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A Feasibility Study on the Implementation of a Solar Powered Water Desalination Plant

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Abstract: Water desalination plants powered by solar energy represent a viable solution for addressing a part of the water needs in areas without reliable water supply. In this case extending the electric grid and water delivery to remote communities remain challenging for some countries. Using Namibia as a case study, this work carried out a feasibility study on the extent of which, solar energy could be used to power the entire desalination process thereby aiding groundwater usable for human consumption. This process includes but not limited to desalination of underground wells and boreholes as solution to the water shortage problem in remote areas. In this study, a solar-powered desalination technique that could enhance the process of clean water provision to villagers is proposed with the aim of implementation. It further compares and analyzed various desalination technologies to determine the best fit based on the dryness of areas. Ohawuwanga Village in Namibia was used for evaluation purpose with a sampling instrument-questionnaire which determine the village's daily water consumption and corresponding power required. Modelling, simulation, and analysis of the system was carried out using MATLAB Simulink in terms of energy consumption. Other parameters considered in this research are cost, water recovery ratio, salt removal factor, durability, and market analysis. The research revealed that electrodialysis is the best technology for desalination in terms of efficient power consumption amidst other factors compared.

Keywords: *Energy, Electrodialysis, MATLAB, Solar power, Water Desalination*

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1. Background to the study

Sustainable development goal six (6), came with the responsibility to ensure that water and sanitation access is guaranteed [1]. Hygiene is one of the very important needs for human healthy living therefore access to clean water is access to good life [2]- [3]. The demand for good water is on the rise in line with the increasing world population. In addition, good water is also required for cultivation purpose, industrialization in various sectors such as energy, mining, mechanical and the rest. Some developed countries are still faced with the challenge of clean water. Ohawuwanga is a village in Namibia's northern Ohangwena region with a very little population, located on longitude and latitude of 17.4026° S, 16.7508° E respectively as shown in figure 1[4]. Based on the findings of this research, villagers of this community are still relying on naturally brackish water from boreholes and hand-dug wells, making it one of the many areas where clean water scarcity remains a challenge [5] – [7]. Renewable energy sources are fast becoming very popular especially in communities that are not connected to the grid. Due to this condition, one of the alternative accesses to clean and desalinated water is to implement a solar powered process of water desalination. Common source of water in the case study are wells and boreholes which is naturally brackish and unfit for human consumption.

Figure 1: Map of Namibia showing Ohawuwanga

The term used for the description of water salinity with a mix of fresh and marine water is called brackish. It is a formative part the sea water. Natural brackish water is dangerous for human health because it contains pollution or salt levels that are higher than the allowable minimums [8]. The alternative to obtaining clean water from brackish sources is to desalinate the water as indicated by Mousa in [9]. A typical brackish water is indicated in figure 2.

Figure 2: Typical brackish water [8]

The life expectancy has been significantly decreased [10], especially in developing and underdeveloped countries, reason not also far from unhealthy water consumption as currently experienced by Ohawuwanga village dwellers. Many diseases can be avoided through sanitation, which calls for the provision of a better water supply. However, fair consideration of financial incentives including low initial expenditures, simplicity of operation, and low maintenance requirements for water treatment technologies are among factors making it difficult to ensure clean water supply in vulnerable areas. Nevertheless, in order to meet the needs of most of the population in remote areas. The choice of desalination technology is influenced by several factors. The salinity of the feed water, the salinity of the generated water, the energy requirements, the environmental impact, and the cost of building the plant are some of these criteria. Desalination systems can use a variety of technologies, including membrane distillation (MD), electrodialysis (ED), and reverse osmosis (RO). However, a desalination plant's total performance is significantly impacted by the technology used in the facility. Since many technologies have a variety of limitations, such as high-power consumption, poor efficiency, low output water capacity, among others. This research investigates various methods of purifying unclean water using Ohawuwanga village in the Ohangwena Region of Namibia as a case study of solar PV water desalination system technology. The overall aim is to find out the suitability of implementing solar powered desalination plant using any of the existing technologies such as membrane distillation (MD), electrodialysis (ED), and reverse osmosis (RO). Figure 3 is an illustration of the desalination process of a brackish water flowing from the well through the various ocean barrier levels to the ground level. For cleansing, such water passes through the desalination plant before subsequent flow to homes and industries for utilization. Again, in urban locations where electricity supply is connected to the grid powering the desalination plant is pretty easier unlike the situation being addressed in this work where rural areas and villages especially in dry terrains such as Namibia are not connected to the grid. Alternative, energy sources are required to power such plants to safe the communist from the disaster associated with bad water consumption. As reflected in the sustainable development goals six (6), for smooth evolvement of human society success and sustainability, securing a steady supply of energy and freshwater is essential. Provision of freshwater to everyone in sufficient quantities is paramount for human survival.

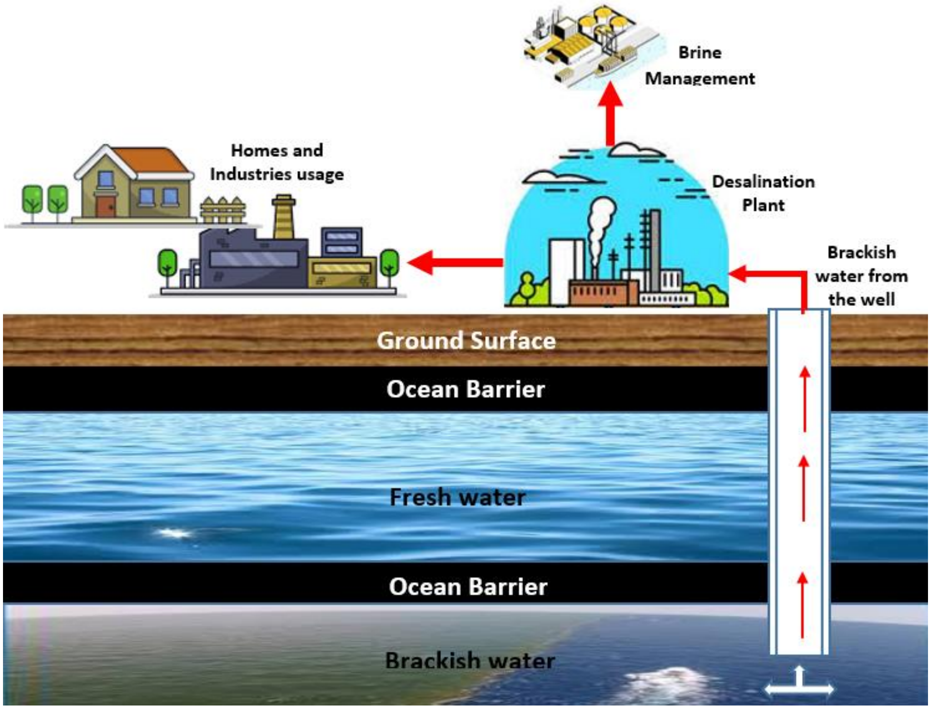

Figure 3: Brackish water extraction and desalination process [8]

The decreasing availability and quality of accessible fresh and brackish water sources is further aggravating the issue of water scarcity. This occurs as a result of both poor water resource management and a lack of an all-encompassing viewpoint in policymaking [11] - [12]. Large-scale infrastructure projects that are implemented quickly, such as dams and irrigation systems for supply-side management, initially mobilize more water resources but ultimately result in a reduction in the amount of freshwater available. While groundwater levels are falling in significant aquifers and fewer rivers are flowing into the ocean. Moreover, Industrial and agricultural enterprises are polluting very significant quantity of freshwater sources [13] - [14]. Water scarcity is a complex issue that involves stakeholders from all facets of society especially the power sector. Engineers are entrusted with creating solutions that address the demands of the developing world as it emerges from poverty as well as the challenges of the rich, unsustainable developed world. Experts in water resource management, however, promote a more nuanced and inclusive strategy, emphasizing the complexities of water policy and the interrelationship between the society, economics, ecology, and engineering. Although experts in water resource management suggest that effective water policies should be prioritized over technology solutions. Seawater desalination is a rapidly developing technological option that may be able to address the water scarcity situation.

