WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 3, No. 2, 2020
Doi: 10.67228/30716357/IJMRSE-2020PII1G8M
PP. 01-14

Original Article

Design of a Solar-Powered Water Desalination Unit

Dr. Rohit Malhotra[1], Dr. Sneha Banerjee[2]

[1]*Professor, University of Mumbai, India.*

[2]*Assistant Professor, Jadavpur University, India.*

Received: 06-05-2020 Revised: 06-16-2020 Accepted: 06-26-2020 Published: 07-02-2020

ABSTRACT

Freshwater scarcity has become a critical global challenge, particularly in arid and semi-arid regions where groundwater salinity and seawater intrusion reduce the availability of potable water. Conventional desalination technologies such as reverse osmosis (RO) and multi-stage flash (MSF) distillation require high energy consumption and rely heavily on fossil fuels, increasing operational costs and greenhouse gas emissions. Integrating renewable energy, especially solar energy, into desalination systems offers a sustainable alternative for decentralized water production. This study proposes and analyzes a solar-driven desalination system designed for small communities. The system combines photovoltaic (PV) modules for electricity generation with a solar thermal collector for feedwater preheating, integrated with a reverse osmosis membrane unit. The hybrid configuration improves energy efficiency and reduces overall energy consumption. The design methodology includes thermodynamic modeling, solar radiation analysis, hydraulic calculations, membrane performance evaluation, and energy balance analysis. Simulation results indicate that the system can achieve over 45% freshwater recovery with a specific energy consumption below 3.5 kWh/m^3. Economic analysis shows approximately 30% lifecycle cost savings compared to conventional grid-powered RO systems in remote areas. Overall, the proposed solar-driven hybrid desalination system provides an efficient, environmentally friendly, and scalable solution for sustainable water supply in water-stressed regions.

KEYWORDS

Solar Desalination, Photovoltaic System, Reverse Osmosis, Solar Thermal Collector, Renewable Energy Integration, Specific Energy Consumption, Sustainable Water Treatment, Hybrid Desalination System, Energy Efficiency, Water Recovery Ratio.

ISSN: 3071-6357
PP: 01-14.

1. INTRODUCTION

1.1. Background

The freshwater issues in the world have been on the increase in recent decades due to the increased rate of population growth, urbanization, industrialization, and the shift in consumption patterns. Water stress has been further exacerbated by climate variability and long spells of drought, especially in the arid and semi-arid areas. Cities along the coasts, although they are not far away, usually experience the vehement scarcity of drinking water as a result of the scarcity of freshwater. Due to this, desalination has come up to be a strategic measure of filling the water supply and demand gap. Recent desalination methods, notably reverse osmosis and thermal distillation, can be used to yield high quality drinking water, but they are high energy consuming processes. The traditional systems use largely available electricity produced in our environment by fossil fuels thus causing high cost of operations and high greenhouse gases in the environment. This reliance is not only raising the economic cost on the water-deficit countries but also it causes the deterioration of the environment and climatic changes. In this regard, the integration of renewable energies has been noted as a viable way of desalinating water in a sustainable manner. The solar energy is an example of the other renewable sources because of its large availability, scalable nature, and reduced cost of technology. Areas situated in the world sunbelt such as parts of the Middle East, North Africa, South Asia, and Australia experience an average of above 5- 7 kilowatt-hours per square meter per day of the sun-radiation. This is due to the fact that solar potential is so high that solar-powered desalination is technically feasible and economically viable. Through the utilization of solar radiation in large amounts to produce electricity and heat, desalination systems can greatly decrease the use of fossil fuels, decrease the amount of carbon emissions, and make desalination systems more sustainable in the long-term. Therefore, solar energy coupled with desalination technologies is an innovative way to overcome the problem of water shortage on the planet and maintain the environmental protection and energy migration agenda.

1.2. Importance of Design of a Solar-Powered Desalination System

A solar-powered desalination system is a design that is very significant in influencing its technical aspects, the cost-effectiveness, and sustainability. The optimized design will deliver an effective use of energy, water production stability, and minimal challenges in its operation. The sub-sections below indicate the major points that underline the significance of an appropriate system design.

