National University of Lesotho

Solar Water Purification System for Rural Areas: A Case Study for Lesotho

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Abstract

This dissertation examines the design, efficacy, and viability of a hybrid solar photovoltaic-thermal (PVT) and ultraviolet (UV) water purification system specifically developed for rural Lesotho, featuring a case study in the Mohale Basin. The system incorporates thermal energy capture by the solar PVT array to preheat feedwater before reverse osmosis (RO) treatment, hence improving membrane efficiency and minimizing fouling hazards. The electricity produced by the PVT array energizes UV disinfection devices and water pumps, while battery storage guarantees continuous operation under low solar irradiance circumstances.

Two optimized setups, that is, 5.2 kWp and 14.4 kWp were simulated by PVsyst, underpinned by mathematical modelling and validated against DuPont WAVE software. The 14.4 kWp configuration exhibits enhanced energy reliability with feedwater preheating to 40 °C, recovery rates of 60%, and specific energy consumption as low as 1.06 kWh/m³. Comparative evaluations solar PV and solar PVT RO demonstrate that the incorporation of PVT preheating with dual-stage RO markedly decreases operating pressures and enhances water quality. Analysis indicated that the smaller 5.2 kWp system, despite its reduced initial expenditure, yields water at a higher Levelized Cost of Water (LCOW) of USD 1.25/m³. The larger 14.4 kWp system on the other hand attained a lower LCOW of USD 0.75/m³, illustrating the benefits of economies of scale in hybrid PVT-RO configurations.

This work demonstrates the viability of scalable solar-driven water purification systems for offgrid rural Lesotho, with implications for sustainable development and climate adaptation, providing a viable approach to furthering Sustainable Development Goals 6 (Clean Water and Sanitation) and 7 (Affordable and Clean Energy) in Lesotho.

Acknowledgements

I wish to express my profound appreciation to everybody who has helped and guided me during the preparation of this Master's thesis.

I extend my sincere gratitude to my thesis supervisors, Professor Enock Jonathan and Mr. Moruti Kao, for their indispensable guidance, expertise, and steadfast support. Their constructive criticism, support, and perceptive input have been important in influencing the trajectory and caliber of this research.

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1. INTRODUCTION

1.1. Background

July 28, 2010 marks the date when the United Nations General Assembly members including the Kingdom of Lesotho, by way of Resolution 64/292, formally recognized the right to safe and clean drinking water and sanitation as an essential human right, fundamental for the full enjoyment of life and all other human rights [1]. At human level, ensuring sufficient clean water supply means ensuring sanitation and hygiene. The element of water, sanitation and hygiene (WASH) is necessary to achieve universal access due to its substantial impact on public health, food security, poverty reduction, and equality, and achievement of Sustainable Development Goal 6 (SDG 6) Clean Water and Sanitation. Despite this acknowledgment, many individuals globally sadly still do not have access to a safe drinking water source.

As per the World Health Organization (WHO), approximately 780 million individuals worldwide do not have access to safe drinking water, posing a significant obstacle to maintain hygiene, good health and prevention of life-threatening dehydration [2]. WHO states that diseases resulting from unsafe water, inadequate sanitation, and poor hygiene practices contribute to over 25% of the global environmental disease burden [3]. The consumption of this unsafe or contaminated water leads to health issues such as diarrhea, creating a substantial burden on communities [3]. Annually, around 1.8 million individuals across the globe, predominantly children under five years old in developing countries, succumb to diarrheal illnesses due to the consumption of unsafe water.
[4].

In rural areas of Lesotho, diarrheal diseases present a significant public health challenge, especially impacting infants and young children as a major cause of sickness and mortality, largely due to the consumption of unsafe drinking water [5]. Figure 1 displays a communal well in rural Lesotho, where bacterial contamination of drinking water considerably increases the prevalence of waterborne diseases. Communal water sources like wells and boreholes may be shielded from fecal contamination but remain untreated, posing health hazards [5] and necessitating the need for water purification technology regardless of the raw water sources.

Figure 1: Water access situation in some rural areas of Lesotho (Rural Water System ProjectLesotho)

Water and energy sustain human life on earth and are interconnected resources that cannot be produced or supplied independently of each other [6]. Energy in the form of electricity is needed to pump and treat raw water in conventional drinking water treatment plants (DWTPs) and therefore, access to safe drinking water relies on the conventional DWTP being connected to the national electricity grid. **Error! Reference source not found.** shows the energy demands for treating raw water from different water sources [1]. The established water treatment process, which involves coagulation, flocculation, sedimentation, and filtration, uses between 0.25 and 1.0 kWh/m³ for river water and groundwater sources, with the majority of this energy being used for pumping, transportation, and distribution [6].

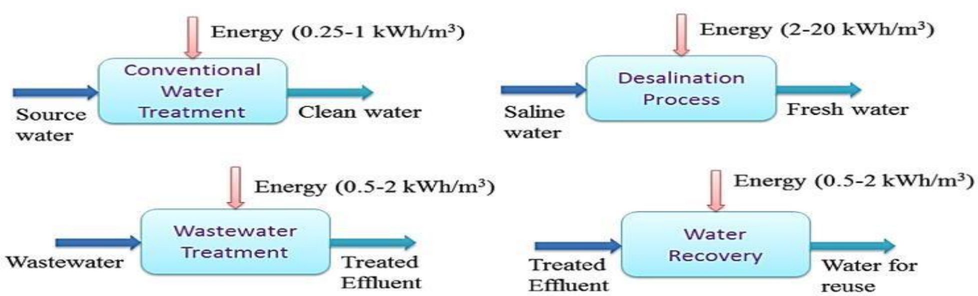


Figure 2: Energy requirements for water production from different water sources [6]

Traditional DWTPs consume a significant amount of energy, which is a concern amplified by the global energy crisis resulting from rising energy demands, depleting oil reserves, and substantial greenhouse gas emissions [7, 8], rendering them energy intensive and precluding their application in the rural settings of developing countries to include Lesotho that are not connected to the national grid. As of 2021, Lesotho's national electrification rate reached 41% of households, with a 10% rural electrification rate [8].The low levels of rural electrification does not only show an inevitable need for alternative sustainable energy in Lesotho, but also the ongoing water treatment problem in the rural areas of Lesotho. As such, there is an urgent need to harness alternative energy forms for decentralized water purification purposes.

Lesotho has the potential to benefit greatly from its abundant renewable energy resources and particularly, in the provision of those services that utilize energy as a service. According to Taele et al. [9], Lesotho possesses a significant renewable energy potential, such as hydro, solar, and wind. The utilization of these resources can address current and future energy challenges in both urban and rural Lesotho on affordable and clean energy as a service, including meeting the sustainable energy requirements for drinking water purification in off-grid rural Lesotho.

Noteworthy, solar energy, the most abundant renewable energy source, is particularly plentiful in developing countries where both clean water and sustainable (affordable and clean) energy are needed [10] as is the case with rural Lesotho. Lesotho receives approximately 3200-4000 hours of sunshine annually. Therefore, there is a scope to harness solar energy as an affordable and clean energy as a service for sustainable safe drinking water provision and also in support of decent sanitation and hygiene services in rural Lesotho.

1.2. Problem statement

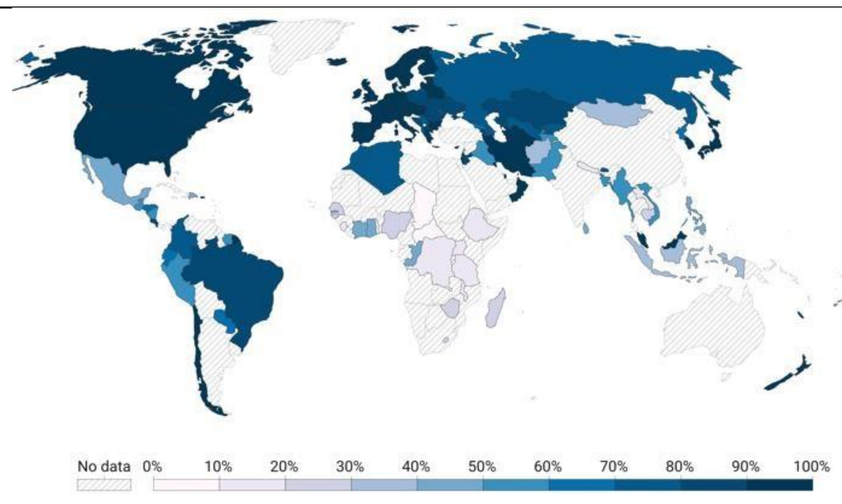
Lesotho in the context of the UN SDGs 2030 is striving for environmental sustainability and building a resilient economy that can withstand the effects of climate change. Therefore, it is vital for Basotho to have access to clean water for drinking, cooking, sanitation, and hygiene, in line with UN-SDG 6, which promotes fair access to safe water.

Despite Lesotho's abundance of rivers and groundwater resources, these are becoming more contaminated, particularly in rural regions. Escherichia coli (E. coli) contamination was found in all investigated water sources in the Mohale Basin, with levels ranging from less than 30 to as high as 4.35×10^2 cfu/100 ml, according to a study by Gwimbi et al. [5]. The study also discovered that 59% of locals defecated in the open, and that bacterial pollution of shared water sources was largely caused by livestock excrement and poorly placed latrines. Due to unsanitary water collection methods, inadequate source design, and a lack of fencing, even "protected" springs displayed pollution.

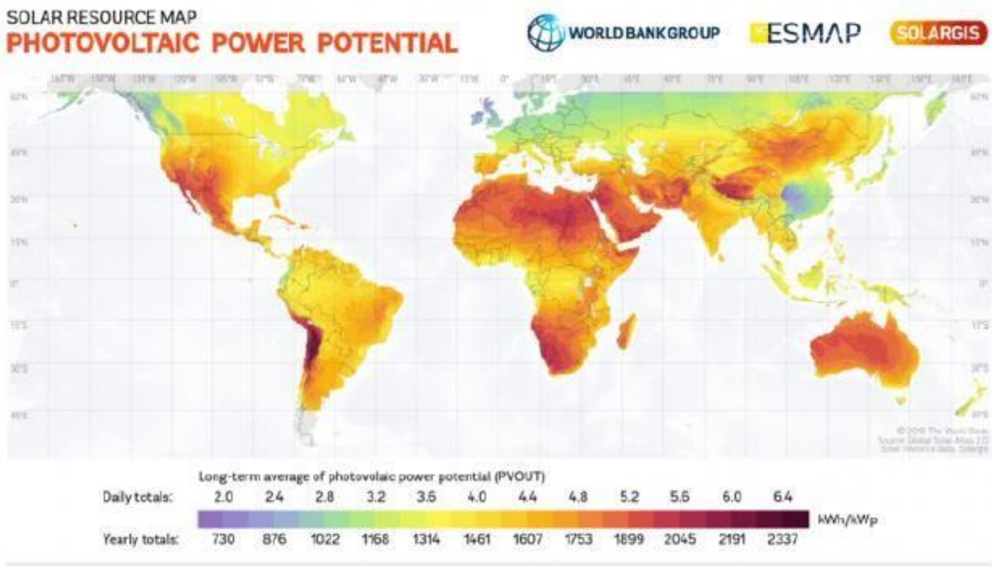
These findings highlight that current purification and protection methods are inadequate for safeguarding drinking water in off-grid rural communities. Existing household-level treatments, such as boiling, chlorine tablets, and solar stills, are often unreliable due to high fuel costs, inconsistent chemical availability, and limited ability to treat turbid or bacterially contaminated water. Furthermore, centralized purification facilities are impractical in such remote areas because they depend on grid electricity and complex infrastructure that are not available in rural Lesotho.

This growing public health concern underscores the urgent need for decentralized, energyindependent water purification systems capable of eliminating microbial contaminants at the point of use. Addressing this issue is essential not only to improve health outcomes and reduce waterborne diseases but also to support climate resilience and sustainable development in rural Lesotho.

In these off-grid areas, traditional drinking water treatment plants requiring connection to the national grid are impractical, but with the abundant solar resource depicted in Figure *3*, solar energy presents a feasible solution. Developing a solar-powered water purification system is crucial for providing clean water to rural communities. Solar energy is renewable, cost-effective, and environmentally friendly, making it an excellent power source for these systems. This approach offers a scalable technological solution to Lesotho's clean water challenges, enabling rural areas to access to safe and clean drinking water. Implementing this technology not only enhances the quality of life but also boosts Lesotho's rural water sector.



(a)



(b)

Figure 3 : Global Maps showing [11] (b) solar resource by the World Bank (a) population percentage with access to safely managed drinking water [12].

The solar water purification method has a rich history. Arab alchemists developed the first solar distillation device in 1551 to create fresh drinking water from contaminated or salty water [13]. In recent times, solar-powered membrane-based technologies are being favored due to their costeffectiveness and environmental friendliness compared to other solar-powered purification methods [14]. Additionally, in Saudi Arabia, Mokheimer et al. [15] introduced the initial theoretical models and optimization for hybrid wind-solar membrane based water filtration systems.

In Sub-Saharan Africa, a solar water distillation unit was developed, tested, and built by Nigeria to purify rural water for the residents of Rafin Tambari village in Bauchi, located at 10.4°N latitude and 9.5°E longitude [16]. The unit was created using only locally available and affordable materials. In 2019, Wydra et al. [17] conducted a research in Nigeria to discover sustainable solar energy-driven water supply solutions for rural communities in Sub-Saharan Africa. This research initiated a trial project in Abuja based on the rural community model, in collaboration with SC

Sustainable Concepts and PV Water International Limited. A solar-powered water disinfection system was installed at a Rural Health Center, providing the community with up to 20,000 gallons of safe drinking water daily and leading to reduced water and power expenses.

This study fills the gap by creating a decentralized solar photovoltaic-thermal (PVT) system combined with reverse osmosis (RO) and ultraviolet (UV) disinfection, offering an efficient, scalable, and climate-resilient alternative for providing safe water in rural areas.

1.3. Research Questions and Objectives

The study will attempt to answer the following questions:

- What are the energy consumption estimates for unit processes of the drinking water treatment plants to sustain community daily water requirements in line with WHO guidelines?
- What is the techno-socio-economic feasibility of using solar PVT and ambient UV to meet the energy consumption of the treatment plant with the long-term goal of energy independence and sustainability?
- How do the land use demands compare against the conventional DWTPs in urban areas?

The main objectives of the study are to:

- Model and simulate hybrid solar PVT-RO-UV water purification system for rural Lesotho.
- Obtain an overview on the situation of drinking water provision in rural regions of Lesotho and define factors that will inform selection of the most appropriate treatment technology.
- Obtain an overview on the one hand on water treatment technologies applied in rural regions of Lesotho and on the other hand commercially available devices for decentralized drinking water purification.
- Couple treatment devices for decentralized drinking water provision to a Solar PVT ambient UV system and to develop by this way, a stand-alone climate-smart green scalable water purification system that is market competitive in the areas of water quality, portability, and self-sustainability.
- To provide a viable business mechanism to stimulate the rural Lesotho economy

1.4. Justification

The 2007 policy for water and sanitation in Lesotho is designed to ensure that all citizens have access to reliable and sustainable water and sanitation services [18]. Nevertheless, many rural families still do not have access to clean water and improved sanitation, with 80% of the rural population depending on unsafe water sources and 66.2% lacking improved sanitation facilities. Provision of safe drinking water is a water-energy nexus problem. Without access to the national grid, rural communities lack the energy access for water purification. This research focuses on exploring off-grid water purification to improve water, sanitation, and hygiene in rural areas. Water-related issues are aggravated by climate change, especially in rural areas that are most severely affected due to the absence of access to the national electric grid. This research aims to create innovative, off-grid, climate-smart solutions, and its results will include practical recommendations for enhancing drinking water provision and proposing solar water purification systems.

1.5. Report Structure

The thesis report consists of five main chapters. The initial chapter provides background information on water access in the region and addresses the issues related to drinking water in Lesotho. It also outlines the objectives of the thesis and includes the problem statement. The second chapter reviews the literature on fundamental concepts and methodologies for developing solar founded drinking water treatment facility utilizing solar-powered membrane-based water purification, solar thermal disinfection, and solar ultraviolet (UV) light disinfection. It also presents a comprehensive overview of the constraints and methodologies related to solar-powered water filtration. The third chapter elucidates the research methodology, data, and constraints. The final two chapters present the results, followed by a discussion and conclusion.

2. LITERATURE REVIEW

2.1. Introduction

Access to clean drinking water remains a significant challenge in many rural regions of SubSaharan Africa, including Lesotho, primarily due to unreliable energy sources. This chapter contextualizes Lesotho's water access challenges and examines how solar-integrated systems can offer sustainable, decentralized water purification solutions for off-grid communities. It reviews key concepts, innovations, and technological advancements pertinent to the design and implementation of solar-powered water filtration systems. The discussion addresses the waterenergy nexus, the potential of solar energy in both thermal and photovoltaic applications, and recent progress in solar-assisted water treatment technologies.

The review concentrates on membrane-based purification systems, such as hybrid photovoltaicthermal (PVT) technologies, thermal desalination, solar ultraviolet (UV) disinfection, and solarpowered reverse osmosis (SPRO). These technologies align with Lesotho's abundant solar resources and the critical demand for low-carbon, decentralized water treatment in remote, offgrid locations. This focus also mirrors the global shift toward integrated, renewable-powered systems that offer modular scalability, enhanced efficiency, and the ability to treat various water sources, including cold-source, brackish, and microbiologically contaminated water, without reliance on centralized infrastructure or fossil fuels.

2.2. Water-Energy Nexus

Water and energy are fundamental natural resources that are intrinsically connected in both their production and consumption [6], [19], [20]. The water-energy nexus describes this interdependence and supports the development of integrated solutions that enhance resource security and sustainability while considering economic feasibility and minimizing environmental impacts [21], [22], [23]. Figure *4* illustrates that water is essential for energy generation, and energy is necessary for water-related processes such as groundwater extraction, surface water withdrawals, transmission, purification, and distribution.

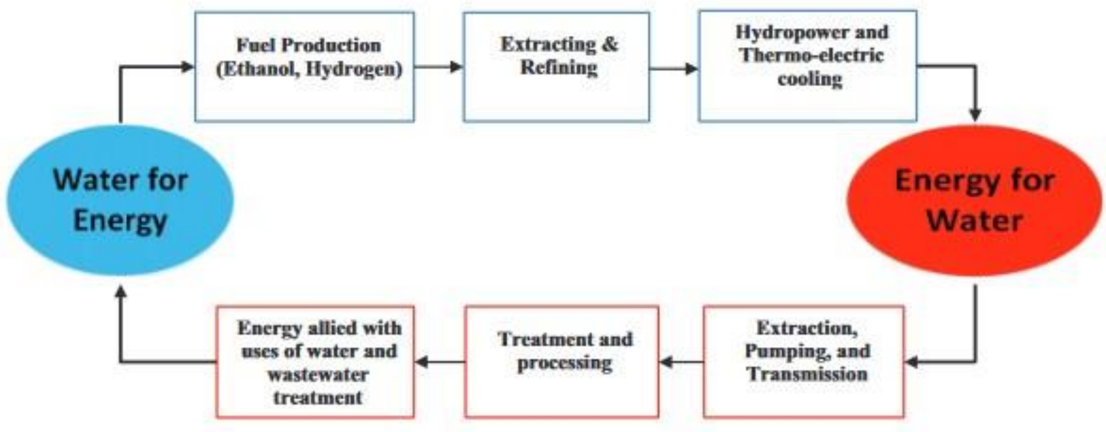


Figure 4: Water-Energy Nexus [20].

Supplying clean water requires significant energy for extracting, moving, treating, and distributing source water. Conventional drinking water treatment plants use about 7% to 8% of the world's grid energy. The amount of energy used depends on factors like the energy source, quality of the raw water, type of pumping system, size and age of the distribution network, materials used, land use, and the area's topography [24], [25], [26].

Most of the world's energy comes from fossil fuels like oil, gas, and coal, which leads to high greenhouse gas emissions. Gute [6] analyses how energy and water systems are connected, showing how water supply, wastewater treatment, and power generation depend on each other. Treating surface water to make it drinkable uses about 0.36 kWh per cubic meter (1.3 kJ per kilogram) [27], and some water treatment plants use as much energy as desalination methods like reverse osmosis.

In countries like Canada and Mexico, the energy needed to supply freshwater varies widely, from 0.25 to 3 kWh per cubic meter in Canada and 0.1 to 4.5 kWh per cubic meter in Mexico [28]. High energy use often comes from moving water long distances or pumping it from deep wells. Building infrastructure to bring water from far away also costs a lot. Smaller utilities usually use more electricity and pay more for each unit of water than larger ones because they cannot benefit as much from economies of scale. About 80% of the electricity goes to motors that pump and move the water [29]. Figure *5* depicts an overview how intense the energy can be at various stages of the water cycle, whereby the average values of the benchmarking studies are used, while **Error!**

Reference source not found. shows average energy use at different stages of the water cycle, from the source to the end user.