Historically, fossil fuel-powered power plants are energy efficient, but recent price instability, erratic availability, and growing environmental concerns have caused new desalination plants to explore for alternative energy sources, such as nuclear or renewable energy. Large-scale nuclear seawater desalination has the potential to be a key component of supplying a secure, economical, and consistent supply of fresh water [15] - [16]. Securing a consistent supply of freshwater is more crucial than ever with the world population expected to reach approximately ten billion people by 2050 [17] – [19]. Meanwhile, the global demand for freshwater is on the rise. The novelty of this research work is to carry out a feasibility study using a case study to determine the total daily water requirement in m^3/day of a typical village under water scarcity condition, evaluate three desalination technologies namely reverse osmosis, electrodialysis and membrane distillation in terms of their energy consumption, cost, water recovery, salt removal factor, durability, market analysis and determine the most optimal desalination technology to be implemented for providing consumable water that will make this solution feasible.

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This research is significant to the relevance of alternative and renewable energy source while helping to alleviate the water scarcity issues and enhancing quality life. However different desalination technologies require a significant amount of energy to operate. Ohawuwanga Village is not connected to the grid therefore an alternative water desalination technology that uses a form of renewable energy is applicable. This study further provides recommendations for the most optimal desalination technology to be used for a solar-powered desalination system in the case study. Although, the desalination technology employed for water desalination in specific plant has a great effect on the overall performance and effectiveness of the desalination plant. A cost analysis is also carried out as part of the feasibility study as well as other optimization techniques to ensure that productivity, strength, reliability, longevity, efficiency, utilization and operational factors are maximized.

2.0 Review of Literature

This section discusses the performance of reverse osmosis (RO), Electrodialysis (ED), and membrane distillation (MD) based on previous literatures. The results of the performance factors for the three technologies under discussion from other studies are explored. Some of the factors of interest include energy consumption, costs, water recovery, membrane efficiency and others. The principle of operation of the three technologies had been reviewed to ascertain their general performance for optimal recommendation. Although the focus of our review is more on the impact of energy consumptions and alternative energy sources especially renewables. Summary of literatures and findings are presented in table 1.

Table 1: Summary of literatures

Author	Year	Aim	Analysis
[20]	2023	worked on a small-scale desalination system towards improving provision of freshwater.	the authors incorporated non-renewable hybrid energy sources using series of combinative methodologies for freshwater productivity. They further analyzed the market share of various desalination technologies vis-a-vis renewable energy systems
[21]	2023	aim at investigating nanomaterials concepts around desalination systems based on current and future standpoints.	considered a bibliometric method to identify future trends and recent development in various desalination processes with respect to their power sources. The comprehensive analysis of the authors also considers water filtration which makes the approach different from other studies however also limited to highly populated regions such as China and some part of the United Kingdom. it does not consider membranes or electrodialysis.
[22]	2022	carried out findings on advance technologies on seawater desalination with focus on membrane distillation.	proposed a method called solar powered membrane distillation with minimum electricity cost using renewable energy technologies. The work is a complete review of integrated system and does not evaluate or compare with other existing methods.
[23]	2021	proposed three different strategies for improving evaporation rate of alternative water sources.	the authors introduced principles of solar driven water desalination technologies called solar-thermal membrane desalination and solar driven electromechanical desalination. A

			further summary of comprehensive review and using a strategic method was presented without major proposal of new solution
[24]	2020	aim at providing an eco-friendly and effective freshwater production with minimal cost.	Used a solar vapour evaporation technique to design a controllable energy conversion system for solving challenges associated with water evaporation. The authors enumerated key challenges at the end and provide a more practical approach to water purification process
[25]	2019	work towards determining integration measures for solar powered desalination to combat freshwater issues in China.	the study is limited to China as a country but a wholistic consideration of reducing greenhouse gas emission was checked using coupling technologies and sustainable energy approach especially considering the very high population in China. The author facilitated diverse perspective and understanding of energy consumption for freshwater production.
[26]	2019	discussed powering desalination process as a sustainable solution. s	emphasized on the growing concerns of merging solar technologies with desalination focusing on improving energy efficiency. The method used by authors is more review oriented with focus various methods.
[27]	2012	provided a wide-range review of desalination technologies within Saudi Arabia context.	embraced a poly-generation method with more emphasis on environmental and economic impacts of renewable energy sources but limited to Saudi Arabia. At the end the authors provided guidelines that are generic in nature for desalination to be considered using alternative energy sources

A comprehensive review of literature reveals that cost analysis modeling and optimization techniques were not considered in most of the previous works which emphasis the significance and the novelty of this work and its contribution to knowledge. Further concepts are presented in the following subsection.

2.1 Operating principles of desalination technologies

Three major desalination technologies are considered for this study ED, RO, and MD. They have different operation principles which is also integrated with their power consumption rate amidst other technical and social economical consideration towards achieving a freshwater production. First is electrodialysis (ED) which, is an electrochemical separation method that runs at atmospheric pressure and employs direct electrical current to transport salt through an ion-selective membrane, leaving freshwater behind. ED differs from all other major desalination procedures in that the dissolved salts are transported away from the supply saltwater, rather than the other way around. When positive salt is fed into the system, ions travel through the cation-permeable membrane to the negative electrodes, whereas negative salt ions migrate to the positive electrode via the anion-permeable membrane. To maintain the system's condition, ED systems can periodically reverse the direction of ion movement by reversing the polarity of the applied electric current. It's called Reverse Electrodialysis in this scenario. Figure 4 depicts a simple sketch of the electrodialysis process.

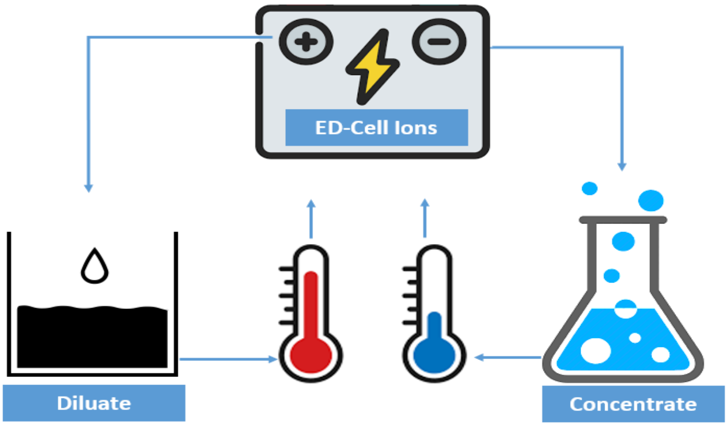

Figure 4: Simple representation of Electrodialysis (ED) process.

