



25501103



同濟大學

TONGJI UNIVERSITY

硕士学位论文
(学术学位)

**太阳能蒸馏技术对平准化水成本的影响
前景：与传统海水淡化的比较分析**

姓 名：菲利克斯

学 号：2393401

学 院：环境科学与工程学院

学科门类：工学

一级学科：环境科学与工程

二级学科：环境科学

研究方向：海水淡化

指导教师：王力

二〇二五年五月



同濟大學
TONGJI UNIVERSITY

A thesis submitted to

Tongji University in partial fulfillment of the requirements for
the degree of Master of Engineering

Prospects of Solar Distillation on Levelized Cost of Water: A Comparative Analysis with Conventional Desalination Technologies

Candidate:	NIYOKWIZERA Felix
Student Number:	2393401
School/Department:	College of Environmental Science and Engineering
Categories:	Engineering
First-level Discipline:	Environmental Science and Engineering
Second-level Discipline:	Environmental Science
Research Fields:	water desalination
Supervisor:	WANG Li

May 2025



25501103

太阳能蒸馏技术对平准化水成本的影响前景：
与传统海水淡化的比较分析
菲利克斯
同济大学



摘要

全球偏远社区获得清洁水资源是一个重大问题，因为这些地区通常无法建设传统的基础设施。本论文回顾了两种由可再生能源驱动的技术——太阳能蒸馏系统和膜电容去离子化（MCDI）——用于为农村地区提供饮用水。这两种技术均利用光伏能源，使其适用于电力匮乏的地区。分析评估了它们的经济、技术、环境和可持续性方面，重点关注一个日耗水量为 50 立方米（年耗水量 18,300 立方米）的村庄社区的平准化水成本（LCOW）。太阳能蒸馏通过蒸发和冷凝利用太阳能净化水，而 MCDI 采用电化学脱盐方法。比较了资本成本、运营和维护费用以及 LCOW，其中太阳能蒸馏的成本为 1.94 美元/立方米，MCDI 为 0.886 美元/立方米，表明 MCDI 具有成本优势。分析采用 20 年系统寿命和 12% 的利率，应用资本回收和偿债基金变量来评估固定成本和残值。研究了环境影响和可持续性以确定长期可行性。结果表明，由于 LCOW 较低，MCDI 在经济上更具优势，但太阳能蒸馏在维护方面可能更简单。环境因素支持两种系统使用可再生能源，尽管 MCDI 的更高效率降低了其生态足迹。建议包括改进太阳能蒸馏的结构以降低成本，以及扩大 MCDI 的应用规模。本分析强调了 MCDI 作为一种成本效益高、可持续的偏远地区供水选择的前景，未来需要进一步改进以提高欠发达地区的可及性和可负担性。

关键词： 水淡化, 平准化水成本（LCOW）, 太阳能蒸馏, 膜电容去离子化（MCDI）, 可再生能源。



ABSTRACT

Access to clean water is a significant issue in off-grid communities around the world, where typical infrastructure is unfeasible. This thesis reviewed two renewable energy-powered technologies Solar Distillation Systems and Membrane Capacitive Deionization (MCDI) for providing drinkable water in rural places. Both leverage photovoltaic energy, making them suited for places with little electricity. The analysis assesses its economic, technical, environmental, and sustainability aspects, concentrating on the Levelized Cost of Water (LCOW) for a village community consuming 50 m³ daily (18,300 m³ annually). Solar Distillation uses solar energy to purify water by evaporation and condensation, while MCDI employs an electrochemical desalination method. Capital costs, operations and maintenance expenses, and LCOW are compared, with Solar Distillation costing \$1.94/m³ and MCDI at \$0.886/m³, suggesting MCDI's cost advantage. The analysis utilizes a 20-year system lifespan and a 12% interest rate, applying capital recovery and sinking fund variables to assess fixed costs and salvage values. Environmental implications and sustainability are studied to determine long-term feasibility. Results indicate MCDI's economic superiority due to lower LCOW, however Solar Distillation may offer simplicity in maintenance. Environmental factors favor both systems for their renewable energy use, although MCDI's efficiency decreases its ecological imprint. Recommendations include enhancing Solar Distillation's architecture to minimize costs and scaling MCDI for greater adoption. This analysis emphasizes MCDI's promise as a cost-effective, sustainable option for off-grid water supply, with future enhancements needed to enhance accessibility and affordability in underserved places.

Keywords: Water desalination, Levelised cost of water(LCOW), Solar Distillation, Membrane Capacitive Deionization (MCDI), Renewable Energy.



TABLE OF CONTENTS

Chapter 1 INTRODUCTION.....	1
1.1 Research Background.....	1
1.2 Basis for Topic Selection.....	2
1.3 Research Objectives.....	2
1.4 Theoretical significance and practical value.....	3
1.4.1 Theoretical Significance	3
1.4.2 Practical value.....	3
Chapter 2 LITERATURE REVIEW OF WATER DESALINATION TECHNOLOGIES	4
2.1 Introduction.....	4
2.2 Conventional Desalination Technologies	5
2.2.1 Reverse Osmosis (RO)	5
2.2.2 Electrodialysis.....	7
2.2.3 Ion Exchange	8
2.2.4 Multi stage flash evaporation(MSF).....	8
2.2.5 Multi-Effect Distillation (MED).....	10
2.2.6 Capacitive Deionization.....	10
2.3 Solar energy desalination.....	12
2.3.1 Solar stills.	13
2.3.2 Influence of Design Parameters on Solar Still Water Production	13
2.3.3 Passive solar stills design.....	16
2.3.4 Active solar still.....	28
2.3.5 Solar still designs distillate production.....	29
Chapter 3 RESEARCH METHODOLOGY	32
3.1 Methods	32
3.1.1 Literature Review	32
3.1.2 Comparative Analysis Framework	32



Table of Contents

3.2 Data Collection	32
3.3 Cost Analysis	33
3.4 Technical Feasibility and Scalability	33
3.5 Environmental Impact Assessment.....	33
3.6 Regional Case Studies	34
3.7 Technical Route	34
3.8 Key Technologies and Difficulties	36
3.8.1 Key Technologies	36
3.8.2 Difficulties	36
3.9 Feasibility analysis.....	36
3.10 Research basis.....	36
3.11 The expected results	37
Chapter 4 THE FINDINGS	38
4.1 Introduction.....	38
4.2 Levelised cost of water	39
4.2.1 Solar Distillation Technology.....	40
4.2.2 The MCDI desalination technology.....	46
4.3 Summary.....	51
Chapter 5 THE DISCUSSION.....	52
5.1 Comparison of Solar Distillation and MCDI LCOW Results	52
5.1.1 Comparison of Capital Costs and Technologies.....	52
5.1.2 Comparison of Operational and Maintenance Costs	53
5.1.3. Comparison of Levelized Cost of Water (LCOW).....	54
5.1.4. Environmental and Sustainability Considerations.....	55
5.2. Conclusion	56
5.3 Recommendations for Future Directions.....	57
REFERENCES	58
ACKNOWLEDGMENT	65
RESUME	66



LIST OF TABLES

Table 2-1 Solar Still Design ,The Operation Conditions and their Distillate Output.....	30
Table 4-1 Summary of LCOW Calculations.	45
Table 4-2 Parameters range for the MCDI technology.....	50



LIST OF FIGURES

Figure 2-1 Desalination technologies distribution in 2019, a) desalination capacity (million m ³ /day b) desalination capacity (%)[10]	4
Figure 2-2 Reverse osmosis counteracts natural osmotic flow by applying pressure to the solution [11]	6
Figure 2-3 The diagram of brine conversion two stage RO seawater desalination system[8] ..	6
Figure 2-4 Schematic of diluate and concentrate produced by electrodialysis process[13]	7
Figure 2-5 Schematic flowsheet of multi-stage flash distillation [4]	9
Figure 2-6 Schematic of adsorption and desorption of ions in CDI[1]	11
Figure 2-7 A schematic diagram of a simple solar still[14]	17
Figure 2-8 Schematic arrangement of a double slope solar still[16]	17
Figure 2-9 Schematic Diagram of a Double Effect Basin Still for Water Distillation [2]	18
Figure 2-10 Simple stepped basin solar still[9]	20
Figure 2-11. Pyramid solar stills with different angles of top glass cover[5]	21
Figure 2-12 Schematic of hemispherical solar distiller design[12]	22
Figure 2-13 Tilted wick type solar still[6]	23
Figure 2-14 .Diagram of solar still with mirrors, and condenser[15]	25
Figure 2-15 Over three days, water was collected from four solar stills with and without porous materials[7]	27
Figure 3-1 Technical Route	35
Figure 4-1 Map of the United Republic of Tanzania, showing Zanzibar Islands where Kibuteni located pointed by arrow[3]	38
Figure 4-2 .The cumulative water productivity of the desalination plant over its lifespan	41
Figure 4-3 The salvage value of the solar distillation system is annualized based on the plant's interest rate	44
Figure 4-4 Decrease in the levelized cost of water from solar distillation based on the plant's lifespan, at an interest rate of 12% per year	45
Figure 4-5 The levelized cost of water for solar distillation increases with the plant's annual interest rate	46



List of Figures

Figure 4-6 An increase in the interest rate, while keeping the lifespan of the MCDI constant, gradually increases the levelized cost of water.....50

Figure 4-7 Increasing in the interest rate and lifespan of MCDI plant gradually decrease the levelized cost of water.51

Figure 4-8 Increasing the lifespan of the MCDI plant at a constant interest rate of 12% effectively decreases the levelized cost of water51



LIST OF ACRONYMS

AC	Annual cost
AMC	Annual maintenance cost
ASV	Annual Salvage Value
CDI	Capacitive Deionisation
CRF	Capital Cost Factor
DS	Double Slope
ED	Electrodialysis
FAC	Fixed Annual Cost
GOR	Gain Output Ratio
i	Interest Rate (%)
LCOW	Levelised Cost Of Water
M	Annual Produced Water(m ³)
MCDI	Membrane Capacitive Deionisation
MED	Multi Effect Distillation
MSF	Multi-Stage Flash Distillation
n	Lifespan(Years)
P	Capital Cost
PV	Photovoltaic
RO	Reverse Osmosis
S	Salvage Value
SFF	Sinking Fund Factor
SS	Single Slope
TDS	Total Dissolved Solids



Chapter 1 INTRODUCTION

1.1 Research Background

The area under extreme water stress will increase and become more intense between 1995 and 2025, rising from 36.4 to 38.6 million Km² worldwide. The population residing in these regions increases from 2.1 to 4.1 billion individuals^[17]. In South Asia, Western Africa, and Southern Africa, the growth is particularly noteworthy. There will be fierce challenge between householders, industry, and agriculture for the limited water supplies in river bases experiencing extreme water stress^[18].

The earth's surface is covered around 71% in water, the majority with 96.5% is found as saltwater in oceans. Only 2.5 percent of the world's water supply is comprised of freshwater, the most of which is either submerged in aquifers or frozen in glaciers and polar ice caps^[19]. Less than 1% of freshwater, mostly found in rivers, lakes, and reservoirs, is still usable for human use^[17, 20, 21]. The high percentage of salinity of the water that is accessible worldwide is unfit for human consumption. Since the lack of water is becoming an indisputable reality in many parts of the world^[22]. Water is one of the prime necessities of life^[23]. We can hardly live for a few days without water as known a man's body constituents, around 70-80% is water^[24].

The water treatment process is the only solution to increase the availability of clean water, as we have mentioned high percentage is saline water which require desalination technology for the removal of salt and contaminants from water. It involves a broad range of technologies that yield access to marginal sources of water such as seawater, brackish, ground and surface water, and wastewater. The levels of heavy metals, such as arsenic, cadmium, mercury, lead, and other salts, in surface and groundwater resources can surpass allowable limits and cause health problems. There is a chance of water adulteration when fresh water is transported using different techniques.

As a result, desalinating salty water with renewable energy that is locally sourced has become crucial. For safe drinking water to be available at a fair price, technologies that achieve greater energy efficiency must be developed. One of the most promising of the many renewable energy sources is solar energy. Even in developed countries, the widespread use of solar energy for desalination is attractive because it greatly lowers greenhouse gas emissions that cause climate change and global warming, especially given the current high rate of fossil fuel-based energy consumption^[25]



By using sunlight to evaporate and then condense water, a process known as solar water distillation efficiently eliminates impurities like salts, bacteria, and minerals. In a basic solar still, impure water is heated in a transparent-covered basin until it evaporates. The vapours rise and condense on the cover, collecting as distilled water, leaving behind impurities. This technique mimics the water cycle in nature. In places that are regarded as remote, like deserts or isolated areas with few freshwater resources, solar water distillation is particularly useful. Solar distillation is a low-cost, eco-friendly method of producing clean drinking water. The device used for solar distillation is called a solar still [26].

1.2 Basis for Topic Selection

The subject "Prospects of Solar Distillation on Levelized Cost of Water: A Comparative Analysis with Conventional Desalination Technologies" is pertinent owing to the increasing worldwide demand for potable water and the environmental issues linked to conventional desalination methods.

Solar distillation, leveraging renewable energy, is a viable alternative for generating drinkable water, particularly in dry areas with ample sunlight. This research examined critical concerns including the reduction of carbon emissions, energy usage, and operational expenses associated with water desalination.

The Levelized Cost of Water (LCOW) serves as a crucial criterion for evaluating the long-term economic feasibility of solar distillation in comparison to convention desalination technologies such as capacitive deionization(CDI), reverse osmosis (RO)and multi-stage flash distillation (MSF). This research examined the technical, economic, and environmental implications of solar energy, emphasizing its potential as a sustainable and cost-effective solution that contributes to worldwide water conservation and renewable energy initiatives.

1.3 Research Objectives

1. To evaluate and compare the Levelized Cost of Water (LCOW) for solar distillation systems alongside to the conventional desalination technologies (e.g. Membrane Capacitive deionization(MCEDI), reverse osmosis(RO), multistage flash) across various operational scales.
2. To analyze the capital, operational, and maintenance costs of solar distillation systems, identifying key cost drivers that affect their competitiveness relative to conventional desalination methods.



3. To assess the impact of geographic factors, particularly solar irradiance levels, on the efficiency and economic feasibility of solar distillation in different regions.
4. To explore the environmental and sustainability benefits of solar distillation, focusing on energy consumption, carbon footprint, and potential resource depletion compared to fossil-fuel-based desalination technologies.
5. To investigate the scalability and long-term viability of solar distillation technologies for large-scale water production, particularly in water-scarce regions and developing countries.

1.4 Theoretical significance and practical value

1.4.1 Theoretical Significance

The research had provided a comparative analysis of solar distillation and conventional desalination techniques, including reverse osmosis and multi-stage flash. This improves the theoretical comprehension of the performance of various technologies based on economic, environmental, and operational parameters, especially with the Levelized Cost of Water (LCOW).

The research provided theoretical cost metrics by emphasizing the Levelized Cost of Water (LCOW), a crucial parameter for assessing the long-term sustainability and economic viability of water production methods. The research developed models for forecasting expenses based on variables such as solar intensity, energy usage, maintenance, and material deterioration.

1.4.2 Practical value

The practical significance of this research was resides in its potential application to mitigate water scarcity, especially in locations abundant in sunlight yet deficient in water resources. Solar energy emerged as a cost-effective alternative to traditional desalination, which is energy-demanding and expensive. By evaluating the LCOW, this research will identify the conditions under which solar solar energy is more cost-effective than conventional desalination, giving a sustainable alternative for governments and corporate entities involved in water management.



Chapter 2 LITERATURE REVIEW OF WATER DESALINATION TECHNOLOGIES

2.1 Introduction

Global water scarcity is drawing more and more attention to the desalination process, particularly in areas with dwindling freshwater supplies. The desalination process mainly has two main techniques for desalination: membrane-based procedures like reverse osmosis (RO) and thermal processes like multi-stage flash distillation. Due to its comparatively low energy needs, RO is now the most used technology; nonetheless, up to 60% of the overall operating cost still comes from energy usage. Desalination technology distribution in 2019

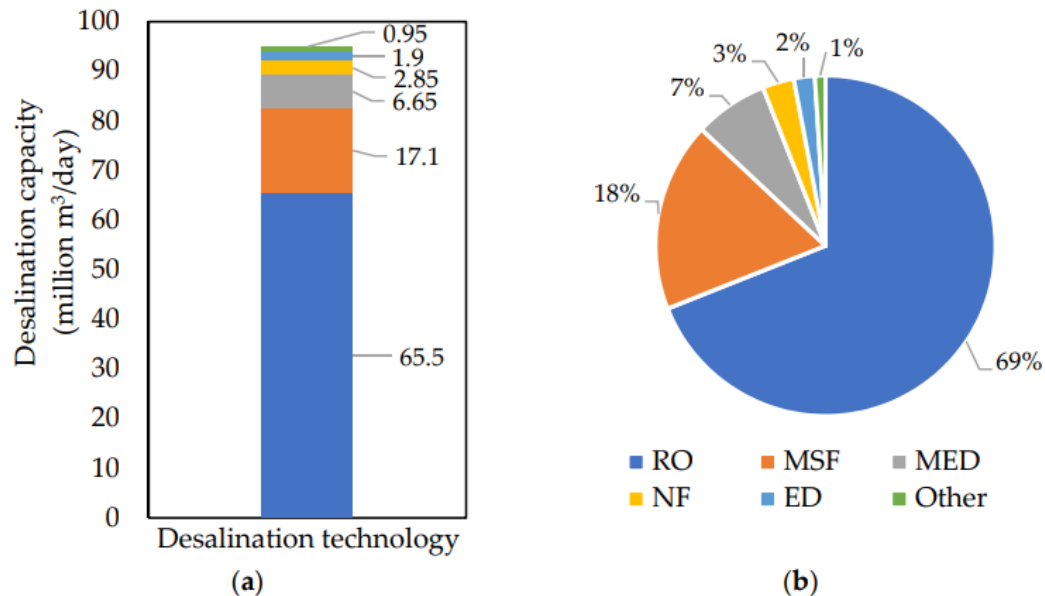


Figure 2-1 Desalination technologies distribution in 2019, a) desalination capacity (million m³/day b) desalination capacity (%)^[10]

Research has also examined other energy sources, such as solar or wind power, in an attempt to reduce the energy footprint of desalination plants. In order to reduce LCOW and make desalination a more viable and sustainable solution, energy recovery devices and other innovations that optimize energy efficiency are crucial. It is thought that the hybrid system provides an inexpensive replacement for standalone systems. It can reduce the strain and stress on energy consumption, scale, and fouling as well as the cost of desalinated water through improved recovery rates and overall water quality^[27].



2.2 Conventional Desalination Technologies

Desalination technologies can be generally classified into two main types according to the specific technics used to produce clean water from saline brackish or sea water and the energy require: thermal and membrane-based processes^[28].

1. Membrane-based desalination, primarily Reverse Osmosis (RO), uses pressure to force seawater through semi-permeable membranes that separate salt and impurities from water.
2. Thermal desalination includes Multi-Stage Flash (MSF) distillation and Multi-Effect Distillation (MED), where seawater is heated to produce vapor, which is then condensed to freshwater.

Other technologies include Electrodialysis (ED) and Capacitive Deionization (CDI). Each method has different energy requirements, costs, and suitability for specific environmental conditions and scales^[28, 29].

2.2.1 Reverse Osmosis (RO)

Reverse osmosis is one of the conventional technologies which is most used in desalination of brackish and sea water. RO is a promising desalination originating from the natural process of osmosis, reverse osmosis involves the passage of water across a semipermeable membrane between solutions with varying concentrations of solutes^[30]. In order to reach an energy equilibrium, osmosis which has been a part of cell wall evolution involves water migrating from regions with low to high solute concentrations. Reverse osmosis counteracts natural osmotic flow by applying pressure to the solution with a greater solute concentration, which causes water to migrate from a higher to a lower concentration. This method, often referred to as hyperfiltration, is essential for desalination and water treatment since it allows for purification by filtering contaminants^[31].

When salt water is first treated, reverse osmosis begins. There are two methods that this can happen: conventional pretreatment, which includes adding acids, flocculants, disinfection, and filtration, and membrane-based pretreatment. Pretreatment extends the materials' usable life and reduces the amount of totally dissolved solids (TDS), which makes it crucial for ensuring higher RO process efficiency. The latter minimizes energy expenditures, which are the primary expense for this kind of procedure and is inversely correlated with pressure demand^[29].



The reverse osmosis process involves applying pressure to the contaminated water, forcing it through a semipermeable membrane. This membrane allows water molecules to pass through while blocking the majority of dissolved salts and other impurities^[32]. As a result, the purified water that emerges on the other side of the membrane is significantly lower in sodium chloride content. The effectiveness of reverse osmosis in desalination depends on different factors such as the quality of the membrane, operating pressure, and feed water conditions. Such as brackish or sea water^[11].

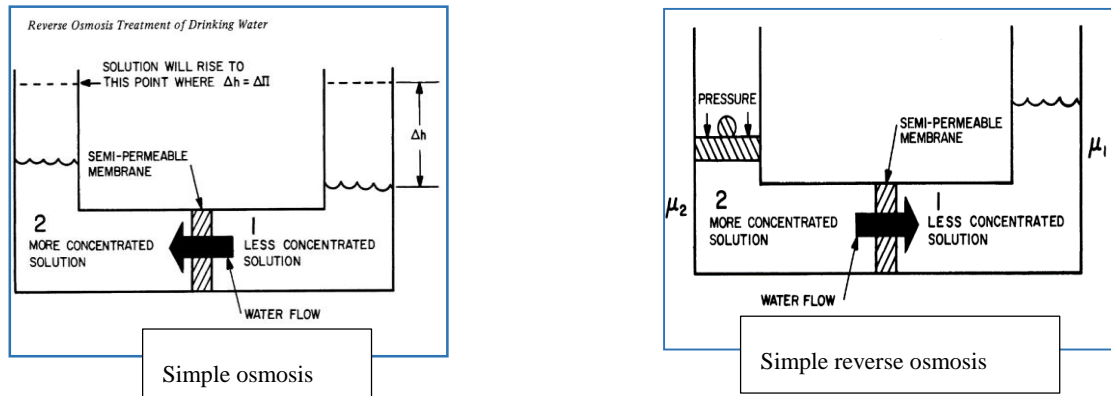


Figure 2-2 Reverse osmosis counteracts natural osmotic flow by applying pressure to the solution^[11]

The reverse osmosis is highly efficient in removing sodium chloride and other contaminants from water, it may also remove beneficial minerals along with the impurities. As a result, some reverse osmosis systems incorporate re-mineralization stages to reintroduce essential minerals back into the purified water, ensuring that it remains healthy for consumption. Reverse osmosis is capable of removing up to 99% of sodium chloride from water, making it an essential process for producing safe and clean drinking water^[33]

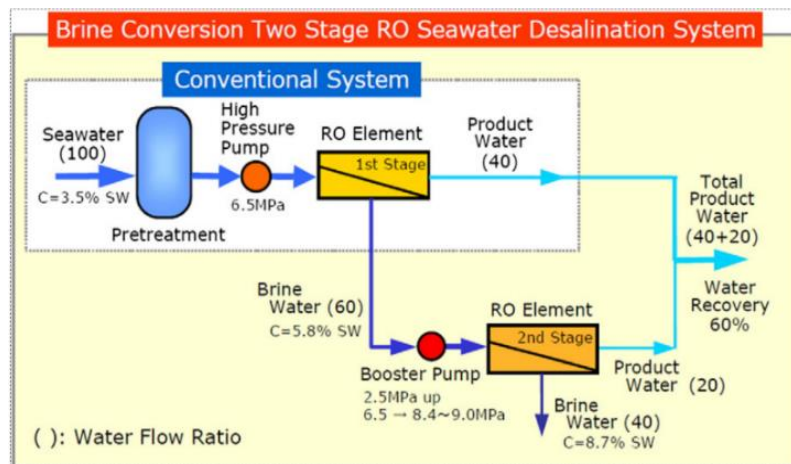


Figure 2-3 The diagram of brine conversion two stage RO seawater desalination system^[8]

The first challenge during operation of RO membranes desalination process is the deposition of colloidal materials and organic macromolecules on the membrane surface and the development of microbes on the membrane^[34]. That leads to cake formation, irreversible adsorption, and growth of persistent biofilms, collectively referred to as fouling which increase energy consumption from pumping systems^[35]

2.2.2 Electrodialysis

Electrodialysis is a membrane-based separation process that utilizes an electric field to transport ions through ion-selective membranes^[36]. This technology has been widely used for the desalination of brackish water and seawater, as well as for the treatment of various industrial effluents. In recent years, electrodialysis has also gained attention for its potential application in the treatment of drinking water to remove sodium chloride and other dissolved salts^[13, 37].