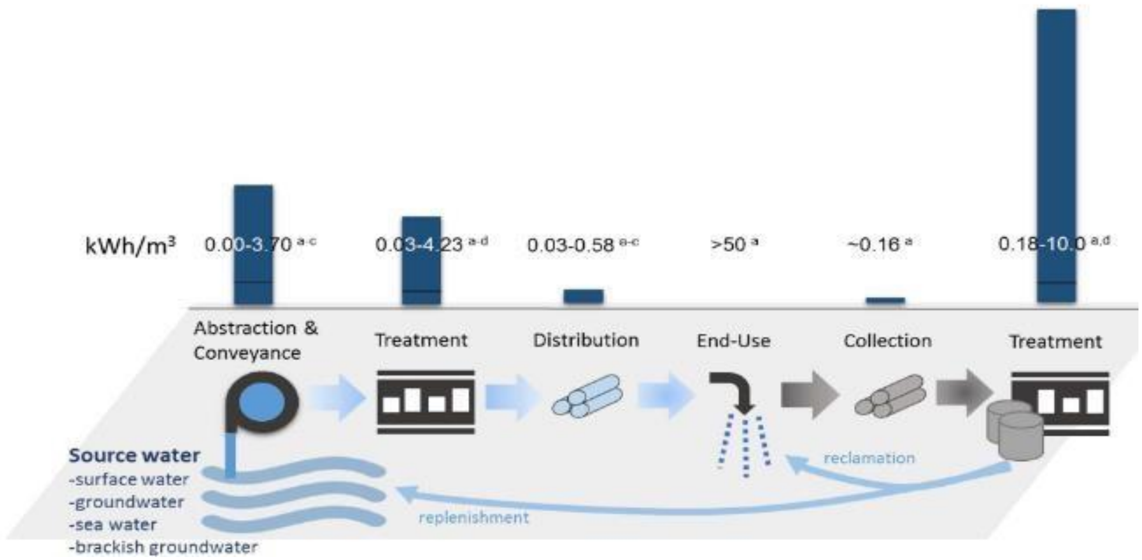


Figure 5: The summary of the energy requirement range at different stages of the urban water cycle using average values of benchmarking studies [24].

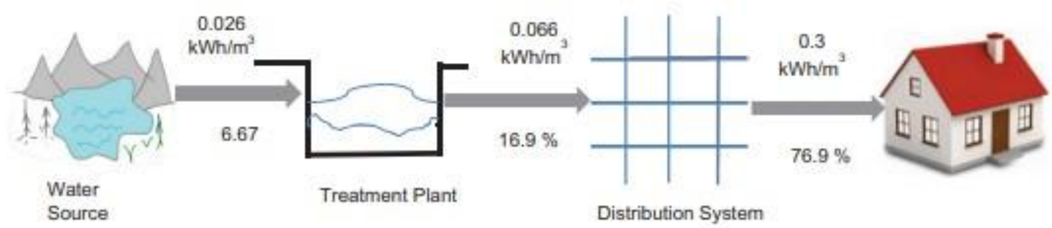


Figure 6: Energy use in each step of drinking water system from source to end user (residential) in flat terrain (developed using data from EPA 2013) [20].

The water-energy nexus in drinking water treatment and distribution highlights the sector's reliance on energy, often referred to as energy embeddedness, which denotes the inherent energy requirements of these processes [26]. Drinking water treatment is essential for public health but remains energy-intensive [7]. Furthermore, the nexus contributes to environmental impacts such as carbon emissions from fossil fuel-based energy sources.

The close link between energy use and drinking water treatment, known as 'energy embeddedness,' makes it difficult for off-grid communities especially in rural Southern Africa to access clean water. This challenge has serious health and sanitation impacts, as highlighted by the UN Sustainable Development Goals. To address this, there is a need for new ways to meet the energy needs of water treatment, such as using alternative or renewable energy sources in off-grid areas. This approach also helps water treatment plants reduce their carbon footprint. Figure *7* shows an example of a stand-alone solar-powered water treatment system.

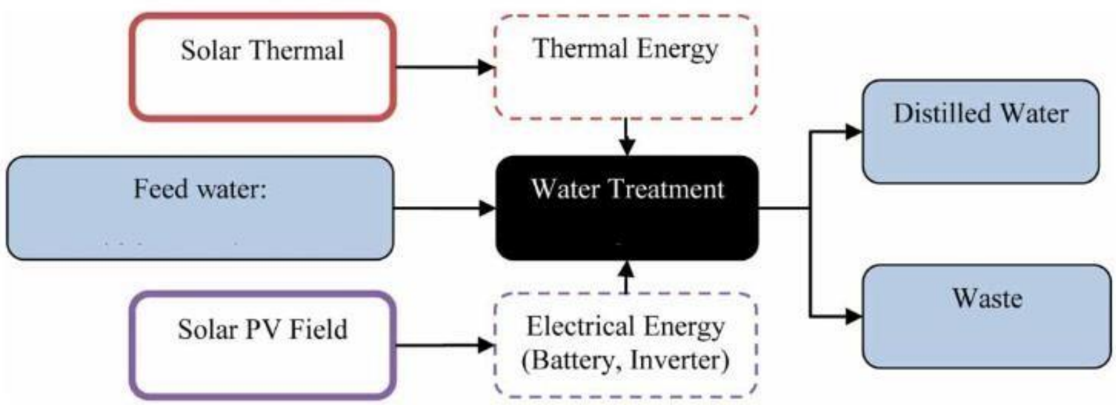


Figure 7: Schematics of stand-alone solar founded water treatment system [30].

Renewable energy sources offer a practical solution to mitigate the environmental damage caused by fossil fuels [31] and enhance energy access in off-grid areas. Solar energy, as a clean resource, enables sustainable drinking water treatment by fulfilling energy needs, reducing greenhouse gas emissions, and promoting energy independence.

2.3. Solar Energy as A Resource

2.3.1. Solar energy review

Solar energy originates from nuclear fusion in the Sun's core, which generates high temperatures and continuously releases substantial energy. This process emits electromagnetic radiation across wavelengths from infrared to ultraviolet [32]. About one-third of this radiation is reflected by Earth's atmosphere, while atmospheric gases, particularly ozone, absorb most ultraviolet wavelengths. As a result, not all solar radiation reaches Earth's surface. The amount of solar radiation received is quantified as irradiance (W/m^2), representing energy per unit area [33].

Solar energy stands out as the most abundant renewable resource, surpassing wind, hydro, and geothermal sources. The Sun, located about 150 million kilometers from Earth, produces an immense amount of energy. Of this, approximately 1.8×10^{14} kW reach our planet [34]. About 60% of that energy, or 1.08×10^{14} kW, arrives at Earth's surface, while the rest is absorbed by the atmosphere or reflected away. If just 0.1% of this solar energy were captured with 10% efficiency, it could generate around 3000 GW—four times the world's current total generating capacity [35].

Lesotho receives daily solar radiation ranging from 5.5 to 6.5 kWh per square meter, with southwestern regions averaging over 7.2 kWh per square meter per day. The country experiences between 3,200 and 4,000 sunshine hours annually, and theoretically receives 60 x 10^{12} kWh of solar power each year [36], [37]. Harnessing this solar radiation for energy production could significantly support water treatment facilities. Figure 8 presents a modified solar map alongside the existing electricity transmission network for Lesotho, as referenced in [36] and [37]. Figure 8 demonstrates that the highest solar potential is found in areas not currently served by the national power grid, highlighting considerable opportunities for renewable energy deployment in these regions. The solar map indicates high solar energy output across most of the country, particularly in remote and off-grid areas where access to the grid is limited or nonexistent. This substantial solar resource base offers a strategic opportunity to implement solar-powered infrastructure, such as water purification systems. Deploying such systems at the water-energy nexus could address both energy and water access challenges, thereby improving the well-being of communities in underserved regions.

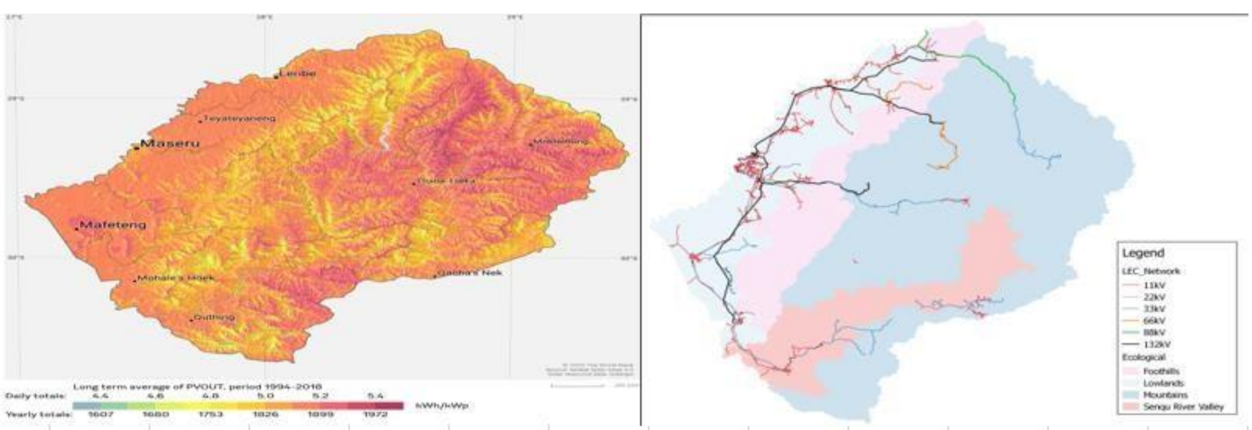


Figure 8: Lesotho’s solar resource (left) and the existing electricity transmission and distribution Network (right) [38], [39].

These areas also have abundance of water. As shown in Figure *9*, the areas have about six big dams and rivers as sources of water.

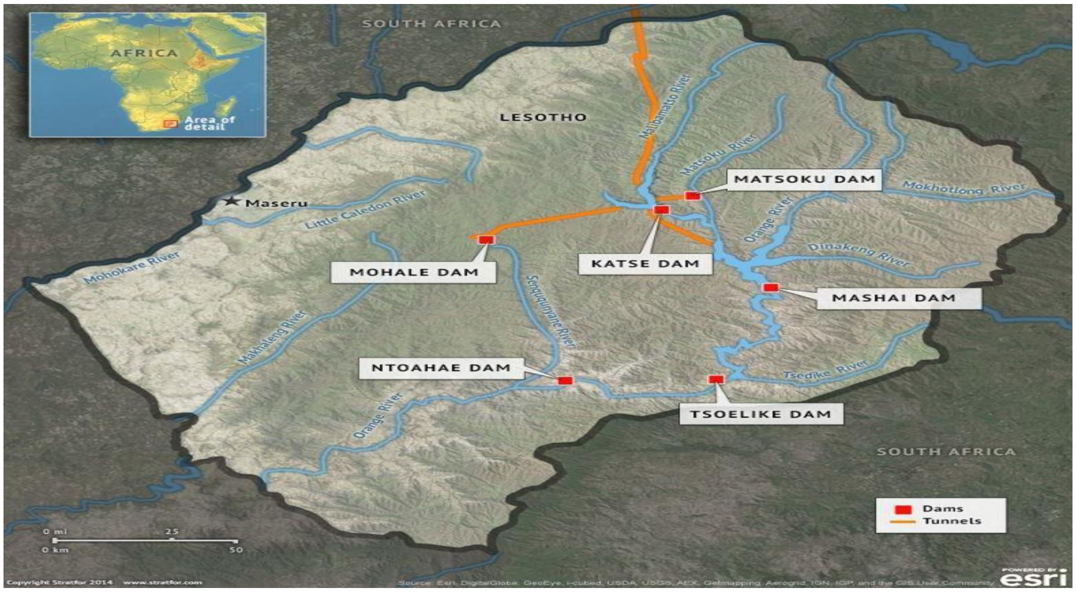


Figure 9: Lesotho hydrology map

2.3.2. Solar as a Spectrum Source

The sun emits a broad spectrum of electromagnetic radiation, including visible light, infrared radiation, and ultraviolet (UV) radiation. Visible light is particularly significant for photovoltaic (PV) systems because its photon energy efficiently excites electrons in semiconductor materials, thereby generating electricity via the photovoltaic effect. Consequently, visible light contributes most to the electrical output of PV panels.

Infrared radiation (IR) is the primary energy source for solar thermal collectors, including flatplate and evacuated tube systems, as it is absorbed to heat air or water. This makes IR essential for applications such as space heating and domestic water heating. In contrast, ultraviolet light possesses a shorter wavelength and higher energy than visible light [40]. Ultraviolet wavelengths range from 100 to 400 nm, but those below 280 nm are absorbed by the atmosphere and do not reach the Earth's surface [31].

Ultraviolet (UV) radiation exposure has both positive and negative impacts on the environment and human health. In humans, brief exposure to UV radiation stimulates vitamin D synthesis and increases skin pigmentation, which provides partial protection against further UV damage. However, UV radiation can cause sunburn, particularly in individuals with certain skin types.

Prolonged exposure also accelerates the development of wrinkles and skin aging, both of which are risk factors for skin cancer [33][35].

Regarding environmental effects, UV radiation can penetrate various materials, including clothing, vegetation, and water. Over a century ago, European researchers demonstrated that sunlight exposure sterilizes the surface layer of lake water [42]. This finding suggests that UV radiation has potential applications in water purification, in addition to its recognized carcinogenic risks.

2.4. Solar Technologies

This section describes technologies used to harness the sun's energy into useful energy. These technologies include solar photovoltaics, solar thermal systems and Solar PVT.

2.4.1. Solar Thermal Systems

Solar thermal technology utilizes solar radiation, specifically infrared radiation, which is absorbed by a solar collector and converted into heat energy. This heat is subsequently transferred to a working fluid such as water, oil, or air [43]. Thermal storage systems retain heat energy for later use, supporting continuous operation during periods without sunlight. In water purification applications, commonly used solar collectors include flat plate collectors, evacuated tube collectors, and concentrated solar collectors [44], [45], [46].

2.4.1.1. Flat Plate collectors (FPC)

Figure 10 illustrates a flat plate collector (FPC) and its components. The absorber plate is typically coated black to enhance solar energy absorption. Copper pipes, which transport water or antifreeze, are soldered or bonded directly to the plate to maximize surface contact and promote efficient heat conduction as the plate heats [47]. High-temperature rigid foam insulation is installed beneath the absorber to minimize heat loss. The assembly is housed within a protective shell that shields internal components from adverse weather, including wind and ice. To reduce reflection, the frostresistant glazing cover is often tinted dark or blue. FPCs operate effectively in diffuse or low-light conditions due to their reliance on heat absorption. However, their performance is optimal when the sun is directly overhead; at lower solar angles, increased reflection from the glazing reduces efficiency. FPCs can achieve maximum operating temperatures of up to 90°C, with typical efficiencies ranging from 40% to 60% [48].

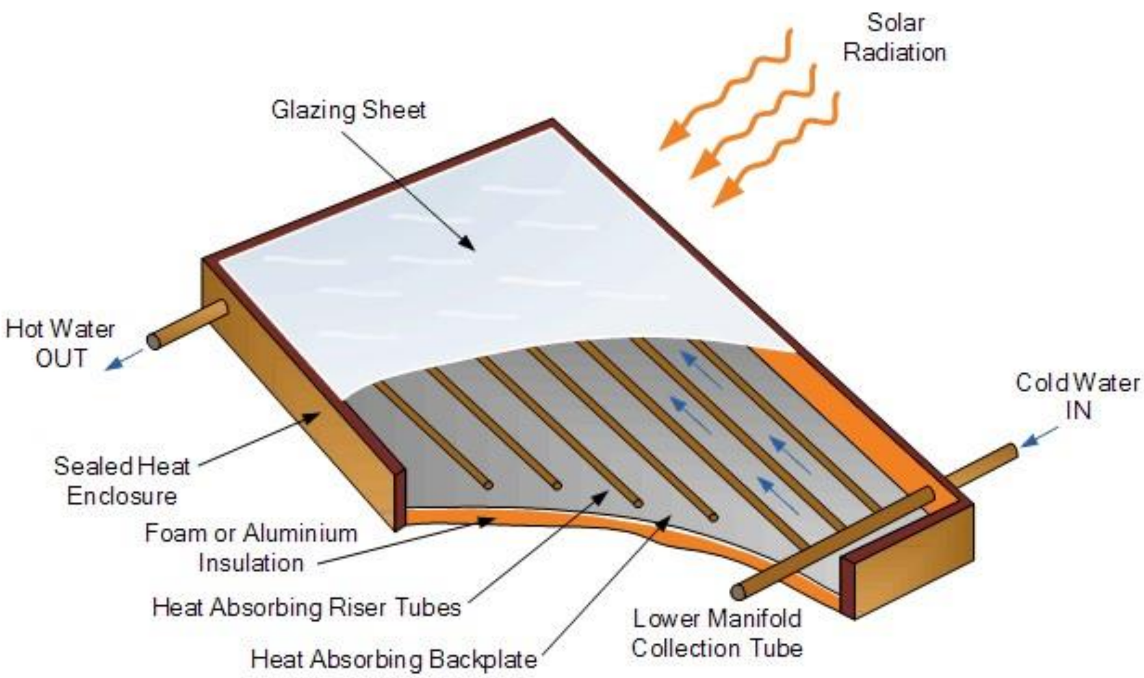


Figure 10: Flat plate collector (glazed) [47].

2.4.1.2. Evacuated tube collector (ETC)

The cylindrical geometry of evacuated tube collectors (ETCs) ensures that sunlight strikes the absorber surface at a nearly perpendicular angle throughout the day, thereby enhancing their effectiveness compared to flat plate collectors (FPCs) [49]. Typically, ETCs are installed in rows on a frame supported by transparent glass. Figure 5 illustrates the structure and components of an ETC. This type of solar collector can withstand extreme temperatures, exceeding 200°C in summer and 50°C in winter [47]. ETCs exhibit high thermal efficiency, particularly at temperatures above 80°C, when equipped with vacuum insulation and a highly selective absorber surface coating.

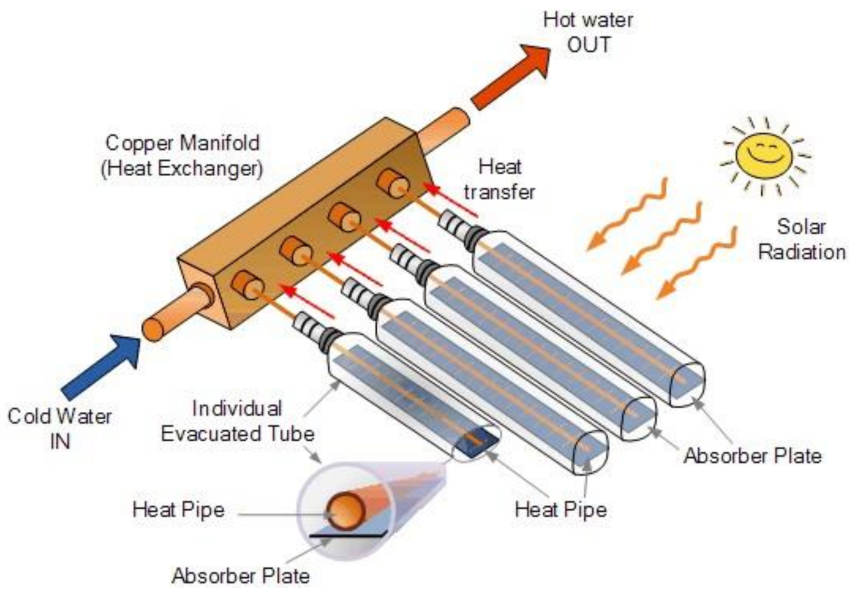


Figure 11: Evacuated tube collector [47].

2.4.1.3. Concentrated Solar collectors

Concentrated solar power (CSP) is a renewable energy technology that uses a photothermal process to convert sunlight into high-temperature heat, which is then used to generate electricity [5]. When integrated with thermal energy storage (TES) systems, CSP is considered a reliable solution for large-scale renewable energy production. CSP technologies, such as solar power towers and parabolic trough collectors, focus sunlight to produce thermal energy that can be stored and later converted into electricity. This capability addresses the intermittency challenges commonly associated with solar energy [50]. The use of molten salts in CSP systems enables both efficient thermal energy storage and heat transfer, allowing plants to operate at higher temperatures and maintain power generation throughout the day. Figure 12 illustrates the various CSP technologies.

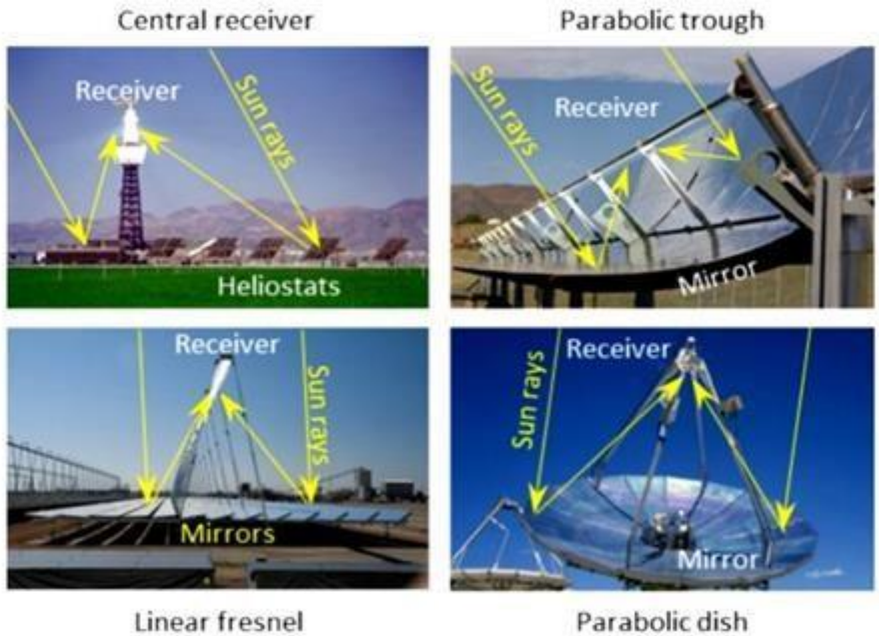


Figure 12: various concentrated solar collector technologies [50].