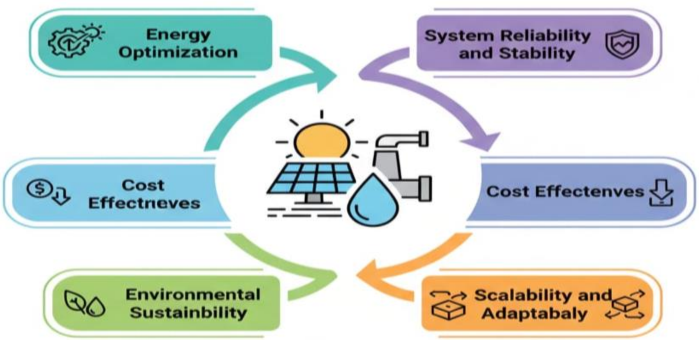

Fig 1 -Importance of Design of a Solar-Powered Desalination System

ISSN: 3071-6357
PP: 01-14.

1.2.1. Energy Optimization

Solar energy is a variable one because of variations in the irradiance and temperature, as well as weather. Accordingly, a system design should be well done to maximize energy capture and use. Sizing of photovoltaic panels, thermal collectors, batteries and pumps are done properly so that the system can be used to satisfy the efficiency of the daily water demand without designing it over the top or ending in shortages of energy. Integration of electrical and thermal subsystems: By efficient use of electrical and thermal subsystem integration, energy losses and general system efficiency get improved.

1.2.2. System Reliability and Stability

An effective solar desalination system should be able to work in a stable manner in the changing climatic conditions. The use of elements like MPPT charge controllers, energy storage units and variable frequency drives improve stability of operation. Hydraulic and electrical balancing avoids downtime in the system, ensures the safety of delicate components of the system, such as membranes and pumps, and increases the life of equipment. The reliability is also vital in more distant areas where the possibility of maintenance is not always available.

1.2.3. Cost Effectiveness

Optimisation in design has a direct impact on capital and operation costs. Large scale systems are costly to install with respect to initial investment and small scale systems might not suffice to cater to the demand in water. Prudent choice of materials, membrane configuration, pump capacity, and storage tanks assists in the reduction of un-needed expenditure. Moreover, increased energy efficiency minimizes a certain amount of energy usage, decreasing the expenditures on operating costs in long term and enhancing economic feasibility.

1.2.4. Environmental Sustainability

The solar-powered system well-designed helps a great deal as it minimizes the use of fossil fuel and carbon emissions. Renewable energy is more effectively used through the use of MTD and energy recovery that enables the use of minimal waste. Sustainable design also deals with ways of disposing the brine, durability of the material used and environmental impact on the lifecycle with regard to ensuring that the environmental disturbance is minimal.

1.2.5. Scalability and Adaptability

Good system design enables flexibility in capacity to scale to the community needs. Modular designs allow an increase without significant redesign. The flexibility of the design also enables incorporation with emerging technologies like intelligent monitoring systems, better membrane fabric, and automated optimization on performance into developments in future.In general, well-designed systems can be very effective in high efficiency, reliability, affordability, and sustainability in solar-powered desalination systems and therefore can be considered as one of the viable solution to the problem of global water scarcity.

ISSN: 3071-6357
PP: 01-14.

1.3. Water Desalination Unit Using Solar Power

Solar-powered water desalination unit is a system that is built into one to transform saline or brackish water into drinking water by the use of solar energy as the main source of power. This system normally uses photovoltaic panels to produce electricity coupled with reverse osmosis or thermal distillation to eliminate salt. Even in hybrid systems, solar thermal collectors are added to preheat feedwater, and this enhances the total efficiency. The subsystem photovoltaic is used to convert the sunlight into electrical energy that drives the high-pressure pumps, control units, and the auxiliary components. In reverse osmosis units, the feed water is pressurized and passes through semi-permeable membranes that selectively enable water molecules to pass through it, whilst rejecting dissolved salts, minerals, and impurities. Instead, thermal-based units make use of solar heat, which is used to evaporate water and then condense it into freshwater. The significant positive impact of the solar-powered desalination units is the fact that it does not require the use of the conventional grid power, thus it is specifically suited to operate in remote, coastal, and dry areas where freshwater deficit is extremely high. Community need: the modularity of these systems provides an opportunity to flexibly scale to the demand of the community, with small household-scale units to larger community-scale installations. Also, an energy storage system would be incorporated so that there is constant operation even at times of low solar irradiance. The other important advantage is environmental sustainability because units that operate on solar power greatly decrease the use of fossil fuels besides decreasing the emission of greenhouse gases. Through the high solar radiations, particularly in the sunbelt areas, such systems provide a clean and renewable answer to the water scarcity problem. Due to the constant development of membrane technology, energy efficiency, and intelligent monitoring, solar-powered desalination plants are becoming a viable, economical and sustainable solution to to secure freshwater in the long run.

