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Pilot demonstration of concentrated solar-powered desalination of subsurface agricultural drainage water and other brackish groundwater sources

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HIGHLIGHTS

- A novel renewable-energy powered desalination system is developed and piloted.
- The system integrates an open-cycle heat pump with multi-effect distillation.
- A large parabolic trough solar concentrator is used to power the process system.
- A 49% reduction in thermal energy consumption is demonstrated.
- High scaling propensity agricultural drainage water is desalinated for reuse.

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ABSTRACT

The energy–water nexus is addressed with the experimental demonstration of a solar-powered desalination process system. This system was designed for high-recovery treatment of subsurface agricultural drainage water as a reuse strategy as well as other brackish groundwater sources. These water sources may exhibit wide fluctuations in salinity and makeup and pose a high risk for operational troubles due to high scaling potential. A first-of-its-kind open-cycle vapor-absorption heat pump is coupled with a multiple-effect distillation train and a large parabolic trough solar thermal concentrator. Without the heat pump, the distillation operation showed a minimum thermal energy consumption of 261.87 $\mathrm{kWh_{th}/m^3}$. With the heat pump, the thermal energy consumption was reduced by more than 49% to 133.2 $\mathrm{kWh_{th}/m^3}$. This reduction in thermal energy requirement directly translates into a 49% reduction in solar array area required to power a process with the same freshwater production rate as a system without an integrated heat pump. An optimized design was modeled and the thermal energy performance of a commercial system is projected at 34.9 $\mathrm{kWh_{th}/m^3}$ using a 10-effect MED operating at 85% recovery.

1. Introduction

The ongoing worldwide water scarcity problem is compounding with population growth, industrialization and development, economic growth, and climate change. The obvious abundance of saltwater sources on Earth has motivated the development and implementation of desalination technologies, primarily in coastal regions, in an attempt to close the water gap (i.e. the water deficit). Such technologies have been widely adopted in the Middle East and North Africa (MENA) regions, accounting for about 50% of the global installed desalination capacity [1,2]. However, water scarcity is a worldwide problem motivating the adoption of desalination technologies in other regions in recent years. For instance, a report by the International Desalination Association (IDA) [3] projects that the fastest growth in desalination over the next five years is expected to take place in South Africa, Jordan, Libya, Mexico, Chile, India, and China, where their installed capacity is expected to double. Astoundingly, a recent review on the current state and future of desalination states that the current worldwide desalination capacity is growing at a yearly rate of 55% [4].

Water and energy have an inherent interdependence that is typically only explored from an economic perspective (i.e., what is the impact of energy cost on water and vice-versa). However, the interdependency goes deeper than this economic perspective since water consumption is tied to power generation and energy consumption is tied to potable water production. Hussey et al. [5] explored the changing landscape of energy and water of recent years and projections into the future. Interestingly, the authors [5] conclude that as energy sources are diversified

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and modified with emphasis on renewables and carbon capture, there is an increased dependence on water. For example, the worst clean energy source in terms of water usage is dry-rock geothermal which consumes more than five times the water that the standard natural gas combined cycle uses and two-and-a-half times that of a standard coal plant [5]. In this case, energy is harnessed with zero carbon emissions but with a very large water footprint. The UN states that 90% of the global power generation is water intensive [6]. They go on to conclude that "meeting ever-growing energy demands will require seeking coherence between water use and climate change mitigation" [6]. However, producing "new" freshwater sources via desalination brings its own challenges in the form of substantial energy requirements to remove salt from water for all proposed technologies and implementations.

In this paper, an advanced desalination process system, based on multiple-effect distillation (MED), is presented that provides a two-fold improvement in first-law (thermal) efficiency and minimizes the dependence on water-intensive power sources by consuming solar thermal power directly as its primary energy source. A pilot was constructed and operated at the Panoche Drainage District in Firebaugh, CA with the purpose of demonstrating high water recovery and energy efficiency for desalination of subsurface agricultural drainage water for reuse. In the next section, the background on the state-of-the-art will be discussed through a review of the relevant literature as well as motivating this work. Following a literature review, the Materials and methods section will discuss the modeling and simulation methods as well as the pilot system and experimental methods. The results of the simulations and the experiments with the pilot system will be presented along with a thorough discussion and comparison. A projection of the design and performance of a commercial system will then be presented and finally the paper will be concluded.

1.1. Background and motivation

When comparing desalination process systems on a thermodynamic basis, two concepts of efficiency will be referred to: first-law efficiency, which is the typical thermal efficiency of the process, and second-law efficiency, which is typically defined as the ratio of useful work output to the useful work input and quantifies the destruction of thermodynamic availability or exergy.