Singh and Tiwari [5] conducted a comprehensive review highlighting the role of concentrated solar collectors, such as solar parabolic dish concentrators, compound parabolic collectors (CPCs), and parabolic trough collectors (PTCs), in improving the thermal efficiency of solar desalination systems. These collectors achieve higher operating temperatures than flat-plate or evacuated tube collectors by focusing solar energy onto a specific line or point. Such elevated temperatures are well-suited for thermal distillation processes, including direct steam generation for water purification and sterilization, as well as multi-effect distillation (MED). Notably, CPCs maintain relatively high optical efficiency even without sun tracking, making them appropriate for mediumtemperature applications in decentralized or rural settings. The review also identified short energy payback periods and environmentally favorable operation, supporting the long-term use of these systems for water filtration in regions with high solar insolation.

Table 1: Comparison of solar thermal collectors

Collector type	Advantages	Disadvantages
Flat plate collector	It is easy to use, long-lasting, and climate-appropriate. Since	Cold or overcast weather reduces efficiency. To reduce heat loss

	the FPCs require absorbed heat to function, they can operate even under foggy or diffused light conditions [48].	during periods of low sunshine, adequate insulation is necessary [47]. The amount of clarity in the sky determines how quickly fluid circulates between a storage tank and a flat plate collector; overcast skies slow down circulation [48]
Evacuated tube collector	Because the vacuum inside the tubes reduces heat loss, they are more effective than flatplate collectors, especially in colder and cloudier conditions. They can even tolerate summer temperatures beyond 200°C [49] [47].	more expensive and brittle because of the glass tubes. Additionally, replacing damaged tubes might be expensive.
Concentrated Solar Collectors (e.g., Parabolic Trough Collectors)	Very effective at heating vast amounts of water, particularly in large-scale or industrial settings. Perfect for places with strong, steady sunshine [51].	costly and difficult to install, needing exact sun tracking and alignment. In general, household use is not recommended [51]. Also uses more land compared to ETCs [52]

2.4.2. Solar Photovoltaic

Photovoltaic (PV) technology refers to the direct conversion of solar radiation, particularly visible light, into electrical energy. Solar PV has demonstrated significant growth in the renewable energy sector. In 2022, it generated 270 terawatt-hours (TWh) of electricity, representing a 26% increase from the previous year. This achievement marked the first instance in which solar PV exceeded wind power in annual growth of electricity generation. Consequently, solar PV has become the third-largest contributor to global renewable energy production [53].

Solar PV systems comprise four primary components. Firstly, solar cells employ the photovoltaic effect to convert light into electricity [54]. Secondly, charge controllers, also known as charge regulators, regulate current and voltage to prevent battery overcharging or overdischarging. Thirdly, batteries store excess energy for use during periods of insufficient sunlight. Finally, inverters convert direct current from batteries or modules into alternating current, which is suitable for standard appliances.

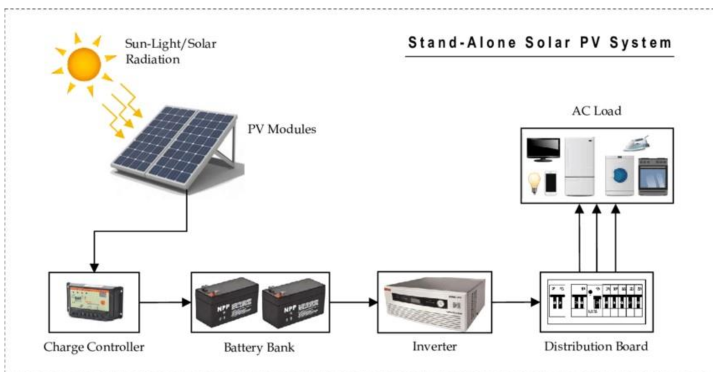


Figure 13: Standalone PV system with battery backup

2.4.3. Solar Photovoltaic Thermal system

Solar Photovoltaic Thermal (PVT) technology combines photovoltaic (PV) and thermal systems into a single unit, generating both electricity and thermal energy simultaneously. This configuration addresses the limitation of conventional PV panels, where excess heat reduces electrical efficiency, by incorporating a thermal collector that captures waste heat for practical uses such as water purification [55]. The development of PVT technology aims to cool PV cells, enhance electrical efficiency, and recover additional thermal energy, thereby utilizing the full spectrum of solar radiation. PVT collectors can achieve overall efficiencies of 60-80%, significantly surpassing those of standalone PV panels [56]. Figure *14* shows a solar PVT collector.

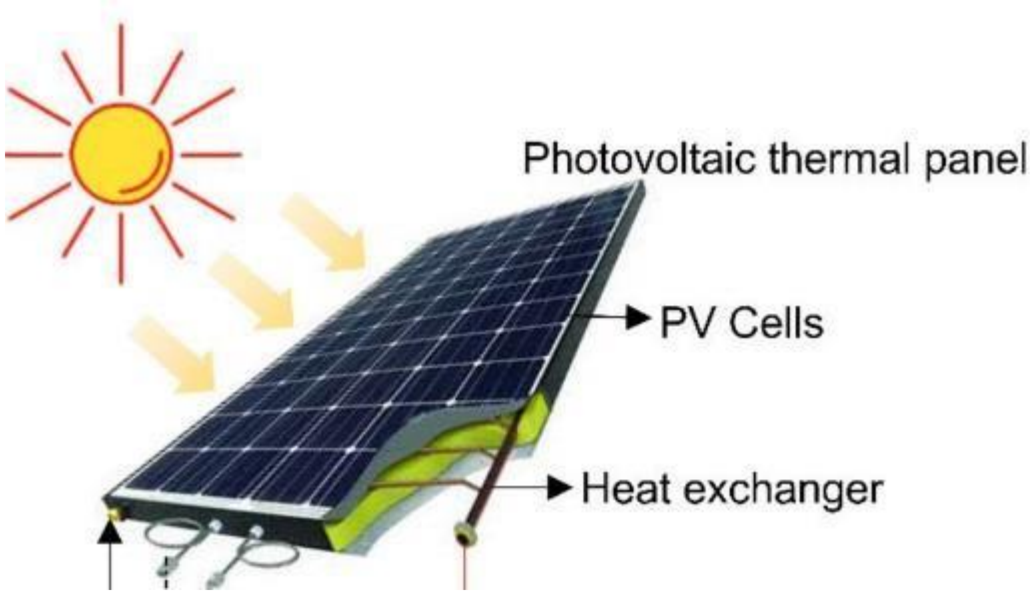


Figure 14: PVT module [57].

Following the literature on solar technologies, Table *2* compares these technologies in terms of their working principle, land use, efficiency and many other aspects including feasibility in Lesotho.

Table 2: Technologies and their shortcomings

Aspect	Solar Thermal	Photovoltaic (PV)	Photovoltaic Thermal (PVT)
Main output	Heat	Electricity	Electricity +Heat
Working principle	Heat absorption by collectors	PV effect using semiconductors	Combines PV cells with thermal collectors
Efficiency	30-70%	15-22%	50-80% combined
Land use	Large area needed for large-scale heat	Medium	More compact than separate systems
Best use case in Lesotho	Water heating for homes, clinics	Lighting, appliances	water heating + power
Cost	Moderate	Moderate to high	High initial cost
System complexity	Moderate (requires plumbing)	Low	High (hybrid integration)

Cold weather impact	Heat losses in winter	Improved perform due to cooling	Improved PV performance due to cooling but reduce thermal performance
Storage	Thermal tank	Battery storage	Dual storage; Battery +tank
Maintenance	Medium (scaling, leaks)	Low	High (dual-system upkeep)
Current Adoption in Lesotho	Growing in urban areas	High	Rare; research stage
Challenges in Lesotho	Heat loss, skill gap	Theft, poor cost, imports	High cost, lack of expertise

2.5. Water Treatment Technologies State of Art

The solar water purification system is a water decontamination system at the household and industrial level based on the direct use of solar energy and indirect use of solar energy to convert it into heat or electricity [13].

2.5.1. Solar ultraviolet based water disinfection

Ultraviolet (UV) irradiation is a widely used water treatment technique for disinfecting drinking water. In the 1990s, its adoption increased due to its demonstrated effectiveness against waterborne pathogens such as Giardia and Cryptosporidium. Low-pressure UV systems produce negligible disinfection byproducts, thereby eliminating the need for chemical additives, unlike conventional methods such as ozonation or chlorination [58]. The process is straightforward, requiring only the placement of water in a transparent container exposed to direct sunlight for several hours. This approach is also cost-effective, with an estimated annual expense of $0.63 per person when using a transparent glass or plastic container [59].

UVA radiation from the sun is generally effective in killing bacteria, whereas UVB radiation is lethal to bacteria, viruses, and protozoa. No adverse effects on water taste have been reported [60]. According to Paidalwar A. A [40], exposure of microorganisms to UV radiation results in a consistent proportion of the population being deactivated over time. This dose-response relationship indicates that a high-intensity UV dose administered briefly can achieve the same inactivation as a lower-intensity dose applied over a longer period. The required UV dose for effective inactivation depends on site-specific factors such as water quality and the desired level of microbial reduction.

2.5.2. Solar Thermal-based Water Purification System

The solar thermal technologies use solar energy to heat water and create steam or vapor, which eliminates impurities like salt and other pollutants and makes the water suitable for drinking or other applications. These devices transform solar radiation into heat, which is then used in a number of purification procedures, such as pasteurization, desalination, and distillation.

Tarik et al. [6] developed an enhanced solar water distillation system by integrating a flat plate solar water collector with a spinning hollow cylinder. The collector preheats the water, while the rotating cylinder increases the evaporation surface area, resulting in higher productivity. The modified system achieves a yield of 3,540 mL per square meter per day at a water depth of 2 centimeters, representing a 188% increase over traditional stills. Incorporating auto-adjusted rotation based on solar intensity further improved performance, resulting in a 310% increase at optimal rotation rates of 0.5 to 1 revolution per minute. Although the system requires a higher initial investment, it reduces water production costs to 136 ID per liter, compared to 175 ID per liter for conventional designs.

Sharma et al. [4] experimentally investigates a single-slope solar water purification system equipped with a series of evacuated tubular collectors (ETCs). The use of 13 ETCs in sequence significantly enhance the thermal performance of the solar still, achieving a maximum freshwater yield of 7.1 kilograms per square meter per day, nearly double that of previous ETC-based systems. The vacuum insulation of the evacuated tubes minimized convective heat losses, enabling higher basin water temperatures, both of which are critical for increasing evaporation and distillate output. Exergoeconomic and enviroeconomic analyses indicate that the system is environmentally sustainable and energy-efficient, with an energy payback period of 1.72 years. These findings underscore the value of ETCs in solar-assisted water purification, particularly in high-altitude or cold regions, such as Lesotho, where thermal energy conservation is crucial for continuous operation.

He et al. [56] identify two primary types of thermal distillation for water purification: passive and active. Passive methods, such as solar stills, use direct thermal energy from sources like solar heat to promote evaporation and freshwater production. Although solar stills are simple and have low initial costs, they are limited by low energy efficiency and restricted water output due to significant heat loss. To address these limitations, researchers have focused on optimizing system design and developing heat recovery techniques to improve energy efficiency. He et al. emphasize the need for efficient thermal energy use, particularly through repeated latent heat recovery, to enhance purification system performance. Recent advances in passive solar thermal (ST) distillation includes novel materials and device designs that increase water production and reduce costs. For instance, nanomaterials have been engineered to localize and concentrate solar heat, minimizing energy losses [61]. Multi-stage devices have also been implemented to recover latent heat, resulting in solar-to-vapor efficiencies of 138-385% and production rates of 1.8-5.8 $L/(m^2 \cdot h)$ [55].

In a solar still, solar thermal water purification relies on heat transfer mechanisms to capture and utilize solar energy. The black bottom of the still absorbs approximately 80% of incident solar radiation, which increases the temperature of both the water and the still's surface [62]. Heat is then transferred from the water's surface to the condensation surface at the top through radiation, convection, and evaporation. Any heat lost through radiation from the water's top and bottom does not contribute to water production and is considered a loss [63]. The glass cover permits solar energy to enter the basin and enhances the greenhouse effect by retaining heat within the solar still.

Effective condensation requires maximizing heat transfer to the upper surface while minimizing heat loss through the side walls. Heat transported from the condensation surface is released into the environment via convection and radiation. The system reaches a steady state when heat intake equals total heat transfer, including losses. Condensation efficiency is defined as the proportion of heat converted into condensation output and is determined by the system's ability to transfer heat for water condensation. To optimize performance, key parameters for heat transfer and mass flow are estimated numerically using MATLAB. Figure 15 illustrates the different heat transfer pathways in a solar still. Checked boxes represent beneficial heat transfer routes, while crossed boxes indicate mechanisms responsible for heat losses.

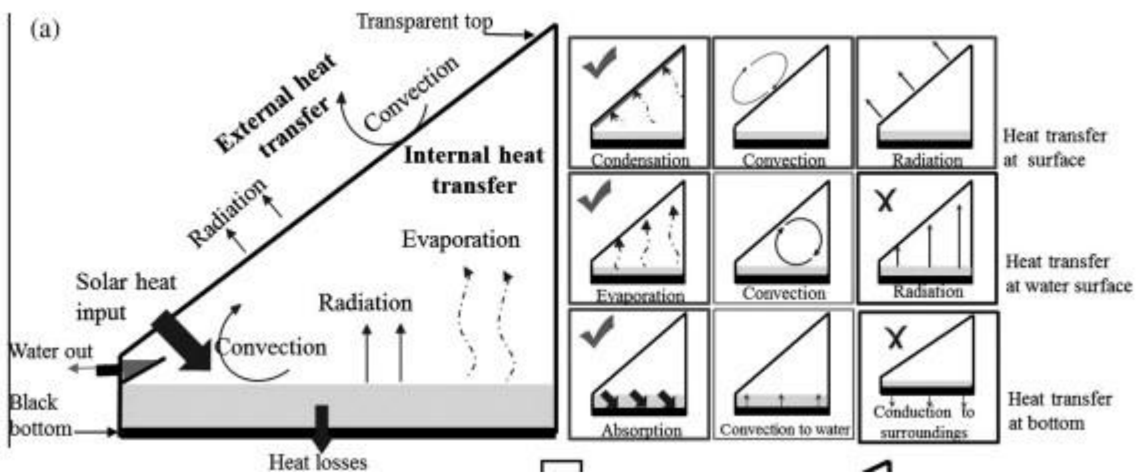


Figure 15: Heat transfer schematic in a solar still [62].

This type of system demonstrates an average distilled water output of 4 to 5 liters per square meter per day and an efficiency of 30 to 40 percent [62]. Various enhancements including integration with flat-plate solar collectors, heat pumps, sponge cubes, phase change materials, energy storage materials, wick materials, sun-tracking systems, vacuum techniques, specialized coatings, and external reflectors, substantially improve daily water production and operational efficiency in solar stills.

Active thermal distillation regulates pressure and temperature to induce the phase change of water into vapor. Multi-stage flash (MSF) distillation exemplifies this approach by heating brine and subjecting it to flash evaporation at progressively lower temperatures and pressures across multiple stages. In each stage, water evaporates from the brine, and the resulting vapor condenses to produce distilled water. The process begins with feed water cooling as it passes over the condenser, followed by gradual heating through subsequent stages. This sequential heating supports continuous cycles of evaporation and condensation, resulting in greater efficiency compared to passive methods [56]. Figure 16 presents the schematic flow sheet of a multi-stage flash distillation system.

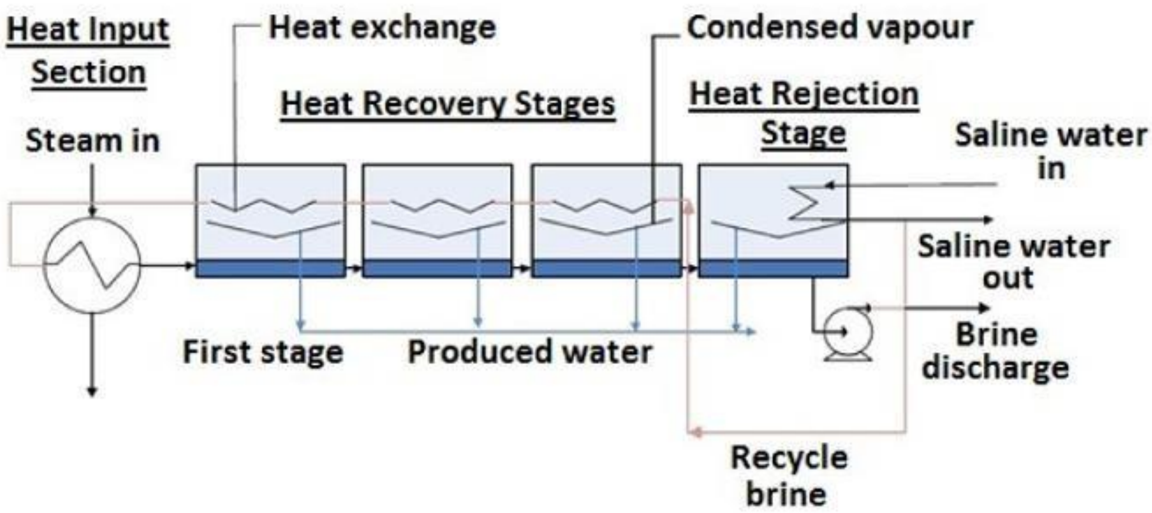


Figure 16: Schematic of a multi-stage flash distillation [64].

2.5.3. Solar PV – based water treatment

Solar powered membrane purification systems

Membrane-based water purification is considered the most promising among solar-powered water purification technologies because of its economic viability and environmental benefits [13]. The primary membrane-based technologies evaluated in this review include solar-powered reverse osmosis (SPRO) [65], solar-powered forward osmosis (SPFO) [66], solar-powered electrodialysis (SPED) [67], solar-powered membrane distillation (SPMD), and solar-powered hybrid membrane systems (SPHMS) [13]. Among these, SPRO is the most widely implemented, accounting for 38% of reported applications.

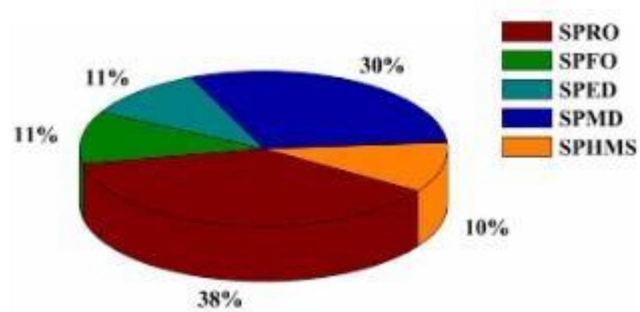


Figure 17: application of the membrane based purification technologies [13].

Membrane-based water purification systems, particularly reverse osmosis (RO), are frequently powered by solar photovoltaics. Saraceno (2005) developed a portable solar-powered water purifier designed to drive a pump and facilitate water flow to the purification unit. Wright (2011) introduced a water purification device that integrates a solar-powered system with a purification filter. Elasaad et al. (2015) constructed and evaluated a photovoltaic-powered reverse osmosis (PVRO) system in a rural region of Mexico [68].

2.5.3.1. Solar Powered Reverse Osmosis (SPRO)

Reverse osmosis (RO) is a pressure-driven membrane separation process that removes ions, proteins, and organic compounds from feed water by applying high pressure to a semi-permeable membrane, thereby reversing the natural osmosis process [1]. RO systems are available in capacities ranging from 0.1 m^3/day to 395,000 m^3/day and are integral to the desalination industry [14]. The modular design and compact footprint of RO technology facilitate integration with other water treatment methods [69]. High pressure is applied to one side of the membrane to drive water molecules through, effectively separating them from contaminants [70].

Reverse osmosis (RO) is a membrane-based water purification technology that can be integrated with solar energy systems for freshwater production from water and wastewater sources, as well as for the cost-effective desalination of brackish and saltwater [13]. RO is highly efficient at removing impurities and desalinating brackish and saltwater to produce potable water. However, the process requires substantial energy input, consuming 0.5 to 2.5 kWh per cubic meter for brackish water and 3 to 10 kWh per cubic meter for seawater. While RO is capable of removing bacteria, it is not recommended for this application because bacterial biofilms on the membrane surface can cause damage [1] [13]. Figure 18 shows a schematic diagram of a solar-powered reverse osmosis system.

Figure 18: A schematic for SPRO system [71].