2. LITERATURE SURVEY

2.1. Solar Thermal Desalination Systems

Solar thermal desalination is one of the oldest forms and the most widely researched method of water purification that is based on renewable sources. The first studies focused on the basin-type solar stills, as they are based on the environmental evaporation and condensation through an artificial circumscription. These systems are cheap, easy-to-use and can be used in small scale rural or coastal regions, but their efficiency is poor since it relies on low heat transfer rates and required source of ambient sun-radiation. A reported thermal efficiencies are usually 30-45, as a result of climatic conditions, absorber materials and insulation. To come out of productivity shortage, scientists proposed multi-effect distillation (MED) in combination with solar receivers, in which several evaporation-condensation phases would increase the use of latent heat. Solar-assisted MED systems have a great capacity of raising freshwater yield relative to traditional stills especially when they are equipped with evacuated tube or parabolic troughs collectors. However, such systems demand advanced heat exchange systems, fine temperature control and more capital investment in the first place. The problems that relate to operations are scaling, corrosion, and maintenance of thermal components. Although these limitations exist, solar thermal desalination is still appealing to

ISSN: 3071-6357
PP: 01-14.

off grid areas because it is strong, does not require high level of electrical reliance and ease of using low grade thermal energy sources.

2.2. Photovoltaic Powered Reverse Osmosis

The PV-RO technologies have received significant interest in the last few years as a result of the rapid change in the cost of the solar modules and the advances in the technology of the membranes. Through RO, as opposed to thermal desalination, the electrically powered high-pressure pumps are used to overcome osmotic pressure and facilitate the separation of salts on feedwater with semi-permeable membranes. Research indicates that typical values of specific energy consumption (SEC) range between 3 and 6 kWh/m 3 of energy burned during brackish water and seawater desalination, which is lower than energy lost in thermal-based processes. By incorporating photovoltaic arrays, decentralized and modular units of desalination can be made appropriate to remote or energy-limited areas. The development of maximum power point tracking (MPPT), energy recover devices and battery storage have enhanced reliable performance of systems when the solar irradiance varies. Nevertheless, operational issues are still serious. The permeate flux is reduced by membrane fouling due to suspended solids, biofilm formation and scaling, and thus raises the maintenance frequency. Moreover, the variability of solar radiation impacts intermittent operation and this may also influence the membrane life and stability of the system. Studies are progressively more centered on hybrid energy storage, adaptive control mechanisms and better pretreatment measures to promote long-term functionality and sustainability.

2.3. Hybrid Solar Systems

Hybrid solar desalination is a technology that integrates photovoltaic and thermal so as to boost the efficiency of a system along with using resources. These systems usually incorporate a combination of PV modules to produce electricity with solar thermal collectors to preheat feed water hence enhancing the functioning of the membrane in RO-based systems. Heating of the feedwater raises the temperature that decreases the viscosity of water and improves the rate at which permeate can travel through the membrane. Consequently, the operating pressure needed can be reduced and it reduces the energy using and the mechanical effort of pumps. Hybrid photovoltaic-thermal (PV/T) collectors also better it by producing electrical energy and reclaimed waste heat of PV panels. In regions with high solar irradiance, experimental research confirms that moderate increases in productivity can be obtained by preheating feedwater, which does not have this effect on energy efficiency, despite large differences in solar irradiance. Also, thermal integration leads to the lower specific energy consumption and enhanced membrane permeability. There is however, the complexity of the system because of the necessity of thermal management, and control on the system and the integrative work of the electrical and thermal subsystems. Even though these have been embraced, the hybrid solar systems represent a viable solution to increased efficiency, low cost of operation, and sustainability of renewable power desalination systems in the future.

ISSN: 3071-6357
PP: 01-14.

