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# Optimal design of fossil-solar hybrid thermal desalination for saline agricultural drainage water reuse

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ABSTRACT

Ultra-high recovery solar thermal desalination of agricultural drainage water is presented as one solution to the historic extreme drought and long-standing salt accumulation problems facing California's fertile Central Valley region. Building on the results obtained from a recent pilot demonstration of a novel solar thermal desalination system, a techno-economic analysis is presented using an existing agricultural region as a case study. Three strategies are considered: continue retiring farmland as crop productivity wanes in future years, desalinate saline drainage water with a novel distillation process using natural gas as the fuel source, and desalinate using natural gas and solar as a hybrid energy source. The study is cast as a parametric optimization problem taking into account natural gas costs and water purchase contract pricing. The results show that with projections of the long-term effects and cost of salt accumulation in the region, solar thermal desalination is economically favorable over both the alternative of doing nothing (retire farmland) as well as implementing conventional (non-renewable) thermal desalination. Most importantly, the results indicate that solar thermal desalination is an economically-viable solution that can increase the sustainability of farming in the region and create a new, sustainable, scalable source of additional freshwater.

## 1. Introduction

### 1.1. Severe and persistent drought

The State of California (CA) is currently facing the worst drought in recorded history. Fig. 1 illustrates the severity of the widespread drought. A recent study using tree rings has concluded this drought is the worst in 1200 years [1]. This unfortunate conclusion was made in light of the findings that although reduced precipitation and high temperatures played an important role compounding the water deficit, they are not historically unprecedented [1]. In other words, California has a delicate water balance that is highly sensitive to perturbations from the norm. Researchers have concluded that global warming arising from human activity (greenhouse gas emissions) is further increasing the probability of conditions leading to the exceptional drought in California [2]. Hence, any proposed solution to water scarcity must also take into account greenhouse gas emissions.

Home to the largest and most productive agricultural region in the US, CA is arguably most affected by water scarcity in the agriculture sector which accounts for nearly 80% of the total water-use in the state [3] (excluding environmental uses). This rich and fertile land of the Central Valley is responsible for supplying more than a third of the total US vegetables and nearly two-thirds of the total US fruits and nuts [4].

In 2014 alone, compounding effects resulted in a 6.6 million acer-ft (8.14 km$^3$) reduction in surface water supply to the agriculture sector [6]. The 2014 drought would end up costing $2.2B and 17,100 jobs in the agriculture sector [6] alone. Of the $2.2B in losses, $810M is from crop revenue losses. A recent report, citing real estate brokers in the region, disclosed that irrigated land in the Paso Robles, CA region was selling for $15,000-$20,000 per acre as opposed to just $3000 per acre for dry land; with the disparity expected to get much worse as the drought continues [7]. The California Department of Food and Agriculture states that the average value of irrigated cropland is $12,000/acre [4] illustrating the massive economic impact of drought on land value.

### 1.2. Salt accumulation and drainage

Water scarcity happens to be only one part of the problem negatively affecting the sustainability of California's agriculture

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operations. The other part is the historic and long-standing issue of salt accumulation and impairment of arable land due to high water tables and poor drainage. In California's Central Valley, water is imported through the State and Federal Water Projects. The Tulare Lake and San Joaquin River Basins alone receive more than 1.8 million tonnes of salt annually through these water projects [8]. Researchers have estimated that since the completion of the Delta–Mendota Canal in 1951, more than 18 million tonnes of salt has been imported into the San Joaquin Valley [9]. The CA Department of Water Resources [10] estimates the net accumulation of salts in the San Joaquin Valley at 2.23 million tonnes annually. This salt import is estimated to contribute over 364 thousand tonnes of salt to the San Joaquin Basin confined aquifer among other untold impacts [8]. The salt import cannot be effectively managed at the source due to the extremely low concentrations (<500 ppm) of naturally occurring minerals. Further, the extraordinarily large volume makes treatment of the source prohibitively expensive.

Agricultural operations also intensify the salt accumulation problem as fertilizers and minerals are added for crop health. Salt accumulation in the region's soil and a shallow water table continue to drive agricultural productivity down as crop roots penetrate high-salinity stratification in the soil [8] and even forces growers to retire once-arable land. On the west side of the San Joaquin Valley, an estimated 379,000 acres, a very significant portion of the irrigated land, is impacted by drainage and salinity [8]. On the west side of the San Joaquin Valley, more than 113 thousand acres (45,700 ha) have already been retired due to salt accumulation and drainage problems [8]. It is expected that by 2030, the total land area affected by shallow saline groundwater is expected to grow by 12%–15% [11].

