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Desalination of Well water by Solar Power Membrane Distillation and Reverse Osmosis and its Efficiency Analysis

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Abstract: The objective of the paper is to desalinate the well water sample and to study the thermal efficiency of solar power thermal membrane distillation and water efficiency of reverse osmosis. Merits and demerits of reverse osmosis and that of thermal membrane distillation (DCMD), applied mainly for the purification of water and desalination process are compared. The present work also provide guidelines for the development of novel technology to reduce the energy consumption using renewable energy. The result shows thermal efficiency is low for membrane distillation with respect to water efficiency for reverse osmosis. Water recovery for an hour operation is calculated as 46 % for solar powered thermal membrane distillation and 67% at 11kg/cm2 for reverse osmosis. This paper fetches an idea for new researchers to make a potential attempt in the area of solar integrated mode of membrane distillation for desalination of various water resources which can solve the global water crisis in arid regions. The present work also contributes on comparison of water quality analysis for well water using both the desalination membrane technology.
Keywords: Desalination, Reverse Osmosis, Solar powered thermal membrane distillation, Solar PV cell, Flux performance, efficiency, water quality.

1. Introduction

The lack of potable water poses a big problem in arid regions of the world where freshwater is becoming very scarce and expensive. Clean drinking water is one of the most important international health issues today. The arid regions are characterized by the increase in ground water salinity and infrequent rainfall. Desalination uses a large amount of energy to remove a portion of pure water from a salt water source [1].So it is necessary to do the process efficiency, flux performance and energy consumption for desalination of brackish water to meet the water crisis problem and global economical challenges. Brackish ground water RO desalination technology (48%) used in large number worldwide for the production of drinking water because of small plant production sea water RO (25%) plant [2]. But RO desalination has few disadvantages which can be overcome by solar power thermal membrane distillation. The most essential steps in the desalination process are based on using evaporation and condensation or membrane technology separation in order to discard the dissolved salt and dissolved minerals from the seawater or other salt water resources to obtain fresh and clean water.

1.1 Membrane Distillation:

Membrane distillation (MD) is a thermally driven separation process that involves phase conversion from liquid to vapor on one side of the membrane and condensation of vapor to liquid on the other side[3]. The exploitation of waste heat energy sources such as solar energy enables MD more promising separation technique for industrial scale. Growing economics and water scarcity are driving desalination as a solution for water supply problems. Membrane distillation in the application of water desalination make this technology a prospective one in the research areas. The membrane facilitates the transport of water vapor through its pores but does not participate in the actual separation process. Low operating temperature (less than 10^{O}C membrane temperature difference) and hydrostatic pressure makes MD attractive technology than any other conventional distillation in the field of desalination and food industry. Membrane distillation can be employed in four different configurations namely direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), Vacuum membrane distillation (VMD) and Sweeping gas membrane distillation (SGMD). Most of the researchers have already focused on the principle, experimentation and application of all the types. But integrated mode of solar power with thermal membrane distillation for potable water utilising low waste heat energy is ongoing research in most of the academic institute. Those of which DCMD and AGMD are best suited for the desalination applications where water is the major permeate component. These two configurations are applied to produce fresh water from a salt solution[4]. The process thermal efficiency of AGMD is higher than that of DCMD by about 6% due to the presence of the air gap. The permeate flux of DCMD is higher than that of AGMD by about 2.3-fold and 4.8-fold for *T*hi 80 and 40 °C, respectively. Increase of the thermal conductivity of the membrane material (*k*m) improves the DCMD process by mainly improving the process thermal efficiency and improves the AGMD process by mainly improving the permeate flux[5].

1.2 Reverse Osmosis Phenomenon:

Reverse osmosis is the process by exerting a hydraulic pressure greater than the sum of the osmotic pressure difference and the pressure loss of diffusion through the membrane can cause water to diffuse in the opposite direction into more concentrated solution. The greater the pressure applied, the more rapid will be the diffusion[6]. Higher water efficiency works under optimum design pressure and varies for different membrane model. RO membrane is hydrophilc in nature. A typical RO system consists of four major subsystems, pretreatment system, high-pressure pump, membrane module, and post treatment system. Using a high-pressure pump, the pretreated feed water is forced to flow across the membrane surface. Brackish groundwater has a much lower osmotic pressure than seawater; therefore, its desalination requires much less energy. Total Energy consumption for SWRO plant is around 3-4 kwhr/m3 for 50% recovery [7].