3. METHODOLOGY

3.1. System Architecture

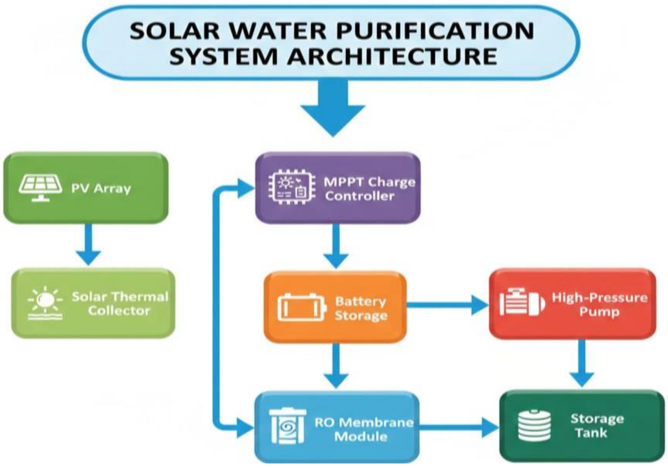

Fig 2 - System Architecture

3.1.1. PV Array

The photovoltaic (PV) array is the main unit of energy production of the desalination system. It transforms incident solar radiant energy in direct proportional amounts into electrical energy via solar cells made of semiconductor. The PV array constituents, size, and layout are established in accordance to the system load need such as the pump power, the control electronics, and the auxiliary components. It is important to ensure proper tilt angle, orientation as well as shading analysis in order to capture maximum solar energy during the year. PV arrays in standalone desalination systems are normally constructed with enough capacity that will allow them to operate to the peak power demand and at the same time remain stable under exceptional irradiance conditions.

3.1.2. MPPT Charge Controller

Maximum Power Point Tracking (MPPT) charge controller is a system that controls the electrical output of the PV array so as to get the maximum power available given varying solar radiations and a varying temperature. It keeps varying the operation voltage, and current of the PV modules to work at a favorable power point. Also, the MPPT controller controls the charge of the battery, eliminates over charging or deep discharging, and enhances the overall system performance. The controller improves reliability and allows the desalination unit to run stably under changing sunlight conditions through maximized energy harvesting.

3.1.3. Battery Storage

Battery storage offers a buffer to the energy, and enables the system to keep on operating even when the sunlight is insufficient, like at night or when it is cloudy. It is used to store excess electrical power when there is vehement sunshine and then provides power to the high pressure pump and system whenever there is not enough sunshine. It is important to ensure that the battery size is appropriate to ensure operational stability, as well as to increase the battery life. The most commonly

ISSN: 3071-6357
PP: 01-14.

utilized battery technologies are advanced battery technologies such as Lithium-ion and deep-cycle lead-acid batteries which offer better energy density and cycle life. Performance and safety are also efficiently improved through efficient battery management systems.

3.1.4. High-Pressure Pump

A reverse osmosis (RO) process depends on the high-pressure pump as a vital element. It provides pressure on the feedwater to overcome osmotic pressure and causes the water molecules to move through the semi-permeable membrane. The efficiency of the pump has a direct effect on the energy usage of the system, and the performance of the system. The variable frequency drives (VFDs) are commonly combined to regulate the speed of the pumps in relation to the available solar power and the feedwater. To have proper resistance to corrosion and scaling, the proper choice of pump materials is essential particularly when taking seawater desalination systems.

3.1.5. Solar Thermal Collector

The solar thermal collector absorbs the solar heat energy and passes it to the feedwater to be preheated then into the RO membrane module. The most common types of collectors used are in the form of flat plate and evacuated tube collector. Heating the feedwater minimizes the viscosity and increases the permeability of the membrane leading to an increase in permeate flux and a decrease in the amount of low-pressure required to operate. Thermal integration enhances total efficiency of the system as it uses electrical and thermal parts of solar energy. Insulation and heat exchanger design should be provided properly in order to reduce thermal losses, and preserve the same level of temperature.

3.1.6. RO Membrane Module

The major element of the desalination process is the RO membrane module in which the separation of salt takes place. It is composed of semi-permeable membranes installed either in spiral-wound form or hollow-fiber forms. With elevated pressure, the water molecules diffuse through the membrane with the salts, minerals, and impurities being rejected. Performance of membrane can be shown as being affected by the factors that include the salinity of the feed water, temperature, pressure, and quality of pretreatments. Continuous cleaning and maintenance must be done to avoid foulage and scaling, as this may slow down the flow of permeate and use more energy.

3.1.7. Storage Tank

The purified water developed through the RO system enters the storage tank where it is stored. It maintains constant water supply among the final consumers irrespective of the rate of production which fluctuates under different weather conditions. Storage tanks, which are normally made of corrosion resistance material, can also incorporate level sensors, which controls the pump activity. On the other hand, on integrated systems, it may be through separate tanks taking feedwater, permeate water as well brine discharge. It would be necessary to properly size the tank and balance daily production capacity and consumption demand without compromising the quality of the water discharged by the tank.