The process of electrodialysis involves the use of an electrical potential to drive the migration of ions through ion-exchange membranes, which selectively allow either cations or anions to pass through^[38]. In the context of treating drinking water contaminated with sodium chloride, electrodialysis can be employed to effectively separate and remove the salt from the water stream. The process typically involves the use of a series of alternating cation-selective and anion-selective membranes, which create compartments for the migration of ions under the influence of the electric field^[39].

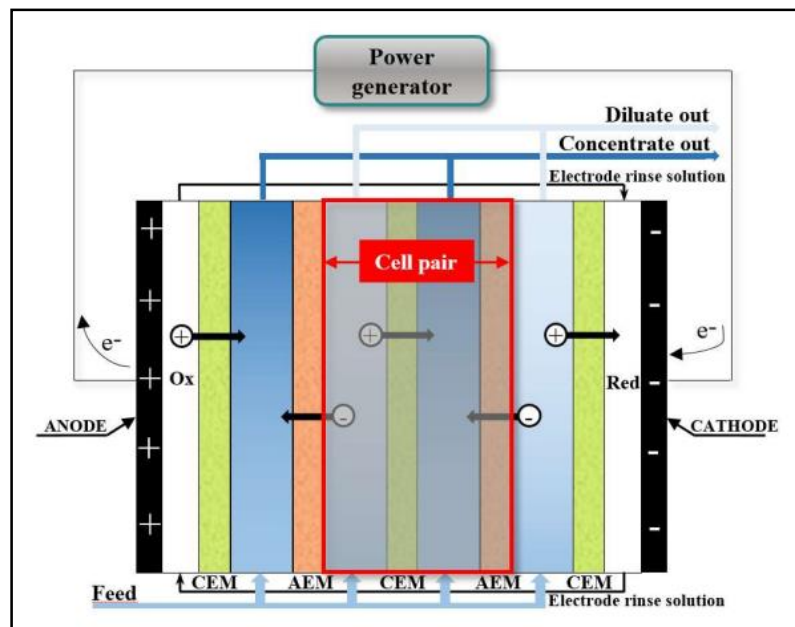


Figure 2-4 Schematic of diluate and concentrate produced by electrodialysis process^[13].



Sodium chloride removal from drinking water, electrodialysis offers several advantages. Firstly, it is a continuous and energy-efficient process that can operate at ambient temperature and pressure compare to the other methods like distillation where high energy is needed to vaporize brackish water^[13].

2.2.3 Ion Exchange

Ion exchange is a water treatment process that involves the exchange of ions between a solid phase and a liquid phase. In the context of treating sodium chloride from saline water such as brackish water, ion exchange can be used to remove excessive sodium ions from the water supply. Sodium chloride, commonly known as table salt, is composed of sodium ions (Na⁺) and chloride ions (Cl⁻)^[40]. The ion exchange process involves the use of a resin material that is capable of exchanging ions with the surrounding solution. In the case of sodium chloride removal, a cation exchange resin is typically employed. Cation exchange resins are designed to selectively remove positively charged ions, such as sodium ions, from the water and replace them with other ions, usually hydrogen ions (H⁺). This results in the reduction of sodium concentration in the treated water^[41, 42].

The sodium ions in the water are attracted to the resin and are exchanged with hydrogen ions on the resin surface. The treated water that emerges from the column has a reduced concentration of sodium ions, while the resin now contains sodium ions. Periodically, the resin needs to be regenerated by passing a concentrated solution of sodium chloride (brine) through the column. This displaces the adsorbed calcium and magnesium ions on the resin and replaces them with sodium ions, restoring its capacity for further ion exchange^[43]. The effectiveness of ion exchange treatment for sodium chloride removal depends on various factors such as the type of resin used, flow rates, contact time, and regeneration procedures^[40].

2.2.4 Multi stage flash evaporation(MSF)

Distillation is a process used to separate components of a liquid mixture based on differences in their boiling points. In desalination process, Saline water is heated until water turns into vapor, then cooling phase turns the vapor condensed back into liquid form. It leaves behind the salt and other impurities. The resulting distilled water is free from sodium chloride and safe for consumption^[44]. This method is particularly effective in areas where access to clean drinking water is limited especially in Middle East and desalination is necessary^[37].



The use of distillation for treating sodium chloride from drinking water has been used extensively in water treatment for desalination process. Researchers have explored various distillation techniques, such as multi-stage flash distillation(MSF) and multi-effect distillation(MED), to improve the efficiency and cost-effectiveness of desalination processes, after Reverse Osmosis Distillation or thermal process take the second place to be effective in desalination process^[4].Distillation is applicable in large-scale desalination facilities, but it may also be used on a small scale to treat a domestic water. Individuals can utilize portable distillation machines, which offer a useful way to filter water in isolated or disaster-affected places when access to clean water is limited.

Multi stage flash evaporation(MSF) is an evaporative desalination technology base on flashing process. MSF is used to convert saline or sea water into freshwater^[45]. MSF desalination consists of multiples stages where each stage containing several flash chambers or vessel arranged in series. MSF is one of the oldest and most widely used desalination technologies^[4].

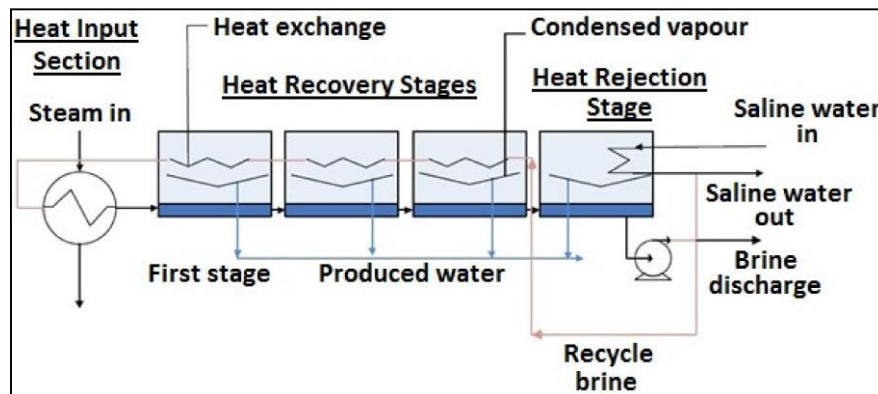


Figure 2-5 Schematic flowsheet of multi-stage flash distillation ^[4]

In MSF, the saline water is heated between 90-110 degree under high pressure, causing it to flash into a steam. This steam is then condensed back into a liquid form, yielding freshwater. Flash distillation begins with a liquid mixture, typically solution containing two or more volatile components, such as a solvent and solute. The mixture is heated to high temperature under reduced pressure, causing the liquid to vaporize rapidly. The decreasing pressure allow water to flash (quickly Vaporized) ^[4]

The process is carried out in multiple stages, in each stages, the feed water undergoes successive flash evaporation cycles, with the pressure decreasing incrementally from stage to stage^[46].



Vapor-liquid separation, as the liquid vaporizes, it forms a mixture of vapor and unvaporized liquid mixture is allowed to enter a separation chamber or vessel. Rapid cooling and condensation inside the separation chamber, the vapor is rapidly cooled, either by contacting a cooler surface or by mixing with a cold stream. This rapid cooling causes the vapor to condense back into liquid form.

Mist separator, also known as demister or entrainment separator, is a device used to remove liquid droplets or mist from vapor stream^[45].

The collection of distillate, the condensed liquid, now enriched in the more volatile components of the original mixture is collected as distillate. Meanwhile, the remaining liquid in the separation chamber, which is now depleted in the more volatile components, is referred to as the bottom product or residue^[47, 48].

2.2.5 Multi-Effect Distillation (MED)

Multiple effect distillation(MED)is a desalination process that use multiple stages of evaporation and condensation to produce fresh water from brackish or seawater^[49].

In MED the heat exchangers are used to transform heat from a heat source (such as steam or hot water) to the brackish water or seawater water being desalinated. MED has also evaporators as the primary components where evaporation happens^[50]. Each evaporator chamber known as an effect operates at progressively lower pressure and temperature. Brackish water or seawater is heated in those chambers, causing it to evaporate and produce vapor. After saline water converted into vapor, the condensers are used to condense the vapor produced turn it back into liquid form^[51]. The Heat released during condensation used to heat the feed water in the subsequent effect, which improve overall energy efficiency. MED has also vacuum injector also known as steam injector or jet injector, is used to create vacuum (approximately zero bar G in the evaporation chamber)^[52].

2.2.6 Capacitive Deionization

Capacitive deionization (CDI) is concept of electrochemical demineralization of water, it is also an innovative technology designed for the desalination of water, it works effective for brackish water, which contains a moderate concentration of salts^[53]. An electrical potential difference is applied between two electrodes, which are usually constructed of absorbent carbon materials, to drive the process^[54]. This approach is a viable replacement for conventional desalination methods like reverse osmosis and distillation since it uses electro-sorption to remove ions from water^[55].

CDI system operates in two stages such as the desalination of water takes during the adsorption phase, and the regeneration of the electrodes takes during the desorption phase. Ions are adsorbed from the water during the adsorption phase, which is triggered by a potential difference across two electrodes. In the case of CDI using porous carbon electrodes, the ions are transferred from the porous carbon electrode's interparticle pores to its intraparticle pores, where they electrosorb to form what are known as electrical double layers (EDLs). The adsorbed ions are released for electrode renewal after the electrodes have reached ion saturation. It is either lowered to zero or the potential difference between the electrodes is reversed. Ions can be washed out of the electrode pores in this manner^[1].

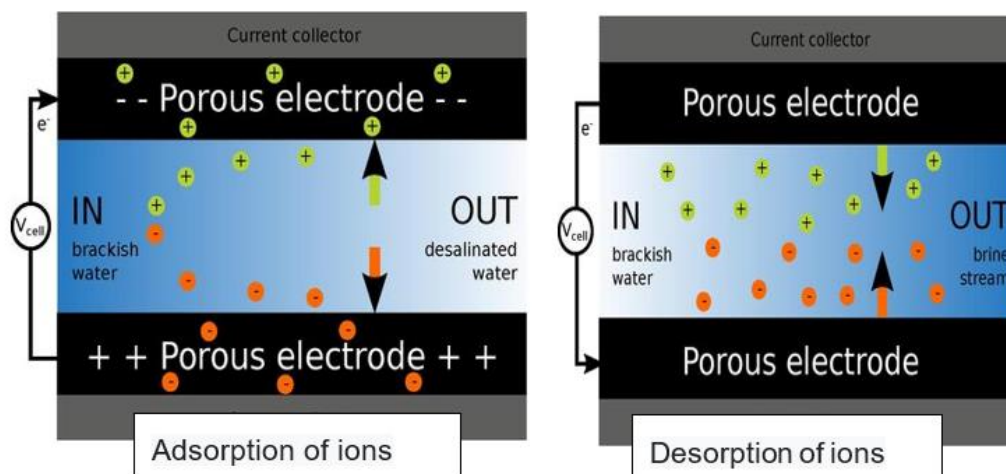


Figure 2-6 Schematic of adsorption and desorption of ions in CDI^[1]

Capacitive deionisation (CDI) is a water desalination process that works on the premise of storing ions in an electrical double layer of charged electrodes and then releasing them when the electrodes are discharged^[56, 57]. Research in CDI and related technologies includes new electrode materials, theoretical models for process performance, system optimisation, selective ion removal, cost modelling, and novel cell configurations^[58]. Membrane CDI (MCDI) uses ion exchange membranes (IEMs) between feedwater and electrodes to prevent ejected co-ions from entering the flow channel, improving CDI charge efficiency^[59]. The flow electrode CDI (FCDI), which uses a flowing slurry, allows for continuous desalination and improved salt removal^[60].



CDI provides operational advantages in that it does not require high-pressure pumps, makes it easier to integrate renewable energy sources^[61], and may be less prone to fouling and scaling-related performance decreases^[62, 63]. CDI may consume less energy per cubic meter is lower than other desalination technologies such as than RO when treating low salinity waters (total dissolved solids, TDS, 2000 mg/L), but a recent analysis shows that CDI achieves "less difficult" separation (e.g., less salinity reduction) and is generally less energy efficient than RO^[64].

CDI systems for desalinating brackish water typically consume less than 1kWh/m², resulting in electricity costs of around 0.07 \$/m³ for a commercial consumer in a low-cost state^[65]. The levelized cost of water (LCOW, \$/m³) indicates the net capital and operational cost per unit volume of product water and is one of the most important criteria for technology evaluation^[55].

2.3 Solar energy desalination

Solar energy has a very promising role to play in addressing water scarcity problems through thermal desalination processes around the world^[66]. The use of sun energy, a solar desalination system turns saline water into freshwater. By using sunlight to evaporate water, leaving behind salts and other contaminants, and then condensing the vapor into drinking water, it replicates the natural water cycle^[67].

While indirect solar desalination combines traditional desalination methods with solar collectors for heat generation, such as multistage flash desalination (MSF), vapour compression (VC), reverse osmosis (RO), membrane distillation (MD), Capacitive deionization(CDI) and electrodialysis , direct solar desalination uses solar energy to produce distillate directly in the solar collector^[68].

There are mostly two types such as systems that are passive, such as solar stills, in which sunshine heat saltwater contained in a basin, leading to evaporation. Freshwater is gathered when the water vapor condenses on a transparent cover. Active systems, which power desalination procedures like reverse osmosis (RO) and multi-effect distillation (MED) using sun energy (either thermal or photovoltaic (PV) electricity)^[69]. Because solar desalination uses renewable energy and emits few emissions, it is environmentally friendly. Although it may be scaled up for communities employing active systems, it is best suited for small-scale application in isolated or dry areas^[70].



Only a small portion of the freshwater generated worldwide, according to estimates, comes from renewable sources. Water and energy legislators should select different approaches to meet the needs based on the local potentials by paying attention to the desalination processes and power systems. This can be achieved by offering a wide range of conventional desalination methods powered by various types of renewable energy technologies worldwide^[71]

2.3.1 Solar stills.

Since the nineteenth century, solar distillation has been carried out using a solar still ^[26]. The use of a free heat source, such as the sun, and technical simplicity are two of the primary characteristics of solar stills. Even with relatively sophisticated designs, numerous attempts have been made to enhance their performance throughout their operating history, but their productivity (a few L/m²d) is still quite low ^[72].

Solar stills fall into two categories: passive and active. A particular kind of still that specifically uses solar energy that is transformed into the still unit is referred to as a passive still. These systems work similarly to the hydrological cycle found in nature. Because it uses the heat that has accumulated in the saline water, evaporation and condensation processes occur inside the still basin. The still unit that aids in heating the saline water in active solar stills, however, needs to be driven by an external thermal energy source or apparatus. This type of energy could be produced using sand concentrators in conjunction with the distillation unit, thermal collectors, and photovoltaic panels. A conventional boiler could provide such external heat, waste thermal energy, or a concentrating solar pane^[73, 74].

2.3.2 Influence of Design Parameters on Solar Still Water Production

The design parameters of a solar still have a significant impact on both its water output and efficiency. The surface area of evaporation and basin water depth, the cover's slope, its material and thickness, the insulation's material and thickness, and the temperature differential between the water and glass cover are some of the important factors influencing evaporation and condensation rates. For solar desalination systems to remain sustainable and increase freshwater production, especially in water-scarce areas, these parameters must be evaluated.

a) Surface area of evaporation and basin water depth

The two main factors affecting distillate production are the surface area of the solar still and the depth of the water. This is due to the fact that the rate at which distilled water evaporates is approximately proportional to the surface area of water that is exposed to sunlight. Therefore, the efficiency of producing distilled fresh water is increased by increasing the



surface area of salt water in the distiller's basin. The productivity of clean water and distillation efficiency are inversely correlated with the basin's water depth [75, 76].

Under constant solar radiation, it has been shown that a dry patch is reached and that the lowest water level corresponds to the highest productivity. The production of the solar still was found to decrease with increasing water depth. Elango and Murugavel looked into how increasing water depth affected both single- and double-basin solar stills, two types of sun distillers, and found that both types of solar stills produced less [77, 78].

Different amounts of water (6 L, 8 L, 10 L, and 12 L) were used to test the impact of the basin's water quantity on solar still production. According to the experiment's findings, the single slope solar still can produce 2490 mL, 2390 mL, 2240 mL, and 2015 mL of distillate cumulatively. Nonetheless, it has been demonstrated that the production of distillate water falls as basin water quantity rises [79, 80].

Overall, in every case examined, the recommended water depth in the basin was between 1 and 5 cm. Since nocturnal productivity follows a reversal pattern, production increases with increasing water depth, even though the opposite happens at night and during the day. The basin's water depth and volumetric heat capacity both rise at night. Consequently, a low rate of evaporation is attained. As the water releases the heat energy it has received, the desalination process continues all night long. Larger amounts of water therefore absorb more energy [77].

b) Solar still cover's slope

The slope of the cover affects the condensation and collection of water vapour, which in turn affects distillate productivity during the solar still design process. An ideal slope minimises re-evaporation and boosts water yield by ensuring that condensed water droplets effectively trickle down into the collection trough. While a very shallow slope can result in droplet accumulation, blocking solar radiation and slowing evaporation rates, an excessively steep slope can restrict the effective condensation time by allowing water droplets to slide too quickly. Research on three different angles (20, 30, and 45⁰) was done by Feilizadeh and his team. They discovered that productivity is higher at 30 degrees due to the greater temperature difference than at the other cover slope angles [81].

c) Cover material and thickness

The thickness and transmissivity of the cover are important variables that affect the still's output. The still yield is impacted by the cover's thermal conductivity. 4.20 L, 3.97 L, and 3.86 L were determined to be the yields of a still with 4 mm, 5 mm, and 6 mm glass, respectively. Consequently, compared to a similar still with a 6 mm glass cover, a still with a



4 mm glass cover generated 14% more fresh water. This is because more solar radiation can enter the still and reach the basin water through thinner glass, which has a higher transmittance^[78].

Dimri and his group investigated how various still cover materials, such as copper, glass, and plastic, affected the highest still productivity. Using plastic materials as a cover has the lowest productivity, while copper has the highest still productivity, according to their experimental results^[82].

d) Insulation material and thickness

In order to optimise the production of distillate, it is crucial to select the appropriate insulation material and thickness when designing a solar still. Higher water temperatures and longer evaporation are ensured by effective insulation, which lowers heat losses from the basin. The thickness and type of insulation are crucial components in solar stills^[83-85]. The average monthly production in June, according to research by Al-Karaghoul and his colleagues, was 2.84 kg/m²d for an insulated still and 2.46 kg/m²d for a non-insulated still^[83]. The study examines solar stills with insulation thicknesses of 30, 60, and 100 mm. The outcomes are contrasted with those of a still that is not insulated. It was found that, up to 60 mm, insulation thickness significantly affects the still's productivity. The productivity of the still may be impacted by the thickness of the insulation by over 80%^[85].

e) The temperature difference of water and glass cover

The productivity yield of the solar still is directly proportional to the temperature differential between the water in the basin and the glass cover. One of the main forces behind a solar still's operation is the temperature differential. Al-Garni discovered that the still yield rose when a cooling water film was applied to the glass cover^[86]. However, Murugavel and his group also discovered that the temperature differential between the glass cover and the basin grew when water was heated using an electric resistance heater^[86]. Therefore, while lower glass cover temperatures increase condensation, higher water temperatures increase evaporation. Thus, it is possible to draw the conclusion that more solar distillate is collected the larger the temperature differential between the water and the glass cover.

f) Other parameters affecting the productivity of solar stills

A device called a solar still was created to produce clean water; because it is solar-powered, its desalination efficiency is increased as solar radiation intensity rises^[87]. Around solar noon, when the intensity of solar radiation reaches its maximum temperature, solar stills usually operate at their highest efficiency. Water evaporation is facilitated and accelerated as a



result. Additionally, the time of year and geographic location—which are influenced by latitude, longitude, and time determine the intensity of solar radiation. Mathematical simulation models predict the intensity of solar radiation [88, 89]. According to reports, a city in northern Egypt experiences varying levels of solar radiation throughout the day, with the summer months seeing the highest levels of solar radiation, not the winter months^[90]. Solar desalination and other heating system operations are impacted by the intensity of solar radiation, which has a major effect on receiving surface temperature^[91]. The efficiency of a solar still is greatly affected by the wind speed across the glass cover and the strength of the sun's rays. As the wind speed increases, convective heat transfer causes the temperature of the glass surface to drop.

2.3.3 Passive solar stills design

Simple, energy-efficient devices known as passive solar stills use solar energy to purify water through evaporation and condensation, without the need for additional energy sources or equipment^[92]. Their standard design includes a transparent cover to capture solar energy, a slanted surface to collect the distilled water, and a basin containing saline or polluted water. Passive solar stills can be distinguished by various features, such as the shape of the still, the number of basins, the shape of the cover, and their operating procedures.

a) Single Slope Basin Solar Still

The most common kind of solar still is the single slope basin design, which is also referred to as the traditional passive solar still^[93]. Numerous researchers showcased architectural designs that were refined through experimental and theoretical testing. A sloping glass cover that is tightly sealed to stop vapour leakage is placed over the container, as seen in Figure 2-7. A hardwood frame that has been properly insulated supports this container. The contaminated water heats up as a result of absorbing solar energy. Water molecules evaporate when the temperature of contaminated water is raised. The air above the water's surface is where convection takes place. After that, the vapours enter the basin and make contact with the glass lid. The vapours then condense as droplets on the tilt cover as a result of heat being absorbed by the cover material.

The distilling channel on the still basin's bottom wall collects the condensate droplets, allowing drainage to later remove all salts and contaminants from the tank [75, 94]. Saltwater and brackish water can be turned into drinkable water using a traditional solar still. It is rarely used because of its low productivity^[95].

