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Process modeling for economic optimization of a solar driven sweeping gas membrane distillation desalination system

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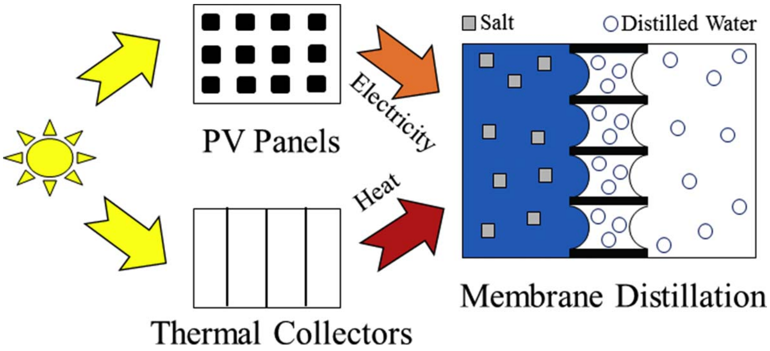
GRAPHICAL ABSTRACT



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ABSTRACT

Water scarcity is especially impactful in remote and impoverished communities without access to centralized water treatment plants. In areas with access to a saline water source, point-of-use desalination by solar-driven membrane distillation (MD) is a possible method for mitigating water scarcity. To evaluate the applicability of MD, a comprehensive process model was developed and used to design an economically optimal system. Thermal energy for distillation was provided by solar thermal collectors, and electricity was provided using photovoltaic collectors. Distillation was performed using sweeping-gas membrane distillation. The cost of water in the optimized system was approximately $\$85/m^3$. Membrane modules and solar thermal collectors made up the largest portion of the cost. Neither thermal nor electrical energy storage was economical within current technologies. The model developed provides a template to optimize MD membrane characteristics specialized for point-of-use applications.

1. Introduction

Over 2.7 billion people are impacted by water scarcity [1]. Population growth and climate change may increase that number to over five billion by 2025 [2]. Many drought-stricken areas also have high poverty rates, which makes coping with water shortages especially challenging. However, the possibility of access to seawater or brackish ground water makes desalination a feasible alternative for mitigating drought. Desalination is energy intensive and therefore relatively expensive. A large fraction of impoverished communities is remote and

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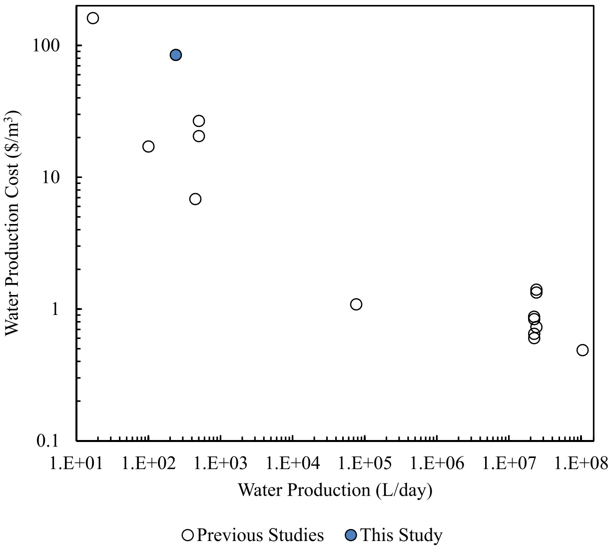

Fig. 1. Reported membrane distillation water production costs (adjusted for inflation since publication [9]) as a function of daily water production. System configuration, energy source, and methods for cost calculation varied. Details are given in Khayet [4].

not electrified; energy requirements must be met without access to a centralized power grid. Point-of-use solar-driven desalination technologies may be appropriate for mitigating water scarcity under these circumstances. One example is membrane distillation (MD), a thermal process in which the energy required for desalination can be provided as solar thermal energy, rather than photovoltaic (PV) energy. Under some circumstances, this provides substantial cost savings over pressure-driven systems [3].

Khayet [4] reviewed energy consumption and cost of MD systems. Reported unit energy consumption varied by three orders of magnitude, and costs varied by nearly four orders of magnitude (Fig. 1). Few studies have considered the cost of small scale MD systems. Four studies shown in Fig. 1 calculated costs for MD systems with daily water production rates relevant to a point-of-use desalination system [5–8], with costs varying from \$4.04/m^3 [6] to \$130/m^3 [5]. Overall, enough is known about solar driven MD technology to suggest that it may provide adequate water production for point-of-use applications. However, additional understanding is needed to anticipate cost savings that are likely to accrue from technology maturation, improved membrane design and selection, and system optimization.