2.5.3.2. Solar Powered Forward Osmosis

Forward Osmosis (FO) utilizes the osmotic pressure differential between two liquids of varying concentrations. In this process, water moves through a semipermeable membrane from a lowsalinity feed solution, such as saltwater or wastewater, to a more concentrated draw solution that may contain salts or sugars [66]. Unlike Reverse Osmosis (RO), which requires high pressure, FO operates without the need for elevated pressure. After permeation, water is separated from the draw solution, a step that can be facilitated by solar heating for regeneration [13]. Solar-powered FO systems typically incorporate solar thermal collectors to supply the low-temperature heat necessary for draw solution replenishment.

Forward osmosis (FO) consumes less energy than reverse osmosis due to its operation at ambient pressure and its lower tendency for membrane fouling, which also simplifies maintenance. However, FO is limited by internal concentration polarization, which decreases water flux, and by the ongoing requirement to replenish the draw solution after water extraction [66].

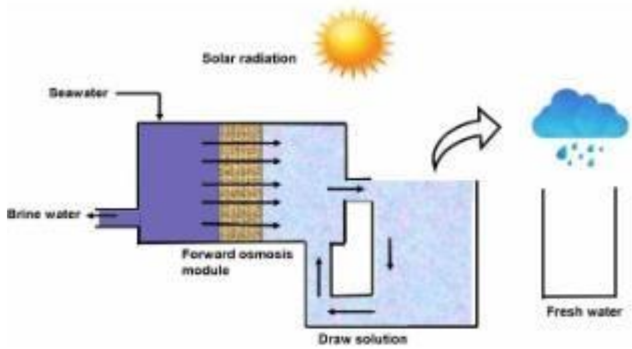


Figure 19: A schematic for SPFO [13].

2.5.3.3. Solar Powered Electrodialysis

Electrodialysis (ED) is an effective technique for desalinating brackish water, offering selective ion removal and relatively low energy consumption for specific applications. Its performance declines with highly saline water, such as seawater, and issues such as fouling and scaling can arise when certain ions are present in high concentrations. Electrodialysis is an electrochemical process that enables the transport of ions across ion-exchange membranes under an electric field. Water passes between cation-exchange and anion-exchange membranes, which selectively permit the movement of positive and negative ions, respectively [67]. This process efficiently removes salts to produce fresh water. In solar-powered electrodialysis systems, photovoltaic panels commonly supply the required electrical power. Because electrical demand increases with higher salt concentrations, electrodialysis is particularly suitable for brackish water treatment, where it consumes less electricity than when treating seawater [13].

2.5.3.4. Hybrid Membrane Systems

Hybrid membrane systems enhance performance and efficiency by integrating multiple membrane technologies, such as Forward Osmosis (FO) with Electrodialysis (ED) or Reverse Osmosis (RO) with Membrane Distillation (MD). This integration mitigates the limitations of individual technologies while leveraging their respective strengths. For example, a FO-RO hybrid system can reduce overall energy consumption by employing FO to draw water through a membrane via osmotic pressure and RO to recover water from the draw solution. Furthermore, hybrid systems can incorporate solar energy in several ways. Solar thermal energy may be applied to heat water for distillation or related processes, and solar photovoltaic (PV) systems can supply power to pumps [13].

Hybrid membrane systems are adaptable to diverse water sources and environmental conditions, providing increased efficiency, higher water recovery rates, and enhanced compatibility with renewable energy sources. However, the implementation of these systems is often associated with significant costs and operational complexity, necessitating advanced control systems and specialized expertise to manage the integrated processes effectively [13].

2.5.4. SOLAR PVT Based Water Purification

Solar photovoltaic-thermal (PVT) technology has become increasingly prominent in sustainable water treatment applications, including desalination and purification. This technology is particularly advantageous in arid and remote regions where both water scarcity and limited access to electricity present significant challenges. The thermal energy generated by the PVT system is used to preheat feed water, which enhances the efficiency of desalination processes such as solar stills, reverse osmosis (RO), and multi-effect distillation (MED). Furthermore, the electricity produced by the system can be utilized to operate auxiliary equipment or stored for subsequent use.

2.5.4.1. PVT collector integrated in a solar Still

Solar-powered distillation is often employed for small-scale water purification in rural areas that lack access to clean water and reliable energy. Kumar and Tiwari [72] studied a hybrid system that combines a 0.66 m^2 PV panel with a 2 m^2 solar flat plate collector. In this setup, water flows behind the PV panel to cool it and absorb its heat, which then warms the water, improving the system's efficiency. Because it can operate independently, this type of solar still works well in remote locations and can produce 3.2 to 5.5 times more water than a standard passive solar still. Currently, producing fresh water with this hybrid system costs approximately 60% more than with traditional solar stills. However, as PV panel demand increases and technology improves, the costs for both PV panels and water production are likely to go down.

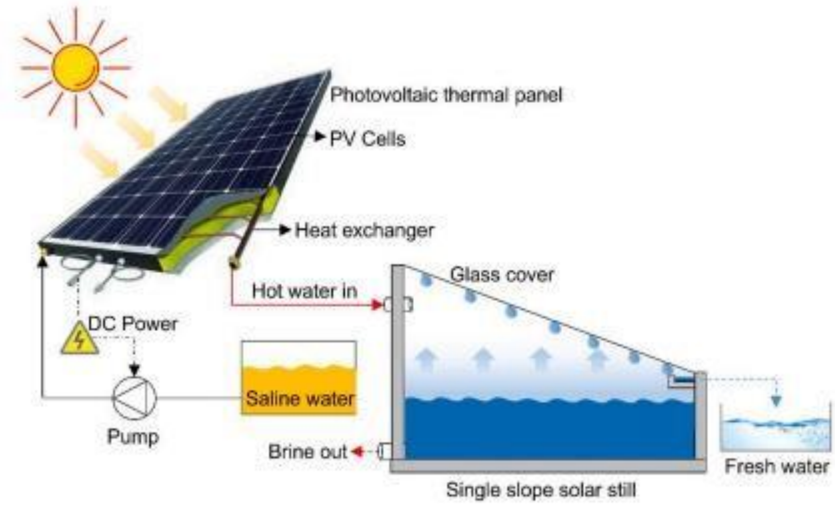


Figure 20: A hybrid solar PVT integrated in a solar still [14].

2.5.4.2. PVT collector integrated in a reverse osmosis system

Electricity serves as the primary energy source for reverse osmosis. The temperature of the feed water has a significant impact on the energy consumption of the water purification process. Higher feed water temperatures enhance water diffusivity and mass transfer, while reducing viscosity and concentration polarization. These changes lower the energy required by decreasing the necessary pressure to achieve a desired permeate flux. Consequently, at a constant feed water flow rate, a direct relationship exists between freshwater production and feed water operating temperature. The percentage change in permeate flux with respect to temperature variation can be expressed as follows:

$$TF = \exp(C_K\left(\frac{1}{273} + T\right) - \frac{1}{298})$$

Equation 1

Whereby TF, C_K and T are temperature correction factor, membrane constant characteristic and feed water temperature in degree Celsius. This comes to a conclusion that the performance of RO water purification can be further improved by using two forms of energy being electrical energy and thermal energy. Hence, photovoltaic thermal panels are more suitable to integrate with RO desalination system than integrating RO with separate PV panel and solar thermal collector. Figure 21 shows a schematic diagram of a solar PVT integrated in RO system.

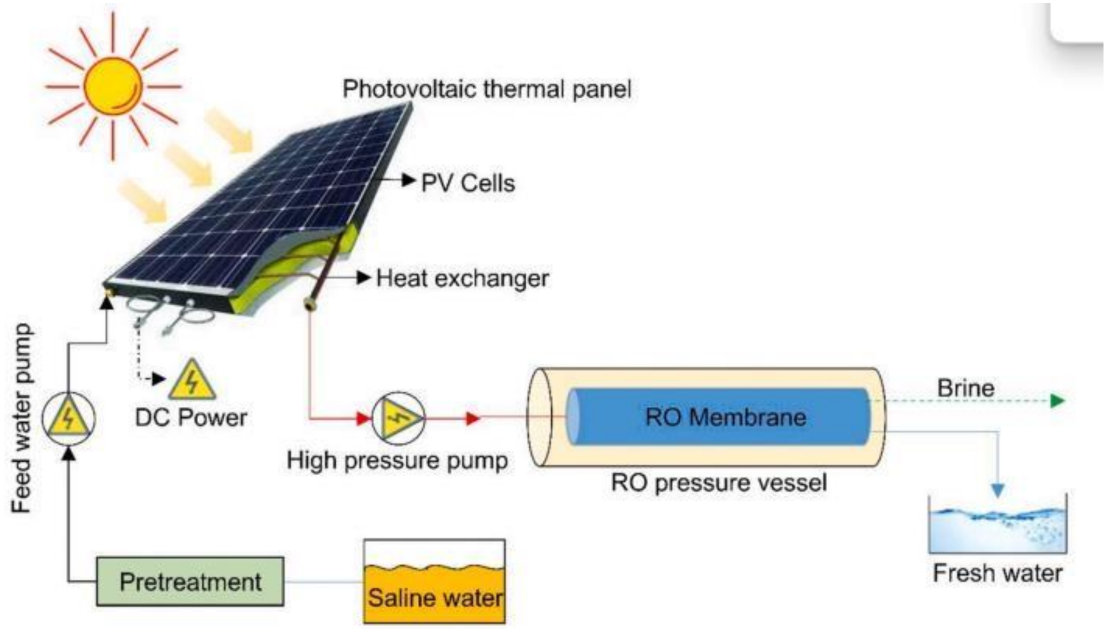


Figure 21:A schematic diagram of PVT integrated with RO desalination [14].

Table 3: Solar water purification technologies

Technique	Combination technology	Performance	Notes on disadvantages	References
Solar UV	SODIS	Basic microbial inactivation	No residual disinfection capacity exists. In order to preserve the disinfection residual in the distribution system, a certain amount of chlorine or chloramines is typically injected.	Paidalwar et al., [42]

			Additionally, Operators must currently rely on secondary measurements (sensor readings, UV transmittance, water flow rates, etc.) because it is not feasible to continuously monitor the UV dose.	

Solar PV	SPRO	High quality water if pressure is maintained	Because of their high cost and short lifespan, which prevents water production at night and on some days, PV solar systems with batteries were not advised for production capacities smaller than 5 m^3. As a result, cooling the PV panel with feed water may save energy and boost output. When	Que et al,. [73]
			compared to hybrid systems, independently operated PVBWRO systems had the lowest operating and total production costs but the largest capital requirements.	

Solar thermal	Solar still	30-40% efficiency	Less fresh water is produced, usually 4-5 L/m^2/day	Cooper [62]
Solar PVT	PVT collector integrated in a solar still	3.2 to 5.5 times more output than a conventional passive solar still	The fresh water production cost is 60% higher compared to traditional solar stills	Kumar and Tiwari [72]

2.6. Design Consideration

In Lesotho, where rural electrification and access to safe drinking water remain significant challenges, the integration of photovoltaic-thermal (PVT) collectors with reverse osmosis (RO) and ultraviolet (UV) disinfection offers a highly suitable and sustainable water purification solution. PVT systems provide both electricity and thermal energy from the same surface area, which is particularly advantageous in regions with limited space and high solar irradiance. Utilizing thermal energy from PVT systems to preheat feedwater improves RO membrane efficiency and reduces the energy required for pressurization [74]. This is especially important in the colder highland areas of Lesotho, where water temperatures are naturally low. Although solarpowered RO systems (SPRO) have demonstrated effective water purification, their reliance on battery storage increases capital costs and restricts nighttime operation, making them less practical for small production capacities below 5 m^3 per day. Furthermore, low-tech solutions such as solar disinfection (SODIS) are cost-effective but lack continuous monitoring, do not provide residual disinfection, and are inadequate for treating turbid or microbiologically contaminated sources, which are prevalent in many rural areas.

While solar stills offer a simple approach, their low water output of just 4–5 liters per square meter each day makes them impractical for serving entire communities. By combining reverse osmosis with photovoltaic-thermal and ultraviolet technologies, the system delivers pure water through multiple layers of protection, reduces the need for expensive batteries, and enhances overall reliability. The thermal aspect of the PVT system enables the reverse osmosis process to thrive even in Lesotho’s chilly climate, and UV treatment ensures safe, chemical-free disinfection. Though the upfront investment is higher, the system’s long-term sustainability, flexible scalability, and minimal operating costs make it a standout choice for bringing clean water to off-grid, rural communities in Lesotho.

2.6.1. The sizing principles for PVT RO systems

Integrating photovoltaic thermal (PVT) technology with membrane-based technology, specifically reverse osmosis (RO), offers a sustainable solution to water scarcity. Achieving efficiency, costeffectiveness, and self-sufficiency requires precise system sizing. Ammous et al. [75] proposed a comprehensive methodology for optimizing the dimensions of critical components, including PVT panels and storage tanks. Their approach employs a three-layer optimization process: identifying monthly surface requirements, validating system configurations, and determining the optimal system design.

2.6.2. The multi-criteria sizing strategy

The process described by M. Ammous et. al [75] is divided into three layers to systematically refine the system design.

Layer 1: Monthly Optimum PVT surfaces

This stage determines PVT collector area required for each month to balance energy production and consumption. By iteratively adjusting the operating temperature, the optimum panel area is calculated as:

$$A_C = \frac{Q}{G\eta_{th}}$$

Equation 2

Whereby Q represents useful thermal energy, G the solar irradiation and η_{th} is the collector efficiency.

Layer 2: validation of configurations

Layer 2 determines the range of photovoltaic-thermal (PVT) panel sizes that can meet annual water requirements. The minimum panel size guarantees adequate water production year-round, whereas the maximum panel size prioritizes cost-effectiveness and limits unnecessary overproduction.

Layer 3: Optimal System Setup

The final step balances multiple objectives, such as system autonomy, cost, and environmental sustainability. This layer guarantees three days of autonomy during periods of low solar irradiance, optimizes the photovoltaic-thermal (PVT) field size and storage tank volume to minimize energy losses, and selects the optimal configuration using a graphical center of gravity method.

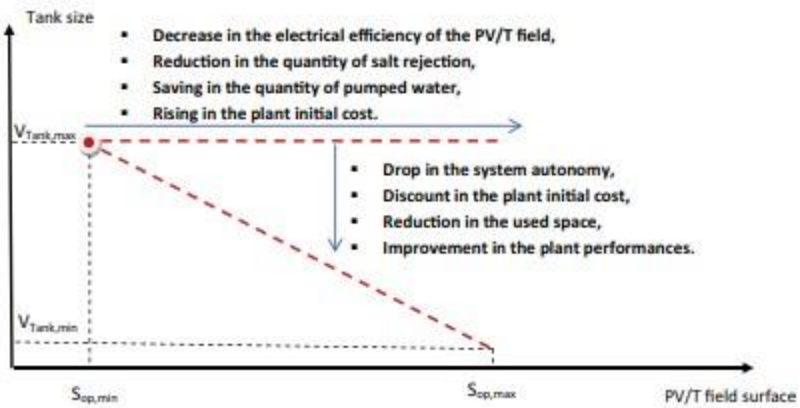


Figure 22: Impacts of the PV/T field expansion and storage tank size reduction [75].

At this stage, the sizing optimization process balances economic considerations, which seek to minimize the photovoltaic/thermal (PV/T) field size, with ecological objectives that prioritize maximizing the heating of pumped water. This strategy is intended to reduce both the volume of water pumped and the quantity of salt rejected.

2.6.3. Thermal electrical energy modelling

PVT systems are distinguished by their ability to generate both heat and electricity, which makes them suitable for reverse osmosis (RO) water treatment. The thermal energy produced is used to heat the feed water, thereby improving RO efficiency. The generated electricity powers the pumps and other system components. The following models are used to describe the energy flows:

Thermal Efficiency (η_{th}): This is the measure of how effectively the PVT system converts solar energy into usable heat and calculated as:

$$(\eta_{th}) = \frac{Q}{A_c G}$$

Equation 3

In this equation, Q represents the heat transferred to the fluid, A_c is the area of the PVT panel and G is the solar irradiance.

Electrical efficiency(η_{el}): This is the PVT system's ability to generate electricity and is influenced by temperature. The electrical efficiency is calculated as follows [74]:

$$\eta_{el} = \eta_{el,ref}[1 - \beta(T_{cell} - T_{a,ref})]$$

Equation 4

Where by $\eta el,ref$ is the reference efficiency, β is a temperature coefficient, $Tcell$ is the cell temperature, and Ta,ref is the refence ambient temperature.

2.6.4. Water purification system requirements

RO systems performance depends heavily on the pressure and temperature of the feed water. Increased feed water temperature improves the recovery ratio and reduces energy consumption, making temperature management critical. There are the following insights on this matter:

Recovery Ratio (*Rec*): The recovery ratio represents the proportion of freshwater extracted from the saline feed water. It is adjusted for temperature using a Temperature Correction Factor (TCF) [14]:

$$Rec = Rec_{ref}.TCF$$

Equation 5

In this equation, Rec_{ref} is the recovery ratio at 25 ˚C. The TCF, defined as a function of feed water temperature, depends on whether the temperature of the water is below or above 25˚C, which is calculated using:

$$TCF \begin{cases} \exp\left(2640\left(\frac{1}{273+T_W} - \frac{1}{273}\right)\right) & if\ T_W < 25^{\circ}C \\ \exp\left(3020\left(\frac{1}{273+T_W} - \frac{1}{273}\right)\right) & if\ T_W > 25^{\circ}C \end{cases}$$

Equation 6

Power Consumption(P_{RO}): This describes the power required for the Reverse Osmosis (RO) process which includes the energy for high-pressure pumps and also accounts for energy recovery.

It is given as:

$$P_{RO} = P_{HP} - P_{ER}$$

Equation 7

Where P_{HP} is the power for high pressure pump and the recovered power from brine is represented by P_{ER}.

2.6.5. Thermal model

The thermal model has been adopted from Alqaed et al [74]. Energy conservation is the foundation of the PVT model equations that calculate thermal and electric energy generation. The estimated array has N_S and N_p panels total, with N_p collectors in parallel and N_S in series. $\dot{Q}_{u,total}$, which is the sum of the heat generated by each of the distinct serial routes of panels, is the total thermal power that the entire array transfers to the fluid, as illustrated.

$$\dot{Q}_{u,total} = N_p \times \dot{Q}_{u,N_s}$$

Equation 8

The quantity $\dot{Q}_{u,N_s}$ represents the thermal power transferred to the fluid flowing though N_S panels in series.

$$\dot{Q}_{u,N_s} = N_S A_C F_R \left[S \left[\frac{1-(1-K_K)^{N_S}}{N_S K_K} \right] - U_L \left[\frac{1-(1-K_K)^{N_S}}{N_S K_K} \right] (T_{fi} - T_a) \right]$$

Equation 9

Each panel's collector area (A_C), heat removal factor (F_R), incident solar radiation (S) per unit area absorbed by the collector (U_L), total thermal conductance (T_{fi}) for heat losses, and ambient air temperature (T_a) are all included in this equation. The value of K_K is given by:

$$K_K = \frac{A_C F_R U_L}{\dot{m} C_p}$$

Equation 10

where C_p is the specific heat capacity and m is the mass flow rate. An individual PVT panel absorbs the following amount of solar radiation per unit area:

$$S = I(\alpha\tau)(1 - \eta_c/\alpha)$$

Equation 11

where I is the intensity of the solar radiation, η_c is the electrical efficiency at cell temperature, α is the collector's absorptance, and τ is the glazing's transmittance. When N_S panels are connected in series, the exit fluid temperature is determined by:

$$T_{fo} = \left[\frac{S}{U_L} + T_a\right]\left[1 - e^{\left(\frac{-N_S A_C F_R U_L}{mC_p}\right)}\right] + T_{fie}^{\left(\frac{-N_S A_C F_R U_L}{mC_p}\right)}$$

Equation 12 The heat removal factor is given by the following Equation,

$$F_R = \frac{mC_p}{U_L}\left[1 - e^{-U_L F'/mC_p}\right]$$

Equation 13

where the collector efficiency factor, F', is constant. The following formula is used to get the PVT cell temperature T_C:

$$T_C = \frac{I(\alpha\tau) + U_{tc,a}T_a + h_{c,p}T_p}{U_{tc,a} + h_{c,p}}$$

Equation 14

where T_p stands for plate temperature and Duffie and Beckman's values for $U_{tc,a}$, and $h_{c,p}$ are used [22].

2.6.6. Reverse Osmosis model

The RO model has been adopted from Harby et al. [76].

Water demand calculation

$$Q_{total} = Number\ of\ people \times Water\ usage\ per\ person\ per\ day$$

Required hourly flow rate:

$$Q_a = \frac{Q_{total}}{Number\ of\ operational\ hours}$$

Equation 15 Membrane mass flow rate (kgs^{-1})

$$\dot{m}_{p,ro} = A_m K_w(\Delta P - \Delta\Pi)$$

Equation 16

Whereby A_m is the membrane area, K_w is the water permeability, $\Delta P$is the transmembrane pressure difference and $\Delta\Pi$ is the osmotic pressure difference.

Permeate concentration (ppm TDS)

$$X_p = K_s CP X_{fc} SR \frac{A_m}{\dot{m}_{p,ro}}$$

Equation 17

In this equation K_s is the salt permeability, CP is the concentration polarization factor, X_{fc} is the average feed concentration, SR is the membrane salt rejection rate.