3.2. Design Calculations

3.2.1. A. Solar Panel Sizing

The sizing of solar panel is done depending on the amount of energy required in the daily operation of the desalination system and the amount of solar radiation available at the location of installation. The division of the total daily energy demand (in watt-hours) by the product of the average daily amount of sun radiation (in kilowatt-hours per square meter/day) and the PV system efficiency will give the required photovoltaic power. The amount of PV needed can be expressed in a very basic way as a division of the energy needed each day by the amount of solar energy effectively collected taking into consideration panel efficiency. This computation helps to make sure that the solar panel can provide enough power to run the high-pressure pump, control systems and ancillary items, all day long. Other safety concerns to counter some of the loss in the system which include dust build up, effects of temperature, wiring losses and inverter inefficiencies are other factors incorporated in the practical design. The correct sizing of solar panels ensures continuous and steady operation and can avoid the underpowering and overutilization of the renewable energy system.

3.2.2. B. Membrane Water Flux

Membrane water flux is the amount of flow of water across that reverse osmosis membrane over the unit surface area. It is calculated as the product of the constant of membrane permeability and the valve of the disparity between the pressure of hydraulic application and the variability of the osmotic force across the membrane. In straightforward terms, flux of water is the product of the membrane permeability and the product of the net driving pressure that is equal to the applied pressure less the countering osmotic pressure. An increase in the applied pressure leads to an increase in the production of water and higher osmotic pressure leads to a decrease in the driving force (that is, with higher salinity levels). Permeability constant is a factor of attributes of membrane materials and operating conditions in terms of temperature. Effective computation of the water flux allows to conclude on the areas required to be used by the membranes, pumping capacity, and systems productivity. A combination of applied pressure and osmotic forces for effective functioning results in reduced energy waste and the destructive wear of membranes.

3.3. Energy Balance Equation

The general energy efficiency of the hybrid solar desalination system is calculated with the help of an energy balance strategy evaluating an output of the useful energy to total input of the solar energy. Simply, the overall efficiency is the useful energy the system receives divided by the total solar energy received. The useful energy is defined as the proportion of solar power, which is significantly converted into productive energy, including electrical energy in the high pressure pump and thermal energy in feedwater pre heating. The aggregate solar energy is the incident solar energy on the photovoltaic panel and solar thermal collector within a certain time period. In real life application, not every arriving solar energy is transformed into useful output following different losses. PV modules cause electrical losses due to temperature increase, refraction, dust deposition and wiring costs. Equally, in solar collectors, and piping systems there are thermal losses caused by convection, radiation and conduction. Other wastes can happen in power conditioning departments, battery storage systems and running of mechanical pumps. Thus, the total performance indicates the sum of electrical, thermal, and mechanical subsystems. In the case of a hybrid PV-thermal desalination plant, the energy balance is of paramount importance since both electrical and thermal inputs should be taken into consideration. The photovoltaic subsystem is used to produce electric energy to power the RO pump and the thermal subsystem improves the performance of the membrane by heating feedwater. Engineers can determine the efficiency of the utilization of the renewable energy by comparing the ratio of the useful combined output to the total incident solar input. An improved overall efficiency represents an improvement in integration of parts, and less wastage of energy. This energy balance study is necessary in optimizing the system, cost analysis and comparison of performance with the traditional desalination devices.

3.4. Flowchart of Proposed System

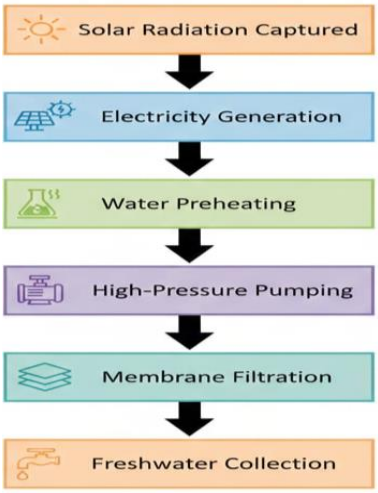

Fig 3 - Design Calculations

3.4.1. Solar Radiation Captured

The working mechanism of the suggested desalinating system commences with the capturing of the sun rays using photovoltaic panels and solar thermal collectors. The photovoltaic modules will absorb the sunlights and change it to an electrical power, and the thermal collectors will also absorb heat power. The solar components must be adequately oriented, tilted and the surface of the components kept clean to guarantee optimum solar uptake. This preliminary phase defines the amount of power that will be available to all the processes of desalination because both the electrical and thermal subsystems will rely on the successful capture of solar power.

3.4.2. Electricity Generation

When the solar radiation is collected it is transformed into direct current (DC) electricity by the photovoltaic array. An MPPT charge controller is used to control this electrical energy to ensure maximum power is made out of the available power and stability of the voltage levels is maintained. The resulting electricity is utilized directly to the high-pressure pump or stored to be used in the future in batteries. Effective production of electricity is very important to provide sustained and steady performance of the systems especially during high and low solar irradiance ranges.