Another concept considered in this work is the membrane distillation. This is an evaporative process in which water vapour passes through a hydrophobic membrane and later separated from the feed water phase by a difference in pressure (temperature). MD is a kind of desalination that combines thermal distillation and membrane desalination. Due to greater pressure and vapour, steam molecular water can be transferred across membrane in form of exchange between the compartment of warmer and the cooler. As divergent of other technologies, the membrane driven machinery primary energy is thermal in nature, which is also used for distillation because electricity is required for supplementary facilities [28] - [29]. (sensors, controllers and pumps). The difficulty of making membranes with equal efficiency is one of the major setbacks for MD to compete with other options. Reviewed literatures revealed that it is more energy-efficient and a preferable alternative to other desalination methods although not commercially viable. The third method considered in this research work is the Reverse Osmosis (RO). This is a process that uses a permeable membrane to separate a solvent (in this case, water) from a solution, leaving behind a concentrated solution. However, the osmotic pressure is ensured is kept below the seawater leaving behind solid salt particles letting the desalinated water to go through semi-permeable membranes. This will further reduce the chances of the membrane precipitation and other substances based on the applicable pressure as limits. In other words, there is a limited amount of feed water that can be recuperated as clean water is reduced because of the limited quantity of feed water passing though the membrane to the RO units.

Physical or chemical filtration and clarity of saltwater can be accomplished using coagulation chambers, flocculation chambers, or dissolved air flotation chambers. Membrane filtration, such as ultrafiltration and microfiltration, can remove bigger particles and colloids, allowing for filtration and clarifying. Chemical pre-treatment may be unnecessary with certain membrane techniques. The incoming water will then be pressured by the pump station. The needed pressure depends on the supply water's quality, which ranges from 17 to 27 bars for brackish water to 55 to 82 bars for seawater [15]. RO uses membranes to separate freshwater from saline or brackish feedwater in the main desalination process (Figure 5). Cellulosic, completely aromatic polyamide, and thin-film composite RO membranes are the three main varieties.

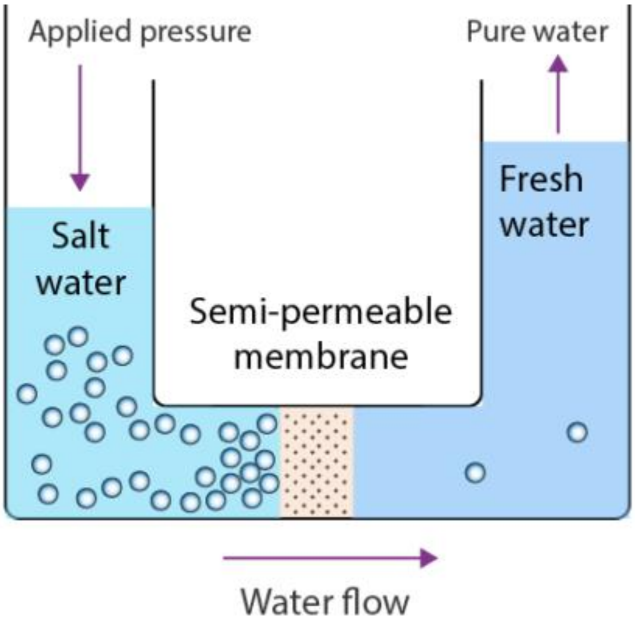

Figure 5: Experimental representation of Reverse Osmosis[30] .

In the past few decades most of the factors considered has witness great improvement to increase the operating pressures and active regions, giving rise to greater rejection and recovery. The maintenance of split between the feed-spacer and the membrane sheets offers an open channel for the feed water flow. In addition, rejected compounds are allowed to be mixed away from the surface of the membrane. The most frequent feed spaces planning in RO modules are the biplanar extruded net [31]. The cost of feed-spacers is usually below $1 per square meter. They are manufactured from polypropylene, chemical inertness, extrudability and a thickness value ranging from 0.6 to 0.9 mm [32]. There could be an increase in fouling as well as decrease in salt rejection due to poor mixing [33]. The permeate spacer usually results in a canal for receiving and moving permeate from the membrane to a tube through the mechanical assistance. The significance is not to lower feed channel pressure that will impact the overall system performance rather to lower the trans-membrane pressure due to permeate production. The permeate spacer is important for element efficiency while the woven polyester is the most prevalent permeating spacer material. Although there are huge old facilities that can be used for spiral wound membrane modules to improve desalination process but the use of Thin Film Composite membranes (TFC) to replace cellulose acetate improved membrane technology by allowing for lower working pressures, larger fluxes, and higher efficiency is fast becoming popular [34] – [36].

Additionally, RO uses solely electrical energy, whereas thermal desalination uses both thermal and electrical energy. Besides, Forward Osmosis (FO) is a revolutionary concept that also uses the principle of osmosis. It uses natural osmosis to dilute a seawater feed stream by utilizing a draw solution with a higher osmotic pressure than the feed, which pulls water from the feed solution across a semipermeable membrane. Using a modest heat source (40°C), the draw solutes are removed from the diluted draw solution and recycled. A combination of ammonia and carbon dioxide gas is commonly employed as a solute. For the membrane phase of the process, specific energy consumption of less than 0.25 kWh/m3 has been documented. When it comes to the amount of thermal energy necessary to regenerate the draw solution, FO is not more efficient than RO [37]. However, because forward osmosis does not require significant hydraulic pressure, it has a lower fouling proclivity.

2.2 Performance of the desalination technologies

Desalination technologies performances are very critical and holistic based on energy consumption, water recovery, membrane efficiency and salt removal. Operational performance has a major impact on how much energy is used to produce a given volume of water. Different desalination technologies operate based on to various principles. As a result, different quantities of energy are needed to generate a given volume of freshwater. [38] discussed about the benefits and drawbacks of the primary membrane desalination systems. The size of the particles that are trapped or permitted to flow through the membrane was said to be the main distinction between each desalination technologies. Results from desalination systems were acquired and compared, including the ability of groundwater and saltwater to remove salt and contaminants. Based on findings in the works of [30] – [32], [37], RO osmosis removes 25–45% of seawater and 90% of brackish water, while groundwater and seawater have corresponding ED values of 95% and 99%. In the work of [38] the power usage and energy production costs of RO technology depend on certain system elements such the membrane configuration, system effectiveness, total amount of dissolved salt in the input water, and so on. The work of [38], further evaluated the three desalination systems in terms of the efficiency and the use of their membranes. Reverse osmosis was found to be the most effective desalination process by [38], who also analyzed the capabilities of the desalination systems.