1.3 Solar power thermal Membrane Distillation:

Solar energy can be used to convert saline water into fresh water with simple, low cost and economical technology and thus it is suitable for small communities, rural areas and areas where the income level is very low. Recent developments have demonstrated that solar powered desalination processes are better than the alternatives membrane desalination technology like RO. Two types of solar power MD is classified as direct and indirect systems.

In direct systems are those where the heat gaining and desalination processes take place naturally in the same device,(Solar still) .In indirect method, the plant is separated into two subsystems, a solar collector and a desalination unit. The solar collector can be a flat plate, evacuated tube, solar pv cell or solar concentrator and it can be coupled with any of the distillation unit types which use the evaporation and condensation principle, such as MSF, MED and MD for possible combinations of thermal desalination with solar energy. Systems that use PV devices tend to generate electricity to operate thermal membrane distillation in Solar thermal MD[8].

MD techniques hold important advantages with regard to implementation of stand alone operating desalination systems. The most important advantages are the operating temperature of the MD process is in the range of 40℃ -100℃. This is a temperature level at which thermal solar collectors perform well. Intermittent operation of the module is possible[9]. According to simulated calculations, Spiral wound membrane module in SPMD pilot plant can distill 150 l/day of water in the summer in a southern country [10].Commercialised solar power membrane distillation like SCARAB plant consumes 5-12 kwh/m3 thermal energy consumption[13].

2. Membranes Characteristics

2.1 Membrane Distillation:

MD membrane should have the following characteristics[11]

- The membrane should be porous,

- The membrane should be hydrophobic,
- No capillary condensation should take place inside the pores of the membranes,
- Only vapor should be transported through the pores of the membrane,
- The membrane must not alter the vapor equilibrium of the different components in the process liquids,
- At least one side of the membrane should be in direct contact with the process liquid.

2.2 Reverse Osmosis:

RO membrane should have the following characteristics,

- Membrane should be easily manufactured with good salt rejection.
- They should be hydrophilic and have high water flux i.e highly permeable to water and less susceptible to fouling.
- The membrane should be chemically, physically and thermally stable in saline waters.
- They need to be strong enough to withstand high pressures and variable feed water quality [12]

3. Applications

3.1 Membrane Distillation:

Advantages:

- Complete rejection of non volatiles (e.g., salts, ions, colloids, cells, and organic non volatiles). Good quality of product water is obtained.
- Operation at near-atmospheric pressure compared to the high operating pressures of membrane processes like RO, etc., and lower operating temperatures (40–100 °C) than conventional multiple-effect distillation.
- Much reduced need for vapor space compared to conventional distillation processes.
- Much reduced mechanical strengths needed for the membrane and the module
- Membranes used in MD are tested against fouling and scaling.
- Chemical feed water pretreatment is not necessary.
- Pilot plant and lab scale research can be performed with less chemical consumables[13]

Disadvantages:

- Cost of membrane is very high to that of RO but the life span is more than 20 years.
- Low productivity and water efficiency compared to RO.
- Less commercialised for large scale desalination plant

3.2 Reverse Osmosis:

Advantages:

- Higher productivity of water and high water efficiency.
- Highly commercialised for large scale desalination plant.

Disadvantages:

- Higher power requirement of pressure pump.
- Membrane fouling is high because of high pressure liquid entry and requires membrane replacement once in 2 years.
- Pretreatment of water is must for free of pathogens and suspended particles for feed water.

- More space for auxillary equipment necessary and requires higher maintenance.
- Brine disposal causes environmental pollution.

4. Materials and Methods

Membrane was purchased from Trinity technologies ltd. Mumbai, for thermal solar powered membrane distillation. PTFE membrane filters used in this experiment for DCMD configuration has the effective membrane area, 5.6 m^2 given by the manufacturers.

The method of operation of desalination for this work is Direct Contact Membrane Distillation configuration. Here the feed is in direct contact with the hot membrane side surface, evaporation takes place at the feed-membrane surface and the vapour is moved by the pressure difference across the membrane to the permeate side and condenses inside the membrane module. It is the simplest configuration capable of producing reasonably high flux. It is best suited for applications such as desalination and concentration of aqueous solutions (e.g., juice concentrates). The schematic flow diagram is shown in Fig.1 well water as feed solution and distilled water as receiving phase.