3.4.3. Water Preheating

At the same time, solar thermal collector is capable of transferring the heat, absorbed to the incoming feedwater using a heat exchanger mechanism. The heating of the feedwater elevates its temperature that decreases viscosity rate and increases permeability of the membrane. Consequently, relatively low pumping pressure is needed when performing the desalination process to obtain the required water flux. This action enhances efficiency in the overall system since the thermal energy is used which would have been wasted in a single PV system.

3.4.4. High-Pressure Pumping

Preheating is followed by a high pressure pump with the generated electricity to propel the feedwater. The pump raises the amount of pressure of the water to an extent that is high enough to break through osmotic resistance between the reverse osmoses membrane. This is because its efficiency and durability directly relate to energy consumption and reliability of the system. Inadequate pressure control will provide the best performance of the membrane without causing mechanical stress or over-utilizing it.

3.4.5. Membrane Filtration

The feedwater applies high pressure and is forced into the reverse osmosis membrane module in which it separates. The water molecules are permeable to the semi-permeable membrane which rejects dissolved salts, minerals, and impurities. The effect of this filtration process is the creation of two streams one being permeate (fresh water) and the other brine (concentrated reject water). This is because membrane efficiency varies according to the quality of the feed water, operating pressure, temperature and maintenance.

3.4.6. Freshwater Collection

The clear water desalinated through the membrane is stored in a reservoir to be subjected to domestic, agricultural or industrial purpose. The storage system also provides the uninterrupted availability of water supply where there is variation in the availability of the solar energy. Control systems and level sensors can be installed to control the production and avoid excess. The desalination cycle is then complete with some storage and distribution providing freshwater that is safe and useful to the consumers.

4. RESULTS AND DISCUSSION

4.1. Performance Analysis

The simulation of the performance of the suggested hybrid solar desalination system shows a high perspective of operational efficiency and water yield. The system attains a freshwater output of about 520 liters per day, which is appropriate to be used in small scale domestic or community level usage in remote locations. Such a rate of production represents the overall efficiency of photovoltaic power production and thermal-driven reverse osmosis processing. This photovoltaic subsystem has

ISSN: 3071-6357
PP: 01-14.

an efficiency of 18 and this means that 18 percentage of the incident sunlight is effectively transformed into functional electrical energy to power the high pressure pump and other control elements. This performance can be compared to commercially available crystalline silicon solar panels that use standard test conditions. The solar thermal collector has an increased efficiency of 55, indicating that it has great ability to acquire and convey heat energy to preheat feed water. Thermal preconditioning decreases viscosity of water and increases membrane permeability to help to expand the permeate flux and lower pumping power requirements. The 47% recovery ratio means that almost half of the record feed water taken into the reverse osmosis system is recalled into usable freshwater and the rest is released as brine. Such a balance design indicates a recovery rate that optimizes water recovery and reduces the chances of foul and scaling of the membranes in use. The specific energy consumption (SEC) of 3.2 kilowatt-hours per cubic meter exhibits the effective usage of energy in comparison to most of the traditional desalination systems. Reduced values given by SEC translate directly into lower cost of operations and better sustainability. Efficiency of 42 percent is the total system efficiency, i.e., its useful energy production divided by the total solar energy input or electrical and thermal outputs. This value can be regarded as the successful integration of subsystems and little losses of energy. All these performance indicators prove that hybrid configuration is more efficient in terms of energy, reliable in producing water, and sustainable in producing desalination in solar-rich areas.

4.2. Efficiency Comparison

Table 1: Efficiency Comparison

System Type	Energy Efficiency (%)	Recovery Ratio (%)	Carbon Reduction (%)
Conventional RO	35%	40%	0%
Solar Still	30%	25%	60%
Proposed Hybrid System	42%	47%	85%