Mass balance along the membrane (kgs^{-1})

$$\dot{m}_f = \dot{m}_{p,ro} + \dot{m}_{b,ro}$$

Equation 18

Here, $\dot{m}_f$ is the membrane feed mass flow rate, $\dot{m}_{p,ro}$ is the membrane permeate mass flow rate and $\dot{m}_{b,ro}$ is the concentrate (brine) mass flow rate.

Salt mass balance along the membranes (kgs^{-1} ppm TDS)

$$\dot{m}_f X_f = \dot{m}_{p,ro} X_p + \dot{m}_{b,ro} X_b$$

Equation 19

Here, X_f,X_p, and X_b are the salinities for feed, permeate and brine waters.

Water recovery rate

$$RR_{ro} = \frac{\dot{m}_{p,ro}}{\dot{m}_f}$$

Equation 20 Transmembrane pressure (kPa)

$$\Delta p = P_f - P_{p,ro} - (\Delta p_{drop}/2)$$

Equation 21

For this equation, P_f resembles the feed pressure, $P_{p,ro}$ the permeate pressure and Δp_{drop} is the pressure drop across the membrane channel

Pressure-drop across the membrane channel (kPa)

$$\Delta p_{drop} = 9.5 \times 10^8 \left(\frac{\dot{m}_f + \dot{m}_{b,ro}}{2\rho}\right) 1.7$$

Equation 22

Concentration polarization factor (ppm TDS)

$$CP = EXP(0.7R)$$

Equation 23 Whereby R is the water recovery rate.

Membrane water permeability

$$k_w = \frac{D_w X_w V_w}{\delta_m RT}$$

Equation 24

Here, D_w,X_w and V_w are the water diffusivity, molar fraction of water in the membrane, and molar volume of water, respectively. While δ_m, R and T are the membrane thickness, the universal gas constant (8.314 J/(mol·K)) and the absolute temperature, respectively.

Salt permeability (kgm^{-2}skpa)

$$k_s = \frac{(1 - SR)\dot{m}_{p,ro}}{SR}$$

Equation 25

Membrane salt rejection rate

$$SR = 1 - \left(\frac{X_p}{X_f}\right)$$

Equation 26

Average feed concentration (ppm TDS)

$$X_{fc} = \frac{X_f ln\left(\frac{1}{1 - SR}\right)}{R} / R$$

Equation 27 Permeate osmotic pressure (kPa)

$$\Pi_p = \Pi_f(1 - SR)$$

Equation 28

Osmotic pressure (kPa)

$$\Pi = n_i C R_g T = 0.0784 X_f$$

Equation 29

Whereby n_i is the Van 't Hoff factor (~1 for NaCl in dilute solutions), C is the Salinity (mol/L), R_g is the Universal Gas Constant = 8.314 J/(mol·K) and T is an absolute temperature (K).

Average feed side osmotic pressure (kPa)

$$\Pi_{cave} = \Pi_f CP \frac{X_{fc}}{X_f}$$

Equation 30

Power consumption of pumps

$$\dot{W}_{pump,ro} = 27.78 \frac{Q_f P_f}{\eta_{pump}}$$

Equation 31

where P_f is the reverse osmosis membrane feed pressure in bar, Q_f is the reverse osmosis membrane feed flow rate in m^3 /h, the constant is the unit conversion factor, and η_{pump} is the efficiency of the motor and pump.

Specific energy consumption of pump and ERD (kWh/m^3)

$$SEEC\ (RO) = \frac{P_f \dot{m}_f (\varepsilon_{pump})^{-1} - P_{b,ro} \dot{m}_{b,ro} \varepsilon_{ERD}}{\dot{m}_{p,ro} \times 3600}$$

Equation 32

2.7. Technoeconomic analysis

The full system capital cost is determined by the following components: PVT array, batteries, RO, storage tank, high-pressure pumps for the RO, and low-pressure pumps for moving water through the PVT. The PVT capital cost computes as the product of the number of panels with a per-panel price. Similarly, the battery capital cost is proportional to its storage capacity (B_{cap}), and the storage tank capital cost is proportional to its volume. The RO capital cost is proportional to production capacity RO_{cap}. All of the individual component costs sum the full capital cost, as follows [74].

$$CC = CC_{PVT} \cdot N_s \cdot N_p + CC_{bat} \cdot B_{cap} + CC_T \cdot V_T + CC_{RO} \cdot RO_{cap} + CC_{HP} \cdot N_{HP} + CC_{LP} \cdot N_{LP}$$

Equation 33

Whereby CC = Total system cost, CC_{PVT}= pvt capital cost, N_s= number of panels in series, N_p= number of panels in parallel, CC_{bat}= battery capital cost, B_{cap}= Battery capacity, CC_{RO}=RO Capital cost, RO_{cap} =RO production capacity, CC_{HP}= High pressure pump capital, CC_{LP}= Low pressure pump capital cost, N_{LP}= number of low pressure pumps, CC_T= Storage tank Capital Cost, V_T = storage tank volume.

The entire system is assumed to operate for a lifetime T_{SYS}, and the loan is amortized over this period of time, leading to the following loan payment.

$$Annual\ Loan\ Payment = CC \cdot \frac{i}{1 - \frac{1}{(1+i)^{T_{SYS}}}}$$

Equation 34

Since the main output is water, rather than energy, The Levelized Cost of Water (LCOW) is calculated instead of the Levelized Cost of Energy (LCOE).

$$LCOW = \frac{\sum_{t=1}^{n} \frac{CC + C_{O\&m} + C_{repl}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{V_{water,t}}{(1+r)^t}}$$

Equation 35

Whereby $C_{O\&m}$ is the annual operating and maintenance costs (e.g., membrane replacement, UV lamps, pumps), C_{repl} is Replacement cost (e.g., batteries, filters, components), $V_{water,t}$ is the volume of purified water produced each year (e.g., m³/year).

2.8. Access to clean drinking water in Lesotho

Access to safe and clean drinking water has a significant impact on social and economic conditions, which in turn affect life expectancy and serve as key indicators for assessing living standards. The availability of clean water is closely linked to socioeconomic development [77]. In developing countries, limited access to clean water and adequate sanitation facilities, particularly in SubSaharan Africa (SSA), impedes progress compared to industrialized nations [78]. According to a 2019 UNICEF report, 1.4 billion people have access to basic water services within a 30-minute walking distance, while 206 million people rely on sources located beyond this range [79]. Disparities in water access across income groups and between rural and urban areas further influence socioeconomic development [80]. Wealthier individuals can enhance their water access through self-supply or premium sanitation services, which improve productivity, reduce disease, and promote better hygiene, thereby positively affecting their socioeconomic status and quality of life. In contrast, low-income populations often depend on external or governmental support, which is frequently inconsistent or delayed [81].

Falk et al. [81] highlight how the lack of safe drinking water ripples through communities, hitting low-income families the hardest as they struggle to afford costly alternatives, such as bottled water. Access to reliable water systems often becomes a marker of privilege, deepening social divides and fueling pressure among those left behind. When clean water is within reach, women and children (who typically shoulder the burden of water collection) gain precious hours for school, work, and community life, while also facing less risk of violence on their journeys. Clean water is a powerful shield against disease, especially for children in underdeveloped regions where waterborne illnesses can be deadly. Improved water and sanitation dramatically cut rates of infections like hepatitis, trachoma, and diarrhea. In sub-Saharan Africa, where fetching water can consume a significant portion of the day, direct access to clean water opens doors to education and personal growth by reducing school absences and freeing up time for learning.

In Lesotho's rural areas, diarrhea illnesses are a severe public health problem and a major cause of morbidity and mortality in infants and young children and most of it is related to faecal pollution of water sources from poor environmental hygiene and sanitation [82]. Approximately 70% of the population practice open defecation, and it is estimated that the child mortality rate was 85.9 deaths per 1000 live births in 2017. Exposures to faecal contamination occur at the community-scale via contaminated public water sources originating from within the community [5].

Approximately 70% of the population in Lesotho resides in rural areas, where most people rely on unprotected springs, rivers, and streams for their water supply. These sources are easily contaminated, and 80% of rural residents still collect drinking water from them. Most people spend over 30 minutes fetching this water [83]. To make it safer, households often use sand filtration, boiling, or sometimes chlorine tablets as recommended by health officials. Boiling water consumes a significant amount of fuel, and rural households are responsible for approximately 80% of all traditional fuel use in Lesotho, which includes wood, shrubs, crop waste, and animal dung [84].

Some families collect rainwater, but if it is not stored properly, it can become unsafe. Rural communities face serious problems like waterborne diseases, including diarrhea, made worse by limited access to clean water and sanitation. Seasonal water shortages are common, and people often have to walk long distances to get water [85].

In urban areas of Lesotho, particularly in its capital city, Maseru, residents primarily rely on piped systems managed by the Water and Sewerage Company (WASCO) as their primary source of water. The systems draw water from storage and also pump it from reservoirs, rivers, or the Lesotho Highlands Water Project, which exports water to South Africa. The water is treated using methods such as pre-settlement, coagulation, flocculation, sedimentation, and chlorination for safe drinking purposes [86]. Diesel, natural gas, and coal-powered power plants frequently supply the electricity required for a water system. These methods of power generation generate significant amounts of greenhouse gas emissions [20]. Lesotho is no exception to this, as it imports a significant amount of electricity from the Electricity Supply Commission (ESCOM) of South Africa, which is produced through the burning of coal [37]. However, in many informal and periurban areas, the tap water is unreliable, and these households typically fetch their drinking water from public taps that are far away or purchase it from private resellers, who sell it at exorbitant prices, exacerbating an already strained financial burden [87]. **Error! Not a valid bookmark selfreference.** shows the Percentage of the household population by drinking water treatment method used in the household and the percentage who are using an appropriate treatment method, according to the Lesotho MICS 2018 [88].

Table 4: Percentage of household population by drinking water treatment method used in the household and the percentage who are using an appropriate treatment method in Lesotho [88].

	Water treatment method used in the household									Percentage of household members in households using an appropriate water treatment method	Number of household members
	None	Boil	Add bleach/ chlorine	Strain through a cloth	Use water filter	Solar disinfection	Let it stand and settle	Other	DK/ Missing		
Total	**81.4**	**17.1**	**0.5**	**0.5**	**0.3**	**0.0**	**0.5**	**0.3**	**0.0**	**17.7**	**32966**
Area											
Urban	69.6	29.7	0.2	0.0	0.6	0.0	0.2	0.1	0.0	30.2	11798
Rural	88.0	10.2	0.7	0.7	0.1	0.0	0.6	0.4	0.0	10.8	21168
Ecological Zone											
Lowlands	77.3	21.7	0.4	0.3	0.3	0.0	0.2	0.2	0.0	22.2	20929
Foothills	91.8	6.5	0.2	0.5	0.2	0.0	1.1	0.1	0.0	6.9	2827
Mountains	86.1	11.1	1.0	0.9	0.3	0.0	1.0	0.6	0.0	12.2	6406
Senqu River Valley	90.4	7.7	0.7	1.0	0.0	0.0	0.9	0.2	0.0	8.2	2804
Education of household head											
Primary or none	87.9	10.5	0.5	0.6	0.1	0.0	0.6	0.3	0.0	10.9	21753
Secondary	75.7	23.2	0.5	0.2	0.3	0.0	0.4	0.2	0.0	23.8	8260
Higher	47.3	51.1	0.9	0.1	1.7	0.0	0.1	0.4	0.0	52.6	2789
DK/Missing	79.9	20.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.1	164
Source of drinking water											
Improved	80.6	18.2	0.5	0.3	0.2	0.0	0.4	0.3	0.0	18.7	29294
Unimproved	87.7	8.7	0.4	2.1	0.6	0.0	1.4	0.2	0.0	9.6	3673
Wealth index quintile											
Poorest	91.7	5.6	0.7	1.3	0.2	0.0	1.0	0.4	0.0	6.4	6594
Second	89.6	8.8	0.5	0.4	0.1	0.1	0.7	0.5	0.0	9.2	6594
Middle	84.5	14.2	0.4	0.7	0.1	0.0	0.3	0.2	0.0	14.6	6595
Fourth	81.1	18.4	0.5	0.0	0.0	0.0	0.2	0.1	0.0	18.6	6596
Richest	60.0	38.7	0.5	0.0	1.0	0.0	0.3	0.2	0.0	39.8	6588

2.9. Discussion

The reviewed literature demonstrates that energy-intensive conventional water purification methods hinder universal access to clean water, particularly in remote areas without access to grid electricity. The interdependence between water treatment and energy supply is emphasized as a critical factor. In Lesotho, the majority of the rural population depends on unprotected and contaminated water sources, which perpetuates public health challenges. Solar energy is identified as the most feasible renewable resource to address both energy and water needs. Lesotho's abundant solar irradiation, ranging from 5.5 to over 7.2 kWh per square meter per day in certain regions, makes it well-suited for decentralized solar water treatment systems. The efficiency of reverse osmosis and other purification technologies can be enhanced by utilizing thermal collectors for water preheating, while photovoltaic systems provide clean electricity for pumps and control units.

Solar-powered reverse osmosis (SPRO) is identified as a prominent technology due to its high purification capacity and proven compatibility with solar photovoltaic systems. Thermal preheating using photovoltaic-thermal (PVT) systems, which recover waste heat from photovoltaic panels, can further optimize energy consumption. In regions with prevalent microbiological contamination, ultraviolet (UV)-based disinfection, particularly solar-driven UV systems, provides a cost-effective and accessible solution suitable for both individual and household applications.

The integration of solar photovoltaic and thermal systems (PVT) represents a significant advancement that combines energy efficiency with water purification effectiveness. These hybrid systems increase energy yield from solar resources and enhance the performance of thermally sensitive purification processes, resulting in synergistic benefits. Furthermore, the application of thermal-electrical modeling and multi-criteria scaling techniques supports optimal system design, particularly for off-grid rural settings with variable seasonal water and energy requirements.

Despite these advantages, the literature identifies several challenges. High initial costs, complex maintenance requirements, and the necessity for local capacity-building to ensure sustainable operation are significant barriers. Additionally, variations in water quality, solar resource availability, and community needs necessitate site-specific customization of many solar purification systems.

2.9.1. Conclusion

The literature firmly establishes the potential of solar-powered water purification systems in rural Lesotho. Integrating solar photovoltaic, thermal, and ultraviolet disinfection technologies into decentralized water treatment strategies is both technically feasible and sustainable. In off-grid communities, these systems are especially effective in addressing the interconnected challenges of unsafe water access and energy poverty.

This approach ensures the availability of clean water and promotes environmental sustainability by utilizing Lesotho's significant solar resources and implementing advanced hybrid systems, such as photovoltaic-thermal and reverse osmosis integrations. The development and deployment of these systems align with both national priorities and international objectives, including the United Nations Sustainable Development Goals 6 and 7. Furthermore, this review identifies key factors, technologies, and frameworks that inform the experimental and design phases of the thesis, supporting the advancement of a context-specific, solar-powered water purification solution for rural Lesotho.

3. METHODOLOGY

Introduction

This study adopts a comprehensive mixed-methods research design to develop and evaluate a climate-smart green scalable water purification system tailored for rural Lesotho. The primary objective is to integrate Solar Photovoltaic Thermal (Solar PVT) technology with UV disinfection to create an off-grid solution for water purification. This approach aligns with global sustainable development goals, specifically UN SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy), and seeks to address critical local challenges such as water scarcity, energy deficiency, and public health concerns.

The main feature is market competitiveness through four aspects: potable water quality in accordance with WHO and or WASCO guidelines, the use of solar energy in line with UN SDG 7, portability in terms of land space footprint and user friendliness. Addressing these challenges will help increase sustainable accessibility and affordability of clean drinking water, the two major issues in water crisis in rural Lesotho.

The presented methodology also describes procedures involved in performing mathematical modeling, software simulation and economic analysis of the model.

3.1. The background of the simulation area

The study focused on rural populations in Lesotho, where it is very difficult to get clean water and dependable electricity. The following criteria was used to carefully choose specific places. (1) Radiation received: To ensure that the system can function in locations with the least amount of solar radiation, the places with the least amount of radiation was chosen. (2) Water Scarcity: Regions that rely heavily on untreated and dangerous water sources, like communal wells, boreholes, and rivers. (3) Energy Deficiency: Villages that are cut off from the national electrical grid, requiring solutions based on renewable energy. (4) Public Health: Areas where waterborne illnesses are prevalent, especially those that impact children and other vulnerable groups. (5) Data accessibility: Regions with readily available meteorological data, the region with the least radiation will be selected for creating the worst-case scenario.

This approach ensured that the system was evaluated under the most demanding operational conditions, providing valuable insights into its performance during peak water demand periods.

By focusing on the month with the highest water demand, the economic analysis accurately assessed the system's financial viability and profitability during critical times. Additionally, conducting an annual economic analysis enabled comparisons with traditional water purification systems or alternative energy sources throughout the year. This comprehensive evaluation highlighted the system's advantages and competitiveness against other solutions. Furthermore, integrating the solar PV/T water purification system into the existing energy infrastructure revealed potential opportunities for cost savings and revenue generation, enhancing its overall economic and operational appeal.

The site selected was The Mohale basin Lesotho. The place was selected to bring a solution to a study conducted by Gwimbi et al. [5], in 2019, whereby thirty drinking water sources in this place were purposively sampled and their water analyzed for E. coli counts. The types of water sources, their protection status and neighborhood sanitation and hygiene practices in their proximity were also assessed. E. coli counts in water samples were compared to water source protection status, neighborhood sanitation, hygiene practices, livestock faeces and latrine proximity to water sources.

The study findings showed that E. coli counts were found in all water samples and ranged from less than 30 colony-forming units (cfu)/100 ml to 4800 cfu/100 ml in protected sources to 43,500,000 cfu/100ml in unprotected sources. A significant association between E. coli counts in drinking water samples and lack of water source protection, high prevalence of open defecation (59%, $n = 100$), unhygienic practices, livestock faeces and latrine detections in proximity to water sources was found in the study ($P<0.05$). The study came to a solution that water sources in studied villages were contaminated with faeces and posed a health risk to consumers of that water. A regional map of TDS indicated that groundwater from the whole country had <500 Mg/L TDS [89], which is then converted into 0.00856 mol/L NaCl.

Figure 23 depicts the climate data for the Mohale Basin Maseru from Photovoltaic Geographical Information System (PVGIS). PVGIS is an online instrument created by the European

Commission’s Joint Research Centre to assess solar energy potential and photovoltaic (PV) system efficacy globally. It employs satellite-derived solar radiation data, terrestrial observations, and climate databases to furnish information including solar irradiation, optimal panel tilt and orientation, temperature impacts, and anticipated energy generation of photovoltaic systems.

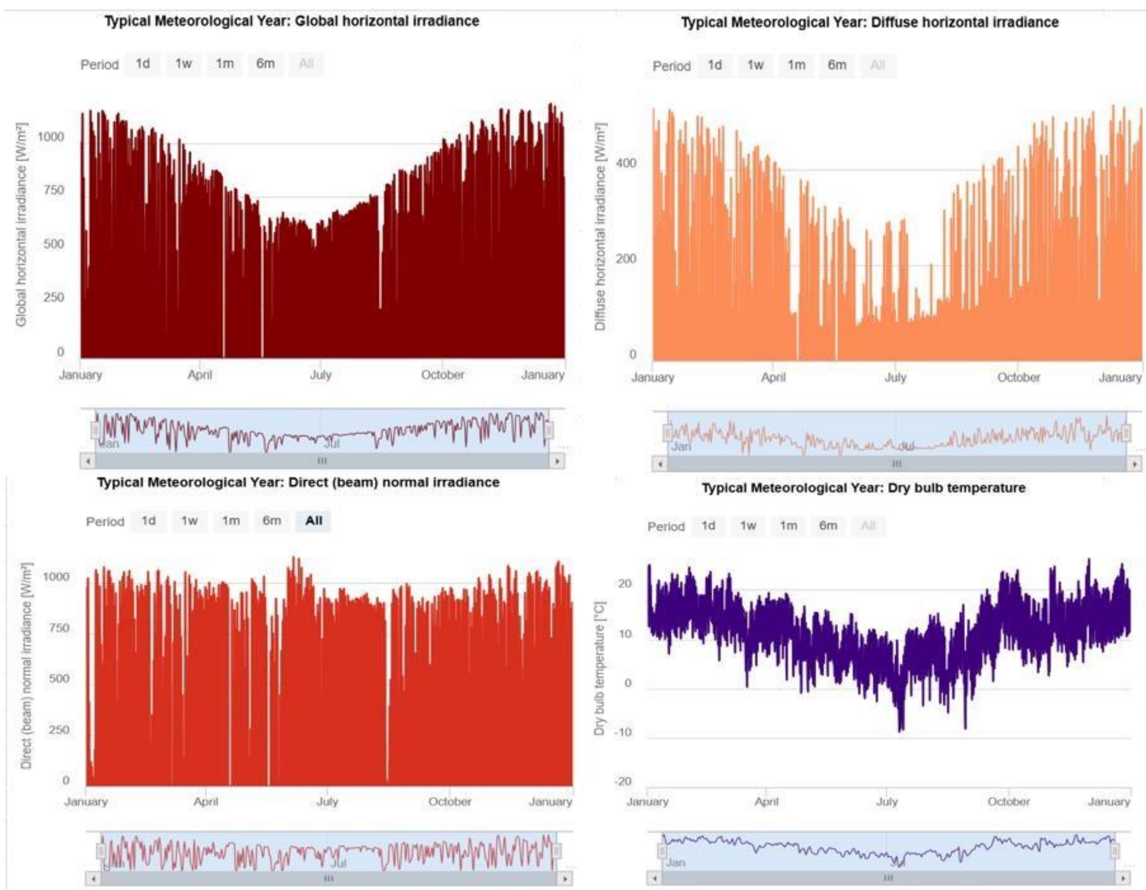


Figure 23: Climate data for Mohale Basin produced by Photovoltaic Geographical Information System.