The functionalities of the technologies were not assessed in relation to a single type of renewable energy source; hence the comparison fell short of being credible. The result was also reached based solely on the technology's initial cost, which is not the only criterion in determining the technology to be used at a particular site. The determination of the best technology or a combination differs from location to region, claims [39]. As a result, caution must be applied while choosing a technology for a particular desalination system in a certain region. The capital cost, operational and maintenance costs, the type and availability of renewable energy sources, energy efficiency, as well as environmental implications, are important variables that influence the choice of the preferred technology. According to Lucas in [40], the combination of RO technology and solar PV energy sources is preferred among other methods. It is important to state that; mechanical auxiliary systems can be driven by RO using only electrical energy, making it the most energy-efficient commercially accessible technology. Although RO is now the most energy-efficient desalination technique commercially accessible, based on the findings of [40]. This logic may or may not given the development of technologies new technologies. Additionally, the specifics of the case study of this research will also either conform with this outcome or provide a new direction.

Authors in [41] – [43] highlighted the importance of the final water cost as a deciding element in the choice of the best technology. The costs of various technologies were recorded in the findings for [42] and [38]. In comparison to MD, computer models conducted in [44] by Pietrasanta et al. based on ten different locations provided an indication that the climate and feed water salinity are key factors in permeate yield. The study also included the production capacity for RO ranges from 0.1 m3/day for marine and domestic uses to 395.000 m3/day for commercial applications, whereas the capacity for ED ranges from 2 to 145.000 m3/day. [31], has several advantages over competing technologies, including a theoretical rejection rate of 100% none volatiles coupled with salts with lower temperatures below the traditional distillation ranges from 60^0C – 90^0C. The pressure is lower in terms of operation when compared with respect to other membrane processes. Furthermore, it requires less space requirements, few equipment among other thermal processes. In contrast, RO and MD does not require pre-treatment. It is also possible to operate the module intermittently. If the membrane becomes dry, there is no risk of membrane damage. The salinity of the feedwater is not depending on the quality of water, product rate and the theoretical system efficiency. Javed et al. [45] conducted a techno-economic study of a hybrid solar-wind-battery for a stand-alone system and investigated the influence of a low loss of power supply probability, finding that it had an enormous influence in direct, and indirect cost.

The Canary Islands were used as a case study by [46] to examine the relationship between energy and desalination methods and to demonstrate the energy and financial implications of desalination. On the other hand, it is noted that there aren't enough research comparing actual investment scenarios of projects to create an analysis of the investment decision. The authors objectives, ambition, predicted impacts, implementation, and methods to maximize impact stand out as some of the characteristics of interest in the first place. In addition, a sensitive analysis was conducted to determine whether the proposed technologies met the requirements for applying for desalination technologies, the dimensions of the facilities, and the impact on the investment decision for the target output. Furthermore, the MD process also has drawbacks, such as membrane wetting, which results in water of poor quality, the use of microfiltration membranes in MD experiments, and lower flow rates as compared to other desalination methods. Additionally, MD requires both heat energy and electrical energy, compared to other membrane technologies. Thermal energy is the primary energy needed for membrane distillation, while electricity demand is minimal and is only required for auxiliary services like pumps, sensors, and controllers.

Norihiko Ishimaru conducted an experimental investigation for remote areas using a solar PV driven ED desalination system [47], while the effectiveness of ED membranes was found to range from 6.0% to 8.2%, that of RO membranes was found to vary between 6.8% and 10.5%. The amount of water generated by RO and ED was discovered to range between 200 mTM and 375 m^3/d, respectively, and the amount of electricity used to create the water was discovered to be less than the intended figure of 1.92 kWh/m3. In Table 2 is a presentation of summary of findings of literature regarding performances of the three major desalination technologies with respect to energy consumption considered in this research.

Table 2: Summary of findings with respect to performance

Desalination technology	capacity(m/day) of plant	Consumption of energy specifically for a (kWh/m^3)	Gain output ratio/ performance ratio (GOR/PR)	Efficiency (%)	Ratio of recovery (%)
Reverse osmosis	>600	1.5-6.0	0.5-8.1	NA	10-51
Electrodialysis	<600	0.8-1.0	NA	8.5	20-95
Membrane distillation	NA	1,2-3.5	NA	NA	NA

Authors in [48] – [51] analyzed the energy usage of the three methods, resulting to a summary of energy required solely depend on the plant's design, the temperature of the feed water, the use of energy recovery devices, and the desired quality of the produced water. However, the quantity of energy needed mostly depends on the salinity of the feed water, the volume of feed water that is converted to freshwater, and the rejection rate, which gauges how effectively the membrane removes salts from the feed water. Various energy consumption results found in, [48] – [51] are tabulated in Table 3 only with the available record on findings.

Table 3: Energy consumptions of main commercial desalination technologies.

Energy consumption	RO	ED	MD
Electrical energy consumption (kWh/m3)	1.5-2.5	0.8-2.5	2-2.5
Thermal Energy consumption (MJ/m3)	-	-	4.5-6.50
Equivalent electrical to thermal energy (kWh/m3)	-	-	12.2-19.1
Total energy consumption (kWh/m3)	1.5-2.5	0.8-2.5	1.45-4.35

The essential performance metrics for brackish water desalination were listed by [52] with respect to the effectiveness of RO using a common evaluation process. To determine the required salinity removal ratio, first define the feedwater salinity (Co), then measure the three indicators that are primarily related to the technology's cost-effectiveness. Specific energy consumption, water recovery ratio, and the output of clean water from processes are the three indicators. The performance of ED and Membrane Capacitive Deionization were compared in [53]. When evaluating ED's performance, several factors were considered, which include energy consumption, thermodynamic efficiency, SEC – a real scale, salt removal, water recovery, and others. The SEC method was employed as the main parameter to assess ED performance in this study. SEC stands for the quantity of energy needed to create a unit volume of product water.

$$SEC = \frac{(NVc+Vel)\times I\times Am}{Nd} \qquad (1)$$

Where N denotes the number of cell pairs in the stack, V denotes the voltage between the cell pairs, V_c denotes the electrodes' redox reaction potential, I denotes the average current density within a cell pair, A_m denotes the area of the ion-exchange membrane, and Q_d denotes the dilute volumetric flow rate per cell pair. A numerical solution of the 2-D Nernst-Planck model was used to calculate the cell pair voltage and the average current density for a given separation. The thermodynamic energy efficiency, n, was another variable that was used to assess ED's effectiveness. The minimum specific energy consumption of separation (SEC_{min}), which is normalized by the SEC, and is represented by equation (2), which is thermodynamic energy efficiency.

$$\text{Declination angle, } \delta = 23.45 \times sin\left(\frac{360}{360}\right) \times (n-1) \qquad (2)$$

2.3 Review of costing parameters

An estimated average capital costs that was used in this feasibility study to evaluate the capital costs for the three technologies for the Ohauwanga Village in Namibia is presented in Table 4. The performance parameters were thoroughly investigated to ascertain their impact on the general performance of a desalination unit in order to assess the performance of the three desalination methods (RO, ED, and MD). Examples of such factors include energy requirement, capital expenses, water costs per unit of product, water recovery, and salt removal membrane efficiency. Each technology's performance characteristics were determined and calculated using distinct sets of data. Data from the locations were collected in some cases; part of these data came from simulations and others from experimental outcomes. Studies have revealed that the salinity of the site feed water and the technology's membrane have a significant impact on a desalination technology's performance. For example, RO technology is a pressure-based technology, thus it consumes more energy compared to ED and MD.