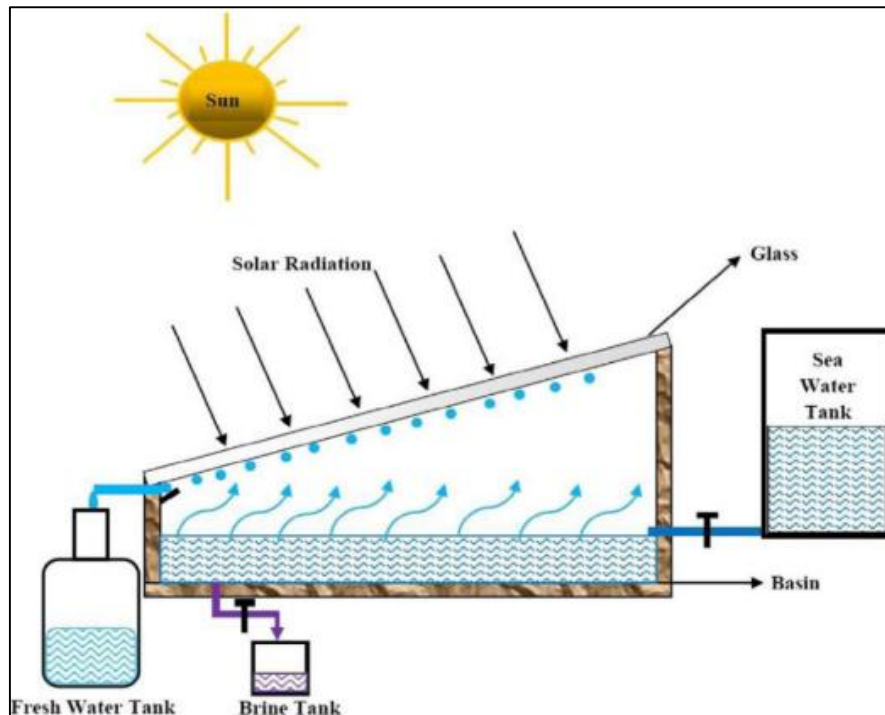


Figure 2-7 A schematic diagram of a simple solar still^[14].

When fully insulated, single solar stills usually reach a maximum efficiency of 50%. Efficiency is reduced by about 14.5% when insulation is reduced. There is a slight 2% drop in still performance when wind velocity is increased from 0 to 1.6 m/s^[14].

b) Double slope solar still

A double-slope solar still is a passive solar device that uses solar energy to desalinate or purify water. It has two glass or plastic slopes on the roof, which is transparent, and a basin with salty or contaminated water in it. The idea of condensation and evaporation underlies how the device works. As the water in the basin gets warmer from the sun, it evaporates.

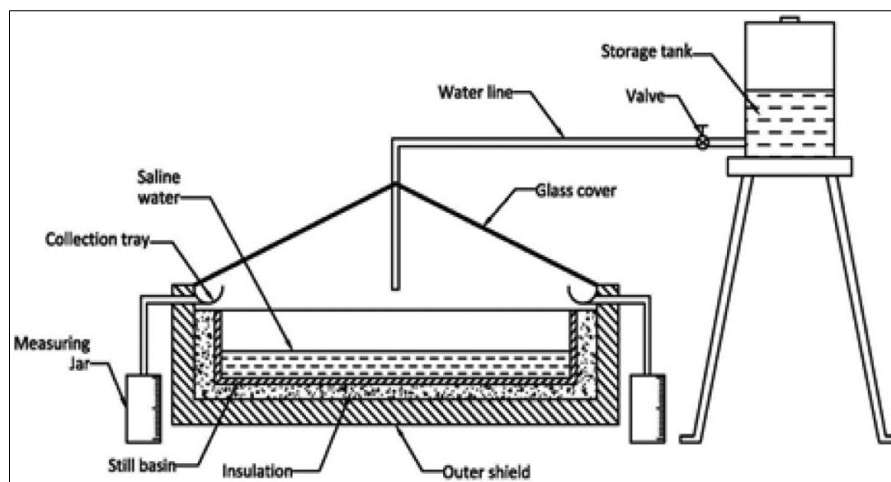


Figure 2-8 Schematic arrangement of a double slope solar still^[16]

Because the inner surface of the sloping roof is colder due to contact with the surrounding air, the vapour rises and condenses there. The sloping surface allows the condensed water droplets to flow down and collect in distinct channels on either side, producing fresh, distilled water. Double-slope solar stills are particularly helpful in areas with strong sunlight because they maximize the surface area that receives sunlight, which boosts efficiency^[96]. The direction, depth, and volume of the feed water are the operational parameters.

The productivity of a double slope (DS) solar still was investigated and contrasted with that of a single slope (SS) solar still in order to determine the effect of operating parameters on internal heat and mass transfer. After setting the orientation, experiments are conducted using SS and DS solar stills of the same size, maintaining the water depth in the basin at 0.01 m, 0.025 m, 0.05 m, and 0.075 m. DS solar still orientated north-south produced a peak distillate yield of 3.07L/m².day at a water depth of 0.01m^[97]. With no maintenance and no need for an outside energy source, they are inexpensive, simple to construct, and environmentally friendly.

c) A Double-Effect Solar Still

A double-effect solar still, also known as a double basin solar still, is designed with meticulous planning to maximise water production efficiency while efficiently harnessing solar energy. The first step is determining the goals, which include the required water output, financial limitations, and environmental factors like ambient temperature and solar intensity.

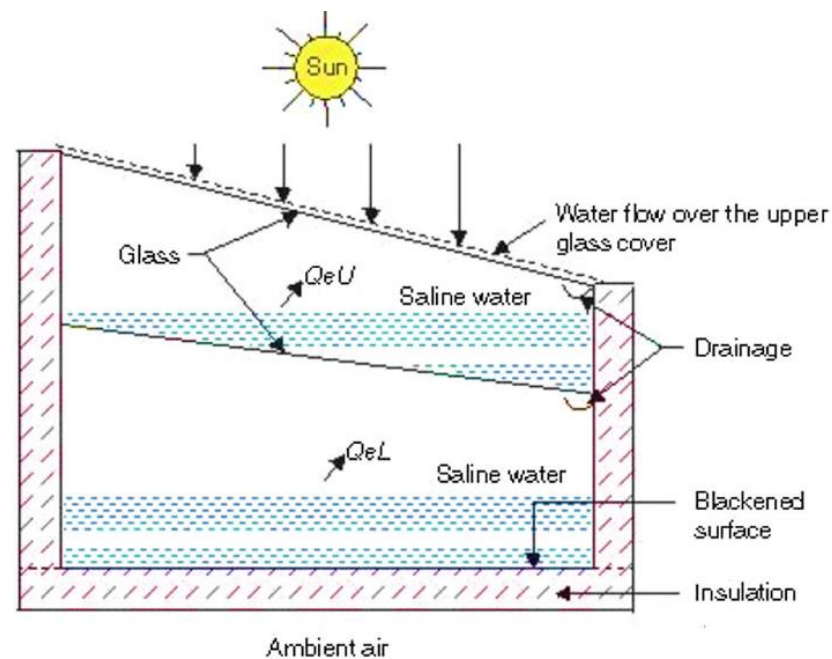


Figure 2-9 Schematic Diagram of a Double Effect Basin Still for Water Distillation ^[2]



The system layout, which usually consists of two stages of evaporation and condensation, as it conceptualised in Figure 2-9. The purpose of transparent covers, which are frequently composed of glass or premium plastic, is to optimise the absorption of solar heat. To effectively retain heat, the basin is designed with the right material for insulation and thermal conductivity. The second stage is made to use the latent heat released during condensation in the first stage to start another evaporation cycle, while the first stage has a saline water basin that uses solar energy to evaporate water. The upper and lower basins of a double effect solar still are separated by sloped glass, and heat is transferred by radiation and evaporation. Compared to a single effect type, this method yields more distilled water^[98].

Heat recovery mechanisms, like thin-film heat exchangers, are used to transfer heat between stages; insulation is added to minimise heat loss; water channels are designed for efficient flow and separation of freshwater from brine; the two basins are sealed to prevent water from leaking into the boxes and stills; the condensed water collection and brackish water feeding occur through the basin's sidewall hole, which is closed with insulating material while still preventing heat and vapour losses^[99]. The simulation was run for eight hours, and the results were compared to the experiment. The analytical results showed that the total distilled output was 3.74 L/m² collected in output, while the experimental results showed a total distilled output of 3.2 L/m² channel. The simulation results were in excellent agreement with each other and followed the same trend as the real data^[100].

d) Simple Stepped Cascade Stills

Simple stepped cascade stills use several inclined steps to increase water evaporation and condensation, which is meant to increase the efficiency of traditional solar stills. A sequence of shallow, angled trays or steps make up the design, which permits thin layers of contaminated or salted water to flow downward while being exposed to sunlight. The water is heated by the greenhouse effect produced by a transparent cover, usually composed of glass or plastic, which traps solar radiation. The vapour that is produced when the water evaporates condenses on the underside of the cover and gathers as distilled water in a different channel.

The rationale behind this design, as illustrated in Figure 2-10, is to minimize thermal losses while increasing the area of water exposed to solar radiation. Using thin water films that heat up and evaporate more quickly, stepped cascade stills differ from traditional basin-type solar stills, which have a relatively high water depth—the distance between the saline water and the still's glass cover. The cascading movement continuously exposes fresh water to solar heat, which raises the rate of evaporation overall. The system can react to changes in solar

intensity more effectively because the design also lessens thermal inertia. Additionally, a convective air current is created by the steps inside the still, improving mass and heat transfer.

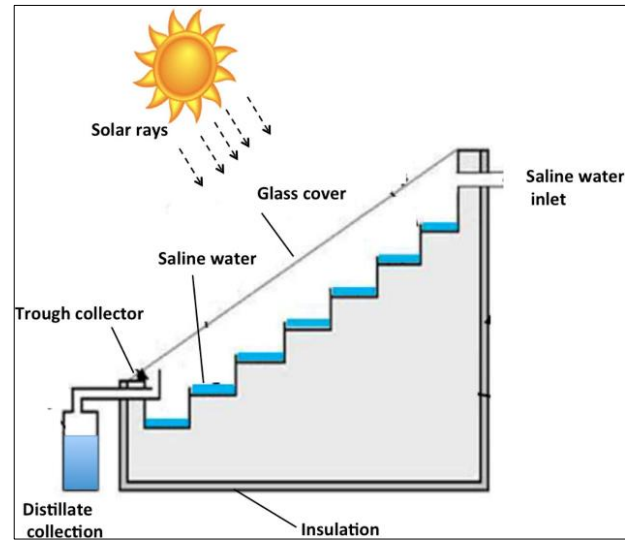


Figure 2-10 Simple stepped basin solar still^[9]

Both passive and active use are possible with stepped solar stills. On the other hand, passive stepped stills are simple to design and operate, and because no electrical pumping power is needed, they have many cost-effective advantages. However, in comparison to active stepped solar, its low efficiency, as indicated by low freshwater production, continues to be a barrier. Condensation-induced latent heat loss through the transparent cover is the cause of this drawback^[9].

In addition, the stepped still's daily efficiency was significantly impacted by the width and depth of the step tray. According to the results of the experiment, the maximum daily productivity of the stepped still was roughly 57.3% greater than that of the conventional one when the tray width was 120 mm and the depth was 5 mm. Moreover, stepped and conventional stills had daily efficiency rates of roughly 53% and 33.5%, respectively. The wicks boosted the stepped still's output by as much as 5%. While feed seawater preheating slightly increased productivity, it also cut the modified system's efficiency in half. At an efficiency of 66.6%, their maximum daily productivity was 6.080 l/m²/day, while their system's maximum theoretical productivity was 9.129 l/m²/day^[101].

e) Pyramid Solar Still

A pyramidal solar still is one that has a pyramid-shaped top cover as Figure 2-11 highlight. Solar still basins come in two shapes: square pyramids and triangle pyramids. Compared to the traditional basin solar still, the pyramid solar still has a few advantages. In contrast to a pyramidal glass solar still, which does not require this, a conventional solar still requires the still to be tracked to face the sun throughout the day in order to receive the maximum incident solar radiation^[102]. For the same basin area, the condensation rate of a pyramid-shaped solar still is significantly higher than that of a traditional single-slope solar still^[103, 104]. An experimental study comparing pyramid-shaped and single-slope solar stills was carried out in Aswan, southern Egypt. Their research showed that the average daily productivity of the still is 2.6 L/m² per year^[104]. These findings suggested that the pyramid solar still design might be a good substitute for the single slope solar still.

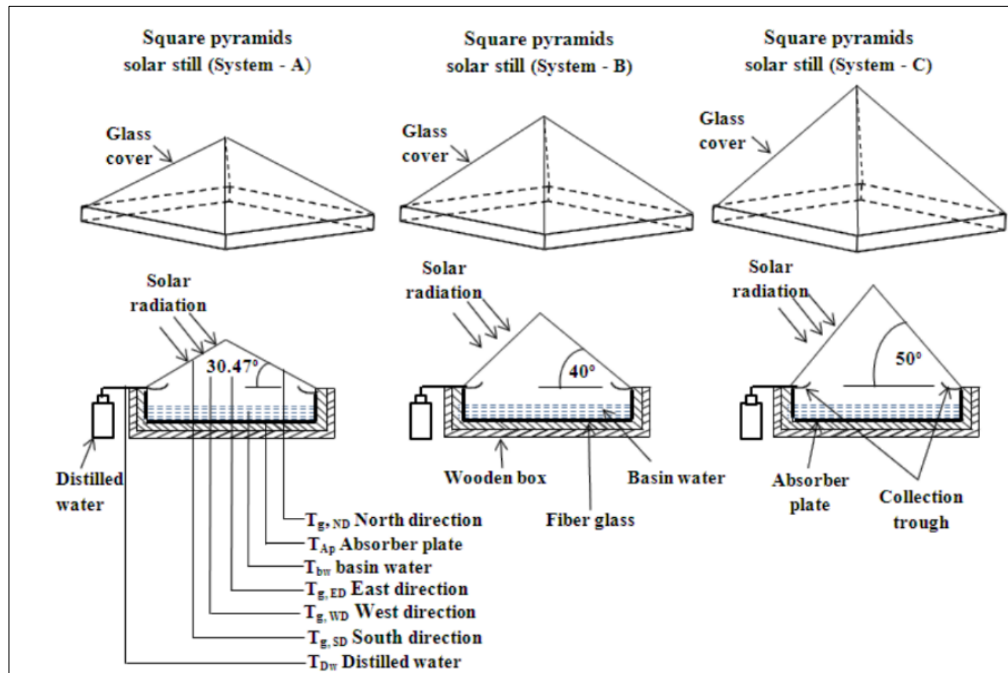


Figure 2-11. Pyramid solar stills with different angles of top glass cover^[5]

A concave basin solar still with a pyramid-shaped top cover has also been studied. The wick supports the concave-shaped basin, increasing the still's daily output. According to their research, an average distillate productivity of 4.1 L/m² could be obtained during the day. The structure is also financially valuable, as evidenced by their system efficiency of 45%, which is higher than the average pyramid solar still's efficiency of 30%, and the concave pyramid-shaped solar still's cost efficiency of 28%^[105].

Water depth has a major impact on still productivity and efficiency, according to experiments done on triangular solar stills^[106]. Additionally, it was found that when the glass cover angle is greater than the latitude angle, the accumulated distillate water productivity from square pyramid solar stills decreases. When the glass cover angle and the latitude angle are equal, square pyramid solar stills produce the most accumulated distillate water^[5].

f) Conical Hemispherical Solar Still

A hemispherical solar still is made up of a circular water basin and a clear acrylic cover. Through the transparent acrylic cover, thermal solar heat is transferred from the salt water in the basin. The heat generated by thermal processes causes brine water to evaporate. The condensed water trickles down the sides of the cap due to gravity, where it is collected^[12]. Under the same weather conditions, the experimental results showed that the daily productivity of hemispherical conical stills was 3.38L/m².day, whereas that of conventional basin solar stills was 1.93L/m².day^[107].

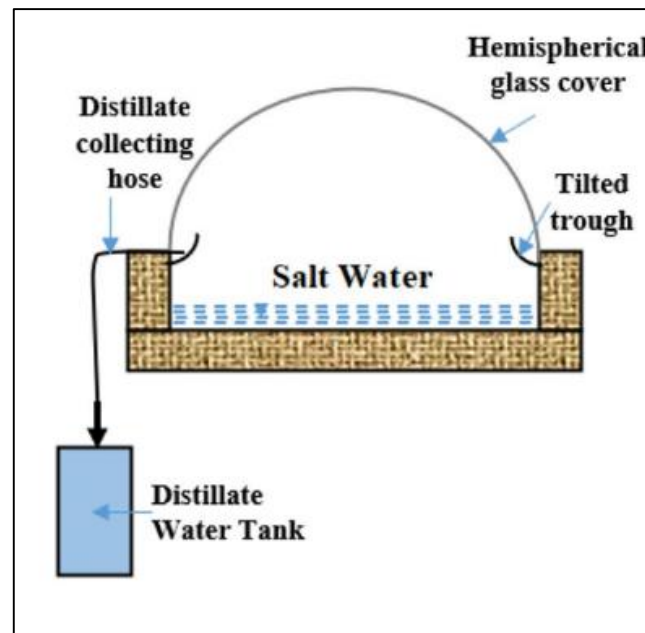


Figure 2-12 Schematic of hemispherical solar distiller design^[12]

According to Ismail, the distillate produced by his study using a hemispherical solar still ranged from 2.8 to 5.7 L/m². day, and the efficacy decreased by 8% for every 50% increase in the still basin's saline water depth^[108].

However, after looking into the factors influencing the hemispherical conical still's performance, Arunkumar and his team discovered that the temperature differential between the glass and water significantly affects the still's productivity. They therefore found that cooling



water over the hemispherical cover increases the amount of distillate collected; this requirement could be satisfied by lowering water or air over the hemispherical cover, since the temperature differential between the glass and water determines the driving force of the solar still. Compared to the conventional flat still, this hemispherical still could accelerate the process by 1.25 times. The still's output is $4.2 \text{ kg/m}^2 \cdot \text{day}$ when the cover is cooled and $3.5 \text{ kg/m}^2 \cdot \text{day}$ when it is not^[109].

g) Wick-type solar still

The glass cover transmits and absorbs solar radiation that strikes it at the wick surface. The water passing through the wick is heated by capillary action using some of the energy. The still retains a lot of heat, and energy moves from the wick surface to the glass cover and then into the surrounding air. In the distillation system, both internal and external modes regulate heat transfers. The external heat transfer mode is brought on by independent convection and radiation and takes place outside the still.

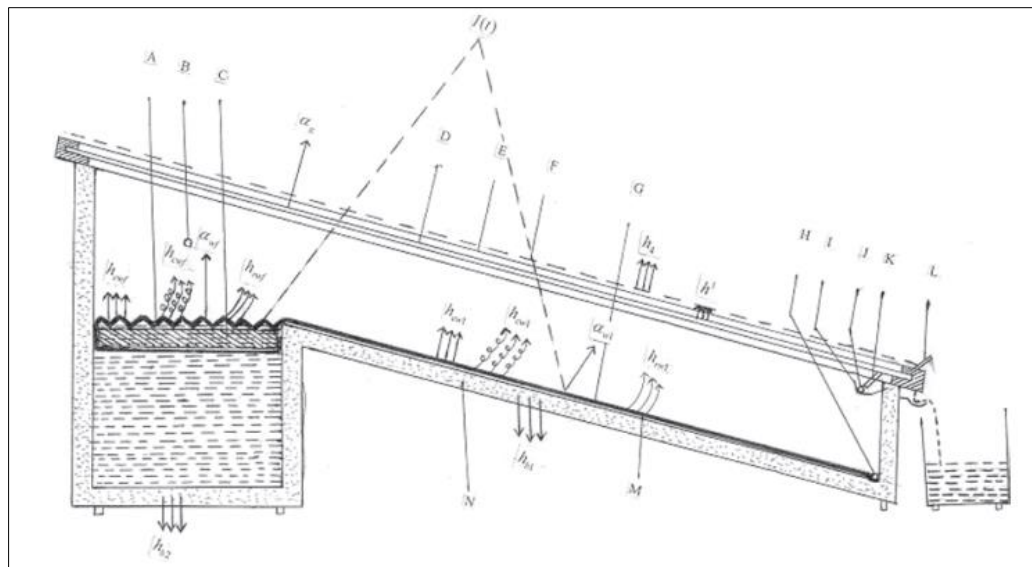


Figure 2-13 Tilted wick type solar still^[6]

The solar distillation unit's internal heat transfer mode is caused by evaporation, convection, and radiation. Convective and radiative heat transfer are combined with mass transfer in the internal heat transfer mode. Vapours are created when heated water evaporates across the wick surface. After the latent heat of vaporisation is released, the saturated water vapour condenses on the glass cover's lower surface. Droplets of condensed water fall and gather in the drainage channel due to gravity^[110].



An inclined solar still's type can also be used to identify a wicked solar still. Wicks are materials that have the ability to absorb sunlight, which raises the still's productivity and efficiency. Radiation-absorbing pads are made possible by the porous nature of these materials^[110, 111]. Several experimental studies have demonstrated that tilting wick materials can increase evaporation rates and that using them increases still productivity^[112]. The absorption capacity of the wick material surface, the floating tilted-wick type, and the lowering water low rate inside the still via the tilted wick portion all contribute to still efficiency^[113].

There are several different kinds of wicked-type solar stills, such as multi-wick type stills, which combine different kinds of wicked materials, like an evaporating wick, a condensing wick, and a sandwich of polytetrafluoroethylene net, to achieve high productivity. It is also possible to convert a wicked-type solar still into a concave-wick type. The evaporation rate of water, which rises as the basin's water level falls, is the basis for this type. A 30% efficiency could boost productivity to 4.1 L/m², according to the study^[114].

h) Solar still with external reflectors

In order to maximise solar energy collection and system performance, a solar still with an external reflector is designed with reflecting surfaces in mind. External or internal reflectors are a good and affordable way to improve the still's distillate efficiency and the amount of solar radiation that reaches the water or basin liner^[115]. Researchers have worked to develop a number of solar still designs in an attempt to boost productivity after demonstrating that the conventional still has limited productivity. They have come to the conclusion that solar stills with reflectors integrated into them are among the most effective and efficient designs^[116]. Using heat and mass transport inside the solar still, numerical analysis was also carried out and compared to experimental data. External reflectors have been shown to significantly increase the solar still's productivity; in this study, an approximate 82% increase in distillate was observed^[117].

Investigations were conducted into the effects of reflector height and angle on solar input, water production rate, and gain output ratio (GOR). The study discovered that a GOR increase of 156% and a water production rate of 5.98 kg/m²·hr were achieved by employing an optimal reflector configuration of 40 mm height and 120° angle. Heat dispersion and thermal efficiency across varying air gaps and solar radiation intensities were examined theoretically. The main heat source in the first stage was evaporation, which achieved 91% thermal efficiency with a 6.5 mm air gap and 1.50 kW/m² of solar energy reflected. On the other hand, due to increased lateral heat loss, a 16 mm gap significantly decreased efficiency to 72% in the final

stage^[118].

i) **2.3.9. Solar still with condenser**

In the condenser solar still, the larger temperature differential between evaporation and condensation within the solar still means that top and bottom losses have a greater impact on production. The solar still's production and productivity are decreased because of the increased temperature differential, which causes vapour to form inside the still and occasionally escape through the glass cover. By reducing heat loss, this temperature differential should be maintained to optimise production. The installation of condensers, fans, reflectors, and water sprinkling minimises heat loss by preserving a smaller temperature differential. The fraction of the still yield that is attributed to purging is $[\text{condenser volume} / (\text{condenser volume} + \text{still volume})]$. Roughly 75 percent of the total still yield comes from natural circulation. An experimental study was carried out to simulate the purging mass transfer mechanism. A 50% increase in still efficiency and outstanding agreement with theoretical expectations are reported by the experimental results^[119].