The design specification of both the desalination technology used in our work is given in table.1.

Reverse osmosis membrane model used for this work is BW30-365 from Lenn Tech membranes.

Reverse osmosis set up for brackish water is automated with proper instrumentation like product flow indicator, reject flow indicator, feed pressure, membrane pressure, total dissolved solids (TDS) indicator etc.

Table No:1 Design specifications of solar power thermal membrane distillation and reverse osmosis.

Thermal Membrane Distillation	**Reverse Osmosis**	**Solar Pv Cell Module:**
Membrane Specifications: Media :0.2µm hydrophobicPTFE.(8cartridges) Support media : Polypropylene Cage/core/endcaps: Polypropylene. Gasket : Silicon. Internal support ring : Stainless steel. **Dimensions:** Nominal length : 9.75 inch Outside diameter: 2.7 inch Inside diameter : 1 inch **Operating conditions:** Maximum pressure difference : 4.1 bar at 20◦c 2.1 bar at 60◦c	**Membrane model:** BW30-365(Thin film composite membrane) **Membrane Specifications:** Membrane size : 8inch Length : 40 inch. Active surface area: 34 m2 Permeate flow rate : 9500gpd. Maximum feed flow rate : 3.2m3/hr Pressure drop : 1 bar. Number of RO elements used : 2	**Solar Pv cell module Specifications:** Maximum power: 100wp Voltage at max. power :17.40v Current : 5.75 A Normal operating cell temperature : 45deg.C Temperature coefficient of maximum power : - .41% Number of Pv cell module used : 10

