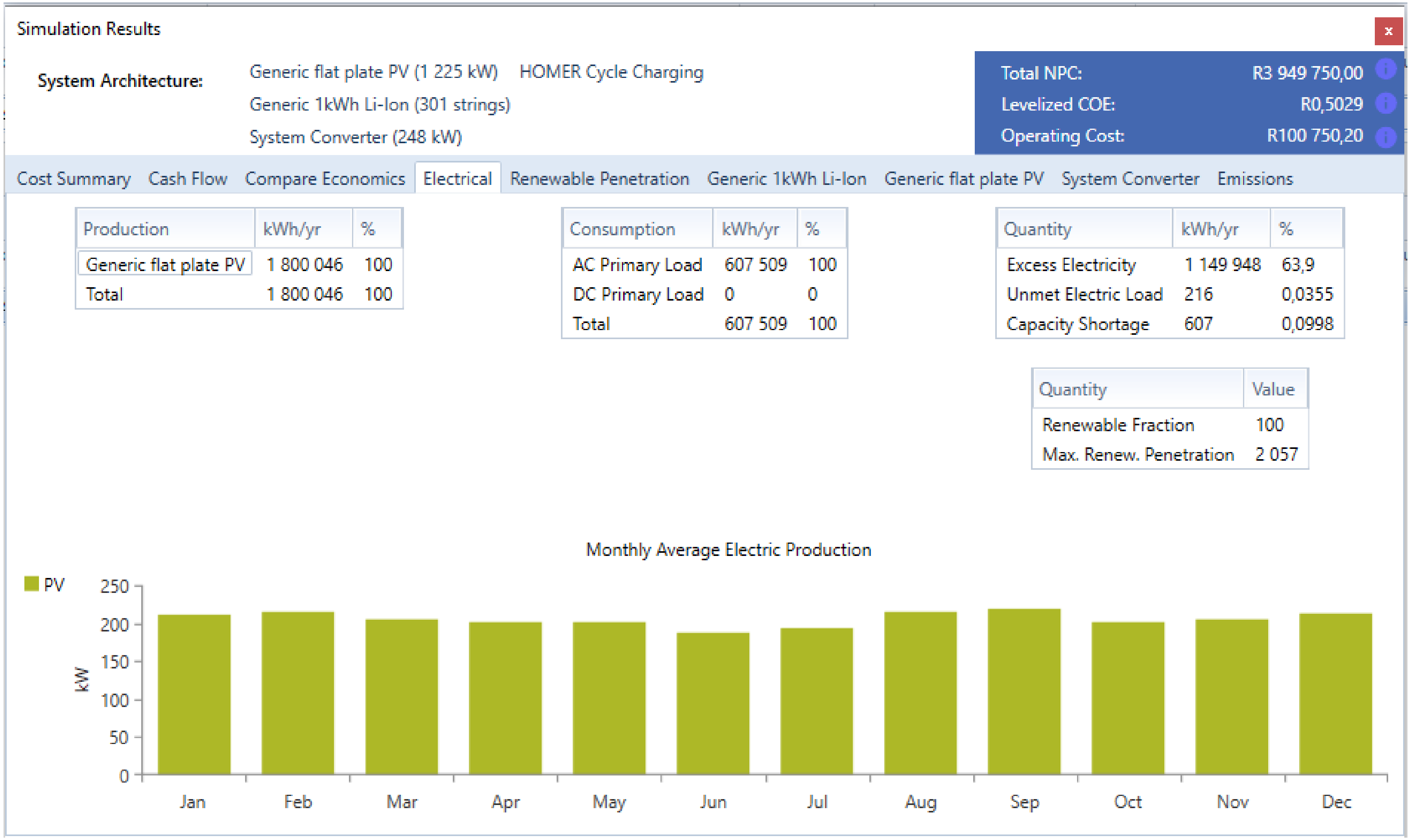
Total NPC:	R3 949 750,00
Levelized COE:	R0,5029
Operating Cost:	R100 750,20

You may choose a different base case using the Compare Economics button on the Results Summary Table.