Table 4: Estimated average capital costs per cubic meter.

Technology	Estimated average cost (N$/m^3)
RO	207.22
MD	148.69
ED	156.50

A summary of literatures and findings on various methods and approaches used in earlier research have provided indications on approaches that are preferable and appropriate for current investigation. The next section will discuss mathematical models and the design specifically for this feasibility study.

3.0 Materials and Methods

The methodology employed in this research covers reverse osmosis, electrodialysis, and membrane distillation as the three desalination technologies evaluated as proposed. This study utilized a quantitative analysis technique. The three technologies' performances were compared, and the preferred technology is suggested for usage in the cases study - Ohauwanga Village's desalination system. To figure out how well the technologies perform, mathematical models were formulated. A MATLAB-Simulink model was also carried out using the package to determine the SEC of each technology. The simulation in MATLAB was used to obtain the SEC of each technology. The research design is illustrated in figure 6. It contains the procedural block diagram of the main procedures that were followed to carry out this research. Data gathered for the desalination plant in the village of Ohauwanga, as well as the design parameters generated from actual secondary data and equations, are the foundation of this study. Each technology's performance factor was identified, and the technologies were compared.

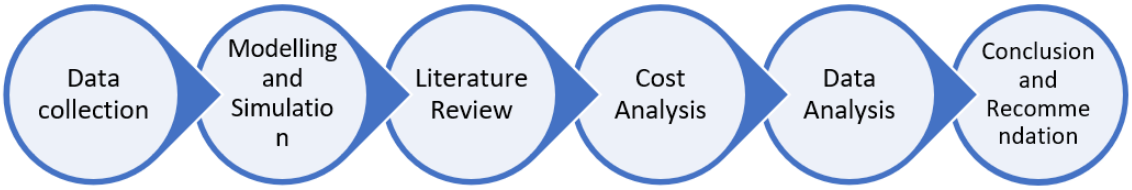

Figure 6: Flow of Methodology and research design

Data collection for this study involved the use of a questionnaire, the feedback received were later used for simulation of the technologies using MATLAB-Simulink model for proper analysis. A total of 157 questionnaires were handed to the households and the main targets were the household owners. Some of the site parameters for Ohauwanga Village were collected. These parameters were: plant capacity, total dissolved salts, expected time of operation of the desalination plant, latitude angle, solar irradiance and hours of full sun with specific energy consumptions, SEC (kWh/m^3). The SEC for each technology was obtained from the simulations done in Simulink from the Renewable Energy Desalination (REDs) library. Furthermore, the cost of the desalination unit and the Photovoltaic (PV) power plant are included in the capital/investment cost. The unit cost obtained by prior studies was used to compute the total capital cost needed for each desalination unit. The Direct Current (DC) power needed for the desalination plant and the PV plant was sized for each technology. The total daily demand for each unit was determined using the SEC for each technology as indicated in section 2. It was expected that ground-mounted systems will cost 51067.80 N$/kW to install. These costs cover the PV array as well as the installation, electrical equipment, and balance-of-system elements for each system.

3.1 PV plant Sizing

First is the determination of the tilt angle of PV, Equation (3) – (5) were used for this sizing accordingly with reference to equation (2).

$$\text{Altitude angle } \beta = 90 - (L + \delta) \tag{3}$$

$$tilt\ angle = 90 - \beta \tag{4}$$

where, L is the latitude angle and n are the days number of the year. The total daily energy demand and the DC peak power were calculated by using (6) and (7) respectively.

$$total\ daily\ energy\ demand = \frac{SEC\left(\frac{Wh}{m^3}\right)}{daily\ plant\ capacity\ \left(\frac{kWh}{m^3}\right)} \tag{5}$$

$$Pdc(kW) = \frac{daily\ energy\ demand}{derate\ factor \times \frac{h}{day} of\ full\ sun} \tag{6}$$

In addition, to calculate capital cost is equation (8)

$$Cost = \ Pdc(kW) \times \frac{1000W}{kW} \times 2.94 \frac{\$}{W} \qquad (7)$$

These calculations also considered water recovery for the three technologies which is assumed to be constant (75%) for membrane efficiency/salt removal. Production of water cost per unit volume, Levelized Cost of Water (LCOW) function uses the formulation in equation (8) to determine the unit water cost per cubic meter of product water. This same method was adapted from the United States Department of Energy and water cost. It was employed as a cost function for the desalination system[54].

$$LCOW = \frac{[(I_{Pj}+F_{Pj})+(I_{xj}+M_{xj})+\left(I_{tankj}+M_{tankj}\right)[\div(1+r)^{j})}{\Sigma\frac{Qwj}{(1+r)^{j}}} \qquad (8)$$

Where: I_p , M_P, and F_p represent the investment, maintenance and operation costs (M&O), and fuel costs (in this case it is a constant for units, hence assumed to be 1), I_{tank} and M_{tank} are the water tank and Investment and maintenance (also assumed to be 1), Q_w and r is the annual quantity of water produced over the analysis period (5 years in this case) and discount rate (3%) respectively. In terms of data comparison, the performance factors for the three technologies were compared. The analysis and comparison were done in terms of energy consumption, water recovery ratio, efficiency, cost, durability, and market analysis of each technology. This section presented the methodology that was carried out to undertake the research. The detailed procedural tasks and equations that were used to evaluate the performance of RO, ED and MD were highlighted and the detailed results and discussion is presented in the next session.

4.0 Discussion of Results

Since this research focus more on feasibility study due to lack of freshwater and reduced water consumption levels for the residents of the case study - Ohawuwanga village. The questionnaire was precisely asking respondents about the estimated normal daily water use for their families. The survey results showed that each home used between 40 and 320 litres of water per day or in some cases an average of 139.2 litres. Additionally, based on the household size of seven people, it can be shown that the daily water consumption per person in Ohawuwanga is 19.9 litres, or nearly 20 litres. It's important to note that the fact that 100% of respondents claimed they augmented their freshwater consumption with rainfall and salt-contaminated well water raises the possibility that the typical person's daily freshwater consumption may really be lower than the reflected values captured in the questionnaire. Table 5 contain the survey's findings in this regard.

Table 5: Questionnaire responses

Respondents (n)	Mean daily consumption (litres/household)	minimum (litres)	Maximum (litres)
157	139.2	40	320

Some of the challenges, based on this feasibility study reflects, 78% of the respondents are having issues with their water supply and either the respondent directly or a member of their household had saline water difficulties. Due to the distance, they must drive to and from town, some inhabitants only purchase potable water when they visit, which is only once a month. Considering the technical feasibility of solar power desalinated plant, from the analysis – this work carefully considered willingness to pay for desalinated water and its processes using modern technologies. This work further investigated to determine how much people in Ohauwanga were generally willing to pay for desalinated water. Residents were initially asked in the survey if they would be willing to pay for dependable, clean freshwater from Ohauwanga Village and, if so, how much they would be willing to pay in total. Additionally, a key premise of the query was that no people accessed any freshwater that came from the village and that all wells and boreholes were salt-contaminated. Ohauwanga village residents are prepared to pay for the dependable and hygienic freshwater, as shown in Table 6 reported at 88% of those surveyed said they would purchase freshwater from the Village if available. Moreover, it was determined that the mean willingness to pay for a 20-liter bottle was 1.92 N$.