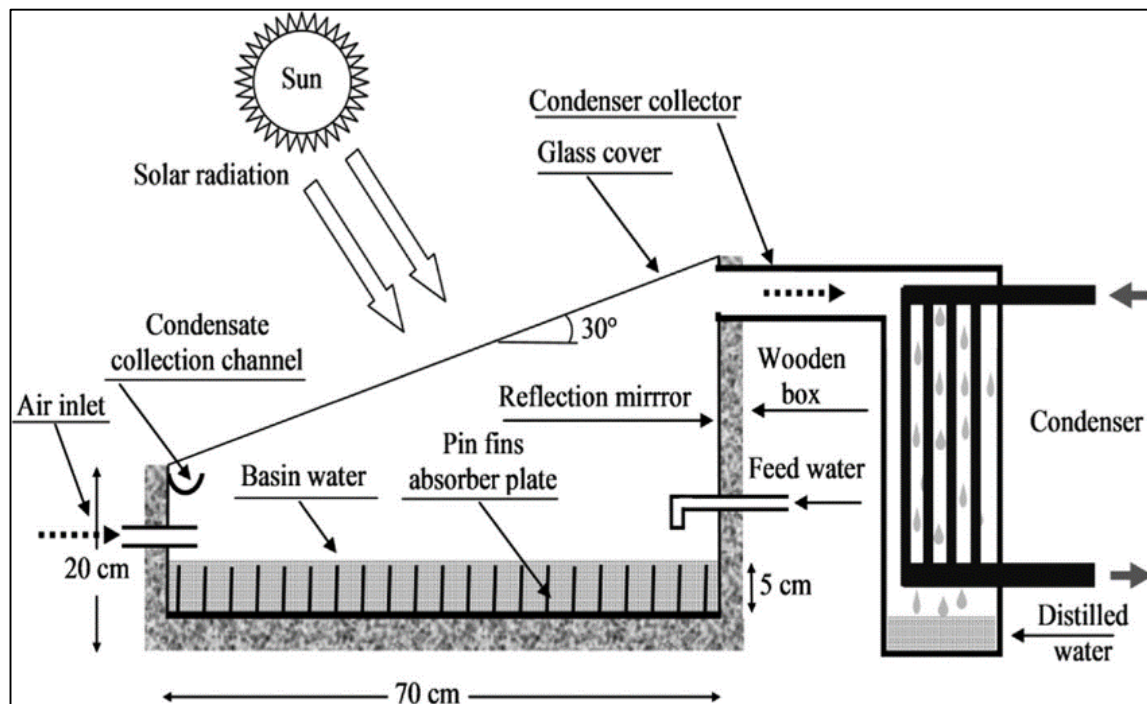


Figure 2-14 .Diagram of solar still with mirrors, and condenser^[15]

The solar still uses a condenser to maintain the temperature differential and minimise heat loss, as seen in Figure 2-14 the fan inside the condenser helps move the vapours produced inside the still so they can condense. The condensed vapour can then be turned into water and



collected inside the condenser's trough^[15]. This process reduces heat loss and increases the distillate yield^[120, 121]. An experiment was carried out by Bhardwaj and his group on the still's basin of 1.8 m². The experiments were conducted with water of different temperatures in a laboratory environment. When the water temperature was 73 °C, the still produced 0.75 l of water per hour. Furthermore, water production increased to more than 0.95 l/h when wind or evaporation cooling were simulated by air flow over the passive condenser or wet tissue, respectively^[122].

j) Phase change materials

A phase transition that a substance experiences in response to heat is known as latent heat storage. For example, a substance can store heat as latent heat of vaporisation to change from a liquid to a vapour or transform from a solid to a liquid by storing heat as latent heat of fusion. The advantages of latent heat thermal energy storage systems over sensible heat storage systems, according to Fath, include high energy storage capacity per volume and a constant temperature for charging and discharging^[123].

Radhwan studied the short-term performance of a compact latent heat thermal energy storage immersed solar still for warming and humidifying agricultural greenhouses. He also discussed how system performance is impacted by air flow rate and wax thickness. By lowering the air flow rate, the greenhouse heat burden was decreased and still production was greatly increased. With an approximate efficiency of 57%, the total production is about 4.6 L/m²^[124].

The researchers looked into the efficiency of different kinds of materials in raising still productivity. Both types of solar stills produced 3.8 and 2.6 L/m² per day, respectively, according to their comparison of the productivity of different solar stills made of aluminium and galvanised iron. Since aluminium has a higher thermal conductivity than galvanised iron stills, this could be the result of the materials' differing thermal conductivity^[125].

Using an energy storage material improved the productivity of distilled water, but increasing the concentration of saline water reduced the still's productivity, according to research by Naim and Mona. The efficiency of the still was increased by higher flow rates and saline water temperatures at the input. When the saline water flowrate was 40 ml/min, the still's maximum productivity was 4.536 L/m² due to stored energy during 6 hours of daytime operation plus nocturnal distillation, yielding a still efficiency of 36.2%^[126].



k) Solar still with Sponges and gravels

A solar still with sponge cubes in the basin increases the efficiency of water evaporation and condensation. The still's translucent cover lets sunlight in, which heats the water. When placed in a basin, sponge cubes increase the surface area available for evaporation by absorbing and holding onto more water. The water evaporating rises and condenses on the lid before falling into a collecting container. The sponges help to retain water, ensuring a steady supply of evaporating moisture, particularly in situations where water levels fluctuate. Still output is increased by up to 273% when sponge cubes are added to the basin water. The sponge cubes increase the surface area where water evaporation occurs^[127].

The efficiency of the solar still when using a variety of spreader materials, such as cotton and jute cloth, a sponge sheet, and porous materials like natural rock and quartzite rock. The researchers verified that the best results were obtained when a black light cotton cloth was used. shown how to temporarily produce fresh water at night using an active single basin solar still with a thin layer of a sensible storage material underneath the still's basin liner^[128, 129].

The daily production reached about 4.005 (L/m²day) with a daily efficiency of about 37.8% when 10 kg of sand was added as storage material. Production dropped to 2.852 L/m²/day without sand, yielding a 27% efficiency. According to research, the still with storage produced 23.8% more per day on average each year than the one without storage^[129]. Nafey and his colleagues looked into how black gravel affected the output of the solar still. Productivities were raised by 19% when 20-30 mm black gravel was used with a brine volume of 20 L/m² and a glass cover angle of 15°^[130].

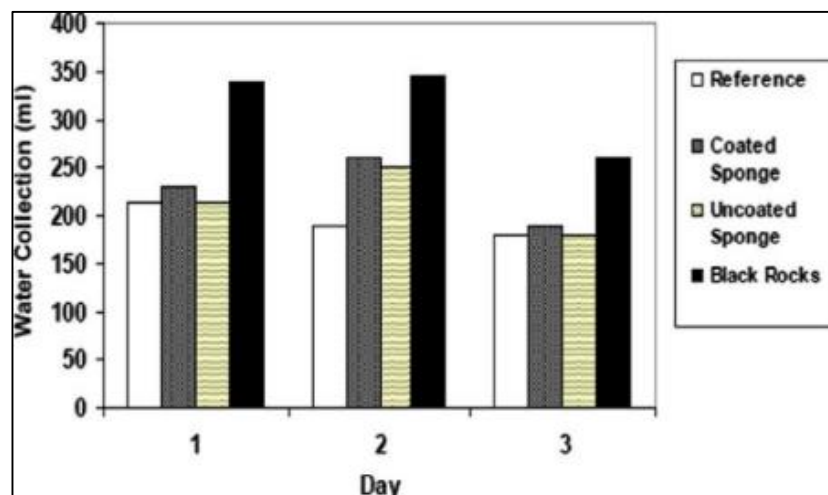


Figure 2-15 Over three days, water was collected from four solar stills with and without porous materials^[7]



Research conducted by Salah Abdallah revealed that the uncoated sponge gathered the most water throughout the day, followed by coated metallic wiry sponges and black rocks. In contrast, coated and untreated metallic wiry sponges and black rocks showed an overall average gain of 28%, 43%, and 60% in distilled water collected overnight, respectively. As seen in Figure 2-15, the black rocks increased the still output by roughly 17–20%. By increasing the overall amount of water collected, the addition of absorbent materials enhanced the still's thermal performance. In comparison to the coated and uncoated metallic wiry sponges, the black pebbles absorbed more solar energy^[7].

2.3.4 Active solar still

The production of the passive solar still is based on the temperature differential between the water in the basin and the interior glass cover surface. The salty water within the basin of a passive still is heated by direct solar radiation. Evaporation consequently takes place, which lowers still production. This is a passive solar still's main disadvantage. Therefore, a number of active solar stills are installed to provide the still basin with additional thermal energy in order to address the previously mentioned problem. As a result, the increased energy accelerates the rate of evaporation, further increasing production. The solar still basin may receive hot water from an outside source, like a solar collector panel. Before being fed into the solar still, water may be heated before being continuously sent at a low rate to the basin^[92].

a) Active solar still enhanced with a flat plate collector.

The components of an active solar still are a pump, reflector, basin, and glass cover. The thickness of the basin insulation is 1.5 mm, the length of the flat plate reflector is 1 m, and the thickness of a glass cover is 5 mm. The brackish water, which is fed into the still, is heated by the sun's energy. Water is evaporated by the sun's rays, collecting on the glass cover and flowing into the distillate channel. It may be affordable to produce drinkable or distilled water using passive solar stills^[131]. A tube connecting a flat plate collector to the basin water or solar still cycled the heated water from the solar collector. The tube transfers heat from the heated water to the basin water by acting as a heat exchanger.

Exergy, energy, temperature, freshwater productivity, and economics have all been studied for the four solar stills. The statistics showed that the solar still's glass temperature was higher than that of a conventional solar still, ranging from 8:00 to 11:30. The solar collector showed the highest average efficiency in terms of energy and exergy. Freshwater output increased by 28.9%, from 0.81 L/m² to 1.0436 L/m² per day, thanks to the glass covers. Additionally, at just 0.193 \$/L/m², the glass cover is the least expensive solar still when



compared to others^[132].

Kerfah and Rabah carried out the experiment at the UDES location in Bouismail, Algeria, over the course of three days from July 24 to July 28, 2016. The results of the daily cumulative production study showed that the condensation chamber contributed significantly, making up 58% of the total production. The daily production was 110% higher with a flat plate collector than with a conventional solar still. The daily production increased by an astounding 176% when the condensation chamber and flat plate collector were both included. Daily output was recorded at 2.1 kg/m² for the basic solar still, 4.5 kg/m² for the active solar still, and 5.9 kg/m² for the active with a condensation chamber. The condensation chamber-equipped active solar still generates more freshwater at a lower cost than the active solar still alone, per an economic study^[133].

b) Active solar still with solar concentrating systems

Solar energy is the cleanest and least cheap renewable energy source. However, obtaining high temperature heat from a source of solar energy is a significant issue in the contemporary day. Solar concentrator collectors have been studied for some years as a method of focusing solar energy for high-temperature applications while also collecting solar energy. Solar concentrators gather and focus light at a single spot. Solar radiation intensity, angle of incidence, and the concentrator's location in relation to the sun and the heated reactor all influence its performance ^[134, 135]. Solar concentrators may be characterized as parabolic trough, dish, or heliostat field concentrators. In Kerman weather conditions, their suggested solar still system produced 55% more pure water during the summer than in the winter using a fixed parabolic trough collector. During the summer, parabolic trough collector and tracking systems generated around 1.266 L /m² day, which was 70% higher than in the winter^[136]. Khairat Dawood evaluated the performance of a solar still equipped with two solar parabolic concentrator linked in series and operating at varied oil flow rates. The phase change material was introduced under the basin and inside the evacuated tubes. The conventional solar still generated 3.182 L/ m² day. The system produces 4.7, 6.2, 8.8, and 11.1 L/ m² per day using 1.5, 1.0, and 0.5 L/ min of oil low rate and 0.5 L min of nano-oil low rate, respectively^[137].

2.3.5 Solar still designs distillate production

Designs for solar stills vary from the original concept to the operating conditions, which also affect the production of distillate. The area of exposed water in a solar still affects how quickly water evaporates, and other outside factors like air flow and sunlight have been found to have a significant impact on the solar desalination system ^[133]. Table 2-1 shows the results of



output distillate from different solar stills designs.

Table 2-1 Solar Still Design ,The Operation Conditions and their Distillate Output.

No	References	Design	Location	Operation condition	Distillate output
1	[79]	single slope basin solar still	Djibouti city(E 43°06.681, N11°32.958)	-S. I: 4.7-7.3 kWh/m ² /day - Base surface area:0.54 m ² .	-Productivity 2490 mL/day -It was found that a low water amount 6L gives the maximum cumulative
2	[100]	A double-effect solar still	India,Kothrud in Pune, (18.516N,73.856E)	-The lower basin area is of 324 mm 9 324 mm, -The upper basin has a dimension of 330 mm 9 324 mm. -Insolation Heat transfer coefficient = 2.5 W/m ² -K	-3.2 L/m ²
3	[101]	Simple stepped cascade stills	Kafrelsheikh university, Egypt, (31.07°N)	-Evaporative cooler -Feed water flow rate 10 L/min is 158.89 N/m ² -0.0263 Watt pumping power	-Production:33.55 L/day -Efficiency:49.01%. -1.25 L/day -Without the cooling unity
4	[138]	Double slope still connected to the FPC	Amman Jordan (31.95° N, 35.91° E)	-Square basin: 0.96 m ² , 0.02 m, Water depth, -0.03 m thick insulation, -Glass cover: 4 mm thick - at 451 inclinations, -FPC: 7 parallel tubes	-Productivity 1.5Kg/m ² . d in conventional - Efficiency 22.26% compared to 28.56% In conventional still
5	[139]	Corrugated wick solar still	Kafrelsheikh, Egypt, (31.07°N)		- Distillate yield 4.1 L/m ² . d -Productivity 145.5% - Efficiency 58% - Still yield 180% higher than the conventional still.
6	[140]	Stepped solar still	Kafrelsheikh, Egypt, (31.07°N)	- Mirror reflector material is used	- Yield 6.35 L/m ² . d -Improvement productivity to 75% over the conventional still without reflectors, - Efficiency 56%
7	[141]	Stepped solar still trays	Kafrelsheikh, Egypt, (31.07°N)	- 5 mm tray depth and 100 mm tray width are used	- Yield 7.4 L/m ² . d -Efficiency 108%~59% -The productivity 165% higher than that the conventional still and efficiency is 66%
8	[142]	Active double effect solar still	New Delhi, India	-Type = single basin solar still -Area = 1 mx1 m	An average of 7.5 l/m ² .day of distilled water was obtained in the active mode with water flow arrangement. In the passive and active modes without arrangements for water flow average output was 2.2 and 3.9 l/day.
9	[143]	Solar still with a flat plate solar collector		-Area of 18 m ² . -Solar irradiance of 672 W/m ² -Vacuum and Inner condenser -Surface cooling.	-Productivity 154.14 kg/d -Efficiency 1.36%



Chapter 2 Literature Review

10	[144]	Basin still with PTC and Nano fluid	Tehran, Iran (35.72° N, 51.33° E)	-S. I. 800W/m ² -T maximum 50 °C -Working fluids contains (Al ₂ O ₃ & CuO, TiO ₂)	-Productivity (15.28 kg/h—15.46 kg/h) with nanofluid use -Efficiency (14.9% to 15.2%)
11	[145]	Effect of aluminum balls on the productivity of solar distillate	Algeria	Area:0.25m ² SI:1100	- Modified Solar Still: 5.09 L/m ² .day -Efficiency 31.6 % -Conventional Solar Still:3.71 L/m ² .day -Efficiency 40.1%
12	[146]	Performance enhancement of a solar still distillation unit: A field investigation	Egypt	-Area 1m ² -sponge thicknesses (0 to 40 mm)	-Production 4.9 L/m ² .day -Efficiency 37%



Chapter 3 RESEARCH METHODOLOGY

3.1 Methods

The methodology for this study focused on comparing the Levelized Cost of Water (LCOW) from solar distillation with conventional desalination technologies such as capacitive deionization (CDI), reverse osmosis (RO) and multistage flash (MSF). The research involved both quantitative and qualitative analyses to assess the technical, economic, and environmental feasibility of solar distillation.

3.1.1 Literature Review

To collect existing knowledge on solar distillation and conventional desalination technologies, with a particular focus on their costs, efficiency, and environmental impacts.

The research used the Peer-reviewed journals, government reports, and case studies on desalination technologies to establish a foundational understanding of current desalination technologies, their challenges, and how solar distillation fits within this context.

3.1.2 Comparative Analysis Framework

The research used a comparative framework to compare solar distillation and conventional desalination methods based on LCOW. Based on:

1. **Capital cost:** Installation, equipment, and infrastructure for solar distillation versus conventional methods.
2. **Operational Costs:** Maintenance, labor, and energy costs, with an emphasis on energy consumption for solar (free sunlight) versus fossil-fuel-based technologies.
3. **Water Production:** Amount of potable water produced relative to the input energy and operational costs.
4. **Environmental Impact:** Carbon footprint, emissions, and long-term sustainability.

3.2 Data Collection

In this research, the researcher will collect Primary Data where Real-world solar distillation case studies from regions with high solar irradiance such as Middle East, North Africa and operational desalination plants using conventional technologies. Secondary Data will be included the Literature and reports on desalination costs, global energy prices, and solar energy potential.



3.3 Cost Analysis

Levelized Cost of Water (LCOW) is an economic term used to examine the cost of generating water through various technologies and processes across the lifetime of the water production system. It shows the average cost per unit of water generated (\$/m³) and is particularly useful for evaluating different water supply choices, such as desalination, groundwater extraction, and water recycling. Here's a breakdown of the important components involved in calculating LCOW:

$$\text{LCOW} = (\text{Capital Costs} + \text{Operating Costs}) / \text{Total Water Produced}$$

Here we have:

Capital Costs: Costs related to constructing solar stills or solar distillation systems and purchasing conventional desalination equipment.

Operating Costs: Energy consumption for solar distillation (minimal due to renewable energy) versus fossil fuel costs for conventional technologies. Labor, maintenance, and repair costs for both systems are also factored in. **Total water produced:** This is the total amount of water that the system is expected to produce over its lifetime. Higher production volumes can lower LCOW, as fixed costs are distributed over a larger quantity of water.

3.4 Technical Feasibility and Scalability

Analyze the potential of solar distillation for large-scale deployment with examine existing solar distillation systems, focusing on their scalability for larger applications. To investigate limitations related to technology such as efficiency of solar collectors, storage systems, and geographical factors like seasonal variations in solar energy availability.

3.5 Environmental Impact Assessment

This research will evaluate the environmental sustainability of solar distillation versus conventional desalination. The Life cycle assessment (LCA) to compare the carbon footprint, energy use, and emissions of solar distillation and fossil fuel-based technologies over their operational lifetimes.



3.6 Regional Case Studies

The research will analyse the specific geographic regions to understand the regional feasibility of solar distillation. Considering the Areas with abundant sunlight and high water scarcity. Comparative LCOW analysis based on regional energy costs, water demand, and solar potential. It will provide understanding of where solar distillation can be most effectively implemented.

3.7 Technical Route

The technical method starts with a comprehensive literature analysis to collect baseline data on solar distillation and conventional technologies' levelized cost of water (LCOW), including capital, operational, and energy costs. A techno-economic model is then created to simulate LCOW under different solar intensity, system efficiency, and regional water demand conditions. The model incorporates solar distillation thermodynamics like heat transfer and evaporation rates with economic parameters like solar collector pricing and maintenance. Designing a small-scale solar distillation prototype to assess water yield and thermal efficiency under controlled conditions is experimental validation. Data from the prototype will be compared with simulations to develop the model, assuring accuracy in cost forecasts and technical assumptions.

The comparison analysis will compare solar distillation versus capacitive deionization (CDI), RO and MSF by quantifying LCOW across several geographical and climatic situations, highlighting places with significant solar potential. Sensitivity analysis will identify major cost drivers, such as energy input and system longevity, to indicate potential for technical improvement. The project seeks to give a robust methodology for analyzing solar distillation's competitiveness, adding to sustainable water production strategies. By merging experimental, analytical, and comparative methodologies, the research will offer actionable recommendations for enhancing solar distillation systems to attain cost parity with conventional desalination while addressing environmental problems including brine disposal and carbon emissions.

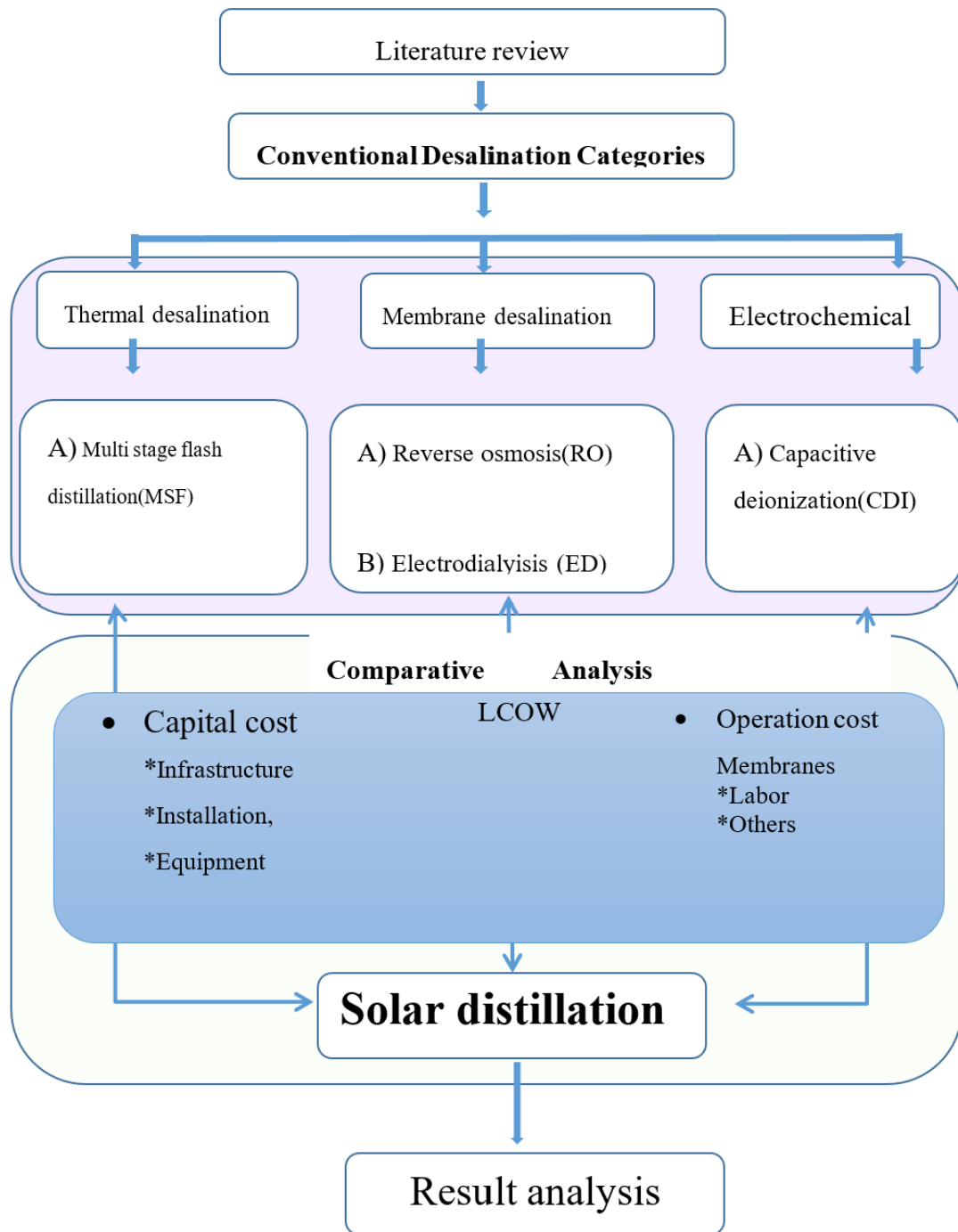


Figure 3-1 Technical Route



3.8 Key Technologies and Difficulties

3.8.1 Key Technologies

Solar stills (single-basin, multi-effect), solar concentrators (parabolic troughs, Fresnel lenses), and hybrid systems that combine sun with traditional desalination or photovoltaic energy are important technology in solar distillation. Efficiency is increased by using advanced materials such as phase change materials (PCMs) and selective absorbers.