	Architecture							Cost	
	⚠				PV (kW)	1kWh LI	Converter (kW)	NPC (R)	Initial capital (R)
Base system					1 225	2 408	248	R3,95M	R2,65M
Current system					1 225	2 408	248	R3,95M	R2,65M

Metric	Value
Present worth (R)	R0
Annual worth (R/yr)	R0
Return on investment (%)	0,0
Internal rate of return (%)	n/a
Simple payback (yr)	n/a
Discounted payback (yr)	n/a

5. Electrical system results



System Architecture:
Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

Total NPC: R3 949 750,00
Levelized COE: R0,5029
Operating Cost: R100 750,20

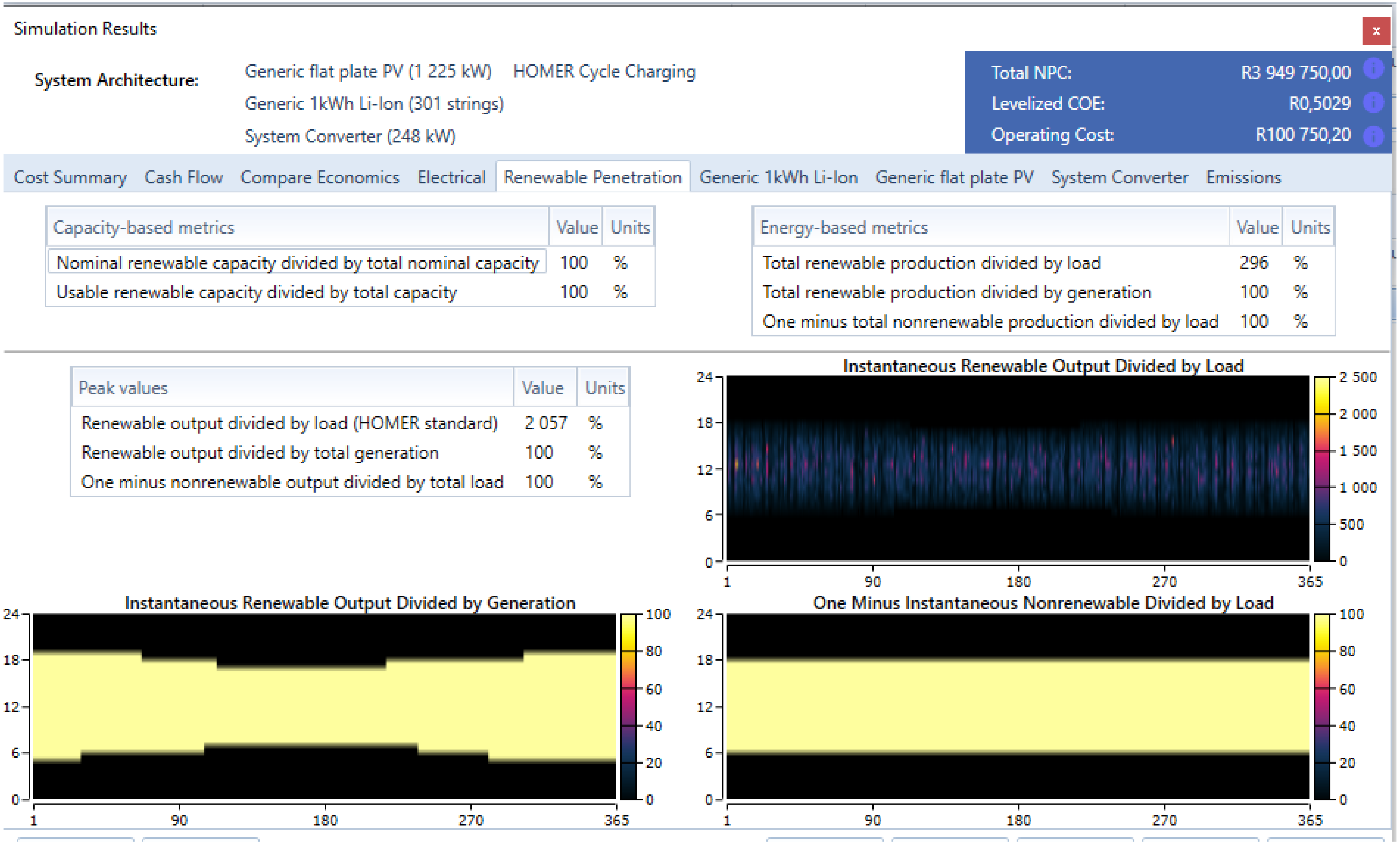
Production	kWh/yr	%
Generic flat plate PV	1 800 046	100
Total	1 800 046	100