Figure 24 presents a Google Earth image depicting a portion of the Mohale Basin communities, particularly surrounding Sekokoaneng, designated as the simulation region for this study. The area features scattered rural communities, uneven mountainous landscapes, and inadequate infrastructure, creating substantial obstacles for centralized water treatment and energy provision.

Figure 24: Google Earth image for the Mohale Basin villages.

3.2. Solar PVT Reverse Osmosis and UV System Layout

According to the LITERATURE REVIEW, Reverse Osmosis (RO) systems are becoming more and more popular, and they currently make up a larger share of the world's desalination capacity. This is mostly due to developments in membrane technologies. Although pumping water at high pressures requires a precious energy resource, such as mechanical energy or electricity, RO systems are especially well-suited for small- to medium-sized applications because to their modular architecture and relatively low energy consumption (about 4–6 kWh/m^3).

The system incorporates a thermal component to warm the water prior to its pumping through the RO membrane, hence improving energy efficiency. As was previously mentioned, the system under analysis in this study combines Solar PVT, RO, and UV SODIS technologies, operating as a cogeneration or combined heat and power system that generates both electrical and thermal energy. A schematic of the system that has been simplified, focusing on its primary components is provided in Figure 25.

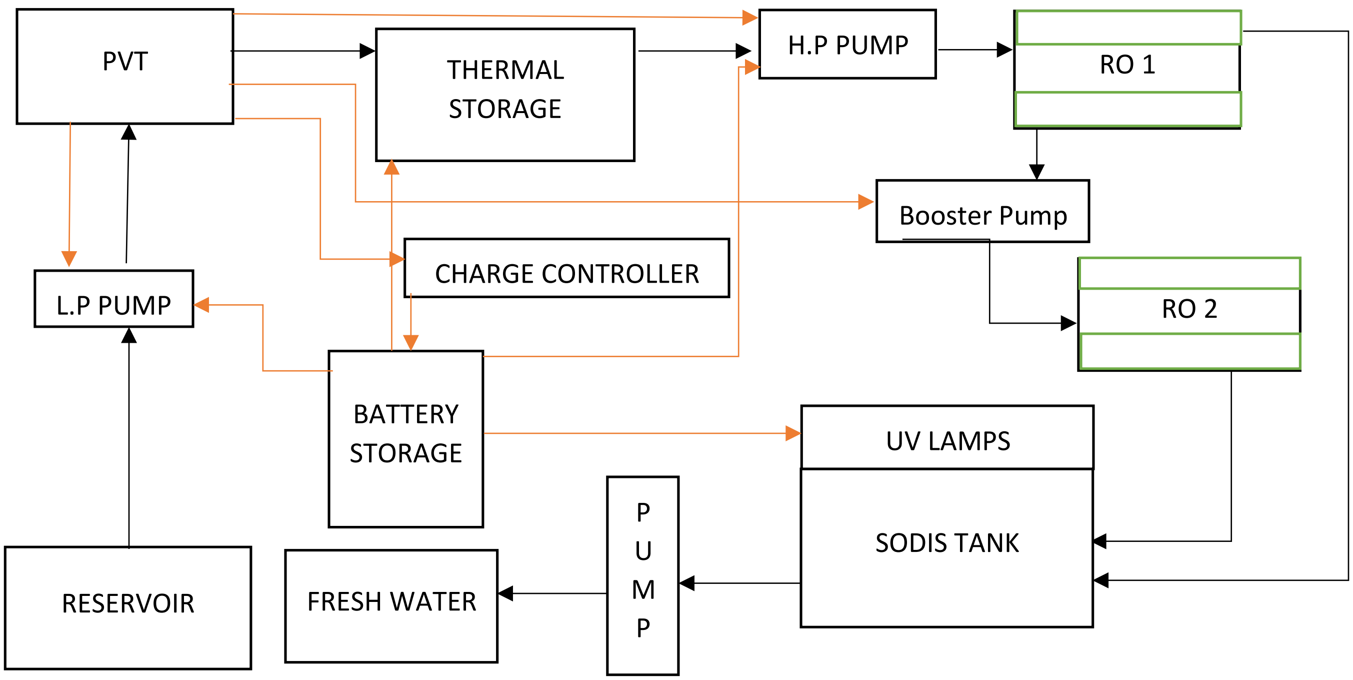


Figure 25: Solar PVT and UV water treatment system layout.

In this system configuration, the red arrows represent the movement of electricity produced by the PV part of the PVT collector, while the black arrows show the water movement throughout the whole system. Water from the reservoir is used to start the process. By the use of the thermal energy from the PVT system, the water is preheated in the PVT system and stored in the Thermal Storage unit after being transported there by the L.P. (Low Pressure) Pump, which is driven by electricity from the PVT collector. In the absence of the sunlight, the electrical energy stored in the battery is used to preheat the water in the thermal storage. The energy requirement for later treatment steps is decreased by this preheating step. The H.P. (High Pressure) Pump subsequently applies pressure to the heated water, which is then sent to the Reverse Osmosis (R.O.) unit.

In order to produce clean water, the R.O. unit acts as the main filtering step, eliminating heavy metals, dissolved salts, and other impurities. However, some bacteria may still be present in the water even after RO filtration. The SODIS Tank is where the filtered water is subsequently stored for ultraviolet (UV) treatment. Any leftover bacteria, viruses, or pathogens are removed by the UV disinfection process, guaranteeing that the water is safe to drink. After being treated, the water leaves the system as freshwater, suitable for cooking, drinking, and other uses. The UV lamps back-ups the UV disinfection process in days of no direct sunlight. A Charge Controller carefully controls the electricity produced by the PVT system and controls how the battery storage is charged. Even when there is little sunlight, this guarantees a steady power source for the pumps and UV system. Adding battery storage further improves the system's dependability by enabling it to operate at night or on overcast days.

3.3. Mathematical modeling of the RO process

The mathematical modelling of the Reverse Osmosis (RO) process, combined with Solar PVT and UV systems as seen in Figure 26, commences with inputs comprising groundwater mass flow rates and water qualities that delineate the system's operational parameters. The governing equations of the RO system incorporate these inputs, solving the ejector equations and computing the system based on critical parameters including membrane properties, pump efficacy, and energy recovery efficiency. The model subsequently integrates governing equations for Solar PVT and UV integration, encompassing mass balance, energy balance, and sizing to enable effective linkage between the thermal and electrical contributions from the PVT collectors and the RO purification process. At this juncture, factors including water characteristics, PVT standards, and system geometry are taken into account. The model generates outputs detailing energy requirements and clean water quantities, serving as a foundation for evaluating the overall performance, practicality, and sustainability of the hybrid solar-powered water purification system.

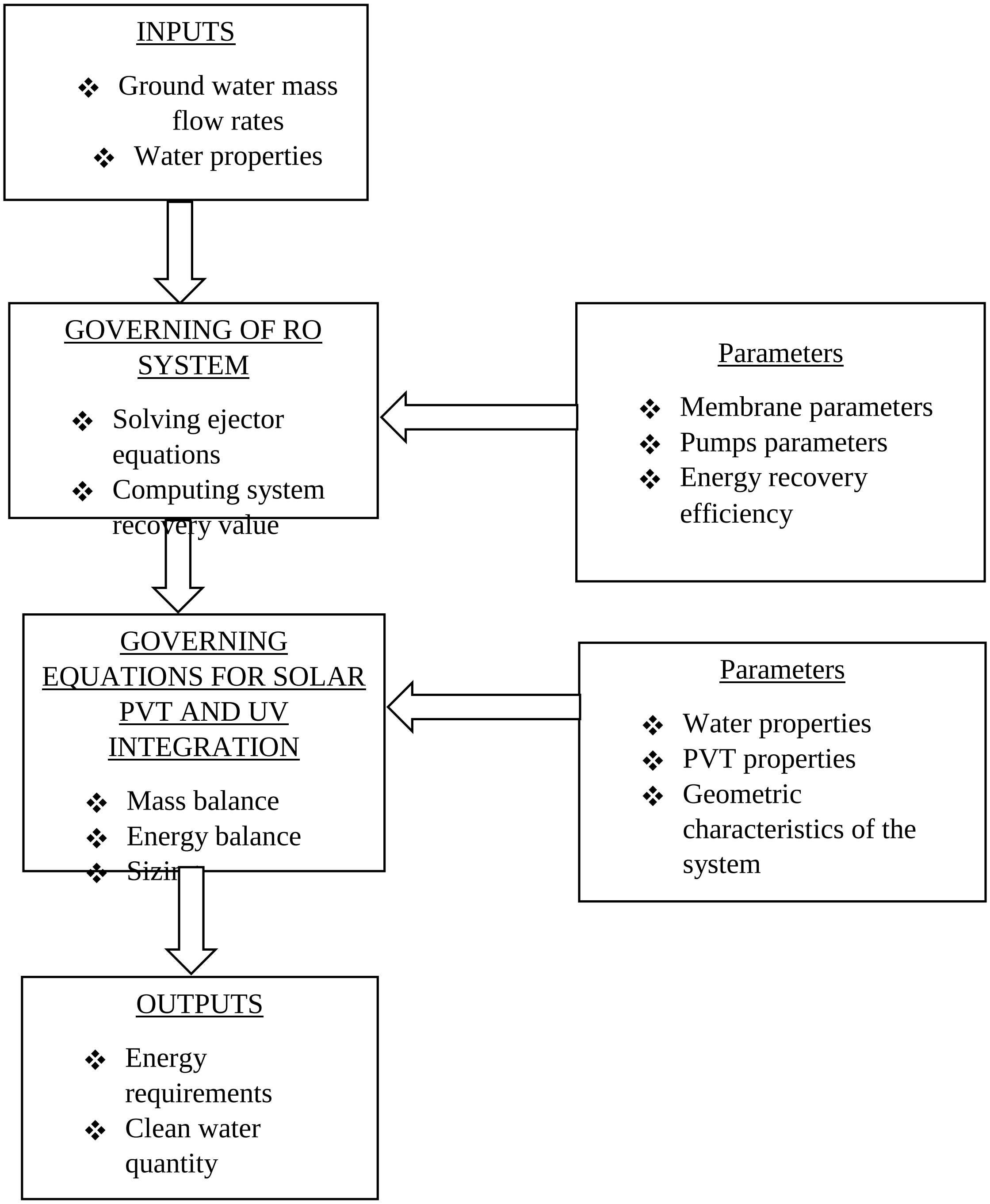


Figure 26: Flow chart for theoretical analyses of the innovated combined PVT and UV RO system

3.3.1. Thermal Model

The thermal model used in this study is based on energy conservation principles, includes governing equations (Chapter 2 Equation 8 to Equation 14) that define heat transfer pathways, quantify thermal and electrical energy generation, and depict the total energy balance for a PVT array. Important factors including collector area, heat removal factor, absorbed solar radiation, thermal conductance, fluid inlet and outlet temperatures, and ambient conditions are all taken into consideration by the calculations. This guarantees that the thermal performance of the PVT system is accurately represented, bringing the current work into line with tried-and-true methods documented in the literature.

3.3.2. RO Model

A thorough set of governing equations (Chapter 2 Equation 15 to Equation 33) that deal with salt rejection performance, membrane mass transfer, water demand prediction, and the connections between feed, permeate, and brine fluxes are all included in this model. It also takes concentration polarization, osmotic pressure effects, and the RO pumping system's energy needs into consideration. A formal foundation for forecasting system behavior under various operating situations is provided by these equations. By applying a modeling technique anchored in wellestablished membrane theory and proven by prior studies, the analysis ensures robust and credible performance predictions for the RO subsystem. Table *5* depicts the comparison between the low energy membranes. This helps in choosing the best suitable membrane for solar RO system for creating an energy efficient water purification system.

Table 5: Comparison of low energy membranes

Membrane Specific Parameters	FILMTEC (BW30 PRO-4040)	TORAY (TGM20-370)	KOSH (8823-ULP-400)
Permeate Flow Rate (m^3/d)	44.0	36.0	32.2
Active surface area (m^2)	37	34	37.2
Maximum operating pressure (bar)	41	25	24

Maximum feed flow rate (m^3/hr)	19.3	8.3	19
Maximum recovery rate (%)	20	15	15-20
Maximum Operating Temperature (°C)	45	45	45
Stabilized salt rejection (%)	99.2	99.5	97
Maximum pressure-drop (bar)	1	0.4	1.04

Table 6: RO mathematical model input parameters

RO MODEL INPUT PARAMETERS			
Membrane Specific Parameters		Feed Water Parameters	
Permeate Flow Rate (m^3/d)	44	Feed Salinity (Xf) (ppm)	500
Active surface area (m^2)	37	Preheated water Temperature	318.15
Maximum operating pressure (kPa)	4100	Initial feed water temperatue	285.15
Minimum operating pressure (kPa)	1030	Van 't Hoff factor (ni) (for NaCl)	1
Maximum feed flow rate (m^3/hr)	19.3	The Universal Gas Constant (Rg) J/(mol·K)	8.314
Maximum recovery rate (R)(%)	60.00%	Feed Salinity (C) (mol/L)	0.0085558
Maximum Operating Temperature (K)	318.15	Daily water demand (m^3/day)	20
Stabilized salt rejection (SR) (%)	99.20%	Operational hours	10
Maximum pressure-drop (kPa)	101.3	Desired permeate Mass flow rate (mp,ro)(kg/s)	0.5556
Efficiency of a pump	84.00%	Salt permeability (Ks) kgm^2/skPa	0.0044806
Efficiency of ERD	0%	Desired membrane feed flow rate (Qf) (m3/hr)	3.3333333
		Feed water required (m^3/day)	33.333333

3.3.3. UV Disinfection modeling

The bacterial inactivation kinetics corresponding to the UV fluence applied in this study are wellestablished in the literature. When waterborne microorganisms are exposed to UV-A radiation over a defined duration (typically ranging from three to six hours) the extent of inactivation is assessed by the reduction in microbial concentration relative to the initial level. This reduction provides a quantitative measure of disinfection efficacy.

The foundation for modeling disinfection kinetics based on concentration decay was originally introduced by Watson [90], who proposed a first-order relationship between disinfectant exposure and microbial inactivation. This conceptual framework was later adapted to the context of UV water treatment by Severin et al. [91]. The relationship between UV fluence and microbial log reduction is typically described by a linear model, as shown in Equation 36**,** which assumes a direct proportionality between fluence (mJ/cm²) and the logarithmic reduction of the target organism.

Further refinements and validations of this approach have been conducted by Rattanakul and Oguma [92], who demonstrated its applicability across a range of microbial species and UV wavelengths, reinforcing its reliability as a predictive tool in the design and assessment of UV disinfection systems.

$$log_{10}\left(\frac{N_t}{N_0}\right) = -k\ \varphi$$

Equation 36

where k (cm^2/mJ) is the inactivation constant, φ is the UV-fluence rate for the *t* length of time, and N_0 and N_t are the microbial concentrations [CFU/mL] initial and surviving after UV irradiation for the *t* duration of time, respectively. The basic unit of measurement for UV-fluence is (mW.sec/cm), which is equivalent to (mJ/cm^2).

Its appropriateness for disinfection applications has been confirmed by an evaluation of the costeffectiveness of UV-A LED technology operating at 365 nm from the standpoint of energy consumption. We use the Electrical Energy per Order (EEO) metric to assess system performance in this study, where contamination levels are rather low. According to Keen et al. (2018), EEO measures the quantity of electrical energy (in kWh) needed to reduce the concentration of contaminants by 1-log (90%) per 1 m³ of water. The following formula can be used to determine EEO for systems with a linear fluence-response relationship:

$$E_{EO} = \frac{A}{3.5 \times 10^3 \times V \times k \times C \times WF}$$

Equation 37

In this context, the irradiated surface area (A) is measured in square centimeters (cm²), while the treated water volume (V) is expressed in milliliters [mL]. The inactivation rate constant (k) represents the efficiency of microbial reduction and is given in (cm²/mJ). The water factor (WF), derived from Equation 38, accounts for water-specific properties such as UV transmittance and absorbance. Similarly, the wall-plug efficiency (C), calculated from **Error! Reference source not found.**, reflects the efficiency of converting electrical input into usable UV output by the LED system. The numerical constant 3.6×10^3 is used to convert the final result into the standard unit of kilowatt-hours per cubic meter (kWh/m³)

$$WF = \frac{1 - 10^{-al}}{al \ln(10)}$$

Equation 38

Here a represents absorption coefficient (cm^{-1}) of 365 nm light and l vertical path length (cm) of the water in the Petri dish ($l = \frac{V\,(mL)}{A\,(cm^2)}$)

$$C = \frac{P_{output}}{P_{input}} = \frac{F_A}{I \times V}$$

Equation 39

In this case, P output and P input indicates the optical power [W] that the UV-LEDs emit, while P input P input indicates the electrical power that the LEDs receive, likewise expressed in watts. The applied voltage (V in volts) multiplied by the applied current (I in amperes) yields the input power. The manufacturer usually specifies the radiant flux (F A), which is measured in watts and represents the total radiant energy emitted per unit of time. Luminus Devices, Inc. provided the radiant flux data for each UV-LED chip used in this investigation for the SBM-120-UV-F34H365-22 model.

The PVT subsystem concurrently produces electricity and absorbs thermal energy. The electricity energizes the RO pumps and UV lamps, while the thermal component preheats the feedwater to around 40 °C, enhancing RO efficiency by lowering the necessary pressure and augmenting permeate flux. The RO subsystem subsequently executes desalination and pollutant extraction, yielding permeate water that is subjected to final disinfection in the UV unit to guarantee microbiological safety. This integration enables the three sub-models to operate collaboratively, with PVT supplying the necessary energy forms for RO and UV, while RO and UV maintain water quality. The integrated modelling approach effectively encapsulates the energy-water interactions and their influence on system performance, reliability, and cost.

3.4. WAVE PRO modelling

The Water Application Value Engine (WAVE) software, which is driven by DUPONT, is used in this study in version 1.82. Several technologies were employed in this software, as illustrated in Figure 27. In this study, one technology (reverse osmosis) was examined. Benefits of WAVE include its adaptable design with various technologies, unit operating combinations, and systemfeed or net-product flow rate options. WAVE was utilized because it has a powerful calculation engine that can execute intricate patterns with extreme precision. The first step is to enter the necessary information for the feed water, such as the temperature (40°C) and the permeate flow rate (2 m^3/h). Furthermore, turbidity, total suspended solids (TSS), and total dissolved solids (TDS) are the most important variables that affect membrane and water quality. Figure 28 provides a summary of all the information needed for feed water analysis.

WAVE was chosen due to its status as an industry-standard tool, calibrated with authentic membrane manufacturer data, hence guaranteeing accurate simulations of salt rejection and energy consumption. However, it possesses limitations: the program streamlines brine treatment, fails to comprehensively consider the impacts of feedwater temperature, and may produce excessively optimistic recovery projections. Consequently, a supplementary Excel-based mathematical model was created to encapsulate temperature sensitivity, brine concentration effects, and intricate system-level interactions. The methodology integrates PVsyst, WAVE, and theoretical modelling to harness the advantages of commercial software while addressing their shortcomings, thereby offering a thorough assessment of the hybrid PVT–RO–UV system.