5. Experimental Setup

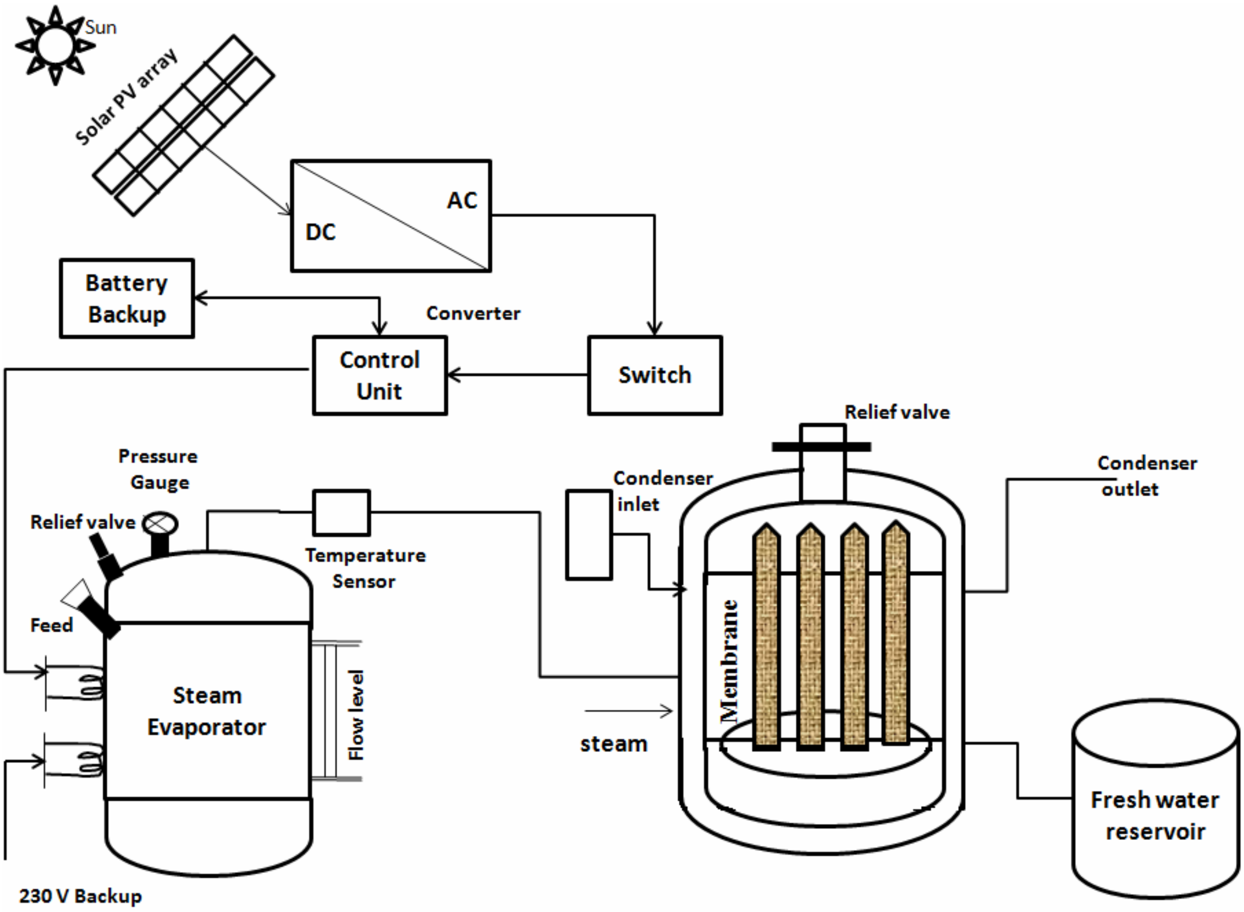


Figure.1. Solar power thermal membrane distillation flow diagram.

6. Experimental Procedure

6.1 Reverse Osmosis:

In the process of reverse osmosis, the feed well water is fed continuously in a single pass mode and the whole process is pretreated before it passes to the hydrophilic membrane and the product water is collected for different time intervals at different operating pressure and feed flow rate, for the calculation of flux performance and its efficiency.

6.2 Solar Thermal Membrane Distillation:

Solar PV array consists of 10pv modules each produce100 watts power, the energy produced by the PV array is transferred through DC/AC charge controller to a battery capable of storing enough energy for intermittent operation, the stored energy is then transferred to the control unit and through the DC/AC inverter. Thus the solar mode is integrated to thermal membrane distillation module (DCMD), producing the design capacity of 150 l/day. Membrane distillation uses hydrophobic membranes as a barrier for contaminated water from which mass transport of vapour is driven by differences in vapour pressure. In this experiment, approximately 30 litres of well water (TDS, 333Ppm) was fed into 50 l capacity of steam evaporator equipment and it is heated at constant temperature of 368k, the apparatus is well insulated for the prevention of heat loss to the environment, steam passes through the pores of membrane, vapour pressure difference occurs across the membrane, then condenses on the other side of the membrane. Permeate temperature measured at the distillate side was 328k. Performance test has been done in the month of January for many trials with different feed sample source around 11a.m to track more solar intensity for better results. Study of permeate flux, thermal efficiency and volume of product of distillate of coupling of solar energy PV cell module with the DCMD module on the permeate stream was carried out.

7. Result and Discussions

7.1 Reverse osmosis:

In reverse osmosis, data of collected product water were recorded during different intervals of time. Water efficiency for different operating pressure were studied for reverse osmosis and the data obtained was shown in the table.2, water efficiency is 67% for the operating pressure 11kg/cm2 as shown in figure.2. It is noted the average flux for increase in pressure increases and it is 8.32 l/m2hr for 11kg/cm2 as shown in figure.3 and it is claimed to be higher energy consuming desalination technology for commercial production.

Table No: 2 Reverse Osmosis of well water

S.NO	Feed Pressure (kg/cm2)	Concentrate flow rate(lpm)	Product flow rate (lpm)	Feed flow rate(lpm)	TDS(ppm)	Recovery ratio.	Water efficiency(%)
1.	4	105	16	121	9.18	0.132	13.2
2.	5	90	20	110	8.93	0.182	18.2
3.	5.5	80	23	103	8.37	0.223	22.3
4.	6.5	72	26	98	7.9	0.260	27
5.	7	64	30	94	7.81	0.319	32
6.	7.5	59	33	92	7.7	0.359	36
7.	8.5	51	35	86	8.1	0.407	41
8.	9	44	38	82	7.84	0.46	46
9.	10	35	41	76	8.7	0.539	54
10.	10.5	26	44	70	9.26	0.629	63
11.	11	23	46	69	9.7	0.667	67