3.8.2 Difficulties

The main challenges are the high starting costs, limited rates of water production, and dependence on variable solar energy. System expansion necessitates large land and financial investments, and material deterioration (corrosion, scaling) raises maintenance expenses.

3.9 Feasibility analysis

The research is feasible, leveraging existing solar distillation systems and conventional desalination technologies such as capacitive deionization(CDI), reverse osmosis, and multi-stage flash distillation that have been widely studied. This will provide a solid foundation for comparing the LCOW of these methods.

Technical Feasibility; Both solar distillation and conventional desalination technologies are well-documented, making it technically feasible to collect data for analysis. Solar distillation systems, which use renewable energy, are gaining popularity, while conventional desalination technologies are well-established. However, advanced solar innovations like nanomaterials, thermal storage may need to be integrated into the analysis to provide a comprehensive outlook on future cost reductions, making the study technically achievable with some added complexity.

3.10 Research basis

The research is grounded in the need to find sustainable, cost-effective solutions for water scarcity. While highly energy-intensive and costly, conventional desalination systems like reverse osmosis and multi-stage flash distillation are successful, especially in areas with limited availability to reasonably priced electricity. By using solar energy to evaporate and condense water, solar distillation offers a renewable substitute that may drastically lower operating costs and have a smaller environmental effect.



The study's foundation is a comparison of solar distillation and traditional desalination techniques' LCOWs, an economic statistic that assesses the overall cost of generating water during a system's lifetime. This entails examining variables such as investment outlay, energy usage, running expenses, and upkeep for various systems. Environmental advantages like less carbon emissions and brine disposal are also a crucial component of the comparison.

3.11 The expected results

The expected results of the research on solar distillation's prospects are that:

It will demonstrate competitive Levelized Cost of Water (LCOW) compared to conventional desalination technologies, particularly in regions with high solar irradiance.

The analysis is anticipated to reveal lower energy consumption and operational costs for solar distillation, making it a more sustainable option.

Environmental assessments are expected to show reduced carbon emissions associated with solar distillation compared to fossil fuel-based desalination methods.

The research provided insights into regional variability and potential innovations that can enhance the scalability and efficiency of solar distillation technologies.

Chapter 4 THE FINDINGS

4.1 Introduction

Regional Case Study: Kibuteni Village of 950 Individuals in Zanzibar

Zanzibar is an archipelago off Tanzania’s coast, faces acute water scarcity due to limited freshwater resources, high salinity in groundwater, and dependence on seasonal rainfall. For a Kibuteni village one of the villages in Zanzibar island from the census of 2022 this village had 701 people^[147]. This study carried out the assuming that in 2025 Kibuteni village has 950 individuals. This case evaluated the feasibility of solar distillation as a sustainable water production solution, compared to conventional desalination technologies like Membrane Capacitive deionization(MCDI). Zanzibar’s tropical climate. Thus, the average rainfall is 1100 mm, below the Island average of 1600 mm. The average annual daily high is 29.3°C and low is 21.1°C. The hottest temperatures are in January and February, averaging 32°C, with high solar irradiance averaging 5.5–6.5 kWh/m²/day, makes it an ideal candidate for solar distillation^[148].

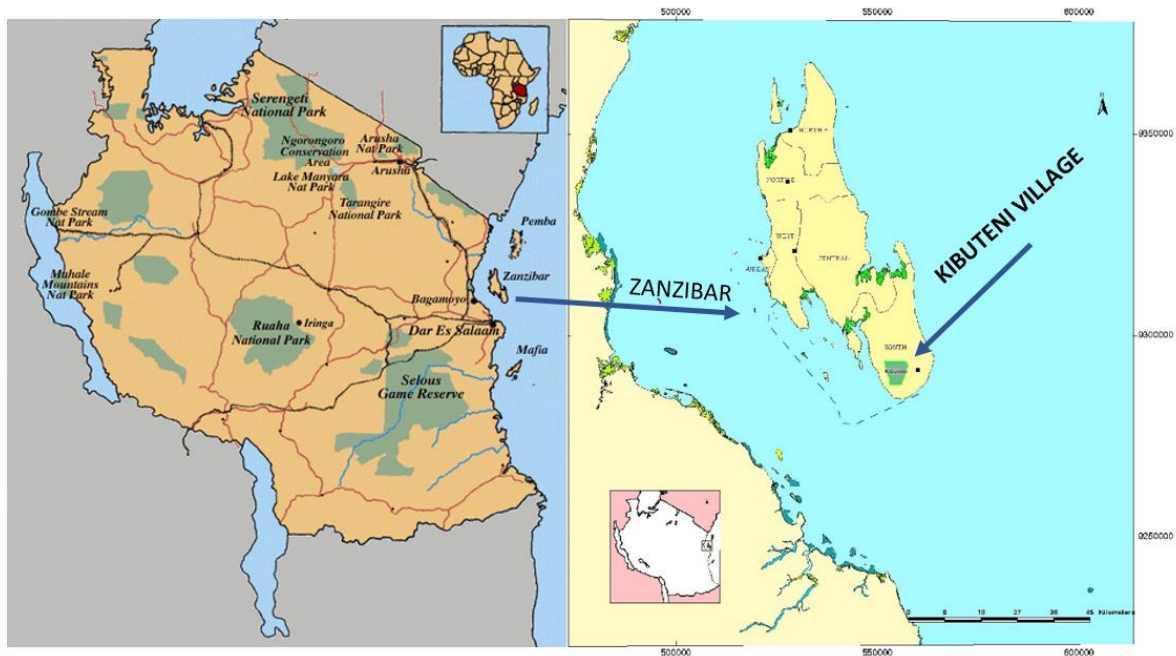


Figure 4-1 Map of the United Republic of Tanzania, showing Zanzibar Islands where Kibuteni located pointed by arrow^[3]



The study focused on a small-scale solar distillation system, such as a multi-effect solar still, to meet the village's daily water demand, estimated at 50 m³ (assuming 50 liters per person). Capital costs for solar stills, including installation and infrastructure, will be compared with CDI systems, factoring in Zanzibar's limited grid reliability, which favors renewable solutions.

4.2 Levelised cost of water

The levelized cost of water (LCOW) refers to the cost per unit volume of product water produced by a water treatment process, it is a measure of efficiency, with lower numbers indicating more effective approaches. LCOW can refer to either drinking or irrigation water.^[149] In many cases, different research groups' total water cost estimates take into account various components that are not universally defined or fully described. The researchers examine also the key cost contributors that are not universally considered, such as the power system, lifting water from a well, waste management, and other costs, such as operator labor and equipment installation.

They also discovered that in the cost literature, the terms technologies, interventions, systems, and options are frequently used interchangeably, making it difficult to understand what is being evaluated, compared, or priced. Amrose et al.^[150] define a safe water system as encompassing all components from source to sip which includes a series of stages such as treatment technologies, protection technologies, delivery models, and last-mile labour before consumption. Costs are frequently reported for individual stages or combinations of stages, which we refer to as safe water approaches because their boundaries begin and end at different points along the source-to-sip chain. Comparing costs between approaches rather than systems has the potential to significantly distort results, especially when the costs of unreported stages are high.

The LCW varies depending on the method used to create drinking water. Desalination, which converts saline water into useable water, has a greater LCW than treating groundwater or surface water. According to research conducted by Upeksha et al. ^[151] shown that developments in decarbonization will cut the levelized cost of water generated by desalination more than half from 2015 to 2025 by using renewable energy such as solar distillations.



4.2.1 Solar Distillation Technology.

The term levelized cost of water (LCOW) refers to an economic statistic that is used for the purpose of evaluating the system lifetime cost of various solar desalination systems that have varying plant sizes and configurations^[152].

The price of the distillate produced by a solar desalination plant depends on a number of parameters. Unit size, site location, feed water characteristics, product water necessary quality, availability of competent personnel, etc. all affect capital and operating and hence overall expenses. One of solar desalination's primary economic benefits is that it should need slight infrastructure and be easy to design, install, operate, and maintain locally^[153]. The cost of producing the distilled water and its suitability determine the higher economic return on investment. The different studies have provided an economic study of a water desalination unit^[104, 154, 155].

a) Capital recovery factor

The CRF (capital recovery factor), the FAC (fixed annual cost), the SFF (sinking fund factor), the ASV (annual salvage value), In the cost analysis of the desalination unit, the primary calculation factors are an average annual productivity (M) and an annual cost (AC). Regular brackish water filling, collecting the distilled water, cleaning the glass cover, removing accumulated salt (scaling), and DC pump maintenance all need the solar still's annual maintenance operating cost, or AMC. The frequency of water entering the basin will decrease with increasing water depth. The maintenance required for the system likewise rises with its lifespan. Consequently, maintenance costs have been calculated at 10% of net current cost.

Lastly, the LCOW (cost of distilled water per cubic meter) is calculated from the annual production of the solar still (M) divided by the annual cost of the system AC yields.

The method of calculation parameters shown above may be written as^[104]

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (1)$$

$$FAC = P(CRF) \quad (2)$$

where **P** is the desalination system's current capital cost; **i** is the annual interest rate, which is taken to be 12%; and **n** is the number of life years, which in this study is taken to be 20.



To determine the area and requirements needed to supply a village with a daily water consumption of 50,000 liters using a wick-type solar still with an evacuated tube collector, we can use the provided specifications: each still has a collector area of 1 m² and produces 24.4 liters of distillate per day during daylight hours (6:30–17:30, or 11 hours). Below is the step-by-step calculation and analysis of the requirements.

$$\begin{aligned}
 \text{Space required for 50,000L} &= \frac{50000}{24.4} \\
 &= 2.049 \sim 2,050 \text{ Square meters}
 \end{aligned}
 \tag{9}$$

M(The annual production of the plant)50x366 = 18,300 cube meters

The research conducted by Omar Eltawil et al. revealed that on DLSW concluded that

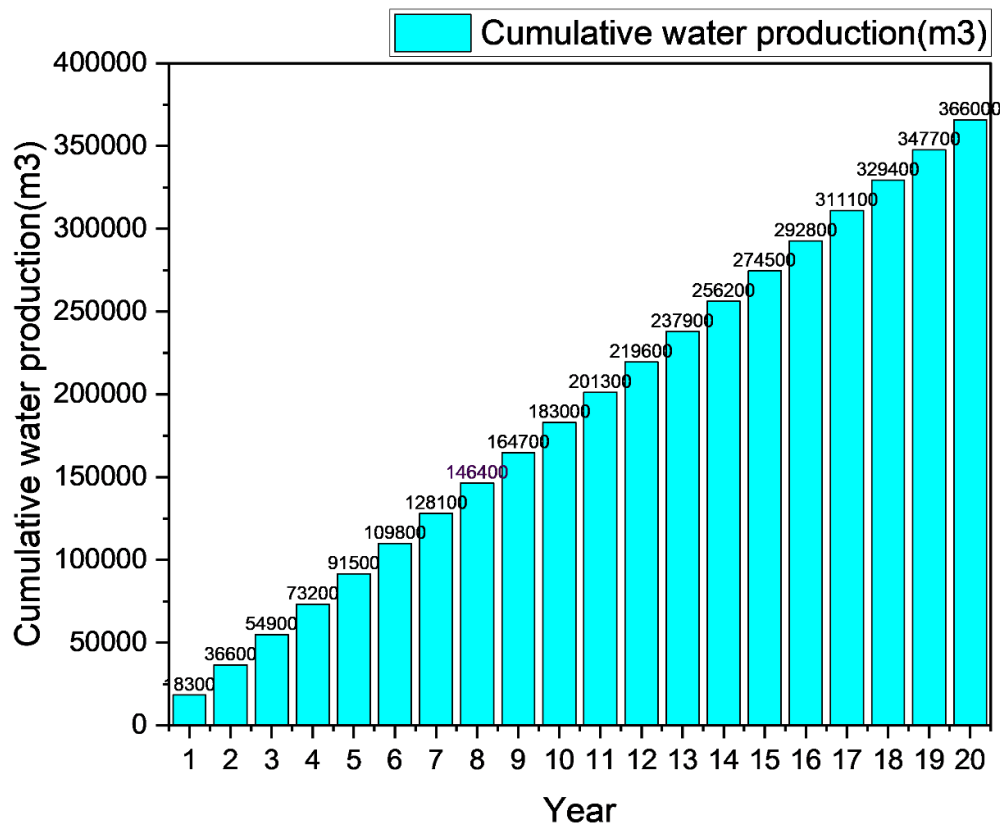


Figure 4-2 .The cumulative water productivity of the desalination plant over its lifespan

without feeding hot brackish water at night, DLSW costs (P) 120 \$ per 1 m² [123].

The total cost of the plant (P):120\$x2,050 square meters= 246,000\$.



Due to darkened color fading and salt accumulation that might obstruct wick holes, replace the jute cloth every two years. Consider the expense of replacing wicks nine times (excluding the initial ones) over the system's estimated lifespan. Assuming wicks cost \$10 (including labor), replacing them costs during 20 years of lifespan per one square meter 10\$ x 9 times wicks replacement for lifespan of plant=90\$per m²

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (1)$$

$$CRF = \frac{0.12(1+0.12)^{20}}{(1+0.12)^{20} - 1} = 0.1339 \sim 13.39\%$$

P is the capital cost of the system and **CRF** is the capital recovery factor, the first annual cost of system, **FAC**, can be determined as:

$$FAC = P(CRF) \quad (2)$$

$$FAC = 246,000\$ \times 13.39\% = 32,939.4\$$$

b) Salvage value of the system

The salvage value (**S**) of a solar desalination plant represents the expected market value of the system at the end of its useful life, typically after 20 years of operation. This value was calculated to estimate a percentage of the initial cost of usable materials, such as plant basins and, structural components, excluding non-recoverable expenses like installation. In this case, the salvage value is considered to be 20% of the usable material cost, reflecting the residual value of recyclable or reusable components. To incorporate this into financial analysis, the annual salvage value (**ASV**) is calculated to account for its contribution to the system's lifecycle cost.

This is done using the equation

$$S = 0.2(P) \quad (3)$$

$$S = 0.2 \times 246,000 = 49,200\$$$

$$ASV = S(SFF) \quad (4)$$

where **SFF** is the Sinking Fund Factor, defined as

$$SFF = \frac{i}{(1+i)^n - 1} \quad (5)$$



$$SFF = \frac{0.12}{(1 + 0.12)^{20} - 1} = 0.0139 \sim 1.39\%$$

$$ASV = 49,200\$ \times 1.39\% = 683.88 \sim 684\$$$

The ASV annualizes the salvage value, allowing it to offset part of the capital recovery cost. By including the salvage value in economic assessments, the levelized cost of water production can be reduced, improving the project's financial viability. For instance, a higher salvage value due to durable materials or favorable market conditions for recycled components can significantly lower annualized costs. This approach ensures a comprehensive evaluation of the plant's long-term economic performance.

c) Operational running cost

Maintenance is a critical operating cost to ensure a solar desalination plant remains in optimal working condition throughout its lifespan. The annual maintenance cost covers expenses for replacing broken parts, cleaning the system, and protecting it from corrosion and scaling, which are common issues in desalination processes. The annual operating and maintenance costs (AMC) encompass the total yearly expenses of owning and operating the desalination unit, including amortization or fixed charges, routine operation and maintenance, and parts replacement costs, it has been calculated at 10% of net current cost. In this study, following Goosen et al., a fixed percentage of the first annual cost (M) is assumed for the AMC, simplifying the cost estimation. This approach accounts for predictable maintenance needs, ensuring the system's efficiency and longevity while contributing to the overall economic analysis of the plant^[156].

$$AMC = 0.1 FAC \quad (6)$$

$$AMC = 0.1 \times 32,939.4\$ = 3,293.94\$$$

d) The annual cost of the plant

The total annual cost (AC) of operating a solar desalination plant is calculated using the formula

$$AC = FAC + AMC - ASV \quad (7)$$

where each component represents a key financial aspect. The Fixed Annual Cost (FAC) includes amortized capital costs, derived using the Capital Recovery Factor (CRF) to spread the initial investment over the plant's lifespan. The Annual Maintenance Cost (AMC) covers



ongoing expenses for repairs, cleaning, and protection against corrosion and scaling, often estimated as a fixed percentage of the first annual cost. The Annual Salvage Value (ASV), calculated as the salvage value multiplied by the Sinking Fund Factor (SFF), offsets part of the costs by accounting for the system’s residual value at the end of its useful life. Together, these components provide a comprehensive estimate of the yearly financial burden, aiding in the economic evaluation of the desalination plant’s viability.

$$AC = 32,939.4\$ + 3,2939.4\$ - 684\$ = 35,549.34$$

$$LCOW = \frac{AC}{M} \quad (8)$$

$$LCOW = \frac{35,549.34}{18,300} = 1.94\$/m^3$$

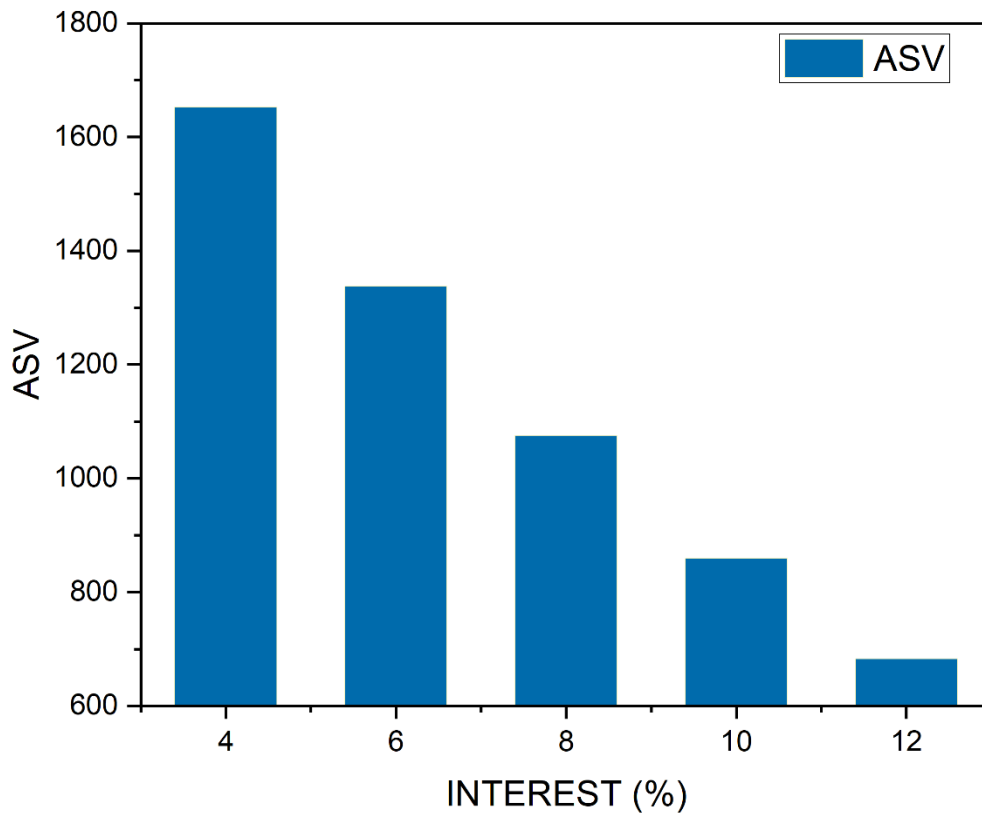


Figure 4-3 The salvage value of the solar distillation system is annualized based on the plant's interest rate.



Chapter 4 The Findings

Table 4-1 Summary of LCOW Calculations.

Captial cost (P)	Liffe Interest(i)%	span	Liffe								
			CRF	SFF	FAC	S	ASV	AMC	AC	M	LCOW
246,000	12	20	0.1339	0.0139	32,934.18	49200	682.84	3,293.42	35,544.76	18300	1.94
246,000	10	20	0.1175	0.0175	28,895.07	49200	859.01	2,889.51	30,925.56	18300	1.69
246,000	8	20	0.1019	0.0219	25,055.64	49200	1,075.13	2,505.56	26,486.08	18300	1.45
246,000	6	20	0.0872	0.0272	21,447.40	49200	1,337.48	2,144.74	22,254.66	18300	1.22
246,000	4	20	0.0736	0.0336	18,101.11	49200	1,652.22	1,810.11	18,259.00	18300	1.00

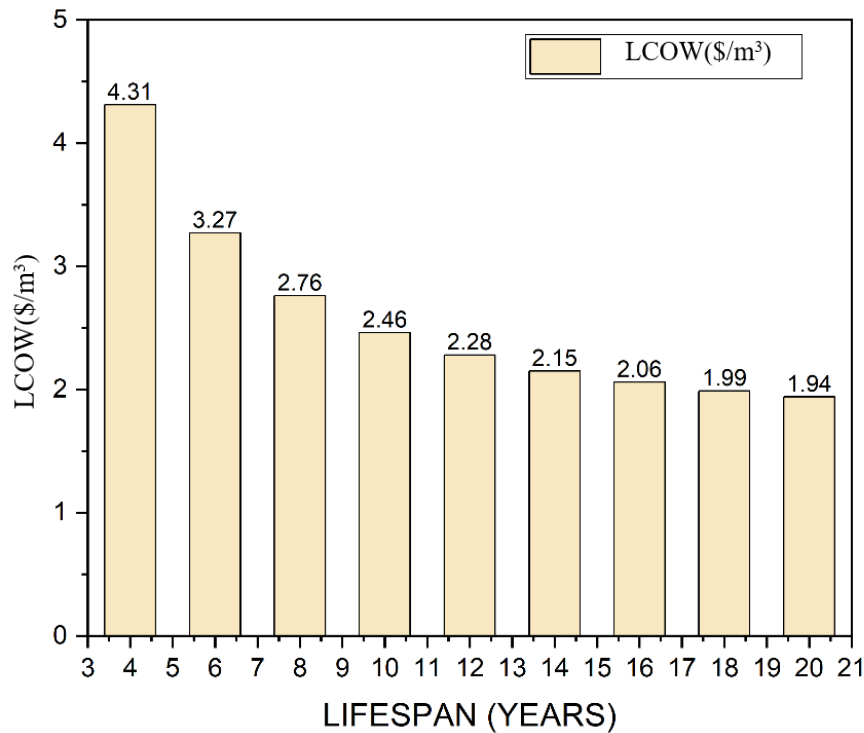


Figure 4-4 Decrease in the levelized cost of water from solar distillation based on the plant's lifespan, at an interest rate of 12% per year.