### 1.3. *Desalination for drainage reuse: an in-valley solution*

Desalination as a reuse strategy has the potential to increase the water-use efficiency of California's agricultural sector while providing a sustainable long-term in-Valley solution to drainage and salt accumulation in the Central Valley. The idea of desalinating saline drainage water is not necessarily novel and although a conventional approach would reduce the overall volume of drainage, without the proper technology and implementation, discharge of concentrated brine streams to the environment would still be an issue. Hence, the long-term success of any desalination approach to these problems hinges on sustainability. The benefits of desalinating saline drainage water over other reuse strategies, such as irrigating salt-tolerant crops, is that not only will it be recovering pure freshwater—which can be used for irrigating higher-value crops or transferred to municipal or other industrial users—but it will also be concentrating, isolating, and potentially sequestering the harmful salts. Since drainage is the product of irrigation activities, by recovering pure freshwater, the total water-use efficiency for irrigated crops is increased.

There are multiple technologies that can be used to desalinate water, in the general case; however, the quality of drainage water and other environmental conditions dramatically affect the technical viability of one solution over another. The feasibility of reverse-osmosis (RO) with respect to treating agricultural drainage in the San Joaquin Valley has been studied [12,13] and continues to be studied in an ongoing effort. One of the largest challenges facing RO is the reliability of the membranes for treating agricultural drainage water having high concentrations of sparingly-soluble salts, particulates, and organic matter [14]. Due to the nature of agricultural drainage water, the application of RO is limited as the chemical costs and energy costs are high. Further, the extent in which the drainage discharge volume can be reduced, which is quantified as the recovery, defined as

$$\%\ \text{recovery} = \frac{\text{freshwater production rate}}{\text{saltwater feed rate}} \tag{1}$$

is limited due to membrane scaling and fouling. The limitation in recovery would require additional treatment, such as downstream forced-circulation thermal crystallization; which, on its own is extremely energy intensive. Lastly, emphasizing renewable energy when considering overall environmental impact, makes RO not a viable solution for desalination of agricultural drainage [15] on its own.

In 2013, researchers deployed a novel implementation of multi-effect distillation (MED) integrated with concentrated solar thermal power (CST), called a concentrated solar still (CSS), to treat agricultural drainage water at the Panoche Drainage District in the San Joaquin Valley [15]. The primary objective of the pilot project was the demonstration of high-recovery treatment and economic feasibility of the technology for this specific application, as well as the energy savings expected with the new technology [15]. However, an economic analysis of the technology implementation and value proposition were not discussed.

Advancements in solar thermal energy technologies are continuing to drive down investment costs, increase ease of deployment, and optimize direct coupling with process systems for process heat. In spite of this, applying CST in California for sustainable desalination at-scale is entirely novel. In this paper, the land-use efficiency and economics of deploying CSSs for agricultural drainage water reuse will be modeled and investigated by a case study of the agricultural region. The comparison will consider the option of deploying CSSs versus the alternative of retiring otherwise-fertile irrigable land which is currently considered an inevitability and part of the ongoing strategy [8,11,16–18]. Solar desalination as an in-Valley solution to drainage and salt accumulation enhances the sustainability of agribusiness in the Central Valley and helps secure the long-term success of one of the most important growing regions in the United States and the world.

## 2. Methods

Within drainage-impaired and salt impaired regions, fertile farmland is being transformed into drainage region and reuse region (growing lower-value salt-tolerant crops), as well as outright retired to control subsurface drainage and salts in order to keep adjacent farmland productive. This is not only a short-term solution since saltwater in the region will continue to accumulate, but it is also an inefficient use of fertile farmland [11]. It is proposed herein that a far more attractive alternative is to deploy CSSs to reduce the drainage region footprint and simultaneously generate revenue by producing freshwater and selling it to downstream municipal and industrial (M&I) users. Both fossil-fuel powered and solar thermal powered (with fossil-fuel backup) systems will be analyzed.

### 2.1. *Solar resource*

A solar array consisting of large parabolic trough solar concentrators (PTC), each with an aperture length of 6m and area of 656 $m^2$, was modeled using recently published methods [19–21] including thermal storage based on the single-tank thermocline design. The model was simulated with data input for the typical meteorological year (TMY) from the NREL Solar Prospector [22] for the San Joaquin Valley site west of Fresno, CA. This data exists in the 8760 h/yr format and allows for dynamic modeling of the solar field over the entire year with hourly resolution. The model parameters used can be found in Appendix A as well as a monthly break-down of the solar irradiance data.