Table 6: Readiness and willingness to pay for desalinated water.

Respondents	**percent of respondents**	**mean WTP for clean and reliable water N$/20L**	**standard deviation**	**minimum WTP N$/20 L**	**Maximum WTP N$/20 L**
157	88	1.92	1.18	0.37	3.74

Nevertheless, very few percentages of the respondents indicated fresh water should be free for the villages irrespective of the process involved to make it available. Other site parameters considered during the feasibility study at Ohawuwanga Village's was the water demand which is calculated to be 7.93 m^3/day. The optimum concentration of treated water was compared to the solid concentration of the water from the case studies boreholes in accordance with acceptable drinking water standards for the country. The table 7 summarizes the case study site parameters.

Table 1: Site parameters of Ohauwanga Village

Parameter	**Value**
Plant capacity (m^3/day)	7.93
Total Dissolve Solids - TDS (ppm)	567
Expected time of operation(h/day)	8
Irradiance (kWh/m^2)	6.6
Hours of full sun (h/day)	5.5

Other factors considered towards obtaining accurate energy consumption specifications uses the SEC for each technology by obtaining MATLAB Simulink results based on the available data using mathematical models formulated in previous sections. The SEC, which is the measure of the amount of energy needed to generate one cubic meter of water, is a crucial component in desalination technology. The energy needed to create portable water increases with a technology's SEC. Therefore, a low SEC desalination process is chosen over a higher SEC technology. The SEC for ED was found out to be 2.563 kWh/m^3 as shown in figure 7 while the SEC for MD was found to be 3.102 kWh/m^3 as shown in figure 8.

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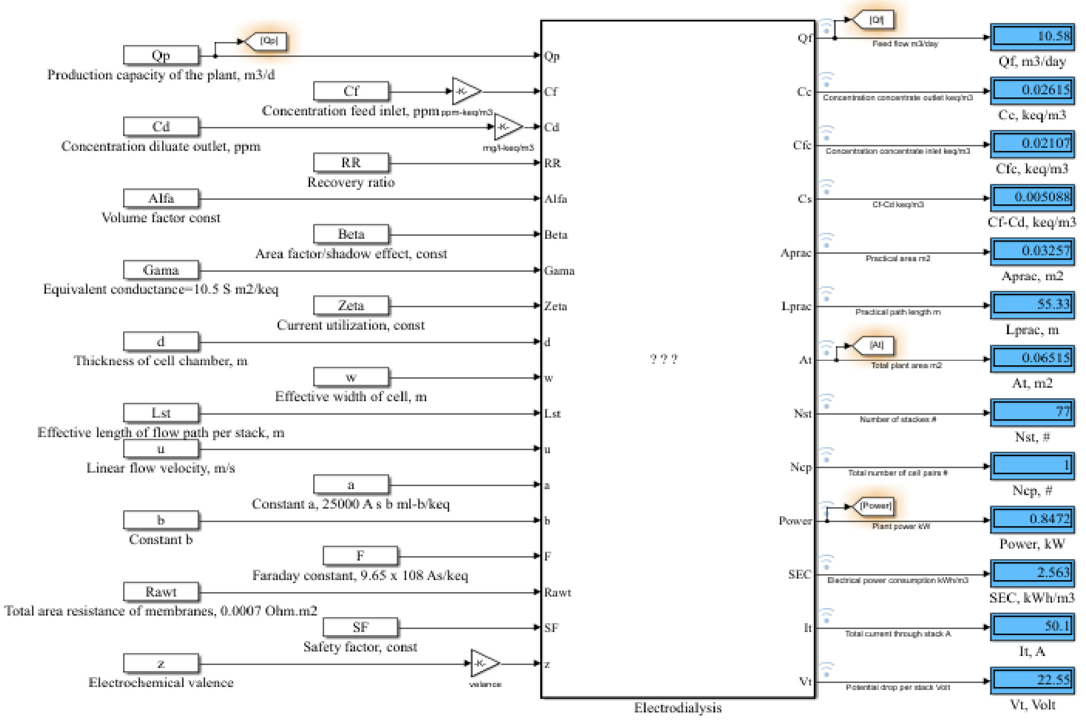

Figure 7: Simulation of Electrodialysis (ED) in MATLAB Simulink

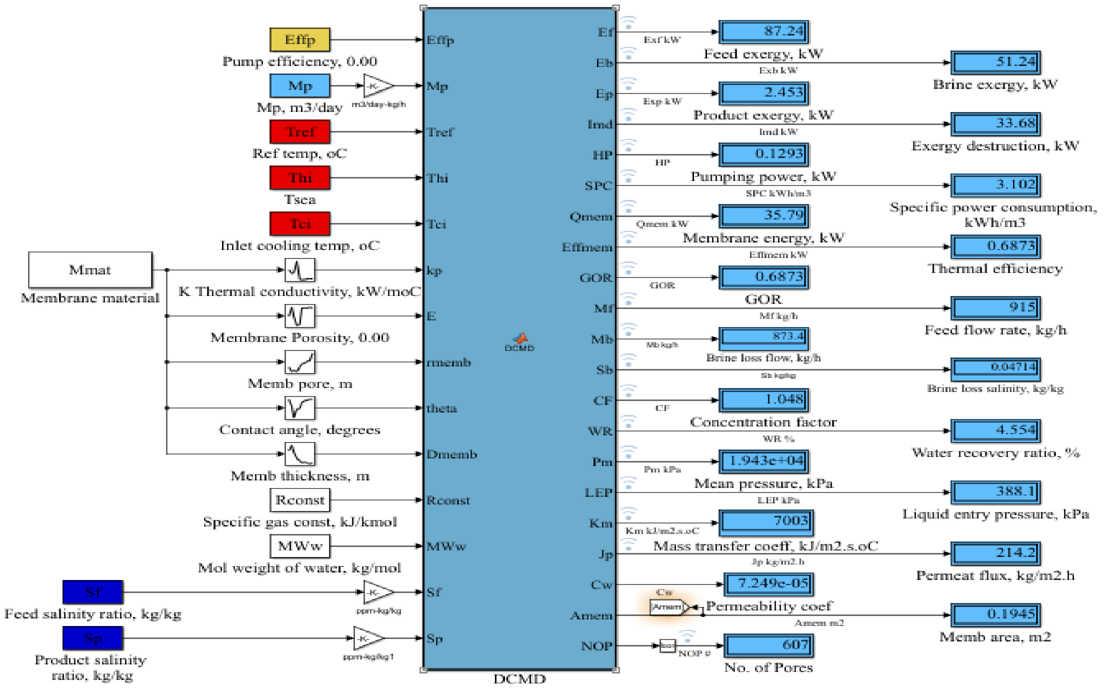

Figure 8: Simulation of Membrane Distillation (MD) in MATLAB Simulink

Similarly, the SEC for RO was found out to be 4.484 kWh/m^3 as shown in the simulation result obtained in figure 9.