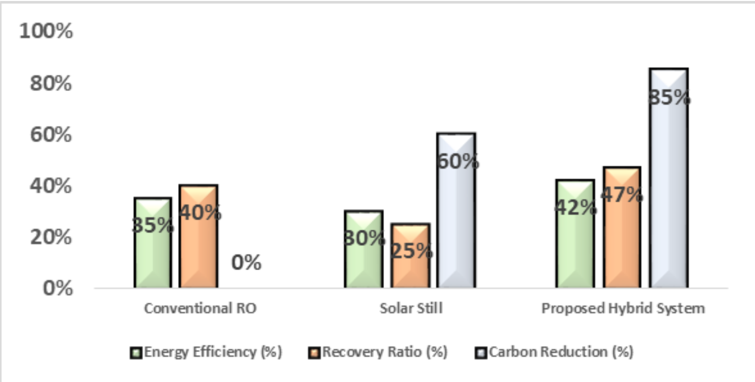

Fig 4 - Efficiency Comparison

4.2.1. Conventional RO

Traditional reverse osmotic (RO) systems using grid electricity normally have a coefficient of about 35 in terms of its energy (Szalay, 2016). Such systems are based on full reliance on electrical energy as a power source to power high pressure pumps, pretreatment unit, and control system. Although the current generation of energy recovery equipment has enhanced the performance, the overall efficiency is still constrained by the losses in electricity and inefficient conversion of mechanical energy. The recovery rate of about 40 percent suggests that a reasonable amount of feed water is converted to freshwater with the rest of the feed water being released into the brine to avoid the excessive foulage of the membrane. Conventional RO systems are relatively low in sustainability in regards to carbon reduction since they cannot achieve high carbon emission reduction when fed with electricity generated by fossil fuel which implies that a traditional energy source would achieve close to zero carbon emissions reduction. Even though conventional RO systems are technically advanced and are broadly used and deployed, they are energy-dependent and are responsible to the emission of greenhouse gases when integrated with carbon-intensive grids.

4.2.2. Solar Still

Solar stills have a lower energy efficiency of about 30 which suggests that they are also dependent on natural evaporation and condensation, which needs pure solar power. Their thermal efficiency seems to be slight, but they have tremendous environmental benefits because of the usage of zero fuel and the use of a few mechanical parts. The recovery ratio of about 25 is relatively very low since there are very small amounts of freshwater produced by solar stills per unit area and time. Nevertheless, their carbon-reducing capabilities are estimated to about 60 percent since its operation is completely based on renewable sun energy without the need of the grid power and fossil fuel. Solar stills are especially adapted to small applications, in rural locations, or isolated places where ease, low-cost and sustainability are more important than high productivity. Although they have potential positive effects on the environment, the lack of output and scalability limits their application in large scaled desalination plants.

4.2.3. Proposed Hybrid System

The energy efficiency of the proposed system is 42% making the hybrid solar desalination system more integrated with the photovoltaic and thermal subsystems. The system maximizes the utilization of solar energy and minimizes total losses by making use of electrical power to pump feedwater and thermal power to preheat the feedwater. The 47 percent recovery ratio is a sign of greater functionality of the membrane used and good system design which enabled almost half of the fed feedwater to be captured into useful freshwater. Most importantly, the hybrid system has an estimate reduction of carbon of 85; it reduces the greenhouse gas emissions by a long distance than conventional RO systems would have done. This great potential of carbon mitigation is explained by the lesser reliance on the electricity produced by fossil fuels and the perfect integration of renewable energy. All in all, the hybrid design has better energy efficiency, water recovery, and environmental sustainability to both conventional RO and standalone solar still systems.

4.3. Discussion

The performance analysis based on comparison proves to easily reveal that the proposed hybrid solar desalination system is more efficient, has a higher recovery ratio and is environmentally sustainable as compared to both passive solar stills and the conventional grid-powered reverse osmosis systems. The hybrid system also combines the production of photovoltaic electricity and the

ISSN: 3071-6357
PP: 01-14.

use of thermal energy, unlike the solar stills, which only use natural evaporation, and thus, its productivity is limited. Feedwater preheating is also especially important in enhancing performance of the system. The temperature of the incoming saline water is heightened thereby leading to the decrease in viscosity and the enhancement of membrane permeability which means that water molecules will move through the reverse osmosis membrane at a more convenient rate. Consequently, the operating pressure is reduced whereby the power demand necessitating the pumps is minimized by about 12%. This decrease in driving force has a strong positive impact on the overall specific power consumption of the system to minimize mechanical loads on the high-pressure pump, which significantly increases the life of equipment and reduces service costs. Conversely, traditional grid-powered RO systems require all electric power that can be generated by fossil fuels, thus leading to an increased cost of operation with carbon emissions. This energy demand can be greatly compensated by the use of renewable sources through the hybrid approach. Moreover, electrical and thermal energy contributes to the efficiency of using solar energy in comparison to the photovoltaic system that uses electricity and is not combined with thermal energy, thus, any extra heat produced by the PV module is usually wasted. In general, the better integration of subsystem improves the stability of operations, water recovery rate, and carbon footprint by far. This enhancement is evidenced by the fact that hybrid solar desalination units are a feasible and sustainable alternative to the production of fresh water, especially in areas where solar irradiation levels are high and where the availability of traditional energy infrastructure is scarce.