To date, few researchers have attempted to optimize MD system design. Chang et al. [10] provided a cost estimate and optimization for air-gap MD. In that study, thermal energy was provided by solar thermal collectors and grid electricity was used to provide electrical power to the system. Membrane performance was modeled from first principles using Aspen Custom Modeler. The cost of water was calculated from a pseudo-steady process model and optimized using a quadratic programming algorithm. The cost of water from the optimized system varied from \$5.16–\$15.7/m^3 for systems with capacities varying from 100 to 1000 kg of water produced per day. As expected, water produced from small capacity systems was more expensive. Optimization improved calculated costs relative to cost estimates performed without optimization. While the results demonstrated the benefit of system optimization, next generation modeling research is needed to address important factors not covered in past studies. These include the effects of using PV electricity instead of grid power and introducing energy storage components into the system, consideration of different MD operating modes, such as sweeping-gas MD (SGMD), and optimization of additional decision variables, including those related to equipment sizes and the times at which the system operates.

Here we present a detailed process model developed to predict the cost of water from a point-of-use SGMD system. Water production rates are determined from first principles using a state-of-the-art membrane model for hollow-fiber modules [11], and the cost of water was calculated using standardized methods [4]. An optimization algorithm was added to minimize the unit cost of water. The economically optimal system was used to evaluate the economic feasibility of SGMD and to make recommendations for future research. Results indicate that water produced from an optimal solar-driven SGMD designed to produce 240 L/day costs approximately \$85/m^3 and remains economically uncompetitive. The operation of the optimal system was analyzed to show that neither electrical nor thermal energy storage provide economic benefit. Further work is needed to develop economical energy storage devices and membranes specialized for MD to improve competitiveness of the technology for point-of-use solar desalination.

2. Navajo Nation case study

The process model presented here is based in part on a pilot system constructed on the Navajo Nation in the southwest United States. The Navajo Nation has a low population density; therefore, a large percentage of the population lives without access to centralized power or water. A point-of-use solar membrane distillation pilot system was constructed to desalinate brackish groundwater to provide drinking water to remote households. The process model and cost calculations presented here are based on this pilot system [12].

Note that consideration of a remote point-of-use desalination system has several effects on the optimization study presented here. First, the system capacity is small (240 L/day), so cost estimated here will be higher than for larger systems. Second, land is readily available, so no plant footprint constraints apply and no size constraints are placed upon the solar collector field. Finally, this study considers only the treatment of brackish groundwater, not the supply. The costs of well drilling and water distribution are not included in the process model and it is assumed that water is infinitely available. There are no restrictions on the recovery of the membrane or on flow rates of untreated water entering the system (streams 3 and 9 in Fig. 3). The SGMD system simulated is shown in Fig. 2. Solar irradiation is collected by independent flat-plate photovoltaic (PV) and thermal arrays. The PV collectors, arranged in parallel, are used to power the pumps and blowers and charge the battery. When there is insufficient electric power from the PV collectors, the battery discharges to satisfy the power demand. The thermal collectors are used to heat the heat exchange fluid, a 50% by volume mixture of propylene glycol and water, which is circulated through a heat exchanger in the hot water tank at a volumetric flow rate, Q_G, (stream 1, Fig. 2) to heat the untreated water. The glycol solution is returned to the thermal collectors (stream 2) to complete the glycol loop. The heated water is fed into the lumen side of the membrane module (stream 4) at flow rate of Q_{HW}. Note that multiple membranes are arranged in parallel. After the module, the remaining brine is returned to the hot water tank (stream 5) to complete the hot water loop. Untreated make-up water (stream 3) is fed into the hot water tank at a flow rate equal to the permeate production rate to maintain a constant liquid volume. A temperature limitation is included to protect the membrane modules from brine temperatures higher than 90 °C, which may damage the membranes [13]. In the system described in [12], the control system defocuses the concentrated cogeneration system and increases the glycol flow rate when the temperature exceeds 90 °C. While the temperature limitation is included in the process model, the control system is not modeled. Instead, the brine temperature is reset to its maximum when the temperature exceeds 90 °C.

Ambient air is fed into the shell side of the membrane module (stream 8) at a flow rate of Q_{AIR}. The humid air stream leaving the membrane module (stream 7) is fed to a condenser. The air stream is cooled using an ambient cooling water stream, assumed to be taken from the same source as the untreated water, at a flow rate of Q_{CW} (stream 9). After the condenser, the cooling water stream is discarded (stream 6). Rejected air leaves the condenser in stream 10, and the