Desalination technologies are most commonly separated into two categories: thermal methods and membrane methods. As of 2012, the installed capacity of reverse osmosis (RO) membrane technologies was roughly 60% whereas traditional thermal technologies made up roughly 34% [4]. The two common goals in the desalination community spanning the diverse technologies are reducing total specific energy consumption (SC), defined as

$$\mathrm{SC} \equiv \frac{\text{energy input (kWh)}}{\text{total water produced }\left(\mathrm{m}^3\right)}, \tag{1}$$

and reducing the total water production cost.

Despite the widespread adoption of RO, the technology is fairly limited to seawater treatment applications and its dependence on application-specific pretreatment makes the technology relatively inflexible. Global water use is dominated by agricultural operations which account for 70% of consumption [6]. In California, agricultural operations account for roughly 79% of the diverted surface waters and pumped groundwater sources [7]. This has motivated the need for desalination of brackish groundwater for agricultural irrigation as well as desalination of agricultural drainage water for reuse. In [8], low-pressure RO was applied to a low-salinity groundwater feed for production of high-purity water for the beverage industry. The authors noted that despite the more favorable conditions for RO, after about 20 weeks, membrane flux decreased by 10% and the pressure drop increased by nearly 10% due to membrane fouling [8]. Besides the treatment of low-salinity feeds, groundwater and agricultural drainage pose a serious technological and environmental challenge for RO. The environmental challenge comes from high-volume brine waste disposal due to limited recovery. In [9], the environmental challenge was considered with the proposal of zero-liquid discharge (ZLD) for solids recovery. However, technological challenges of the implementation persist. For instance, the highest salinity considered by the authors was 1500–3000 ppm total-dissolved solids (TDS) and in the best case, the system would be operated at 95% recovery producing a brine waste stream with 30,000 ppm TDS [9] or just 3% dissolved solids. In this case, the authors' simulation results predict the SC value of the RO (without ZLD) to be 4.4 $\mathrm{kWh_e/m^3}$.[1] They conclude that, as compared to seawater RO desalination, their approach is more favorable for inland applications [9]. Since the paper was more of an initial feasibility study, the authors did not provide an analysis of scaling and fouling for such source waters at high recovery which is expected to be detrimental to the long-term viability of the proposed solution.

In 2010 McCool et al. [10] investigated the feasibility of RO for treating agricultural drainage in the San Joaquin Valley (the same region as the pilot demonstration in this paper). They considered water sources with salinities ranging within 7000–23,000 ppm TDS with wide relative yearly variations. They show that with proper scaling mitigation techniques, the recovery limits are between 44% and 68% across the region [10]. However, they conclude that any implementation of RO for treating these water sources would require site-specific process optimization as well as real-time monitoring for fouling mitigation as a result of feed chemistry variations [10]. Such a monitoring device was constructed and tested using agricultural drainage water at the Panoche Water District in the San Joaquin Valley by Thompson et al. [11] for rapid field evaluation and optimization. The study verified the effectiveness of such a monitoring device and validated the expectations of rapid scaling causing dramatic performance decline at 65% recovery from a 14,400 ppm TDS source [11]. Despite these advancements, due to the high scaling propensity of brackish groundwater and subsurface agricultural drainage water sources, pretreatment costs are high and recovery is limited for RO technologies and therefore cannot adequately address the environmental issue of brine waste disposal.

Of the major advancements in energy reductions, RO stands out partly due to its currently being the dominant technology worldwide but also because the improvements have been quite extreme in the last 40 years. In [12] the authors present a very striking chart that shows the energy consumption of RO decreasing to about 12% of its value in 1970. This reduction primarily represents major advancements in membrane technology over the years. However, the authors state that conveyance and pretreatment still require a relatively high amount of energy input (>50% of the membrane requirement), representing limitations in the technology even if the membranes are operating at their theoretical maximum efficiency [12]. Cohen-Tanugi et al. [13] further explored this idea and concluded that minimal improvement in overall water cost can be realized even if membrane permeability was to increase three-fold. Furthermore, despite reductions in the SC value, the high-pressure pumps required for RO are still electrically driven. Therefore, they require substantial amounts of electrical power at-scale which poses new challenges when considering the energy–water nexus, such as requiring a high thermodynamic availability energy source, as well as the technological and environmental limitations for the application to brackish groundwater and agricultural drainage water.

The two popular thermal desalination technologies are multi-stage flash (MSF) and MED, also referred to as multi-effect evaporation (MEE). Due to its early adoption in desalination, MSF still has the highest installed capacity of all thermal methods [4,14,15]. However, MED has the competitive advantage over MSF as it offers greater efficiency and reduced water cost due to lower capital costs as well as operating and maintenance costs [14,16–18]. Furthermore, for the same overall performance, MED requires substantially less electrical energy

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[1] The subscript 'e' denotes electrical energy and 'th' will denote thermal energy.