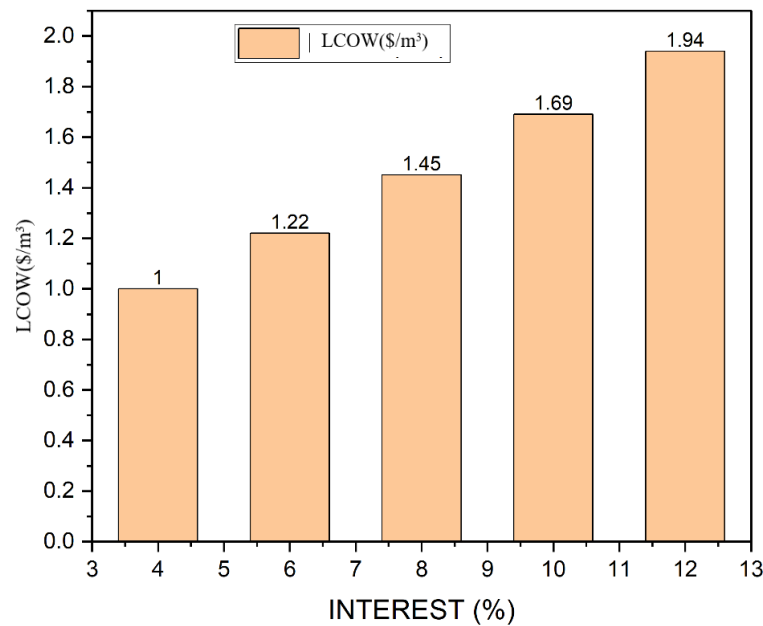


Figure 4-5 The levelized cost of water for solar distillation increases with the plant's annual interest rate

4.2.2 The MCDI desalination technology

The MCDI desalination technology can be used in Kibuteni village as response Surface Model (RSM) from Bales et al. (2023), which predicts key performance metrics such as current efficiency, water recovery, product flowrate, and energy consumption, based on influent electrical conductivity (EC), flowrate, and applied current^[157]. The target conductivity of 900 $\mu\text{S}/\text{cm}$ corresponds to 600 mg/L of total dissolved solids (TDS), aligning with Drinking Water Guidelines for acceptable taste. This value was derived using the formula $\text{TDS (mg/L)} = 0.64 \times \text{EC } (\mu\text{S}/\text{cm})$ ^[158].

The system targets brackish groundwater with an influent EC of 1500 $\mu\text{S}/\text{cm}$, typical for Zanzibar's coastal aquifers, to produce potable water with a product EC of 900 $\mu\text{S}/\text{cm}$, meeting a daily demand of 50 m³ Powered by photovoltaic (PV) panels with battery backup. The system leverages Zanzibar's high solar irradiance of 5.5–6.5 kWh/m²/day to ensure 24-hour operation. It incorporates 80% energy recovery through buck-boost dc/dc converters, reducing energy consumption by up to 40%, as noted by Bales et al. (2023)^[157]. The design evaluates scenarios with and without brine disposal costs, critical for cost optimization, given brine disposal's 6–13% contribution to LCOW. Optimized for maximum production rate, the system requires 10–25 electrode modules, depending on influent electrical conductivity (EC) reduction, ensuring cost-effectiveness and compatibility with off-grid conditions while addressing Zanzibar's water quality challenges^[157].



a) Calculation of dependent variables

The λ is dependent on Δc ($\mu\text{S}/\text{cm}$), flowrate which passing by the electrodes and Q_{elec} (L/S), The applied, I (A)^[53, 159, 160].

$$\lambda = \frac{\Delta c Q_{\text{elec}} F z_{\text{equivalent}}}{I} \quad (1)$$

Where, F represents the Faraday constant (96,485 C/mol), with 1 ampere equal to 1 coulomb per second (1 A = 1 C/s) and $Z_{\text{equivalent}}$ is used to convert electrical conductivity from $\mu\text{S}/\text{cm}$ to milliequivalents per liter (meq/L), reflecting both molar concentration and ionic charge. For typical groundwater, z is approximately 1.0×10^{-6} equivalents^[161]. In this study, z was calculated using the influent electrical conductivity for the NaCl-based model. The value of Δc represents the difference between the influent conductivity and the average conductivity of the treated water

The WR (water recovery) is calculated from the amount of product water over the total amount of influent water^[160]:

$$\text{WR} = \frac{V_{\text{prod}}}{V_{\text{prod}} + V_{\text{brine}}} \quad (2)$$

Where, V_{prod} is the volume of water produced in L and V_{brine} is the volume of brine produced in L.

Water recovery can be increased to nearly 90% depending on the specific desalination conditions by employing low-flow or no-flow discharge methods^[162, 163]. The recovery rate also depends on the product cut-off point, which is the effluent conductivity threshold: effluent with conductivity below this level is directed as product water, while effluent above it is sent to the brine stream.

The flowrate of the produced water Q_{prod} (L/min) is calculated from^[160]:

$$Q_{\text{prod}} = \frac{V_{\text{prod}}}{\Delta t_{\text{cycle}}} \quad (3)$$



Where Δt_{cycle} is the total cycle time in minutes.

The electrode energy consumption per unity of water produced E_{tot} (KWh/m³) given by^[160]:

$$E_{\text{tot}} = \frac{E_{\text{in}} - \eta E_{\text{out}}}{V_{\text{Prod}}} \quad (4)$$

Where:

$$E_{\text{in}} = \int_{\Delta t_{\text{cycle}}} IV dt \quad \text{where } IV > 0 \quad (5)$$

$$E_{\text{out}} = \left| \int_{\Delta t_{\text{cycle}}} IV dt \right| \quad \text{where } IV < 0 \quad (6)$$

Where V is the electrode voltage (v) and η is the efficiency of recoverable energy.

Energy recovery is possible during the discharge phase [8,10]. However, the setup used in the current experiments did not incorporate any energy recovery system. Response Surface Models (RSMs) were created for energy E_{tot} with $\eta=0$ and E_{tot} , 80 assuming $\eta=0.8$.

b) LCOW Calculation

The LCOW is calculated as the total annualized cost of the MCDI system divided by the annual water production. The formula is:

$$LCOW = \frac{\text{Capex} \cdot CRF + \text{Opex}}{\text{Volproduced}} \quad (7)$$

where Capex (\$) is the initial capital investment, Opex (\$) is the ongoing maintenance cost per year, vol produced is the amount of water produced per year and α is the amortisation factor where:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (8)$$

with discount rate $i = 12\%$ and investment period $n = 20$ years.

Annual water production ($50 \text{ m}^3/\text{day} \times 366 \text{ days} = 18,300 \text{ m}^3/\text{year}$)



The initial capital cost (Capex) covers expenses for electrode modules (including ion exchange membranes), pre-treatment components like filters, pumps, piping, valves, housing, photovoltaic systems, and brine disposal. The operating cost (Opex) includes periodic replacement of electrode modules every five years, filter replacements, regular maintenance, replacement of photovoltaic batteries. The amount of each component scales with the number of electrode modules. The required number of electrode modules ($n_{\text{electrodes}}$) is determined based on the total flow rate of the desired product water (Q_{total} , L/min):

$$n_{\text{electrodes}} = \frac{Q_{\text{total}}}{Q_{\text{prod1}} \eta_{\text{engineering}}} \quad (9)$$

where $Q_{\text{prod,1}}$ (L/min) is the flowrate of product water from one electrode module

and the efficiency factor η , which accounts for system downtime, is set at 0.9 in different studies^[164-166].

c) PV System Sizing

The photovoltaic (PV) system for the MCDI setup in Kibuteni village is sized to meet the energy demands of producing 50 m³/day of potable water, based on total system energy consumption of 0.71–1.60 kWh/m³, as per Bales et al^[157]. This translates to a daily energy demand of 35.5–80 kWh. Leveraging Zanzibar's solar irradiance of 6 kWh/m²/day and assuming 80% system efficiency to account for losses, a PV array of 7.4–16.7 kWp is required. To ensure 24-hour operation, lithium-ion batteries are sized for a storage capacity of 37.4–84.2 kWh, assuming a 50% depth of discharge (DoD) and 95% round-trip efficiency. This configuration supports continuous desalination in off-grid conditions, optimizing energy use while aligning with the region's high solar potential.

d) Predictive model for energy consumption

Water desalination with Membrane CDI, Electrode modules, contributing 28–33% to the Levelized Cost of Water (LCOW), require replacement every 5 years. Photovoltaic (PV) system with capacity of 19.35 Kwh the costs include a capital expenditure for PV panels. Maintenance costs are estimated 10 % of capital expenditure (Capex) annually.



Table 4-2 Parameters range for the MCDI technology.

No	Item description	Unity	Quantity
1	Flowrate of water to be produced per day	m/day	50
2	Electrode module comprises 340 electrode pairs corresponding to an electrode area of roughly 7.5 m per module	Set	11
3	Energy(electrode module)	Kwh/m ³	0.387
4	PV system and battery	Kwh/day	19.35

The parameters shown in Table 4-2 indicate the requirements for MCDI technology to produce 50 m³/day of fresh water to meet the water demand of Kibuteni Village. The levelized cost of water (LCOW) is calculated based on all expenses incurred during treatment. Several parameters affect the treatment process, including influent water conductivity, electrode properties, plant lifespan, and interest rate. Bales et al. showed that small and medium MCDI plants powered by photovoltaics (PV) the plant capital cost setup can also be calculated based

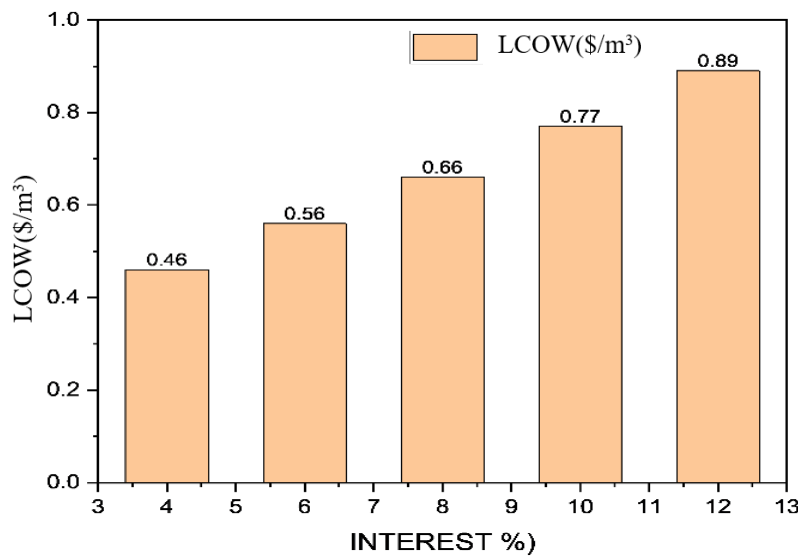


Figure 4-6 An increase in the interest rate, while keeping the lifespan of the MCDI constant, gradually increases the levelized cost of water.

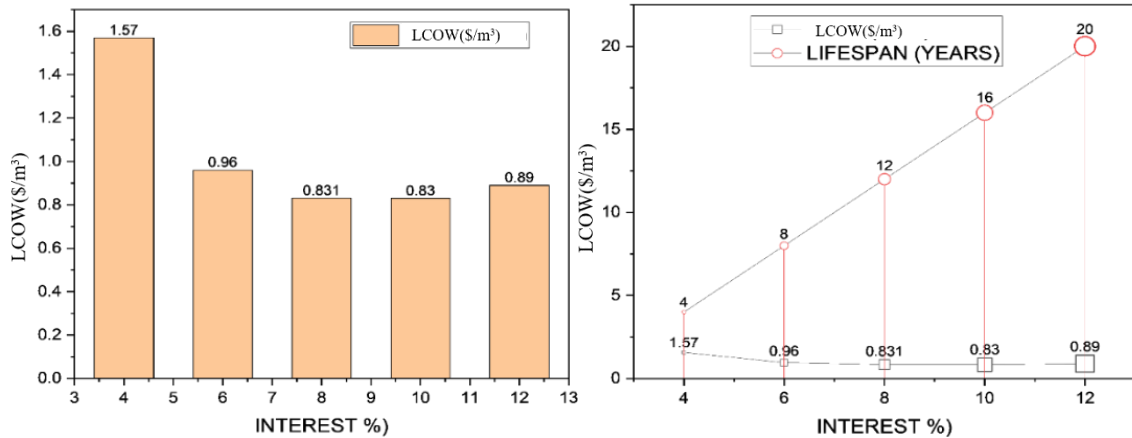


Figure 4-7 Increasing in the interest rate and lifespan of MCDI plant gradually decrease the levelized cost of water.

on the dairy fresh water production where 1cubic meter production plant can cost 2245.46\$^[157].

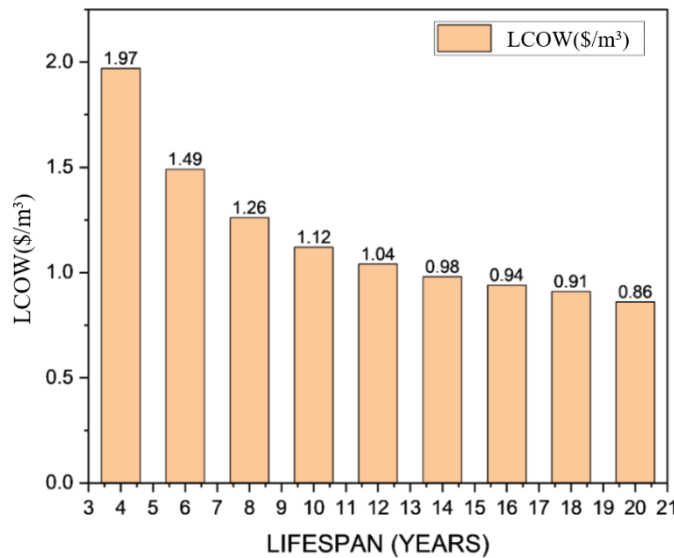


Figure 4-8 Increasing the lifespan of the MCDI plant at a constant interest rate of 12% effectively decreases the levelized cost of water

4.3 Summary

According to the finds, the solar distillation and MCDI systems are both built to last for 20 years and employ a 12% interest rate in their financial computations. Salvage values and fixed annual costs are calculated using the sinking fund factor (SFF) and capital recovery factor (CRF), respectively. Significant cost disparities are indicated by the LCOWs of \$0.886/m³ for MCDI and \$1.94/m³ for Solar Distillation. The causes of these variations and their effects on off-grid water supply will be examined in detail in this report



Chapter 5 THE DISCUSSION

5.1 Comparison of Solar Distillation and MCDI LCOW Results

5.1.1 Comparison of Capital Costs and Technologies

The capital costs of water treatment systems are a major element in their adoption, particularly for resource-constrained off-grid villages. Solar Distillation Systems have a capital cost of \$246,000, much greater than the \$112,273 required for MCDI driven by PV. This discrepancy originates from the varied technological requirements and infrastructure needs of each system. Solar Distillation Systems rely on large-scale solar collectors and distillation machines to heat water, evaporate it, and condense it into drinking water. These systems require sturdy materials to endure high temperatures and continuous exposure to sunlight, resulting in greater upfront costs. Additionally, the infrastructure for Solar Distillation involves substantial pipeline and storage systems to manage the distilled water, further raising expenses.

In contrast, MCDI systems are more compact and rely on electrochemical techniques to remove salts and pollutants from water. The method employs electrodes to attract ions, which are subsequently washed out, generating clean water. The lower capital cost of MCDI is related to its simpler design, requiring less materials and less physical space. The integration of PV panels as the energy source adds to the cost but is comparable to the solar energy infrastructure in Solar Distillation. Both systems have a lifespan of 20 years, suggesting similar durability, however the cheaper initial expenditure for MCDI makes it more accessible for communities with little financing. The capital recovery factor (CRF) of 0.1339, calculated using a 12% interest rate, turns the capital cost into a fixed annual cost (FAC) of \$32,934.18 for Solar Distillation and \$15,030.97 for MCDI, highlighting the heavier financial burden of the former.

Technologically, Solar Distillation is a thermally powered process that specialises in treating extremely saline or contaminated water, as it physically separates water from pollutants through evaporation. However, it is energy-intensive and relies on continuous solar radiation, which may restrict its efficiency in foggy or low-sunlight regions. MCDI, on the other hand, is an electrically driven technique that is more energy-efficient and adaptable to different water conditions. Its reliance on PV power assures operating constancy, providing there is ample sunlight for electricity generation. The modularity of MCDI systems allows for simpler scalability, making them suited for small to medium-sized communities. In contrast, Solar



Distillation systems are less adaptable, as scaling involves significant extra investment in solar collectors and distillation machines.

The technological intricacy of Solar Distillation also necessitates skilled maintenance, which may pose issues in distant places with insufficient technical experience. MCDI systems, despite requiring understanding of electrochemical processes, are often easier to maintain because to their fewer mechanical components. The higher capital cost of Solar Distillation may inhibit adoption in budget-constrained areas, despite its ability to manage different water sources. Conversely, MCDI's reduced cost and adaptability make it a more feasible solution for off-grid villages, provided the water source is not overly saline, as MCDI is less effective for high-salinity water compared to distillation.

The operational variations between these technologies considerably influence their LCOW. sun Distillation's higher LCOW of \$1.94/m³ arises from its greater capital and maintenance expenses, coupled with decreased throughput due to dependency on sun availability. MCDI's LCOW of \$0.886/m³ benefits from its cheaper initial investment and superior operating efficiency, enabling greater water production per unit of energy input. The data also reveals the Sinking Fund Factor (SFF) and Capital Recovery Factor (CRF), both at 0.0139 and 0.1339, respectively, for both systems, suggesting identical financial assumptions across their 20-year lifespans. However, the Annual Salvage Value (ASV) for Solar Distillation (\$682.84) and MCDI (\$311.64) represents the proportional difference in their original investments, further accentuating MCDI's cost advantage.

5.1.2 Comparison of Operational and Maintenance Costs

Operational and maintenance costs are essential in determining the long-term affordability of water treatment methods. The data suggests that Solar Distillation has an annual maintenance cost (AMC) of \$3,293.42, much higher than MCDI's \$1,503.10. This disparity is partly due to the mechanical complexity of Solar Distillation Systems, which involve components like as solar collectors, condensers, and extensive piping. These components are prone to wear and tear, particularly in harsh weather conditions, demanding constant cleaning, repairs, and replacements. The heat nature of the process also requires continuous maintenance to prevent scaling or corrosion, further raising costs.

MCDI systems, by comparison, have minimal maintenance requirements due to their electrochemical design. The primary maintenance duties comprise cleaning or replacing electrodes and ensuring the PV panels are operating. The simplicity of the system decreases the frequency and expense of repairs, making it more cost-effective over time. The annual



salvage value (ASV), calculated using the sinking fund factor (SFF) of 0.0139, is \$682.84 for Solar Distillation and \$311.64 for MCDI, indicating the proportional difference in their salvage values (\$49,200 and \$22,454.60, respectively). The ASV offsets a small fraction of the annual costs, although its impact is negligible compared to maintenance charges.

The fixed annual cost (FAC), which amortizes the capital cost over the system's lifespan, is \$32,934.18 for Solar Distillation and \$15,030.97 for MCDI. When combined with maintenance costs and adjusted for salvage value, the total annual cost (AC) is \$35,544.76 for Solar Distillation and \$16,222.43 for MCDI. This sharp contrast illustrates MCDI's economic benefit, as its lower FAC and AMC result in a significantly decreased financial burden. For an off-grid hamlet generating 18,300 m³ of water yearly, the higher operational expenses of Solar Distillation translate to a greater per-unit cost of water, hurting affordability for residents.

Operational efficiency also plays a factor in cost differences. Solar Distillation is energy-intensive, needing substantial solar energy to achieve evaporation, which may lead to inefficiencies in places with changeable sunlight. MCDI, while dependent on PV power, consumes less energy per unit of water treated, boosting its operational efficiency. The lower energy demand and maintenance needs of MCDI make it a more sustainable solution for long-term operation in off-grid environments, where resources for maintenance and repairs are often scarce

5.1.3. Comparison of Levelized Cost of Water (LCOW)

The Levelized Cost of Water (LCOW), which is represented as a cost per cubic metre, is a comprehensive statistic that captures all expenses related to water production across the system's lifetime. The two technologies' LCOWs differ significantly: The LCOW of MCDI is \$0.886/m³, whereas that of Solar Distillation is \$1.94/m³. As was previously mentioned, the greater initial, ongoing, and maintenance expenses of solar distillation are the main cause of this discrepancy. The overall yearly cost of \$35,544.76 for solar distillation makes it more expensive per unit than MCDI's \$16,222.43 for a small village that uses 18,300 m³ of water annually, and 50 m³ per day.

The LCOW calculation divides the annual water production by the fixed annual cost (FAC), annual maintenance cost (AMC), and annual salvage value (ASV). Due to the substantial capital investment, Solar Distillation's FAC of \$32,934.18 dominates the cost structure. While the ASV of \$682.84 offers no respite, the AMC of \$3,293.42 raises the LCOW even more. On the other hand, a more favourable LCOW is produced by MCDI's reduced FAC (\$15,030.97), AMC (\$1,503.10), and ASV (\$311.64). Off-grid communities may afford MCDI



because of its cheaper construction and operating costs, which directly translate into a cost advantage.

The economic feasibility of each technique is significantly impacted by the LCOW differential. Residents in low-income communities may have less access to water due to Solar Distillation's greater cost of \$1.94/m³. With a lower LCOW of \$0.886/m³ than Solar Distillation, MCDI provides a more affordable option that fits the financial limitations of off-grid communities. This financial benefit might make clean water more widely available, enhancing people's health and standard of living.

However, the entire context of technological suitability is not captured by LCOW alone. Since solar distillation's thermal process is more efficient in eliminating a variety of contaminants, its higher LCOW may be justified in situations when water supplies are extremely saline or contaminated. Even though MCDI is inexpensive, some water sources might need to be pre-treated, which could raise prices in some situations. MCDI's lower LCOW makes it the better option in the given case, where both systems produce 18,300 m³ yearly, unless water quality requires Solar Distillation's strong treatment capabilities.

5.1.4. Environmental and Sustainability Considerations

Environmental and sustainability issues are critical when considering water treatment technology for off-grid applications. Both Solar Distillation and MCDI rely on sustainable solar energy, lowering their carbon impact compared to fossil fuel-powered systems. Solar Distillation employs solar thermal energy to fuel the evaporation process, while MCDI leverages PV panels to generate electricity for electrochemical desalination. This reliance on renewable energy matches with global sustainability goals and minimises greenhouse gas emissions, making both technologies environmentally acceptable.

However, the environmental impact of each system extends beyond energy use. Solar Distillation Systems demand large materials for solar collectors, condensers, and pipelines, which have a greater embodied energy and environmental cost during manufacturing. The disposal of these components at the end of the system's lifecycle may cause issues, particularly in remote places with insufficient waste management infrastructure. Additionally, the thermal process can produce concentrated brine as a byproduct, which requires cautious disposal to prevent environmental damage, such as soil or groundwater salinization.