Figure .2. Feed pressure Vs Water efficiency in RO

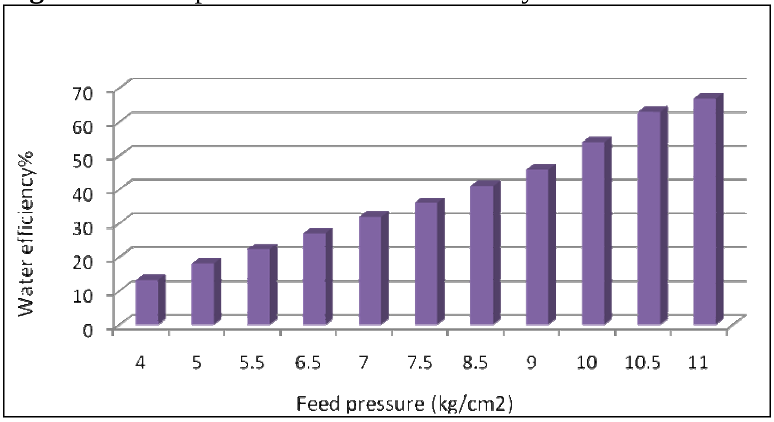
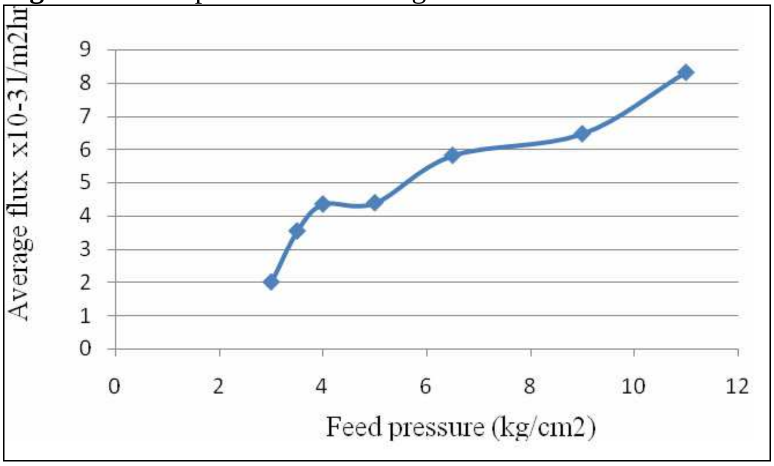


Figure .3. Feed pressure Vs Average flux in RO



7.2 Solar power membrane distillation:

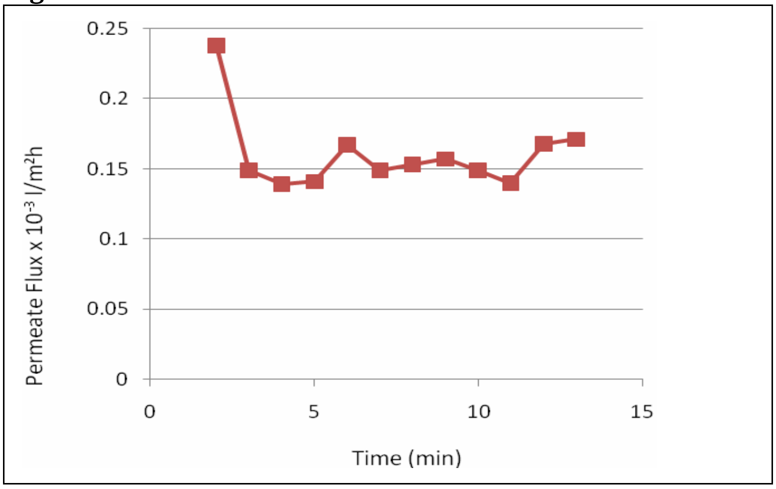
In solar power membrane distillation, the data obtained as a collection of volume of product distillate as a function of time was given in the table.3. It is inferred from figure.4., that the flux increases with time initially and then declines on further increase of time, that may be due to temperature polarisation effect and low vapour pressure due to loss of convective heat transfer across the membranes. This effect is more pronounced for the process of thermal MD without solar power mode. The product distillate achieved is 67.2 l/day and the permeate flux is 0.16 l/m^2 hr, and it is low power consuming desalination technology because of utilising low waste heat energy and requires less auxillary equipments unlike RO. The flux value and heat efficiency for solar power membrane distillation are in good agreement with the reported values found in literature[15,16]. Thus from the calculation of effectiveness of both the desalination techniques, it is inferred that solar powered thermal efficiency 41.8% compared to water efficiency of RO was 67% for optimum design pressure. Electric power consumption for solar mode was measured as 1.86kwh and for RO measured as 3kwh .The observed decrease of the permeate flux and thermal efficiency is probably also influenced by a significant decrease of convective heat transfer coefficient across the membrane for solar power thermal membrane distillation.Process efficiency of membrane distillation depends upon the operating variables such as optimum temperature, flow rate and feed concentration. Higher thermal efficiency can be obtained when operating conditions that increase the permeate flux are used in the membrane distillation process[14].