Consumption	kWh/yr	%
AC Primary Load	607 509	100
DC Primary Load	0	0
Total	607 509	100

Quantity	kWh/yr	%
Excess Electricity	1 149 948	63,9
Unmet Electric Load	216	0,0355
Capacity Shortage	607	0,0998

Quantity	Value
Renewable Fraction	100
Max. Renew. Penetration	2 057

6. Renewable penetration



System Architecture:

Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

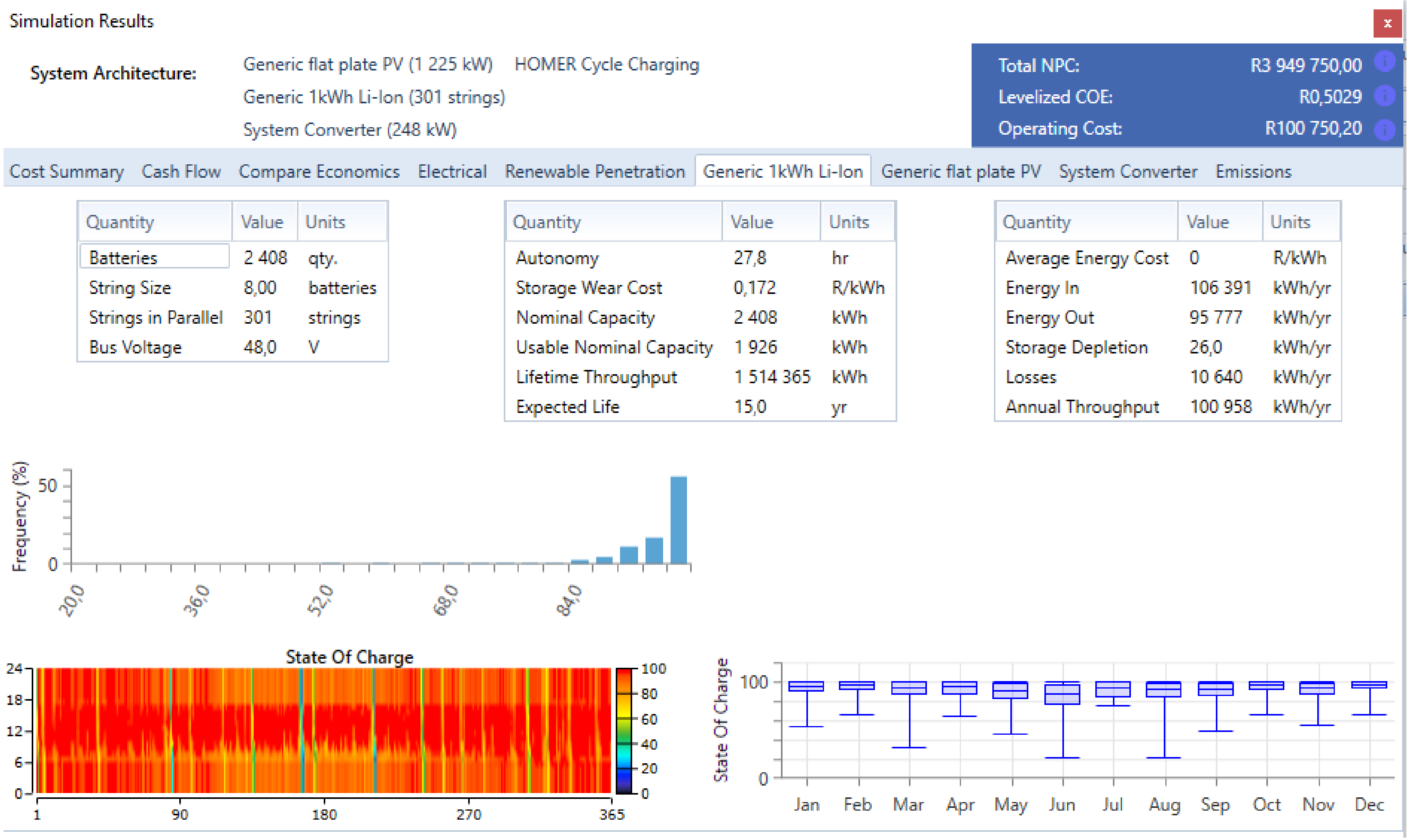
Total NPC: R3 949 750,00
Levelized COE: R0,5029
Operating Cost: R100 750,20

Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Energy-based metrics	Value	Units
Total renewable production divided by load	296	%
Total renewable production divided by generation	100	%
One minus total nonrenewable production divided by load	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	2 057	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

7. Battery bank optimization results



Simulation Results

System Architecture: Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

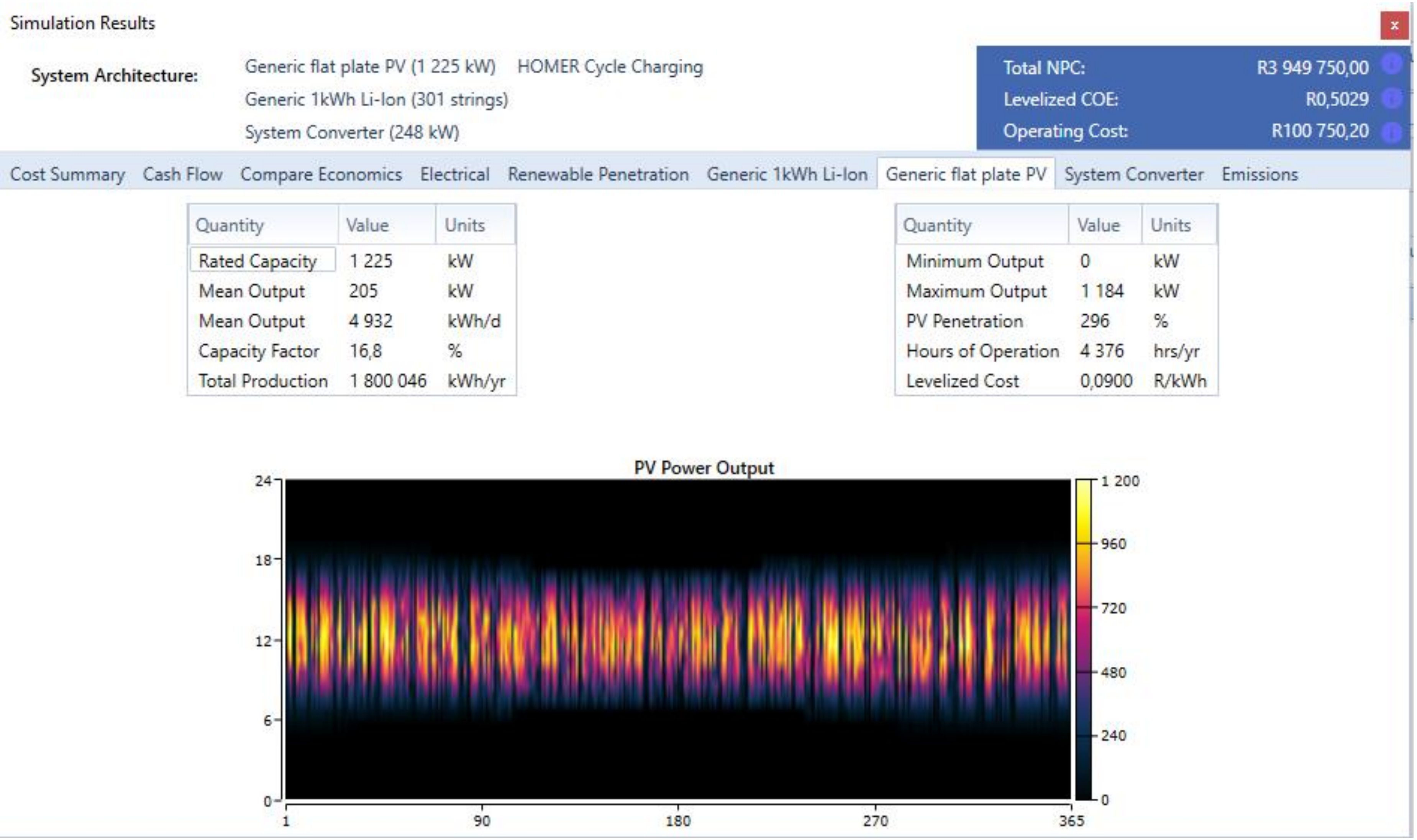
Total NPC: R3 949 750,00
Levelized COE: R0,5029
Operating Cost: R100 750,20