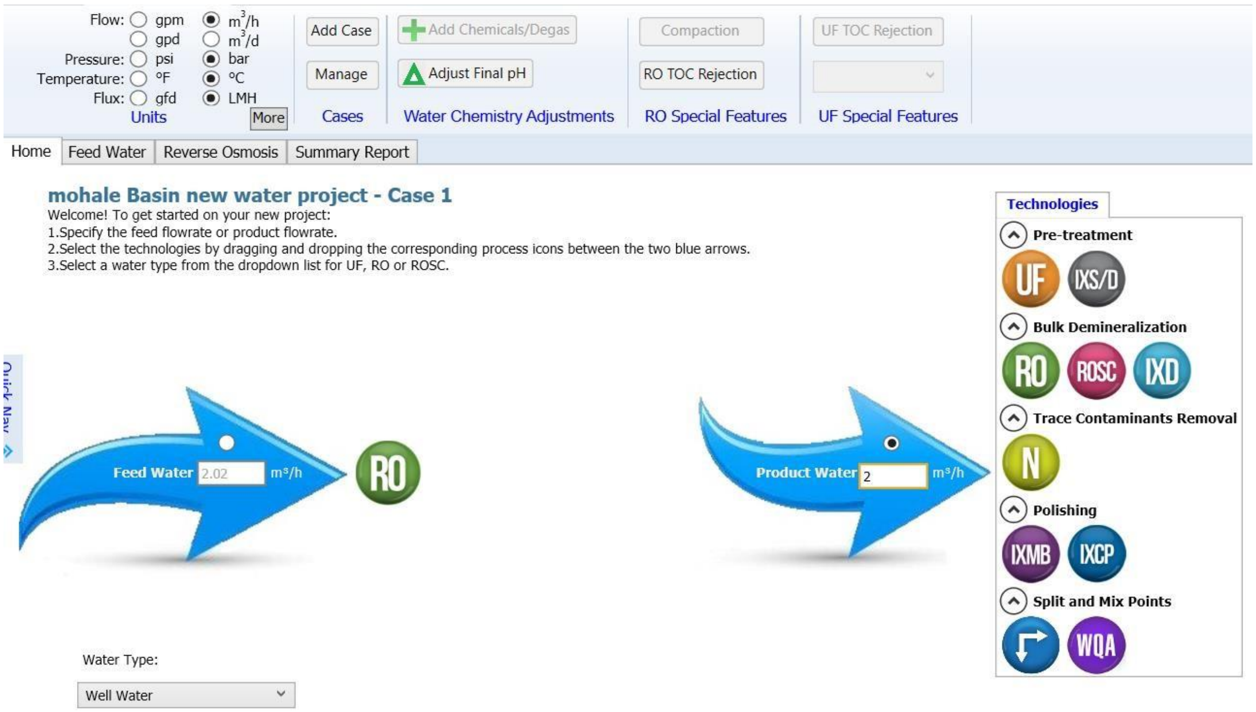


Figure 27: Technology home page for WAVE software

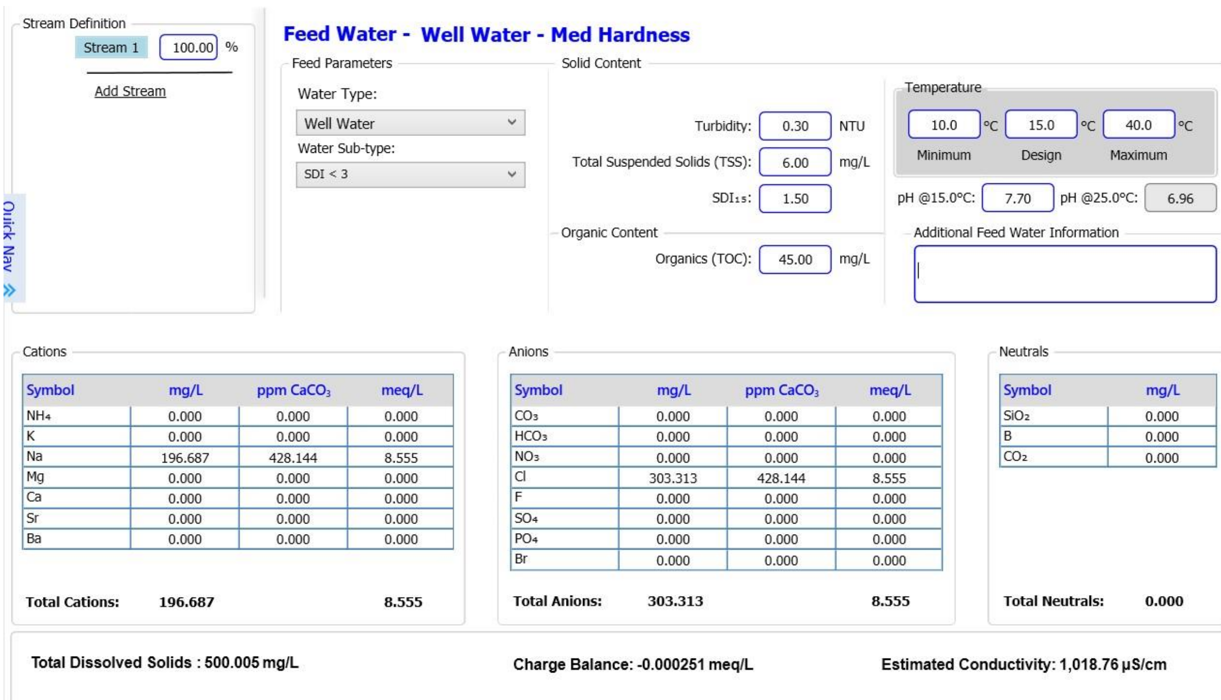


Figure 28: Feed water input parameters

The individual development of the RO, thermal, and UV models is essential for the functionality of the hybrid PVT–RO–UV system. The PVT subsystem generates electricity and heat: the thermal energy preheats the feedwater, decreasing viscosity and osmotic pressure to enhance RO efficiency, while the electrical output powers both the RO pumps and UV disinfection. The RO unit subsequently eliminates dissolved salts and chemical pollutants, while the UV stage finalizes the process by inactivating microorganisms in the permeate. This relationship guarantees that thermal, electrical, and membrane processes operate cohesively, with PVT improving RO performance, RO maintaining chemical water quality, and UV providing microbiological safety. The methodology captures both the performance of the subsystems individually and the synergistic advantages of their integration, which is the distinctive aspect of this research.

3.5. Use of PVsyst Software for System Sizing

The number of solar panels and battery storage needed for the Reverse Osmosis (RO) water purification system was estimated and optimized using PVsyst7.4, a sophisticated photovoltaic (PV) system simulation program created by the University of Geneva. Grid-connected, standalone, and hybrid PV system design and performance analysis are common uses for the software. Its primary tasks include sizing the system, simulating energy yields, and assessing losses and system efficiency over time using technical specifications and meteorological data.

PVsyst was selected for this study due to its extensive validation as a tool for photovoltaic and hybrid system analysis, offering precise irradiance modelling and performance ratios across diverse climatic conditions. This rendered it especially appropriate for evaluating the hybrid PVT component in Lesotho's fluctuating solar climate. PVsyst primarily emphasized electrical performance and inadequately accounted for thermal energy contributions, necessitating additional thermal modelling.

Two independent solar PV systems with battery storage components were modeled in this study using PVsyst: a 14.4 kWp system for high pressure and a 5.2 kWp system for low pressure. The RO system's energy requirements and the amount of solar radiation present in Mohale, Lesotho, were taken into consideration when choosing these setups. The software determined the ideal number of panels and battery bank size to meet the 20 m^3/day water purification target by entering important parameters such as the location's meteorological data (temperature and solar irradiance), the RO system's load profile, the number of autonomy days that were desired, and the technical specifications of PV modules and batteries.

Monthly and annual energy production, performance ratio, system losses, and battery state-ofcharge behavior were among the outputs from PVsyst. This made it possible to thoroughly assess the system's performance in the local climate and assisted in improving the system's design to guarantee the water purification process's sustainability, dependability, and efficiency. Figure 29 shows the homepage for the PVsyst Software.

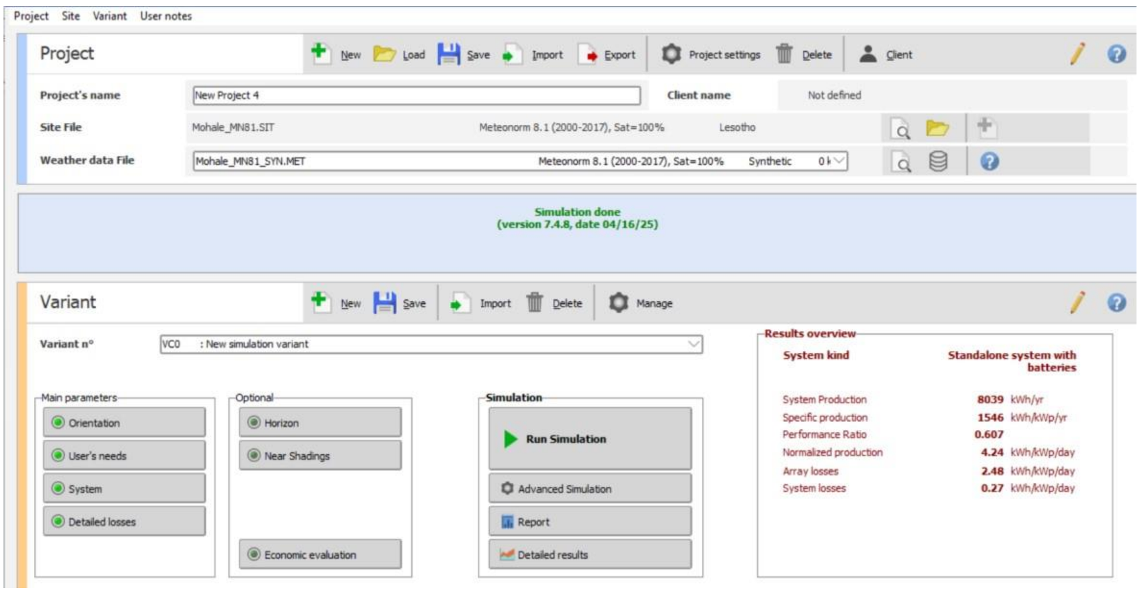


Figure 29: Home Page for the PVsyst7.4 software

3.6. Economic Analysis

The economic model used in this study and connected its structure to well-established costmodelling techniques for water purification systems powered by renewable energy. The model calculates the overall yearly plant cost by adding the annual operating and maintenance costs and the amortized loan repayment on the system's capital cost (see **Error! Reference source not found.** and **Error! Reference source not found.**). The size of the PVT array, battery capacity, and storage tank volume are used to express both cost components.

The PVT array, battery storage, RO unit, water storage tank, high-pressure RO pumps, and lowpressure circulation pumps are among the primary system components whose costs are added together to calculate the overall capital cost. The cost of each component is determined in proportion to its capacity or quantity; for instance, the cost of a battery is proportional to its storage capacity, while the cost of a PVT is the product of the number of panels and the price per panel. **Error! Reference source not found.** provides the entire capital cost, and Equation *34* uses an amortization formula to determine the annual loan payment, assuming a fixed interest rate and a system lifetime. This methodology for economic analysis, which is based on tried-and-true technoeconomic evaluation techniques, guarantees that the system's financial performance is assessed in accordance with accepted standards in hybrid solar water purification research. Since the main output is water rather than electricity, the Levelized Cost of Water (LCOW) is calculated using Equation *35* . Table *7* depict the input parameters used in the economic analysis. Table 7: Relevant parameters used in economic analysis

Parameter	value
System lifetime	20 years
Battery life	10 years
Discount rate	7.75%
Initial investment	$28000
Annual operation cost	$650
Annual maintenance cost	$650

Capital expenditures encompassed the photovoltaic array, reverse osmosis membranes, ultraviolet disinfection equipment, pumps, controllers, storage tanks, and housing. These were derived from manufacturer datasheets, supplier quotations, and analogous techno-economic analyses in South Africa. The discount rate was based on the rate published by the Central Bank of Lesotho. Operation and Maintenance (O&M) expenses included membrane replacement, UV lamp replacement, pump service, and cleaning chemicals, represented as a proportion of capital expenditure (often 3–5% annually). Replacement costs were integrated utilizing component lifespans: 7–10 years for batteries, 5 years for UV lamps, and 3–5 years for RO membranes.

4. RESULTS AND DISCUSSION

Several theoretical and experimental investigations in the literature currently under publication offer trustworthy information for confirming the suggested hybrid Photovoltaic-Thermal Reverse Osmosis (PVT-RO) system. As a result, a comparison between the simulation results of the suggested system and well-established findings published in the literature is part of the validation procedure for this work. In particular, a traditional solar PV-powered standalone RO setup is used to compare the performance of the integrated solar PVT and ultraviolet (UV) water purification system.

The outputs of the standalone RO model were compared with findings produced by DuPont's Water Application Value Engine (WAVE) software in order to verify the model's robustness.
Performance evaluation using WAVE software, validation of the thermal model for preheating the RO feed water, analysis and discussion of PV-battery system sizing in relation to RO pressure and thermal energy requirements, and performance evaluation of the fully integrated solar PVT-ROUV purification system comprise the four main components of the analysis presented in this section.

4.1. RO Specifications

Three BW30 PRO-4040 [93] membrane elements were used in each of the two steps of the singlepass, reverse osmosis (RO) process. This membrane type was used for both WAVE simulation and the mathematical model. The membrane specifications are shown in Figure 30.

Membrane Type	Polyamide Thin-Film Composite
Maximum Operating Temperature[1]	113°F (45°C)
Maximum Operating Pressure	600 psi (41 bar)
Maximum Pressure Drop	
Per Element	15 psi (1.0 bar)
Per Pressure Vessel	50 psi (3.5 bar)
pH Range	
Continuous Operation[1]	2 - 11
Short-Term Cleaning (30 min.)[2]	1 - 13
Maximum Feed Flow[3]	
4040 Elements	16 gpm (3.6 m^3/h)
2540 Elements	6 gpm (1.4 m^3/h)
Maximum Feed Silt Density Index (SDI)	SDI 5
Free Chlorine Tolerance[4]	< 0.1 ppm

Figure 30: Membrane specifications *[93]*.

4.2. Wave software results

The DuPont-supplied elements were chosen due to their excellent chemical tolerance, which allows them to resist a broad pH cleaning range (1–13), and their large active membrane area, which improves membrane cleanability, permeate productivity and low energy. This arrangement maintains operational flexibility for fouling control and membrane maintenance while guaranteeing effective salt rejection and water recovery.

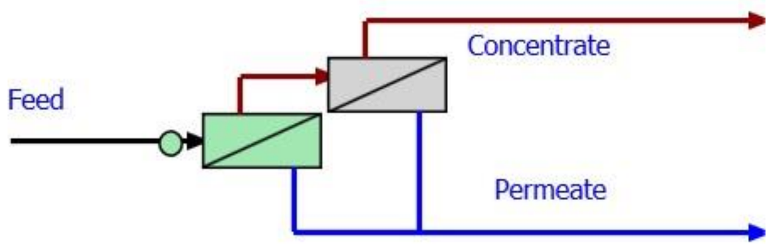


Figure 31: 2 Stage RO system configuration from WAVE

By contrasting the simulated outcomes of the suggested hybrid solar PVT-RO water purification system with information from publicly available sources and simulations carried out with the Water Application Value Engine (WAVE) software, the system's performance was validated. By lowering Total Dissolved Solids (TDS) from 500.2 mg/L to 14.49 mg/L at maximum pressure and 19.73 mg/L at minimum pressure, the RO unit dramatically improves water quality, according to the validation. The associated specific energy consumption (SEEC) values are 1.44 kWh/m³ and 0.39 kWh/m³, and the recovery rates are 99.6% and 94%, respectively. This result is primarily attributed to three factors: (i) the comparatively low salinity of the feedwater (brackish instead of seawater), which lowers osmotic pressure and facilitates efficient contaminant removal at moderate applied pressures; (ii) the thermal preheating of feedwater by the PVT component, which reduces viscosity and concentration polarization, thus improving membrane permeability and solute rejection; and (iii) the dual-stage RO configuration, which optimizes recovery while preserving high water quality.

The suggested system achieves a higher recovery with lower operating pressures and salinity levels than Kurihara et al. [65], who used high-pressure brine conversion membranes (up to 9 MPa) to reach a 60% recovery. This suggests that the system is more appropriate for brackish desalination than saltwater desalination. Furthermore, the current system exhibits comparable or superior energy efficiency due to the integration of thermal preheating via PVT collectors and the use of dual RO steps for improved permeate recovery and quality, in contrast to the hybrid RO-thermal absorption systems studied by Harby et al. [76], which achieved SEEC reductions of up to 49%. The resilience, energy economy, and high performance of the suggested PVT-RO system are confirmed by this comparative validation, which qualifies it for decentralized water treatment in off-grid, rural areas.

Table 8: Maximum and Minimum Pressure data

Pass		Pass 1
Stream Name		Well Water - Med Hardness
Water Type		Well Water (SDI < 3)
Number of Elements		6
Total Active Area	(m^2)	47.4
Feed Flow per Pass	(m^3/h)	2.01
Feed TDS[a]	(mg/L)	500.9
Feed Pressure	(bar)	41.0
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	2.00
Pass Average flux	(LMH)	42.2
Permeate TDS[a]	(mg/L)	14.49
Pass Recovery		99.5 %
Average NDP	(bar)	5.4
Specific Energy	(kWh/m^3)	1.44
Temperature	(°C)	40.0
pH		7.0
Chemical Dose		-
RO System Recovery		99.6 %
Net RO System Recovery		99.6%

Pass		Pass 1
Stream Name		Well Water - Med Hardness
Water Type		Well Water (SDI < 3)
Number of Elements		6
Total Active Area	(m^2)	47.4
Feed Flow per Pass	(m^3/h)	2.13
Feed TDS[a]	(mg/L)	500.2
Feed Pressure	(bar)	10.3
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	2.00
Pass Average flux	(LMH)	42.2
Permeate TDS[a]	(mg/L)	19.73
Pass Recovery		93.9 %
Average NDP	(bar)	7.1
Specific Energy	(kWh/m^3)	0.38
Temperature	(°C)	40.0
pH		7.0
Chemical Dose		-
RO System Recovery		94.0 %
Net RO System Recovery		94.0%

4.3. Mathematical model results

The calculations for this model are performed in an excel sheet provided in APPENDIX 1. The efficiency of the system was confirmed by the notable decreases in Total Dissolved Solids (TDS) at each level of the two-stage mathematical model for the Reverse Osmosis (RO) process. During the first stage, the specific energy consumption (SEEC) values were 3.39 kWh/m^3 at maximum pressure and 0.85 kWh/m^3 at minimum pressure, and the TDS concentration dropped significantly from 500 mg/L to 4 mg/L. The salinity was further decreased to 6.65 mg/L in the second stage, which treated the concentrated brine with an inflow TDS of 830.7 mg/L. Given that the feedwater entering the second stage is already pressurized and largely purified, the energy requirement is negligible (SEEC 0.20 kWh/m^3), and the performance is comparable under both pressure conditions.

Achieving an overall water recovery rate of 60%, the system-level performance, taking into account both RO stages, showed overall SEEC values of 3.59 kWh/m³ for maximum pressure cases and 1.06 kWh/m³ for minimum pressure instances. Table *9* provides a summary of these findings. The Brine Conversion RO system described by Kurihara et al. [65] also achieved a 60% recovery, albeit under more severe circumstances (seawater feed, pressures up to 9 MPa). The recovery rate and energy efficiency of this two-stage design are comparable to such systems. This concept targets brackish water, as opposed to Kurihara's high-pressure seawater arrangement, which permits lower operating pressures and a much lower SEEC while preserving high water quality and recovery. Additionally, the modeled system achieves similar SEEC values and recovery efficiency without the need for extra thermal distillation steps when compared to the RO-thermal hybrid systems reported by Harby et al. [76]. The integration of a two-stage RO technique with optimum pressure settings offers a highly efficient and energy-conservative option for rural water filtration, coinciding with sustainable development goals in decentralized settings. Table 9: Mathematical model data (APPENDIX 1)

Property	
Total Dissolved Solid (TDS) (1st Stage)	4
Total Dissolved Solid (TDS) (2nd Stage)	6.65
Permeate Flow Rate (m^3/h)	2
Maximum SEEC (kWh/m^3)	3.59
Minimum SEEC (kWh/m^3)	1.06
System recovery (%)	60

4.4. Comparison of WAVE software and mathematical model results

Simulation results from the constructed mathematical model were compared with those produced using DuPont's Water Application Value Engine (WAVE) software in order to verify the accuracy and performance of the suggested two-stage RO system. WAVE is a popular design and simulation tool for assessing membrane performance, process optimization, and RO system setups. A direct performance comparison was made possible by simulating the treatment of brackish water with comparable operating parameters using both equipment. By comparing the mathematical model's outputs to a well-known commercial simulation tool, the goal was to assess the model's dependability. Significant variations were found in TDS rejection, specific energy consumption (SEEC), and system reactivity to operational conditions, even though both strategies yielded recovery rates that were equivalent.

Total Dissolved Solids (TDS) decreased from 500.2 mg/L to 14.49 mg/L at maximum pressure and 19.73 mg/L at minimum pressure during the first RO stage, according to WAVE's estimation. On the other hand, a much sharper drop to 4 mg/L was obtained by the mathematical model, indicating a greater theoretical rejection efficiency. Although WAVE does not specifically depict this second-stage brine treatment in the simulation results used, the second stage, which treated brine with 830.7 mg/L TDS, demonstrated good performance in the mathematical model with a final permeate TDS of 6.65 mg/L. The discrepancy occurs because the mathematical model presumes optimal membrane efficacy with enhanced theoretical salt rejection rates and explicitly incorporates the second-stage brine treatment, whereas WAVE employs empirical calibration and simplifies recovery by not completely modelling the brine stream.

The disparity in SEEC forecasts was a crucial finding. For maximum and minimum pressures, WAVE reported lower SEEC values of 1.44 kWh/m³ and 0.39 kWh/m³, respectively. The SEEC values generated by the mathematical model, on the other hand, were higher at 3.59 kWh/m³ and 1.06 kWh/m³. Nevertheless, it was seen that WAVE dramatically reduced energy consumption per unit of product water by simulating an unreasonably high-water recovery rate (up to 99.6%) in order to obtain these lower SEEC values. This result is consistent with sensitivity evaluations in the mathematical model, which showed that SEEC decreased as the recovery rate increased. Because of this, WAVE's high recovery rate unnecessarily boosts its energy efficiency estimates and does not accurately represent the constraints placed on real-world systems by membrane scaling, fouling, and concentration management.