MCDI systems have a lower material footprint due to their compact design and simpler components. The production and disposal of electrodes and PV panels also generate environmental repercussions; however, these are often less severe than those of Solar



Distillation. MCDI also creates brine, but the volume is often lower due to its targeted ion removal procedure. The modularity of MCDI systems allows for easier updates or replacements, boosting their sustainability by prolonging the system's effective lifespan. Furthermore, MCDI's decreased energy usage lessens the demand on PV panels, potentially lessening the environmental effect of solar panel production.

Sustainability also involves social and economic factors. MCDI's lower LCOW and maintenance costs make it more accessible to low-income communities, enabling equal access to clean water. Solar Distillation, while effective, may strain community budgets, limiting its long-term viability. Both systems require local capability for operation and maintenance, although MCDI's simpler design may be easier to handle in communities with less technical experience. Overall, MCDI looks to have a minor edge in environmental and sustainability performance due to its lower resource needs and cost-effectiveness.

5.2. Conclusion

The comparison of Solar Distillation with MCDI for off-grid water supply reveals significant strengths and trade-offs. Solar Distillation Systems, with a capital cost of \$246,000 and an LCOW of \$1.94/m³, are strong and capable of treating severely contaminated water but are restricted by high upfront and operational costs. MCDI, with a capital cost of \$112,273 and an LCOW of \$0.886/m³, offers a more cost-effective and sustainable solution, benefiting from lower capital, maintenance, and energy requirements. The technological contrasts thermal distillation versus electrochemical desalination effect their applicability for certain water sources, with Solar Distillation excelling in high-salinity settings and MCDI giving flexibility and scalability.

Economically, MCDI is the clear victor, as its reduced LCOW makes clean water more cheap for off-grid communities. Environmentally, both systems are sustainable due to their reliance on solar energy, but MCDI's lower material and energy demands offer it an advantage. Operationally, MCDI's simpler maintenance requirements make it more practicable for remote areas. However, Solar Distillation may be favoured in circumstances when water quality necessitates strong treatment, despite its greater price. The decision between these technologies depends on the individual demands of the community, including water source characteristics, budget limits, and technical capacity.

The MCDI powered by PV emerges as the most realistic alternative for most off-grid settlements due to its economic and operational advantages. Its lower LCOW and maintenance



costs correspond with the financial reality of resource-constrained societies, while its environmental footprint encourages long-term sustainability. Solar Distillation, while successful, is better suited to specialised applications where water purity is a significant issue. By recognizing these trade-offs, stakeholders can make informed decisions to handle water scarcity efficiently.

5.3 Recommendations for Future Directions

To optimize the usage of Solar Distillation and MCDI in off-grid water delivery, numerous strategies can be explored. First, research and development should focus on reducing the capital expenses of Solar Distillation Systems. Innovations in materials, like as lightweight and durable solar collectors, could cut initial costs and make the technology more competitive with MCDI. Additionally, enhancing the efficiency of solar thermal processes could minimise energy consumption, cutting operational costs and LCOW.

For MCDI, future work should attempt to enhance its performance with high-salinity water sources. Advances in electrode materials and system design could broaden its usefulness, making it a more adaptable option. Integrating energy storage technologies, such as batteries, with PV-powered MCDI might assure consistent functioning in low-sunlight settings, further enhancing reliability. Both technologies would benefit from modular designs that allow for progressive scaling, enabling communities to increase systems as need develops.

Capacity building is crucial for long-term success. Training programs for local technicians should be implemented to guarantee communities can operate and maintain these systems independently. Partnerships with NGOs and governments could facilitate funding and technical support, particularly for MCDI, given its cost-effectiveness. Environmental management measures, such as brine disposal systems, should be devised to limit the ecological impact of both technologies.

Finally, experimental trials comparing Solar Distillation with MCDI in varied off-grid locations could provide valuable data on their real-world performance. These programs should examine water quality, community acceptance, and long-term cost savings to optimise implementation techniques. By addressing these areas, stakeholders can boost the accessibility and sustainability of clean water solutions, ensuring off-grid villages have reliable access to drinkable water for years to come.



REFERENCES

- [1] Natarajan D P, Saravanan K. Review on Capacitive Deionization: A Novel Method of Water Purification [J]. 2017.
- [2] Fath H. Multi-effect solar stills [J]. *Renewable Energy Systems And Desalination*, 2010, 3.
- [3] Hussein Hassan I. Reliability of Payment for water Resources as an Environmental Service towards the sustainable management of watershed forests in Zanzibar, Tanzania: A Case study of Kiwengwa-Pongwe Forest Reserve [Z]. 2007
- [4] Toth A J. Modelling and optimisation of multi-stage flash distillation and reverse osmosis for desalination of saline process wastewater sources [J]. *Membranes*, 2020, 10(10): 265.
- [5] Kabeel A E, Abdelgaied M, Almulla N. Performances of pyramid-shaped solar still with different glass cover angles: experimental study; proceedings of the 2016 7th International Renewable Energy Congress (IREC), F, 2016 [C]. IEEE.
- [6] Janarthanan B, Chandrasekaran J, Kumar S. Performance of floating cum tilted-wick type solar still with the effect of water flowing over the glass cover [J]. *Desalination*, 2006, 190(1-3): 51-62.
- [7] Abdallah S, Abu-Khader M M, Badran O. Effect of various absorbing materials on the thermal performance of solar stills [J]. *Desalination*, 2009, 242(1-3): 128-137.
- [8] Kurihara M, Yamamura H, Nakanishi T. High recovery/high pressure membranes for brine conversion SWRO process development and its performance data [J]. *Desalination*, 1999, 125(1-3): 9-15.
- [9] Shmroukh A N, Ookawara S. Stepped solar stills' development and improvement for seawater desalination [J]. *SVU-International Journal of Engineering Sciences and Applications*, 2021, 2(2): 26-36.
- [10] Do Thi H T, Pasztor T, Fozer D, et al. Comparison of desalination technologies using renewable energy sources with life cycle, PESTLE, and multi-criteria decision analyses [J]. *Water*, 2021, 13(21): 3023.
- [11] Saavedra A, Valdés H, Mahn A, et al. Comparative Analysis of Conventional and Emerging Technologies for Seawater Desalination: Northern Chile as A Case Study [J]. *Membranes*, 2021, 11(3).
- [12] Kabeel A E, Attia M E H, Bellila A, et al. The impact of the corrugated absorber shape on the performance of a hemispherical solar still for water desalination: an experimental study [J]. *Applied Water Science*, 2023, 13(4): 108.
- [13] Banasiak L J, Kruttschnitt T W, Schäfer A I. Desalination using electrodialysis as a function of voltage and salt concentration, *Desalination* [J]. 2007, 205(1–3).
- [14] Kaushal A, Varun. Solar stills: A review [J]. *Renewable and Sustainable Energy Reviews*, 2010, 14(1): 446-453.
- [15] Mevada D, Panchal H, Sadasivuni K K, et al. Effect of fin configuration parameters on performance of solar still: A review [J]. *Groundwater for Sustainable Development*, 2020, 10: 100289.
- [16] Rajamanickam M R, Velmurugan P, Ragupathy A, et al. Use of thermal energy storage materials for enhancement in distillate output of double slope solar still [J]. *Materials Today: Proceedings*, 2021, 34: 416-419.
- [17] Eslami M, Tajeddini F, Etaati N. Thermal analysis and optimization of a system for water harvesting from humid air using thermoelectric coolers [J]. *Energy Conversion and Management*, 2018, 174: 417-429.
- [18] Bruun C. Water shortage and surplus in the ancient world [Z]. Leuven: Peeters Publishers. 2000: 215-224
- [19] Shatat M, Riffat S B. Water desalination technologies utilizing conventional and renewable energy sources [J]. *International Journal of Low-Carbon Technologies*, 2014, 9(1): 1-19.
- [20] Mendoza-Escamilla J A, Hernandez-Rangel F J, Cruz-Alcántar P, et al. A feasibility study on the use of an atmospheric water generator (AWG) for the harvesting of fresh water in a semi-arid region affected by mining pollution [J]. *Applied Sciences*, 2019, 9(16): 3278.
- [21] Ajit, Kumar Gupta N. Progresses in Solar Still Technology with Phase Change Material [J]. *IOP Conference Series: Materials Science and Engineering*, 2021, 1116(1): 012055.



References

- [22] Jamaly S, Darwish N, Ahmed I, et al. A short review on reverse osmosis pretreatment technologies [J]. *Desalination*, 2014, 354: 30-38.
- [23] Wang L, Zhang Y, Moh K, et al. From capacitive deionization to desalination batteries and desalination fuel cells [J]. *Current Opinion in Electrochemistry*, 2021, 29: 100758.
- [24] Manoj Kumar , Puri A. A review of permissible limits of drinking water [J]. 2012.
- [25] Kaushik S, Ranjan K, Panwar N. Optimum exergy efficiency of single-effect ideal passive solar stills [J]. *Energy efficiency*, 2013, 6: 595-606.
- [26] Murugavel K K, Anburaj P, Hanson R S, et al. Progresses in inclined type solar stills [J]. *Renewable and Sustainable Energy Reviews*, 2013, 20: 364-377.
- [27] Al Bloushi A, Giwa A, Mezher T, et al. Chapter 3 - Environmental Impact and Technoeconomic Analysis of Hybrid MSF/RO Desalination: The Case Study of Al Taweelah A2 Plant [M]//GUDE V G. *Sustainable Desalination Handbook*. Butterworth-Heinemann. 2018: 55-97.
- [28] Mechell J K, Lesikar B. Desalination methods for producing drinking water [J]. E-249, 2024.
- [29] Ahdab Y D, Lienhard J H. Desalination of brackish groundwater to improve water quality and water supply [M]. *Global Groundwater*. Elsevier. 2021: 559-575.
- [30] Silva W F D, Santos I F S D, Botan M C C D O, et al. Reverse osmosis desalination plants in Brazil: A cost analysis using three different energy sources [J]. *Sustainable Cities and Society*, 2018, 43: 134-143.
- [31] Eisenberg T N, Middlebrooks E J. Reverse osmosis treatment of drinking water [M]. Elsevier, 2013.
- [32] Shamel M M, Chung O T. Drinking water from desalination of seawater: optimization of reverse osmosis system operating parameters [J]. *Journal of Engineering Science and Technology*, 2006, 1(2): 203-211.
- [33] Jeppesen T, Shu L, Keir G, et al. Metal recovery from reverse osmosis concentrate [J]. *Journal of Cleaner Production*, 2009, 17(7): 703-707.
- [34] Shenvi S S, Isloor A M, Ismail A. A review on RO membrane technology: Developments and challenges [J]. *Desalination*, 2015, 368: 10-26.
- [35] Amy Childress, Roy A. *Frontiers of Engineering* [M]. 2017.
- [36] Sadrzadeh M, Mohammadi T. Sea water desalination using electrodialysis [J]. *Desalination*, 2008, 221(1-3): 440-447.
- [37] Delyannis E. Historic background of desalination and renewable energies [J]. *Solar energy*, 2003, 75(5): 357-366.
- [38] Al-Amshawee S, Yunus M Y B M, Azoddein A a M, et al. Electrodialysis desalination for water and wastewater: A review [J]. *Chemical Engineering Journal*, 2020, 380: 122231.
- [39] Campione A, Gurreri L, Ciofalo M, et al. Electrodialysis for water desalination: A critical assessment of recent developments on process fundamentals, models and applications [J]. *Desalination*, 2018, 434: 121-160.
- [40] Vaaramaa Kaisa , Lehto J. Removal of metals and anions from drinking water by ion exchange. *Desalination*, 155(2), 157-170. [J]. 2003.
- [41] Arthur J D, Langhus B G, Patel C. Technical summary of oil & gas produced water treatment technologies [J]. All Consulting, LLC, Tulsa, OK, 2005.
- [42] Levchuk I, Mårquez J J R, Sillanpää M. Removal of natural organic matter (NOM) from water by ion exchange—a review [J]. *Chemosphere*, 2018, 192: 90-104.
- [43] Bergquist A M, Choe J K, Strathmann T J, et al. Evaluation of a hybrid ion exchange-catalyst treatment technology for nitrate removal from drinking water [J]. *Water Res*, 2016, 96: 177-187.
- [44] Parker A. Potable water from sea-water [J]. *Nature*, 1942, 149(3772): 184-186.
- [45] El-Ghonemy A. Performance test of a sea water multi-stage flash distillation plant: Case study [J]. *Alexandria engineering journal*, 2018, 57(4): 2401-2413.
- [46] Khoshrou I, Nasr M J, Bakhtari K. New opportunities in mass and energy consumption of the Multi-Stage Flash Distillation type of brackish water desalination process [J]. *Solar Energy*, 2017, 153: 115-125.
- [47] Farwati M. Theoretical study of multi-stage flash distillation using solar energy [J]. *Energy*, 1997, 22(1): 1-5.
- [48] Shahzamanian B, Varga S, Soares J, et al. Theoretical performance assessment of a multi-effect distillation system integrated with thermal vapour compression unit running on solar energy [J]. *International Journal of Low-Carbon Technologies*, 2024, 19: 908-921.
- [49] Al-Shammiri M, Safar M. Multi-effect distillation plants: state of the art [J]. *Desalination*, 1999,



References

- 126(1-3): 45-59.
- [50] Romo S A, Storch M, Srebric J. Operation modeling and comparison of actual multi-effect distillation and reverse osmosis desalination plants [J]. *Desalination*, 2024, 571: 117046.
- [51] Askari I B, Ameri M. A techno-economic review of multi effect desalination systems integrated with different solar thermal sources [J]. *Applied Thermal Engineering*, 2021, 185: 116323.
- [52] Druetta P, Aguirre P, Mussati S. Optimization of multi-effect evaporation desalination plants [J]. *Desalination*, 2013, 311: 1-15.
- [53] Anderson M A, Cudero A L, Palma J. Capacitive deionization as an electrochemical means of saving energy and delivering clean water. Comparison to present desalination practices: Will it compete? [J]. *Electrochimica Acta*, 2010, 55(12): 3845-3856.
- [54] Kim S, Lee J, Kim C, et al. Na₂FeP₂O₇ as a Novel Material for Hybrid Capacitive Deionization [J]. *Electrochimica Acta*, 2016, 203: 265-271.
- [55] Wang L, Dykstra J E, Lin S. Energy Efficiency of Capacitive Deionization [J]. *Environmental Science & Technology*, 2019, 53(7): 3366-3378.
- [56] Murphy G W, Caudle D D. Mathematical theory of electrochemical demineralization in flowing systems [J]. *Electrochimica Acta*, 1967, 12(12): 1655-1664.
- [57] Johnson A M, Newman J. Desalting by means of porous carbon electrodes [J]. *Journal of the electrochemical society*, 1971, 118(3): 510.
- [58] Rommerskirchen A, Linnartz C J, Müller D, et al. Energy recovery and process design in continuous flow–electrode capacitive deionization processes [J]. *ACS Sustainable Chemistry & Engineering*, 2018, 6(10): 13007-13015.
- [59] Kim Y-J, Choi J-H. Enhanced desalination efficiency in capacitive deionization with an ion-selective membrane [J]. *Separation and Purification Technology*, 2010, 71(1): 70-75.
- [60] Shanbhag S, Whitacre J F, Mauter M S. The origins of low efficiency in electrochemical deionization systems [J]. *Journal of the electrochemical society*, 2016, 163(14): E363.
- [61] Tan C, He C, Tang W, et al. Integration of photovoltaic energy supply with membrane capacitive deionization (MCDI) for salt removal from brackish waters [J]. *Water Research*, 2018, 147: 276-286.
- [62] Liu X, Whitacre J F, Mauter M S. Mechanisms of humic acid fouling on capacitive and insertion electrodes for electrochemical desalination [J]. *Environmental Science & Technology*, 2018, 52(21): 12633-12641.
- [63] Wang L, Lin S. Intrinsic tradeoff between kinetic and energetic efficiencies in membrane capacitive deionization [J]. *Water Research*, 2018, 129: 394-401.
- [64] Lin S. Energy efficiency of desalination: fundamental insights from intuitive interpretation [J]. *Environmental Science & Technology*, 2019, 54(1): 76-84.
- [65] Ramachandran A, Oyarzun D I, Hawks S A, et al. Comments on “Comparison of energy consumption in desalination by capacitive deionization and reverse osmosis” [J]. *Desalination*, 2019, 461: 30-36.
- [66] Bacha H B, Abdullah A S, Omara Z M, et al. Enhancing freshwater production in solar distillation: Hemispherical absorber modification and reflectors integration [J]. *Sustainable Energy Technologies and Assessments*, 2024, 61: 103576.
- [67] Shalaby S M, Hammad F A, Zayed M E. Current progress in integrated solar desalination systems: Prospects from coupling configurations to energy conversion and desalination processes [J]. *Process Safety and Environmental Protection*, 2023, 178: 494-510.
- [68] Ullah I, Rasul M, Khan M M. An overview of solar thermal desalination technologies [DS]. 2013,
- [69] Chen Y, Chen Z, Wang D, et al. Co-optimization of passive building and active solar heating system based on the objective of minimum carbon emissions [J]. *Energy*, 2023, 275: 127401.
- [70] Singh D, Singh D, Mishra V, et al. Sustainability issues of solar desalination hybrid systems integrated with heat exchangers for the production of drinking water: A review [J]. *Desalination*, 2023, 566: 116930.
- [71] Esmailion F. Hybrid renewable energy systems for desalination [J]. *Applied Water Science*, 2020, 10(3): 84.
- [72] De Koning J, Thiesen S. Aqua Solaris—an optimized small scale desalination system with 40 litres output per square meter based upon solar-thermal distillation [J]. *Desalination*, 2005, 182(1-3): 503-509.
- [73] Jeevadason A W, Padmini S, Bharatiraja C, et al. A review on diverse combinations and Energy-



References

- Exergy-Economics (3E) of hybrid solar still desalination [J]. *Desalination*, 2022, 527: 115587.
- [74] Sharshir S, Elsheikh A, Peng G, et al. Thermal performance and exergy analysis of solar stills—A review [J]. *Renewable and Sustainable Energy Reviews*, 2017, 73: 521-544.
- [75] Tiwari G, Sahota L. *Advanced solar-distillation systems: basic principles, thermal modeling, and its application* [M]. Springer, 2017.
- [76] Tony M A. From biomass residue to solar thermal energy: the potential of bagasse as a heat storage material [J]. *Euro-Mediterranean Journal for Environmental Integration*, 2020, 5(1): 17.
- [77] Elango T, Kalidasa Murugavel K. The effect of the water depth on the productivity for single and double basin double slope glass solar stills [J]. *Desalination*, 2015, 359: 82-91.
- [78] Agrawal A, Rana R S, Srivastava P K. Heat transfer coefficients and productivity of a single slope single basin solar still in Indian climatic condition: Experimental and theoretical comparison [J]. *Resource-Efficient Technologies*, 2017, 3(4): 466-482.
- [79] Mohamed-Awal A M, Elmi I M, Egueh A-N D, et al. Design, Construction and Experimental Study of a Solar Still for Brackish Water Purification under Djiboutian Climate [J]. 2021.
- [80] Le T H, Pham M T, Hadiyanto H, et al. Influence of various basin types on performance of passive solar still: A review [J]. *International Journal of Renewable Energy Development*, 2021, 10(4): 789-802.
- [81] Feilizadeh M, Soltanieh M, Karimi Estahbanati M R, et al. Optimization of geometrical dimensions of single-slope basin-type solar stills [J]. *Desalination*, 2017, 424: 159-168.
- [82] Dimri V, Sarkar B, Singh U, et al. Effect of condensing cover material on yield of an active solar still: an experimental validation [J]. *Desalination*, 2008, 227(1): 178-189.
- [83] Al-Karaghoul A A, Alnaser W E. Performances of single and double basin solar-stills [J]. *Applied Energy*, 2004, 78(3): 347-354.
- [84] Mohamad M A, Soliman S H, Abdel-Salam M S, et al. Experimental and financial investigation of asymmetrical solar stills with different insulation [J]. *Applied Energy*, 1995, 52(2): 265-271.
- [85] Khalifa A J N, Hamood A M. Effect of insulation thickness on the productivity of basin type solar stills: An experimental verification under local climate [J]. *Energy Conversion and Management*, 2009, 50(9): 2457-2461.
- [86] Al-Garni A Z. Productivity Enhancement of Solar Still Using Water Heater and Cooling Fan [J]. *Journal of Solar Energy Engineering*, 2012, 134(3).
- [87] Tony M A, Tayeb A, Zhao Y. An alternative arrangement for the alum sludge management: minimising waste with low-cost solar techniques [J]. *Am J Chem Eng*, 2016, 4(2): 30-37.
- [88] Taha A T H. Estimation of hourly global solar radiation in Egypt using mathematical model [J]. *Misir Journal of Agricultural Engineering*, 2010, 27(4): 2033-2047.
- [89] Tony M A. Valorization of undervalued aluminum-based waterworks sludge waste for the science of “The 5 Rs’ criteria” [J]. *Applied Water Science*, 2022, 12(2): 20.
- [90] Tony M A, Lin L-S. Performance of acid mine drainage sludge as an innovative catalytic oxidation source for treating vehicle-washing wastewater [J]. *Journal of Dispersion Science and Technology*, 2021, 43(1): 50-60.
- [91] Akash B A, Mohsen M S, Nayfeh W. Experimental study of the basin type solar still under local climate conditions [J]. *Energy Conversion and Management*, 2000, 41(9): 883-890.
- [92] Khadim M a a A, Abd Al-Awahid W A, Hachim D M. Review on the types of solar stills; proceedings of the IOP Conference Series: Materials Science and Engineering, F, 2020 [C]. IOP Publishing.
- [93] Katekar V P, Deshmukh S S. A review on research trends in solar still designs for domestic and industrial applications [J]. *Journal of cleaner production*, 2020, 257: 120544.
- [94] Tony M A, Lin L-S. Iron coated-sand from acid mine drainage waste for being a catalytic oxidant towards municipal wastewater remediation [J]. *International Journal of Environmental Research*, 2021, 15: 191-201.
- [95] Abdallah S, Badran O, Abu-Khader M M. Performance evaluation of a modified design of a single slope solar still [J]. *Desalination*, 2008, 219(1-3): 222-230.
- [96] Sangeetha A, Shanmugan S, Alrubaie A J, et al. A review on PCM and nanofluid for various productivity enhancement methods for double slope solar still: Future challenge and current water issues [J]. *Desalination*, 2023, 551: 116367.
- [97] Rajamanickam M, Ragupathy A. Influence of water depth on internal heat and mass transfer in a double slope solar still [J]. *Energy procedia*, 2012, 14: 1701-1708.