Quantity	Value	Units
Batteries	2 408	qty.
String Size	8,00	batteries
Strings in Parallel	301	strings
Bus Voltage	48,0	V

Quantity	Value	Units
Autonomy	27,8	hr
Storage Wear Cost	0,172	R/kWh
Nominal Capacity	2 408	kWh
Usable Nominal Capacity	1 926	kWh
Lifetime Throughput	1 514 365	kWh
Expected Life	15,0	yr

Quantity	Value	Units
Average Energy Cost	0	R/kWh
Energy In	106 391	kWh/yr
Energy Out	95 777	kWh/yr
Storage Depletion	26,0	kWh/yr
Losses	10 640	kWh/yr
Annual Throughput	100 958	kWh/yr

8. PV system optimization results



Simulation Results

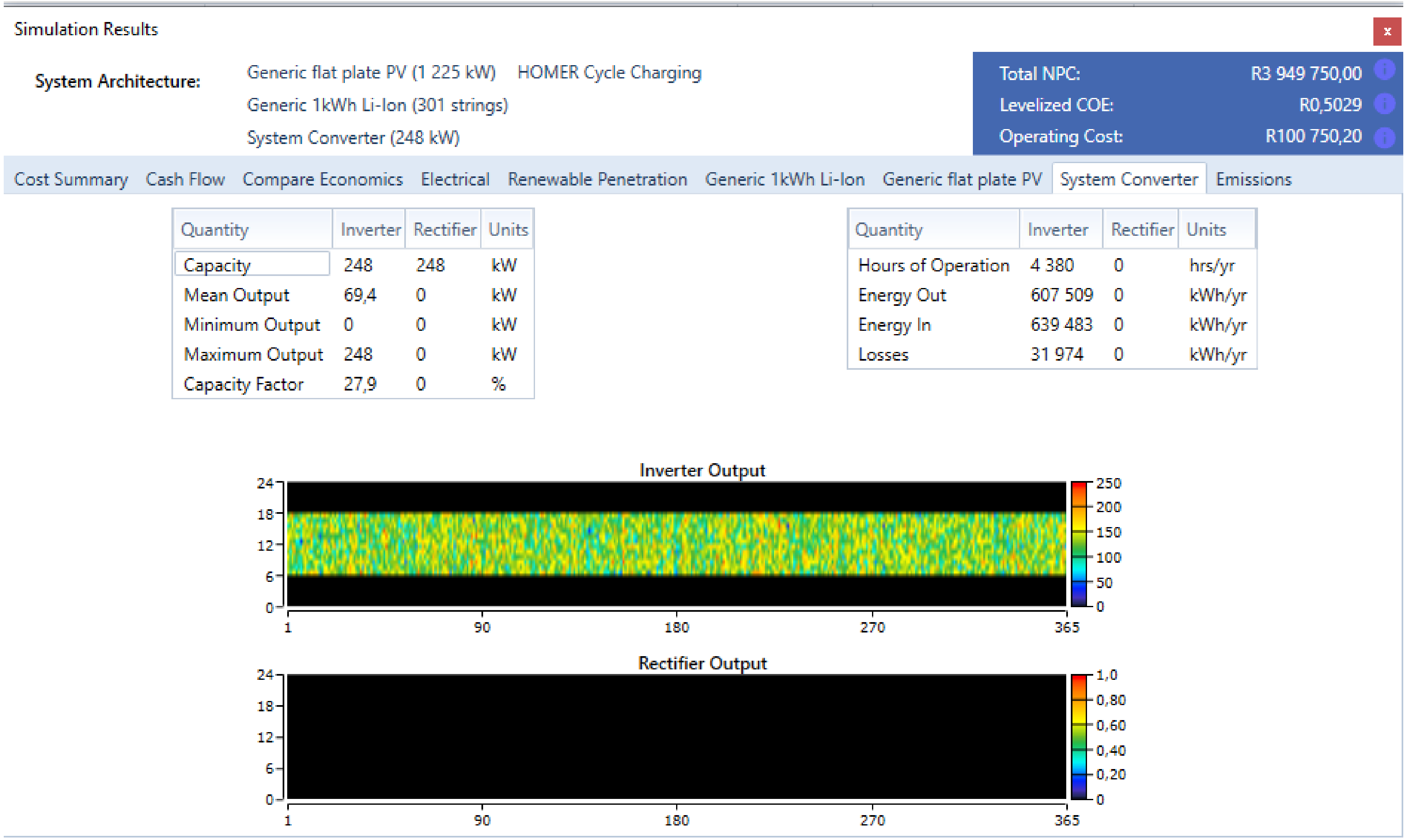
System Architecture: Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

Total NPC:	R3 949 750,00
Levelized COE:	R0,5029
Operating Cost:	R100 750,20

Quantity	Value	Units
Rated Capacity	1 225	kW
Mean Output	205	kW
Mean Output	4 932	kWh/d
Capacity Factor	16,8	%
Total Production	1 800 046	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1 184	kW
PV Penetration	296	%
Hours of Operation	4 376	hrs/yr
Levelized Cost	0,0900	R/kWh