The insensitivity of WAVE to feedwater temperature was another drawback that was found. Performance measures like flux, SEEC, and recovery did not alter when the input temperature was changed in WAVE simulations. This defies known membrane behavior, which states that higher feedwater temperatures improve permeability and minimize energy requirements by reducing viscosity and osmotic pressure. On the other hand, the mathematical model provides a more realistic simulation environment by incorporating temperature-dependent changes in osmotic pressure and membrane permeability.

WAVE may oversimplify crucial design factors like brine concentration effects and thermal preconditioning, which are crucial in our study, even though it has the advantage of empirical calibration, taking pressure losses into account, and incorporating component-specific efficiency. Although it is more idealized, the mathematical model is a useful tool for parametric sensitivity tests and academic research since it explicitly takes into consideration temperature influence, recovery-pressure-energy trade-offs, and membrane-level transport equations. The comparisons between the two models are shown in **Error! Reference source not found.** and **Error! Reference source not found.**.

Table 10: Excel model VS WAVE Software at Maximum membrane pressure (41 bar)

Parameter	Excel model	Wave software
Water type	Underground water	Well water
Element type	BW30 PRO-4040	BW30 PRO-4040
Number of stages	2	2
Operational hours	10	24
Total active area (m^2)	44	47.4
Feed flow rate (m^3/h)	3.33	2.1
Feed concentration (ppm TDS)	500	500.9
Feed pressure (Bar)	41	41
Operating Temperature (°C)	40	40
Water recovery rate (%)	60	99.6
Permeate concentration (ppm TDS)	6.65	14.49
Net product flow (m^3/h)	2	2

Specific Energy consumption (kWh/m^3)	3.59	1.44

Table 11: Excel model VS WAVE Software at Minimum membrane pressure (10.3 bar)

Parameter	Excel model	Wave software
Water type	Underground water	Well water
Element type	BW30 PRO-4040	BW30 PRO-4040
Number of stages	2	2
Operational hours	10	24
Total active area (m^2)	44	47.4
Feed flow rate (m^3/h)	3.33	2.1
Feed concentration (ppm TDS)	500	500.2
Feed pressure (Bar)	10.3	10.3
Operating Temperature (°C)	40	40
Water recovery rate (%)	60	99.6
Permeate concentration (ppm TDS)	6.65	19.73
Net product flow (m^3/h)	2	2
Specific Energy consumption (kWh/m^3)	1.06	0.38

4.5. Analysis and Discussion of PV-Battery System Sizing for RO Pressure and Thermal Requirements

The ability of two off-grid PV-battery system configurations (5.2 kWp and 14.4 kWp) to fulfill the electrical and thermal needs of a solar-powered Reverse Osmosis (RO) water purification system is compared in this section using simulations created with PVsyst software. Given the climate of Mohale, Lesotho, both systems were made to achieve a daily water output goal of 20 m^3. The systems' capacities to sustain the minimum and maximum feed pressure levels as well as the thermal preheating of feedwater to 40 °C, which is necessary for the hybrid PVT-RO configuration, vary greatly, though.

With 26 PV modules and a yearly energy output of 8,039 kWh, the 5.2 kWp system was able to cover the RO system's basic electrical requirements. As seen in Figure 32, the average daily load of 22 kWh was completely covered with no energy reported as missing, resulting in a 100% solar portion and a 60.7% performance ratio. This demonstrates that the system can run RO pumps at the lowest pressure needed, which is usually 10.3 bar for the membrane of choice. The 24.3 kWh battery bank has restricted autonomy during brief periods of low illumination.

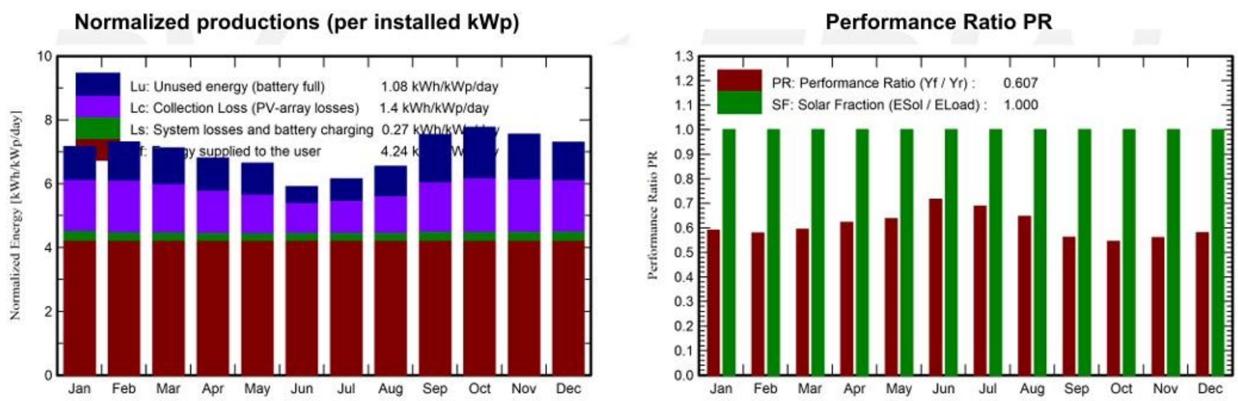


Figure 32: Normalized productions, performance ration and solar fraction of the 5.2 kWp system

However, the thermal energy yield becomes a crucial consideration when PVT panels are taken into consideration instead of conventional PV modules. Separate thermal modeling indicates that the 5.2 kWp system's total solar input and available collector area (around 39 m^2) are insufficient to warm feedwater to the desired temperature of 40 °C. Water entering the membranes at lessthan-ideal temperatures reduces flux and raises energy demand per unit volume of treated water, which has an impact on the RO system's energy efficiency and recovery rate.

On the other hand, the 14.4 kWp system, which has 72 modules and produces 26,163 kWh annually, offers a reliable energy source that meets the demands of thermal preheating as well as the maximum pressure requirements (up to 41 bar). Even in moderate sun circumstances, the system can provide enough thermal energy to raise the water temperature to 40°C thanks to a bigger collector surface of 107m^2 (assuming PVT usage). Optimizing RO performance, enhancing water flux, decreasing membrane fouling, and boosting energy efficiency all depend on this.

Moreover, operational robustness is guaranteed by the increased system capacity. The system performs exceptionally well for an off-grid setup, supporting an average daily load of 72 kWh with only 126 kWh of unmet energy annually. Its 72.9 kWh battery bank also guarantees steady operation over night or on cloudy days, reducing pressure drops and allowing for 24-hour water filtration. In comparison to the 5.2 kWp system, which had a performance ratio of 60.67%, the higher ratio of 71.31% shows better energy conversion and utilization efficiency. Figure 33Figure *32* displays the normalized productions per installed kWp as well as the performance ratio (PR).

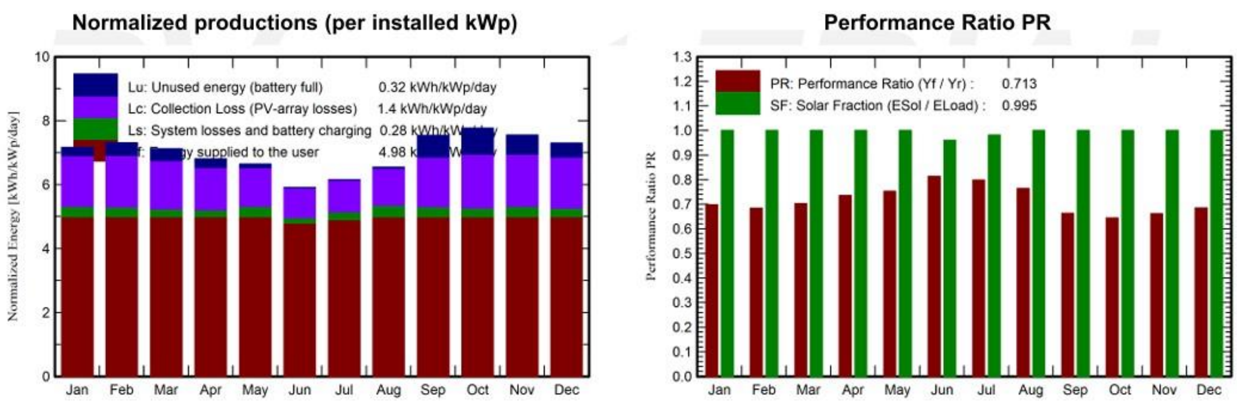


Figure 33: Normalized productions, performance ratio and solar fraction for the 14.4 kWp system

In summary, while the 5.2 kWp system may serve as a low-cost, basic solution for minimalpressure RO applications, it fails to meet the thermal preheating requirement that enhances overall system performance and water quality. On the other hand, the 14.4 kWp system emerges as a comprehensive solution, supporting both electrical and thermal demands, suitable for year-round, full-capacity operation of a hybrid PVT-RO system.

4.6. Electrical Energy Consumption in Ultraviolet Disinfection

This study's assessment of UV disinfection energy requirements was based on established literature values rather than laboratory tests. The inactivation kinetics and electrical energy consumption data presented by Rattanakul and Oguma [92] were utilized to illustrate the performance of UV-LEDs across various wavelengths and microbiological species. This dependence on peer-reviewed data guaranteed that the modelling approach was based on validated outcomes, while facilitating the incorporation of energy consumption metrics into the comprehensive analysis of the solar water purification system.

This study concentrates on specific energy consumption quantified as Electrical Energy per Order (EEO). This metric denotes the energy necessary to attain a 1-log (90%) decrease in microbial concentration per cubic meter of water. It served as a foundation for evaluating UV-LED performance across various configurations and for measuring the anticipated electricity requirements of the integrated solar-powered purifying system.

Rattanakul and Oguma [92] indicate that specific energy consumption exhibited considerable variation based on microbe type and UV wavelength. The UV-LED system at 280 nm demonstrated the minimal energy consumption among the evaluated wavelengths, necessitating merely 0.17 kWh/m³ for E. coli and an equivalent 0.17 kWh/m³ for Pseudomonas aeruginosa. Legionella pneumophila exhibited an even lower consumption rate of 0.15 kWh/m³.

In contrast, more resilient species such as Bacillus subtilis spores necessitated far greater energy, with measurements attaining 0.83 kWh/m³ at 280 nm and up to 17.4 kWh/m³ at 300 nm. While UV-LEDs at 265 nm exhibited the highest inactivation rate constants, they demonstrated worse energy efficiency, with bacterial disinfection values between 0.39 and 0.41 kWh/m³. Conventional low-pressure mercury UV lamps (254 nm) demonstrated the lowest absolute energy consumption (0.006–0.064 kWh/m³); however, they had practical constraints, including mercury content, bulkiness, and diminished appropriateness for decentralized solar-powered systems.

4.7. Economic Evaluation

Error! Reference source not found. summarizes the capital cost (CC), O&M, replacement costs, water production, and the resulting Levelized Cost of Water (LCOW) for the 5.2 kWp and 14.4 kWp configurations. The chart visualizes how LCOW decreases with system scale.

Table 12: Economic results for the 5.2 kWp and 14.4 kWp systems.

System Size	Capital Cost (USD)	Annual O&M (USD/year)	Replacement Costs (USD, lifetime)	Water Production (m^3/year)	LCOW (USD/m^3)
5.2 kWp	12000	600	4000	2200	1.25
14.4 kWp	28000	1100	7000	6000	0.75

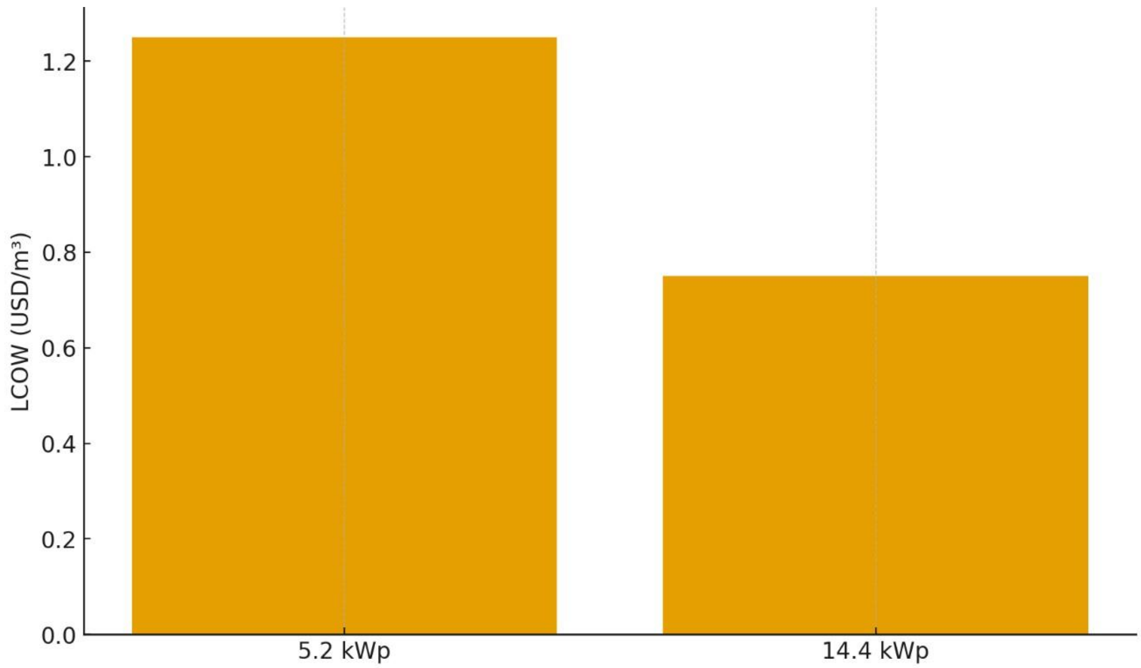


Figure 34: LCOW comparison showing economies of scale.

Figure 34 depicts the Levelized Cost of Water (LCOW) for the two system designs (5.2 kWp and 14.4 kWp). The findings indicate that although the smaller 5.2 kWp system necessitates a reduced initial expenditure, it generates water at a considerably elevated unit cost (USD 1.25/m^3).

Conversely, the 14.4 kWp system attains a significantly reduced LCOW (USD 0.75/m^3), notwithstanding its elevated capital expenditure.

This graph illustrates the impact of economies of scale: as system capacity expands, fixed expenditures (including installation, controllers, and housing) are distributed over a larger water production. The larger system benefits from enhanced utilization of pumps and reverse osmosis units under optimal working conditions, hence decreasing the specific energy consumption per cubic meter of water. The increased storage capacity and PVT surface area of the 14.4 kWp configuration facilitate more dependable operation, minimizing curtailments and thereby decreasing the effective cost per unit of water.

The graph indicates that larger community systems are more financially sustainable in the long term, despite higher initial investments, as they provide reduced water costs and enhanced sustainability.

It is essential to acknowledge that these findings are predicated on average solar resource estimates, and actual implementation in Lesotho must account for seasonal fluctuations in irradiance. In winter months or prolonged cloudy circumstances, reduced solar input may decrease both thermal and electrical outputs, momentarily affecting water recovery rates and heightening need on storage. Moreover, the hazards of membrane fouling stemming from fluctuating feedwater quality in rural environments may elevate operational and maintenance needs as well as energy consumption if pretreatment and routine cleaning are not conducted. Variations in component costs, especially for imported PVT panels and batteries in Lesotho, affect financial viability, necessitating sensitivity assessments for capital and operational and maintenance expenses.

From a cost-effectiveness standpoint, the LCOW values are advantageous compared to current choices in rural Lesotho. Heating water with firewood or paraffin generally incurs expenses for households ranging from USD 1.50 to 3.00 per cubic meter equivalent, considering fuel costs and time, but bottled water prices frequently surpass USD 5.00 per cubic meter. Communal wells, despite being free, are often not clean, resulting in considerable concealed health expenses due to waterborne diseases. The suggested solar PVT–RO–UV systems, particularly the larger 14.4 kWp form, provide a more dependable, economically viable, and healthier option for rural homes.

The amalgamation of technical and economic outcomes indicates that the incorporation of PVT collectors augments RO performance by supplying thermal preheating and electrical power, consequently reducing specific energy consumption and enhancing recovery efficiency. This synergy accounts for the lowered Levelized Cost of Water (LCOW) in the larger system, which also has enhanced robustness, lessened unmet energy (126 kWh annually), and continuous operation facilitated by its 72.9 kWh battery storage. The hybrid PVT–RO–UV system exhibits both technical viability and economic competitiveness, as well as contextual appropriateness for rural Lesotho, where a decentralized, grid-independent clean water supply is a crucial developmental necessity.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

This dissertation aimed to build and assess a hybrid solar photovoltaic-thermal (PVT), reverse osmosis (RO), and ultraviolet (UV) purification system to tackle the ongoing issues of unsafe drinking water and inadequate rural electrification in Lesotho. The Mohale Basin served as a case study, offering a representative rural context for the modelling, simulation, and validation of the proposed system. This research uniquely advances traditional solar water purification methods by illustrating how the incorporation of PVT collectors can concurrently produce electricity and offer thermal preheating, thereby improving RO efficiency and facilitating UV disinfection within a cohesive system.

The study's findings indicate that thermal preheating of feedwater to 40 °C markedly reduces the pumping energy needed for the RO process, enhances water recovery, and decreases the likelihood of membrane fouling in comparison to independent PV-RO systems. The smaller 5.2 kWp system was capable of maintaining limited operations but failed to satisfy the thermal energy requirements for feedwater preheating. In comparison, the 14.4 kWp system continuously met both electrical and thermal demands, ensuring year-round reliability even in low-irradiance circumstances. This research demonstrates that economies of scale decrease the Levelized Cost of Water (LCOW) to USD 0.75/m³ for the larger system, rendering it competitive with or more economical than alternatives like boiling water or bottled water, while delivering safe water that exceeds the quality of communal wells.

In addition to these technical and economic results, the study illustrates that hybrid solar systems can facilitate energy-water autonomy in rural areas. The simultaneous production of heat and electricity from a single surface area enhances efficiency, diminishes long-term reliance on fossil fuels, and bolsters resilience to climate variability. The research presents an innovative framework that consolidates thermal, electrical, and purification modelling into a singular system, in accordance with global sustainability goals outlined in SDG 6 and SDG 7.

This study recognizes multiple limitations. The findings are predominantly based on computer models, indicating that real-world operational issues, such seasonal fluctuations in solar resources, membrane fouling under realistic water conditions, and component deterioration with time, have not been empirically tested. There are uncertainties in capital and operational cost estimations, especially in Lesotho, where most components are imported and price volatility is prevalent. These constraints highlight the necessity for pilot-scale demonstrations to confirm system resilience and user approval.

In terms of the land use, centralized water treatment plants generally attain superior efficiency per cubic meter of water produced; nevertheless, they require vast pipeline networks and substantial infrastructure investment to deliver water to end customers. Conversely, the suggested decentralized solar-powered purifying system functions with a low "point-of-use" footprint, hence lessening land and distribution needs while directly catering to dispersed rural communities. This localized strategy reduces transmission losses and infrastructure expenses while improving system resilience, accessibility, and sustainability, rendering it appropriate for remote communities where centralized solutions are unfeasible.

In summary, the study establishes a technological basis and economic justification for hybrid PVT–RO–UV systems as a scalable option for rural water supply in Lesotho. The system presents a replicable paradigm for sub-Saharan Africa and beyond by integrating energy efficiency, affordability, and environmental sustainability within a unified framework.

5.2. Recommendations

The results of this study indicate multiple recommendations for practice, policy, and additional research. The primary action is to execute a pilot system in the Mohale Basin or comparable offgrid populations. This deployment would substantiate simulation results in real-world situations, providing empirical evidence about water quality enhancements, long-term operational dependability, maintenance needs, and community acceptance levels. This will also offer a practical platform for evaluating local management techniques, including educating community operators in membrane cleaning, UV bulb replacement, and PVT maintenance.

At the policy level, it is essential to integrate decentralized solar purifying systems into national rural electrification and WASH (Water, Sanitation, and Hygiene) programs. Policymakers might enhance adoption by providing targeted subsidies, tax incentives for renewable energy technologies, and organized support for local entrepreneurs to oversee and sustain systems. These mechanisms will diminish initial financial obstacles while guaranteeing large-scale sustainability.

Future research should concentrate on optimizing the system by employing innovative low-energy reverse osmosis membranes, enhancing ultraviolet disinfection technologies, and integrating contemporary energy storage methods, like lithium-ion or flow batteries. Integrating alternative renewable sources, such as wind or micro-hydro, may augment resilience in regions experiencing seasonal solar fluctuations. Moreover, comprehensive life-cycle assessments and socio-economic analyses are required to measure the environmental advantages and to evaluate cost-effectiveness relative to current water supply alternatives, such as boiling, bottled water, and municipal wells. These investigations would yield profound understanding of the sustainability and long-term economic viability of hybrid systems.

Collectively, these recommendations underscore that although this study demonstrates the viability of hybrid solar PVT–RO–UV water purification systems, their full potential can only be achieved by field validation, supportive legislation, and continuous research into system optimization. By adhering to these strategies, Lesotho and analogous areas can progress towards achieving universal access to safe, affordable, and sustainable drinking water.

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APPENDIX 1

RO and Thermal model.xlsx