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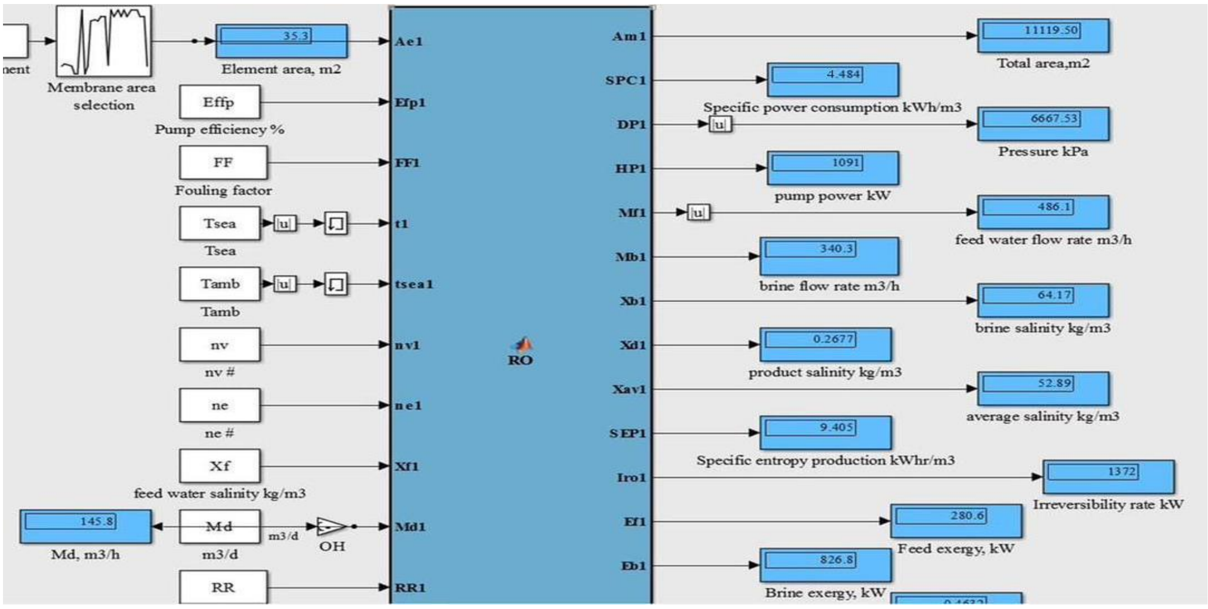

Figure 9: Simulation of Reverse Osmosis (RO) in MATLAB Simulink

The specific energy consumption for each technology was obtained from the simulations carried out in MATLAB Simulink. The SEC for each technology is tabulated in table 8.

Table 2: SEC of each technology as obtained from the simulation.

Technology	**Specific Energy Consumption (kWh/m^3)**
Electrodialysis (ED)	2.563
Membrane distillation (MD)	3.102
Reverse osmosis (RO)	4.484

4.1 Recovery ratio and Cost Analysis

The brackish water recovery ratio used in this investigation was set at 75% for all methods. Any technology can have a variable water recovery ratio. It is a variable value that varies as the plant runs. This factor is therefore constant for the three technologies under consideration. Also, the cost analysis is this study is the sum of four major components i.e. cost of the desalination process, the second component is the cost of the PV plant, storage tank and as well as fuel cost. The capital cost for the desalination process include desalination membranes, pumps, and labour. The estimate of the capital cost per cubic meter of fresh water is presented in table 9.

Table 3: Capital cost of each of desalination plant foe each technology

Technology	**Estimated average cost (N$/m^3)**
Reverse osmosis (RO)	207.22
Membrane distillation (MD)	148.69
Electrodialysis (ED)	156.50

The daily capacity for the case study was found to be 7.94 m^3/day. Therefore, the total capital costs for the three desalination technologies were calculate and the results are shown in table 10.

Table 4: Estimated average cost of water.

Technology	Estimated average cost (N$)
Membrane distillation (MD)	1645.32
Electrodialysis (ED)	568.27
Reverse osmosis (RO)	1242.61

4.2 Capital cost for PV power Plant

It is worthy to note that the desalination technology had a different SEC. As a result, it was discovered that each technology had a varied daily energy requirement. In order to accommodate each technology's daily energy needs, the PV plant was sized uniquely for each technology. The costs of the PV modules and inverters were factors considered while determining the cost of the PV plant. To power the plant, the sizing was carried out for all the three technologies used; Daily solar irradiance = 6.6 kWh/m² which is estimated to 5.5 hours of full sun. Therefore, the PV plant sizing for electrodialysis is**;**

$$\text{Total daily energy} = 2.563\text{kWh/day} \times 7.9344\text{kWh/day} = \ 20.3359\ \ \text{kWh/day}$$

$$\text{Pdc(kW)} = \frac{\text{daily energy demand}}{\text{derate factor} \times \frac{\text{h}}{\text{day}}\text{of full sun}}$$

$$= \frac{20.3358\ \text{kWh}}{0.76 \times 5.5\frac{\text{h}}{\text{day}}\text{of full sun}}$$

$$= 4.865\ \text{kW}$$

Similarly, the PV Plant sizing for membrane distillation is;

$$\text{Total daily energy} = 3.104\text{kWh/day} \times 7.9344\text{kWh/day} = \ 24.628\ \ \text{kWh/day}$$

$$\text{Pdc(kW)} = \frac{\text{daily energy demand}}{\text{derate factor} \times \frac{\text{h}}{\text{day}}\text{of full sun}}$$

$$= \frac{24.922\ kWh}{0.76 \times 5.5\frac{h}{day}of\ full\ sun}$$

$$= 5.8919\ kW$$

And the third PV plant sizing for reverse osmosis is given by;

$$\text{Total daily energy} = 4.484\text{kWh/day} \times 7.9344\text{kWh/day} = \ 35.578\ \ \text{kWh/day}$$

$$Pdc(\mathrm{kW}) = \frac{\text{daily energy demand}}{\text{derate factor} \times \frac{\mathrm{h}}{\mathrm{day}} \text{of full sun}}$$

$$= \frac{35.578\ \mathrm{kWh}}{0.76 \times 5.5 \frac{\mathrm{h}}{\mathrm{day}} \text{of full sun}}$$

$$= 8.511\ kW$$

With the analysis presented, it infers that the solar panels must be able to produce a power of 8.511 kW. It also gave room for assumption of ground-mounted systems cost to an estimated value of 51,067.80 N$/kW watt to install. These costs cover the PV array as well as the installation, electrical equipment, and balance-of-system elements for each system. Table 11 summarizes the electrical energy requirement and cost of the PV plant for each technology.

Table 11: Electrical energy requirement cost summary for the three desalinated technologies.