9. Power converter optimization results



Simulation Results

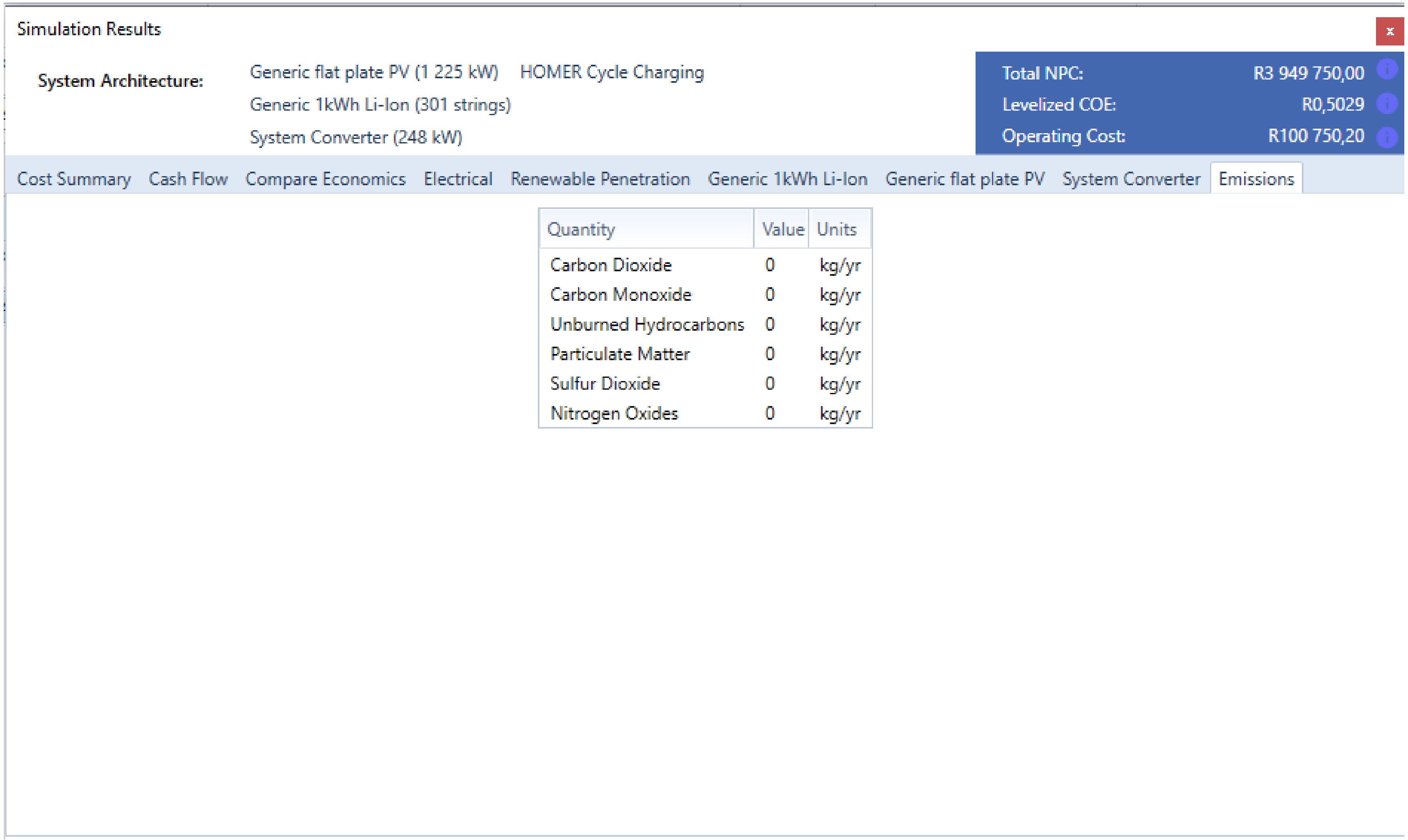
System Architecture: Generic flat plate PV (1 225 kW) HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

Total NPC: R3 949 750,00
Levelized COE: R0,5029
Operating Cost: R100 750,20

Quantity	Inverter	Rectifier	Units
Capacity	248	248	kW
Mean Output	69,4	0	kW
Minimum Output	0	0	kW
Maximum Output	248	0	kW
Capacity Factor	27,9	0	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	4 380	0	hrs/yr
Energy Out	607 509	0	kWh/yr
Energy In	639 483	0	kWh/yr
Losses	31 974	0	kWh/yr

10. Carbon dioxide emissions



System Architecture:

Generic flat plate PV (1 225 kW)
HOMER Cycle Charging
Generic 1kWh Li-Ion (301 strings)
System Converter (248 kW)

Total NPC: R3 949 750,00
Levelized COE: R0,5029
Operating Cost: R100 750,20

Quantity	Value	Units
Carbon Dioxide	0	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	0	kg/yr