Table No:3 Solar thermal membrane distillation

At constant feed temperature 368k, feed flow rate, 6.05x10-2 l/hr and Permeate temperature 328k.

S.NO	Time(minutes)	Permeate volume(ml)	Permeate flux x 10-3(l/m2hr)
1.	1	80	0.238
2.	2	100	0.149
3.	3	140	0.139
4.	4	190	0.141
5.	5	280	0.167
6.	6	300	0.149
7.	7	360	0.153
8.	8	420	0.157
9.	9	450	0.149
10.	10	470	0.140
11.	11	620	0.168
12.	12	690	0.171

Figure .4. Time VS Permeate flux in solar thermal membrane distillation



7.3 Thermal efficiency calculation:

Heat energy consumed is given by the heat flow rate equation and it is calculated as 469KJ/hr for solar thermal membrane distillation with the known value,' Cp', specific heat capacity of feed , measured value of feed inlet and outlet temperature , 368k and 328k and calculated product flow data , 2.8l/hr for solar integrated mode MD. Thermal efficiency was calculated using the below formula by substituting 'J' permeate flux, 'A' ,membrane module area ,

The thermal efficiency (ηT) was calculated using the equation [14]

$$\eta T = J H_v A \; / \; m_F \, Cp \, (T_{F\,inlet} - T_{F\,outlet})$$

where T_F inlet and T_F outlet are the feed inlet and outlet temperature at the MD module , Hv is latent heat of evaporation at the feed inlet temperature, m_F is feed mass flow rate, and Cp, specific heat capacity respectively.

Here for H_v, 2270 KJ/Kg at 368 k, thermal efficiency was found to be 41.8%. Specific thermal energy consumption is the ratio of latent heat of vapourisation to that of volume of fresh water produced for the given time and it is measured for solar integrated MD system as 811kwhr/ m^3. For solar powered MD water productivity was found to be 66%, water recovery 46.3% . The values are in agreement with the reported values found in literature, specific thermal energy consumption at feed temperature (60℃ -85℃) is 140-200kwhr/m3, distillate output 20-30l/hr for larger design capacity of 600-800 l/day with72m^2 membrane area[9,13]

7.4 Water Quality Analysis:

TDS of well water present initially was around 333mg/l and electrical conductivity was 610 mho/cm, salt concentration was completely zero after the experimental run, the quality of water obtained was pure even it can be used for pharmaceutical industry in a small scale level. The water quality analysis after membrane distillation trials was given in the table.4. as follows,

Table No: 4 Water Quality Analysis

S.NO	Parameters	Well Water	RO Treated water	Solar Thermal MD treated water
1.	PH	7.8	8	7.4
2.	TDS , mg/l	333	9	8
3.	TOTAL HARDNESS as $CaCO_3$,mg/l	265	7.5	5.5
4.	SODIUM ,mg/l	18	0	0
5.	ELECTRICAL CONDUCTIVITY, mho/cm at 25℃	610	15	11

8. Conclusion

A novel technology of coupling of thermal membrane distillation with solar energy for the design and operation of DCMD for desalination was investigated. It was well understood that there is a greater scope for the feasibility of solar powered MD for good quality of product flow, high rejection of salts, low energy consumption and efficiency in desalination of water process provided extensive research is to be focused for constant success of work. Solar mode of integration would decrease thermal energy demand of thermal MD technology, thereby achieving higher performance. Rural remote areas don't profit from well established reverse osmosis desalination technology, hence integrated solar MD will be a boon for long run operation with less maintenance, less energy consumption and one time capital investment which is more economical.

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