References

- [98] Baraya J, Sani M H, Mu'awuya S M, et al. Performance Analysis of a Single Basin Double Slope Solar Still under Kano Climate [J]. 2025.
- [99] Al-Karaghoul A, Alnaser W. Performances of single and double basin solar-stills [J]. *Applied Energy*, 2004, 78(3): 347-354.
- [100] Nadgire A R, Barve S B, Ithape P K. Experimental investigation and performance analysis of double-basin solar still using CFD techniques [J]. *Journal of The Institution of Engineers (India): Series C*, 2020, 101: 531-539.
- [101] Kabeel A, Khalil A, Omara Z, et al. Theoretical and experimental parametric study of modified stepped solar still [J]. *Desalination*, 2012, 289: 12-20.
- [102] Sathyamurthy R, Kennady H J, Nagarajan P, et al. Factors affecting the performance of triangular pyramid solar still [J]. *Desalination*, 2014, 344: 383-390.
- [103] Nayi K H, Modi K V. Pyramid solar still: a comprehensive review [J]. *Renewable and Sustainable Energy Reviews*, 2018, 81: 136-148.
- [104] Fath H E, El-Samanoudy M, Fahmy K, et al. Thermal-economic analysis and comparison between pyramid-shaped and single-slope solar still configurations [J]. *Desalination*, 2003, 159(1): 69-79.
- [105] Kabeel A. Performance of solar still with a concave wick evaporation surface [J]. *Energy*, 2009, 34(10): 1504-1509.
- [106] Ahsan A, Imteaz M, Thomas U A, et al. Parameters affecting the performance of a low cost solar still [J]. *Applied Energy*, 2014, 114: 924-930.
- [107] Gad H, El-Din S S, Hussien A, et al. Thermal analysis of a conical solar still performance: An experimental study [J]. *Solar Energy*, 2015, 122: 900-909.
- [108] Ismail B I. Design and performance of a transportable hemispherical solar still [J]. *Renewable Energy*, 2009, 34(1): 145-150.
- [109] Arunkumar T, Jayaprakash R, Denkenberger D, et al. An experimental study on a hemispherical solar still [J]. *Desalination*, 2012, 286: 342-348.
- [110] Manikandan V, Shanmugasundaram K, Shanmugan S, et al. Wick type solar stills: a review [J]. *Renewable and Sustainable Energy Reviews*, 2013, 20: 322-335.
- [111] Awasthi A, Kumari K, Panchal H, et al. Passive solar still: recent advancements in design and related performance [J]. *Environmental Technology Reviews*, 2018, 7(1): 235-261.
- [112] Kassem T K. Optimization the performance of single basin solar still with corrugated wick surface at high places [J]. *Int Res J Eng Technol*, 2016, 3: 1094-1024.
- [113] Aruna R, Janarthanan B. Study of clearness and cloudiness index at tropical locations [J]. *International Journal of Scientific & Engineering Research*, 2014, 5(2): 161-169.
- [114] Sivakumar V, Sundaram E G. Improvement techniques of solar still efficiency: A review [J]. *Renewable and Sustainable Energy Reviews*, 2013, 28: 246-264.
- [115] Omara Z M, Kabeel A E, Abdullah A S. A review of solar still performance with reflectors [J]. *Renewable and Sustainable Energy Reviews*, 2017, 68: 638-649.
- [116] Omara Z, Kabeel A, Abdullah A. A review of solar still performance with reflectors [J]. *Renewable and Sustainable Energy Reviews*, 2017, 68: 638-649.
- [117] Al-Garni A Z. Effect of external reflectors on the productivity of a solar still during winter [J]. *Journal of Energy Engineering*, 2014, 140(1): 04013002.
- [118] Ardekani R A, Kianifar A. Synergizing theory and experiment: Enhancing solar distillation performance with external reflector in a passive 4-stage model [J]. *Desalination*, 2024: 117815.
- [119] Fath H E, Elsherbiny S M. Effect of adding a passive condenser on solar still performance [J]. *Energy Conversion and Management*, 1993, 34(1): 63-72.
- [120] Ashwinbhai D V, Parikh S R, Patdiwala U. Evaluation of basin type solar still by optimizing the condenser [J]. *Desalination*, 2019, 5(4): 503-511.
- [121] Kabeel A, Omara Z, Essa F, et al. RETRACTED: Solar still with condenser—a detailed review [Z]. Elsevier. 2016
- [122] Bhardwaj R, Ten Kortenaar M, Mudde R. Inflatable plastic solar still with passive condenser for single family use [J]. *Desalination*, 2016, 398: 151-156.
- [123] Omara Z M, Eltawil M A, Elnashar E A. A new hybrid desalination system using wicks/solar still and evacuated solar water heater [J]. *Desalination*, 2013, 325: 56-64.
- [124] Radhwan A M. Transient performance of a stepped solar still with built-in latent heat thermal energy storage [J]. *Desalination*, 2005, 171(1): 61-76.
- [125] Tony M A, Nabwey H A. Recent advances in solar still technology for solar water desalination [J].



References

- Applied Water Science, 2024, 14(7): 1-29.
- [126] Naim M M, Abd El Kawi M A. Non-conventional solar stills Part 2. Non-conventional solar stills with energy storage element [J]. *Desalination*, 2003, 153(1): 71-80.
- [127] Abu-Hijleh B a K, Rababa'h H M. Experimental study of a solar still with sponge cubes in basin [J]. *Energy Conversion and Management*, 2003, 44(9): 1411-1418.
- [128] Murugavel K K, Chockalingam K K, Srihar K. An experimental study on single basin double slope simulation solar still with thin layer of water in the basin [J]. *Desalination*, 2008, 220(1-3): 687-693.
- [129] El-Sebaili A A, Yaghmour S J, Al-Hazmi F S, et al. Active single basin solar still with a sensible storage medium [J]. *Desalination*, 2009, 249(2): 699-706.
- [130] Nafey A, Abdelkader M, Abdelmotalip A, et al. Solar still productivity enhancement [J]. *Energy Conversion and Management*, 2001, 42(11): 1401-1408.
- [131] Singh H, Tiwari G. Evaluation of cloudiness/haziness factor for composite climate [J]. *Energy*, 2005, 30(9): 1589-1601.
- [132] Sibagariang Y, Napitupulu F, Kawai H, et al. Investigation of the effect of a solar collector, nozzle, and water cooling on solar still double slope [J]. *Case Studies in Thermal Engineering*, 2022, 40: 102489.
- [133] Kerfah R, Benabdelaziz F K, Tigrine Z, et al. An experimental exploration of modified basin solar still performance through integration of flat plate collector and built condenser [J]. *Environmental Progress & Sustainable Energy*, 2024, 43(6): e14493.
- [134] Joardder M, Halder P, Rahim M, et al. Solar pyrolysis: converting waste into asset using solar energy [M]. *Clean energy for sustainable development*. Elsevier. 2017: 213-235.
- [135] Kodama T. High-temperature solar chemistry for converting solar heat to chemical fuels [J]. *Progress in energy and combustion science*, 2003, 29(6): 567-597.
- [136] Amiri H, Aminy M, Lotfi M, et al. Energy and exergy analysis of a new solar still composed of parabolic trough collector with built-in solar still [J]. *Renewable Energy*, 2021, 163: 465-479.
- [137] Khairat Dawood M M, Nabil T, Kabeel A E, et al. Experimental study of productivity progress for a solar still integrated with parabolic trough collectors with a phase change material in the receiver evacuated tubes and in the still [J]. *Journal of Energy Storage*, 2020, 32: 102007.
- [138] Badran O O, Al-Tahaine H A. The effect of coupling a flat-plate collector on the solar still productivity [J]. *Desalination*, 2005, 183(1): 137-142.
- [139] Omara Z M, Kabeel A E, Abdullah A S, et al. Experimental investigation of corrugated absorber solar still with wick and reflectors [J]. *Desalination*, 2016, 381: 111-116.
- [140] Omara Z M, Kabeel A E, Younes M M. Enhancing the stepped solar still performance using internal reflectors [J]. *Desalination*, 2013, 314: 67-72.
- [141] El-Samadony Y, Abdullah A, Omara Z. Experimental study of stepped solar still integrated with reflectors and external condenser [J]. *Experimental heat transfer*, 2015, 28(4): 392-404.
- [142] Kumar S, Tiwari G. Performance evaluation of an active solar distillation system [J]. *Energy*, 1996, 21(9): 805-808.
- [143] Wang L, Zheng H, Zhao Y, et al. Solar-driven natural vacuum desalination system with inner condenser [J]. *Applied Thermal Engineering*, 2021, 196: 117320.
- [144] Rafiei A, Loni R, Mahadzir S B, et al. Hybrid solar desalination system for generation electricity and freshwater with nanofluid application: Energy, exergy, and environmental aspects [J]. *Sustainable Energy Technologies and Assessments*, 2022, 50: 101716.
- [145] Attia M E H, Driss Z, Manokar A M, et al. Effect of aluminum balls on the productivity of solar distillate [J]. *Journal of Energy Storage*, 2020, 30: 101466.
- [146] Salem M R, Salem M R, Higazy M G, et al. Performance enhancement of a solar still distillation unit: A field investigation [J]. *Solar Energy*, 2020, 202: 326-341.
- [147] Brinkhoff. T. National Bureau of Statistics Tanzania [Z]. 2022
- [148] Said M K, Misana S B. Land cover changes and their determinants in the coral rag ecosystem of the South District of Unguja, Zanzibar [J]. *Journal of Ecology and the Natural Environment*, 2018, 10(7): 129-146.
- [149] Amrose S E, Cherukumilli K, Wright N C. Chemical contamination of drinking water in resource-constrained settings: Global prevalence and piloted mitigation strategies [J]. *Annual Review of Environment and Resources*, 2020, 45(1): 195-226.
- [150] Amrose S, Burt Z, Ray I. Safe drinking water for low-income regions [J]. *Annual Review of Environment and Resources*, 2015, 40(1): 203-231.



References

- [151] Caldera U, Breyer C. Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems [J]. *Energy*, 2020, 200: 117507.
- [152] Patel S K, Lee B, Westerhoff P, et al. The potential of electrodialysis as a cost-effective alternative to reverse osmosis for brackish water desalination [J]. *Water Research*, 2024, 250: 121009.
- [153] Zheng Y, Hatzell K B. Technoeconomic analysis of solar thermal desalination [J]. *Desalination*, 2020, 474: 114168.
- [154] Kumar S, Tiwari G. Life cycle cost analysis of single slope hybrid (PV/T) active solar still [J]. *Applied Energy*, 2009, 86(10): 1995-2004.
- [155] Tiwari G. Economic analysis of some solar energy systems [J]. *Energy Conversion and Management*, 1984, 24(2): 131-135.
- [156] Goosen M F A, Sablani S S, Shayya W H, et al. Thermodynamic and economic considerations in solar desalination [J]. *Desalination*, 2000, 129(1): 63-89.
- [157] Bales C, Wang Y, Lian B, et al. Predictive performance and costing model for Membrane Capacitive Deionization (MCDI) at operational scale [J]. *Desalination*, 2023, 557: 116595.
- [158] Nhmrc N. Australian drinking water guidelines paper 6 national water quality management strategy [J]. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra, 2011: 5-7.
- [159] Suss M E, Porada S, Sun X, et al. Water desalination via capacitive deionization: what is it and what can we expect from it? [J]. *Energy & Environmental Science*, 2015, 8(8): 2296-2319.
- [160] Hawks S A, Ramachandran A, Porada S, et al. Performance metrics for the objective assessment of capacitive deionization systems [J]. *Water Research*, 2019, 152: 126-137.
- [161] Technology E W. Concentration Quantities and Unit Conversions in Water Chemistry [Z]. 2021
- [162] Tan C, He C, Fletcher J, et al. Energy recovery in pilot scale membrane CDI treatment of brackish waters [J]. *Water Research*, 2020, 168: 115146.
- [163] Ramachandran A, Oyarzun D I, Hawks S A, et al. High water recovery and improved thermodynamic efficiency for capacitive deionization using variable flowrate operation [J]. *Water Research*, 2019, 155: 76-85.
- [164] Bales C, Lian B, Fletcher J, et al. Site specific assessment of the viability of membrane Capacitive Deionization (mCDI) in desalination of brackish groundwaters for selected crop watering [J]. *Desalination*, 2021, 502: 114913.
- [165] Liu X, Shanbhag S, Bartholomew T V, et al. Cost comparison of capacitive deionization and reverse osmosis for brackish water desalination [J]. *ACS ES&T Engineering*, 2020, 1(2): 261-273.
- [166] Hasseler T D, Ramachandran A, Tarpeh W A, et al. Process design tools and techno-economic analysis for capacitive deionization [J]. *Water Research*, 2020, 183: 116034.



ACKNOWLEDGMENT

I am deeply grateful to Almighty God for His boundless grace and strength, which have guided me through this academic journey with resilience and clarity. His divine provision has been my cornerstone, enabling me to pursue and complete my master's studies at Tongji University. This opportunity to grow intellectually and personally in China would not have been possible without His unwavering presence, and for that, I offer my heartfelt thanks.

My sincere appreciation goes to my supervisor, Professor Wang Li, whose expertise, patience, and unwavering support have been instrumental in shaping this thesis. I am equally thankful to the dedicated staff of the College of Environmental Science and Engineering at Tongji University and the Institute of Environment for Sustainable Development (IESD) for providing a nurturing academic environment. Their encouragement and constructive feedback have significantly enriched my work. I also extend my gratitude to the Chinese government for the MOFCOM Scholarship, which funded my studies, and to the Rwandan government for granting me the opportunity to pursue my master's degree in China. Additionally, I thank my thesis committee for their insightful feedback and valuable contributions, which refined my research and strengthened my arguments.

I am immensely grateful to my friends, Aaron Bizimana and Habarugira Fabrice Nelly, who played a pivotal role in helping me integrate into academic and social life in China. Their companionship, encouragement, and shared experiences made this journey less daunting and more fulfilling. Their support provided me with a sense of belonging, enabling me to focus on my studies and adapt to a new environment with confidence.

In conclusion, my deepest gratitude goes to my family, whose love and support have been my greatest motivation. To my beloved wife Ruth Ishimwe, and our two precious sons Ineza Niyo Kellan and Izere Niyo Kian, your unwavering love and patience have been my anchor. I am equally thankful to my father Renzaho Samuel, my mother Immaculee Mukasharangabo, my brothers, sisters, and extended family and friends for their constant encouragement and belief in me. Your sacrifices and prayers have fueled my determination, and I am forever grateful for your presence in my life.



RESUME

First name: Felix
Last name: NIYOKWIZERA
Sex: M
Marital Status: Married
Date of birth: 23rd March 1991
Nationality: Rwandese
Contact: Tel :(+250)788551636
(+86)18321914023
E-mail:niyofelix91@gmail.com

EDUCATION BACKGROUND

2023-2025: M.Sc. In Environmental Management & Sustainable Development, Tongji University, Shanghai, China

2012-2015: I studied Environmental design (Landscape, Interior, furniture, soft furnishing, Painting and sculpture design) in College of science and Technology (CST), at Nyarugenge campus, University of Rwanda (UR).

During my bachelor's studies I got different certificate from the school of Architecture and built environment (SABE)

5. Super academic performance in INSTRUMENTAL DRAWING Module
6. Super academic performance in PHOTOGRAPH II Module
7. Super academic performance in LANDSCAPE DESIGN Module
8. Module Super academic performance in SOFT FURNISHING module

2008-2010: A' level I did Physics, Chemistry and Mathematics (PCM) In GAFUNZA High School, In West province, Nyamasheke District, Shangi sector

2005-2007:O'level in E.A.V.Ntendezi, in West province, Nyamasheke District, Ruharambuga Sector

1998-2004: Primary school in West province, Nyamasheke District, Ruharambuga Sector

Languages

- **English – Proficient Speaker**
- **French–Advanced**
- **Chinese – Elementary Speaker**



SKILLS

In my career, I have developed proficiency in a diverse set of software tools essential for creating innovative and visually appealing designs. My skills include AutoCAD, ArchiCAD, and SketchUp for precise drafting and 3D modeling, alongside Adobe Photoshop, Illustrator, and InDesign for creating stunning visual presentations and detailed graphics. I am also adept in CorelDraw for vector-based design and Microsoft Office for project documentation and communication. Additionally, I utilize Realtime Landscaping Architect, a professional software tailored for landscape design, enabling me to craft realistic, immersive outdoor environments with efficiency and creativity, enhancing project outcomes.

PROFILE

He is passionate about living environmental solutions. Especially in creating a sustainable interior and landscape environment. In the different design projects, he likes to focus on the design process, site inventory, checking material properties and quality, and appropriate plants according to the use of landscape or space; Supervision of the execution of the approved projects. He is also able to work under pressure and work effectively with team members.

PROFESSIONAL EXPERIENCE

2021 up to now:Tutorial Assistant at University of Rwanda/College of Science and Technology

2015-2021:Senior Designer in Granite construction and Consult

Responsibilities:

9. Assessed expected technical challenges and developed proactive solutions.
10. Follow up of design process and supervision in implementation of the design.
11. Supervision of approved design during site marking.
12. Material specifications and a quality analysis.
13. Joints and finishing of materials supervision.
14. Implementation of new technological to increased efficiency.

Partitioning projects:

1. Interior design and sitting arrangement for Radiant Insurance Company Headquarter in Chic building and its implementation.
2. Partitioning works in KAMI HOUSE (Wasac Headquarter, AOS Headquarter, ATL)
3. Headquarter, Bboxx in KAMI HOUSE
4. Headquarter, SGF, NURC and RLRC) in KAMI HOUSE
5. Partitioning works for WASAC Headquarter in Centenary House.
6. Partitioning works for DALBERG Headquarter in Kigali height.



7. Partitioning works for AVIATION TRAVEL&LOGISTIC at Career center building.

Construction projects

1. Mwito pre-primary school
2. Kirambo warehouse for RTC
3. Rebero Estate Bwerankori
4. GC&C Apartment at Kicukiro
5. Residential house G+2 at Rebero
6. Residential house G+3 at Kicukiro

Publication

1. Niyokwizera F, Oseni S, Twizeyemungu J, et al. The Impact of Solar Still Design on the Efficiency of Distillate Production: A Comprehensive Review [J]. *European Journal of Applied Science, Engineering and Technology*, 2025, 3(2): 194-214. [https://doi.org/10.59324/ejaset.2025.3\(2\).17](https://doi.org/10.59324/ejaset.2025.3(2).17)
2. Shamusideen O., O., Felix, N., & Raphael, D.-S. (2025). Global Plastic Pollution and the Nigerian Dimensions. *Journal of Geography, Environment and Earth Science International*, 29(3), 26-42. <https://doi.org/10.9734/jgeesi/2025/v29i3871>
3. Juvins T, Innocent K, Felix N, et al. Challenges and Solutions for Drinking Water Quality Management in Rwanda: A Comprehensive Review [J]. *Journal of Geography, Environment and Earth Science International*, 2025, 29(2): 99-112. <https://doi.org/10.9734/jgeesi/2025/v29i2866>
4. Herman N, O O S, Felix N. A New Approach to Measuring Household Food Waste and Strategies for Sustainable Prevention: A Comprehensive Review [J]. *Journal of Geography, Environment and Earth Science International*, 2025, 29(5): 166-183. <https://doi.org/10.9734/jgeesi/2025/v29i5900>



同济大学学位论文原创性声明

本人郑重声明：所提交的学位论文《太阳能蒸馏技术对平准化水成本的影响前景：与传统海水淡化的比较分析》，是本人在导师指导下，独立进行研究工作所取得的成果。除文中已经注明引用的内容外，本学位论文的研究成果不包含任何他人创作的、已公开发表或者没有公开发表的作品的内容。对本论文所涉及的研究工作做出贡献的其他个人和集体，均已在文中以明确方式标明。本学位论文原创性声明的法律责任由本人承担。

学位论文作者签名: Niyotwizena Felix
Niyotwizena Felix
日期: 2025 年 05 月 29 日

同济大学学位论文授权使用授权书

本人完全了解同济大学关于收集、保存、使用学位论文的规定，同意如下各项内容：按照学校要求提交学位论文的印刷本和电子版；学校有权保留学位论文的印刷本和电子版，并采用影印、缩印、扫描、数字化或其它手段保存论文；学校有权提供目录检索以及提供本学位论文全文或者部分的阅览服务；学校有权按有关规定向国家有关部门或者机构送交论文的复印件和电子版；允许论文被查阅和借阅。学校有权将本学位论文的全部或部分内 容授权编入有关数据库出版传播，可以采用影印、缩印或扫描等复制手段保存和汇编本学位论文。

本学位论文属于（在以下方框内打“√”）：

保密，在_____年解密后适用本授权书。

不保密。

学位论文作者签名: Niyotwizena Felix
指导教师签名: 王功
日期: 2025 年 05 月 29 日 日期 2025 年 05 月 29 日



25501103

七、学位论文答辩委员会决议 Conclusion of the Defense Committee

姓名	菲利克斯	学号	2393401	所在学科/专业	环境科学
指导教师	王力	答辩日期	2025.5.29	答辩地点	明净楼4楼报告厅
论文题目	太阳能蒸馏技术对降低海水淡化成本的影响前景：与传统海水淡化的比较分析				
<p>该论文聚焦于解决全球水资源短缺背景下，如何为资源匮乏地区提供可持续、安全、经济的供水方案。选题紧密结合当前环境与可持续发展议题，响应联合国可持续发展目标，具有重要的理论价值和现实意义。</p> <p>该论文构建了一个多维度的评估框架，系统比较了太阳能蒸馏系统与膜电容去离子技术(MCDI)在技术性能、经济成本和环境可持续性等方面的差异，弥补了以往研究中缺乏综合分析的不足。通过生命周期评价和单位水成本的量化分析，明确指出 MCDI 在多数情境下具有更优的经济性，为资源有限区域的技术选择提供了数据支撑。此外，论文还结合典型应用场景，提出了两种系统的差异化部署建议，增强了研究成果的实践指导意义。这些工作不仅对理解两种脱盐技术在离网条件下的适应性具有重要价值，也在方法上体现出较强的系统性和创新性。</p> <p>论文文献调研充分，研究方案合理，写作规范。答辩过程中，表述清楚，回答问题切题。表明作者已掌握了本学科的基础理论和专业知识，具备了从事科学研究工作的能力。</p> <p>经答辩委员会无记名投票表决，一致认为该论文已达到本专业硕士学位的学术水平和学位标准，同意通过菲利克斯同学的硕士学位论文答辩。</p>					
答辩委员会主席签名:			杨宇		2025年5月29日
答辩委员会共 <u>5</u> 人，经表决， <u>5</u> 人建议授予申请人硕士学位。根据《同济大学学位授予工作细则》 ^[注] （在□内划“√”）： <input checked="" type="checkbox"/> 建议授予申请人硕士学位。 <input type="checkbox"/> 申请人可在一年内修改论文，申请重新答辩一次。 <input type="checkbox"/> 建议不授予申请人硕士学位。					
<input type="checkbox"/> 推荐为同济大学优秀硕士学位论文。					
答辩委员会成员签名	职务	姓名	职称	单位	签名
	主席	杨宇	研究员	上海交通大学	杨宇
	委员	王力	教授	同济大学	王力
	委员	张清然	研究员	同济大学	张清然
	委员	李雪松	副教授	同济大学	李雪松
	委员	黄海宁	助理教授	同济大学	黄海宁
	秘书	刘超	助理教授	同济大学	刘超

注：根据《同济大学学位授予工作细则》第十一条规定：1. 申请人获得全体答辩委员会成员三分之二以上（含）同意票，为建议授予申请人硕士学位；2. 申请人获得全体答辩委员会成员二分之一以上（含）、三分之二以下（不含）同意票，申请人可在一年内修改论文，申请重新答辩一次；3. 申请人获得全体答辩委员会成员二分之一以下（不含）同意票，为建议不授予申请人硕士学位。