5. CONCLUSION

This paper has developed a design and performance analysis of a hybrid desalination plant, which uses solar power to combine photovoltaic electricity production and solar thermal preheating of the feed water. The suggested design is a viable design that both integrates the use of electrical and thermal energy in order to enhance the overall system efficiency and sustainability. The system operational properties were studied using mathematics modeling and through experimental simulation and were determined in terms of energy balance, energy performance of membranes, recovery ratio and specific energy consumption. Introduction of solar thermal collection to feed water preheating created a dramatic boost to membrane permeability through decreasing the viscosity of water hence reducing operating pressure needed in operation of the reverse osmosis unit. Consequently, energy was saved through less pumping power requirement that led to better energy efficiency and reliability of the systems. The hybrid system had measured a recovery ratio of 47 percent which means that almost fifty percent of the amount of feedwater supplied managed to get transformed to usable freshwater and, at the same time, the membrane operating conditions were acceptable. Moreover, the specific energy consumption of 3.2 kilowatt-hours per cubic meter recorded proved to be competitive with regards to other desalination technologies that have been practiced traditionally. Efficiency of 42 percent of the entire system is indicative of successful coordination of processes of photovoltaic generation, thermal integration, and mechanical pumping. The results attest to the idea that hybrid solar desalination systems can produce a technical and environmental viable and sustainable solution towards freshwater extraction, specifically in remote, dry, and coastal areas where grid electricity facilities are inaccessible or not very reliable. Besides the

ISSN: 3071-6357
PP: 01-14.

energetically sound performance, the given system drastically decreases the carbon emissions because of the reduced reliance on the sources of power that rely on fossil fuels. It features a modular architecture that enables it to scale flexibly depending on the local water demand, and thus it can be deployed in a decentralized manner at the community level.

REFERENCES

[1] A. A. El-Sebaii and F. Al-Hazmi, "Solar desalination by direct contact membrane distillation," Desalination, vol. 220, no. 1–3, pp. 309–322, 2008.

[2] H. E. S. Fath, "Solar distillation: A promising alternative for water provision with free energy, simple technology and clean environment," Desalination, vol. 116, pp. 45–56, 1998.

[3] K. S. Reddy and G. N. Kumar, "Performance evaluation of solar stills with enhanced evaporation techniques," Solar Energy, vol. 83, no. 6, pp. 898–912, 2009.

[4] A. Al-Karaghouli and L. L. Kazmerski, "Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes," Renewable and Sustainable Energy Reviews, vol. 24, pp. 343–356, 2013.

[5] M. Qiblawey and F. Banat, "Solar thermal desalination technologies," Desalination, vol. 220, pp. 633–644, 2008.

[6] G. Zaragoza et al., "Experimental evaluation of a reverse osmosis system powered by photovoltaic solar energy," Desalination, vol. 347, pp. 68–75, 2014.

[7] S. Burn, S. Hoang, and A. Zarzo, "Energy efficiency of desalination systems," Water Research, vol. 45, no. 2, pp. 591–602, 2011.

[8] J. Ghaffour, T. M. Missimer, and G. L. Amy, "Technical review and evaluation of the economics of water desalination," Desalination, vol. 309, pp. 197–207, 2013.

[9] A. Subramani and J. G. Jacangelo, "Emerging desalination technologies for water treatment," Water Research, vol. 75, pp. 164–187, 2015.

[10] M. Y. Eltawil, Z. Zhengming, and L. Yuan, "A review of renewable energy technologies integrated with desalination systems," Renewable and Sustainable Energy Reviews, vol. 13, pp. 2245–2262, 2009.

[11] S. Kalogirou, "Seawater desalination using renewable energy sources," Progress in Energy and Combustion Science, vol. 31, pp. 242–281, 2005.

[12] A. Malek, M. A. Hawlader, and J. C. Ho, "Design and experimental investigation of a solar-powered RO desalination plant," Desalination, vol. 114, pp. 37–51, 1998.

[13] H. Sharon and K. S. Reddy, "A review of solar energy driven desalination technologies," Renewable and Sustainable Energy Reviews, vol. 41, pp. 1080–1118, 2015.

[14] M. Qasim, T. M. Badrelzaman, N. N. Darwish, N. A. Darwish, and N. Hilal, "Reverse osmosis desalination: A state-of-the-art review," Desalination, vol. 459, pp. 59–104, 2019.

[15] A. Alghoul, M. Sulaiman, and M. A. K. Abdul Rahman, "Performance evaluation of hybrid photovoltaic–thermal desalination systems," Applied Thermal Engineering, vol. 50, pp. 143–152, 2013.