Technology	**Total Energy Demand ($\mathbf{kWh/m^3}$)**	**peak watts of DC (kW)**	**Cost ($)**
Electrodialysis (ED)	20.336	4.865	248444.85
Membrane distillation (MD)	24.628	5.892	300891.50
Reverse osmosis (RO)	35.578	8.511	434638.05

Taking reference from related works, the cost of water storage tank per m^3 is also considered to be at N$ 4429.35, the tank total cost is 4429.35×7.94 = N$ 35169.04. The maintenance costs for PV plant and storage tanks were estimated to be 3% of the capital costs, while the maintenance costs for the desalination processes were estimated to be 10% of their initial costs. The membrane life of the three technologies was found to be more than five years. In this study the durability of the desalination plant was anticipated to be to be ten years. The cost of maintenance of the PV plant, desalination unit and the storage tank are given in table 12.

Table 12: Maintenance cost of PV plant, desalination process and storage tank

Technology	**PV plant(N$)**	**Desalination process(N$)**	**Storage tank(N$)**
Electrodialysis (ED)	74533.45	115185.68	9314.49
Membrane distillation (MD)	91342.75	109444.90	9314.49
Reverse osmosis (RO)	130391.41	152516.94	9314.49

RO desalination process requires a lot of maintenance due to membrane fouling, which is the build-up of salt on the effective membrane area. On the other hand, ED requires more maintenance than MD due to build-up of ions on the ion exchange membrane. MD requires minimum maintenance, hence the lower maintenance costs. The efficiency range of the three desalination technologies are shown in table 13.

Table 135: The range of efficiencies of the three technologies

Technology	Salt removal/membrane efficiency (%)
Electrodialysis (ED)	65-85
Membrane distillation (MD)	54-85
Reverse osmosis (RO)	65-95

The LCOW equation (8) was used to calculate the unit cost of water at a rate, r of 3% for 10 years each technology: When the required parameters were obtained in the previous sections the results are presented in table 14 as the cost of water production.

Table 6: The levelized cost of water (LCOW) of each technology

Technology	Levelized cost of water-LCOW (N$/$m^3$)
Electrodialysis (ED)	4.38
Membrane distillation (MD)	3.77
Reverse osmosis (RO)	4.35

Having discussed the results obtained from the methodology formulations, data collected and simulation. The three-desalination unit's growth rate and demand rate are covered in this section of the research. The general effectiveness of the three technologies is covered in this part. In general, RO's performance is preferred for the case study based on the feasibility for large-scale applications and locations with greater feedwater salinities. The extensive literature review also showed that, desalinating feedwater with a salinity of greater than 5000 mg/L using RO is economical. On the other hand, due to its affordability, ED is preferred for small-scale and sites with lower feedwater salinity (5000 mg/L) due to its low energy requirements, low operating pressure and temperature, and status as a low-cost alternative to established technologies like RO and MD. Membrane distillation is thought to have enormous potential but for some of its identified drawbacks in the literature section, it is not commercially viable. Drinking water can be effectively purified using the MD method, which can get rid of all kinds of non-volatile ions. However, in terms of market share based on the peculiarity of areas under consideration, the RO holds a significant market share in terms of technology, and it is anticipated to dominate the market for water desalination plants in terms of volume throughout the forecast period. The RO process's supremacy can be due to its higher efficiency and lower energy needs. However, MD is leading in terms of growth. ED was the first membrane-based desalination technology to be commercialized. Albeit the preferential adoption of RO ensures supplies in a minor portion of the drinking water industry today.

5.0 Conclusion and Recommendations

It is economically and technically viable to deploy a solar powered desalination system based on the study carried out in this research considering the nature of data obtained in the village used as case study. The outcome of this research is applicable for other similar terrains with common parameters. The installation of a solar-powered desalination system in areas where freshwater is a serious challenge would enable residents to access safe, clean water for consumption and lessen the health problems caused by brackish water. It is feasible that the Village may experience financial gains from owning, developing, and operating a solar powered desalination plant after analyzing the cost of the solar powered desalination technology taken into consideration in this study. It is clear from the energy usage data that RO requires more energy to produce a volume of 7.94 m3/day. It takes 21.3% less energy for ED to produce 7.93 m^3 per day than it does for RO. It has been shown that MD uses the least amount of energy to create the same amount of water. It was discovered that the energy requirements for MD were roughly 13% fewer than those for ED and 16.8% less than those for RO. As a result, it was determined that

RO needs more inverters and PV panels to meet its energy needs. As a result, RO often has greater capital expenses than ED and MD. On the other hand, the number of PV panels, as well as inverters required for ED and MD, were found to be relatively less than that of RO.

The unit cost of product water for RO was discovered to be greater than the unit cost of product water for ED and MD as a result of higher SEC. The higher energy needs of RO are brought on by the high osmotic pressure pumps. For all three systems, it was expected that the water recovery would remain constant. For all the analyses that were done, it was maintained at 75%. Based on how RO functions in general. For each technique, the range for salt removal from feed water was determined. The findings indicate that MD has the greatest range and the lowest potential for salt removal from feed water. In terms of salt removal, RO was determined to have the highest membrane efficiency. Following the analysis, it was determined that RO was economical in facilities with feed salinities more than 5000 mg/L. The cost-effective technology for plants with a feed salinity less than 5000 mg/L was ED. The market study that was conducted based on literatures and alignment with the realities led to the conclusion that MD is still used at an experimental level but has not yet reached a commercial or industrial level. The contents of the case study borehole water contain more cations and anions than the other two, as indicated in previous sections. It was also discovered that ED has a good ion removal ratio compared to the other two. These factors led to the conclusion that ED was the best technology for the desalination plant in the area of study if this will be considered in isolation. Irrespective of the factor of interest, it was discovered that; close attention should be paid to the pre-treatment equipment for a more cost-effective RO plant. Pre-treatment requires more power, which raises the cost. Although, the use of energy recovery devices can lower the specific energy consumption of a desalination technology. A reduction of the power drawn by a desalination unit leads to a significant reduction in capital costs and as a result, lowers the cost of freshwater which makes water affordable by most of the people living in villages prone to the problem addressed in this work.

Finally, it is important to state that energy consumption increases with the membrane's/salt removal's efficiency. The outcomes of the MD and RO tests had demonstrated that MD had the lowest daily energy demand and the lowest salt removal ratio. On the other hand, RO was found to be the most effective at removing salt content; as a result, RO used more energy to generate 7.94 m3/day. The ideal desalination unit for different sites can be found using the results of this study. With the results of this work, the desalination site parameters can always serve as inputs for proper comparism of outputs in accordance with the identical procedures used in this study before subsequent construction and implementation. Capital expenses can be reduced by using the best or most appropriate desalination technology for every facility. Further study could focus on the use of hybrid energy source such as solar and wind or any other power source to power the desalination plant. An incorporation of plant optimization configuration, team turbine design as well as any other optimisation techniques could also be considered in future to ensure maximum productivity, strength, reliability, efficiency, and reduction of operational limitations. Hence this research has fulfilled its objectives by considering environmental effects of having an alternative powered desalination plants towards providing vulnerable communities with clean water which is an essential factor of development.

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