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Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture

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HIGHLIGHTS

- A PV powered pumping and desalination system without energy storage was modeled.
- Optimal system configurations were identified as a function of available resources.
- Sensitivity analysis was used to evaluate the impact of input parameters.
- System economics evaluated through the integration of agricultural data.
- Case studies illustrate economic viability for scenarios in the Jordan Valley.

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ABSTRACT

Global growing demand for agricultural production has put increased pressure on freshwater resources in various global locations with renewed interest in utilizing desalinated brackish water. In order to determine the economic feasibility of solar-powered water pumping and desalination for agriculture, an engineering system model that performs hourly simulations of a variable speed PV pumping and desalination systems operating at variable speed without electrical energy storage was developed. Based on resource availability inputs and system requirements, the optimal architecture is determined by simulating three types of power supplies (PV, diesel, grid), four inverter configurations, four membrane types, two RO system recovery rates, and the integration of energy recovery device options. Economic results for water pumping show a clear advantage for PV based systems compared to diesel and grid based systems. Oversizing requirements to meet water demand in agriculture negatively impacts the economics of the modeled PV desalination system. Several case studies in the Jordan Valley were evaluated to illustrate the economic viability of solar-based systems with simulation results including a direct comparison to diesel and grid-connected alternatives. Results show the need for favorable locations in terms of water resource and crop selection for system implementation.

1. Introduction

Water scarcity is a growing problem in many areas of the world, with increasing pressure from population growth [1,2]. The majority of global freshwater consumption, 70%, is currently used for agriculture [3]. Irrigation with brackish water from marginal-quality aquifers is largely practiced in Middle Eastern countries, but is limited by a variety of drawbacks such as lower crop yields and limited crop selection [4–6]. Desalination is one method of increasing the availability of freshwater in these water-scarce areas, and providing opportunities for growing high-value crops. Desalination in agriculture has not been widely adopted primarily due to the economics associated with the procurement and operation of systems and limited access to electricity. However, some countries have successfully utilized desalination for agriculture. More than 200 desalination plants ranging in size from 100 to 5000 m^3 day^{-1} were installed for agricultural use in Spain between 1995 and 2000 [7]. Unexpected challenges such as exhaustion of groundwater resources and uncontrolled brine discharges impacted the private operation of the systems. The majority of these systems have since been replaced with larger, public desalination plants and are still used for agriculture [7]. Farms in southern Jordan have recently been investing in diesel-based desalination systems for the production of high-value crops, such as bananas. High diesel fuel prices and limited access to the grid in rural areas make photovoltaic (PV) powered water pumping and desalination systems a promising alternative.

A variety of commercial desalination technologies currently exist, including reverse osmosis (RO), multi-stage flash, multiple-effect

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distillation, electro dialysis, vapor compression, and others [8]. Reverse osmosis (RO) currently represents the most cost-effective solution for most agricultural applications due to low energy consumption and a modular design which can be scaled to fit small- or large-scale systems [9,10]. Photovoltaic-powered reverse osmosis (PV-RO) systems have previously been evaluated and tested. One of the challenges associated with the integration of solar systems with traditional RO systems is that RO systems typically operate at a nearly constant flow rate and pressure. Due to the variability in power from PV arrays, large and expensive battery banks are required for fixed speed operation. Challenges associated with the operation of battery systems in hot climates further complicate and limit deployment. These systems have been intensely studied, and many small scale PV-RO systems integrating batteries have been implemented and are currently commercially available [11–13]. A significant limitation to the large-scale development of PV-RO systems is the high up-front cost of large solar arrays and battery systems. Recent advancements have facilitated the development of direct-coupled PV- or wind-powered RO systems that can operate at variable power and speeds without the need for a large battery storage system [14–19]. These systems have the ability to consume the electrical energy directly and store treated water at a low cost and for long periods. Existing small-scale systems have demonstrated that direct-coupled, variable speed PV-RO systems are technically feasible, but flow rates, pressures, and membrane recovery rates must be carefully controlled to avoid membrane damage or fouling [15,17,20]. Membrane manufacturers also advise users to avoid sudden pressure or cross-flow variations which may result in membrane damage. A variable speed PV-RO system was implemented by Bilton et al. [15] which showed that PV-RO systems produce water at a lower cost than a diesel-powered RO system in areas such as Africa, Australia, the Middle East, and select regions in North and South America. Thomson and Infield [16] demonstrated an integrated PV-powered seawater pumping and desalination system without batteries to be implemented in Eritrea. ITN Energy systems, Inc. built a small-scale PV-RO system which operated at variable speed [19]. ITN recommended that a recovery rate control method be used in variable speed PV-RO systems because the system quickly encountered scaling issues. When medium to large-scale brackish water desalination systems for agriculture are considered, all of the PV-RO studies mentioned share the following drawbacks: 1) systems were designed for small scale applications, 2) PV costs and RO unit performance data are outdated, 3) systems were designed for seawater desalination, which requires much more energy than brackish water desalination, and 4) water was used for drinking so agricultural applications were not investigated. There exists a need to understand the economic viability and optimization of system architecture of integrating direct-coupled PV-RO systems into brackish water desalination for use in agriculture.

PV-powered water pumping and desalination systems have both been researched independently and have proven to be technically feasible with commercial systems operated successfully. Due to a variety of advancements including decreases in PV costs and development of inverters specifically tailored for solar pumping, PV-powered water pumps are expected to be economically viable over a wide range of locations and pumping scenarios. This study develops a comprehensive evaluation of medium to large-scale, variable speed, direct-coupled PV pumping and desalination systems. Hourly simulations over the course of a year are used to evaluate system performance and optimize architecture. Optimal system configurations are determined by simulating a wide range of system architectures, including three types of power supplies, four inverter configurations, four membrane types, two RO system recovery rates, and the integration of energy recovery device options. Agricultural factors such as crop salt tolerance, water requirements, yields, and net profits are used to identify crops most suitable for desalination in agriculture. An economic analysis is performed to determine water unit pumping and desalination costs, internal rate of return, payback periods, and total lifetime costs. A sensitivity analysis is used to make the results applicable to other locations and input parameters. Several case studies are evaluated in order to illustrate the economic viability of variable speed direct-coupled PV-, diesel-, and grid-powered water pumping and desalination systems for agriculture in the Jordan Valley.

2. Methods

System optimization and evaluation of direct-coupled PV water pumping and desalination systems is performed through the development of sub-process models integrated into a system model. Sub-process models include various PV configurations, inverters, control systems, pumps, RO elements and agricultural farming. The system model is used to analyze the energy efficiency, performance, and cost-effectiveness of different system configurations and control strategies. Detailed descriptions of the sub-process models are presented in the following sections. Hourly PV performance is modeled using HOMER [21] and the remainder of the system modeling, optimization, and economic evaluation is performed in MATLAB. This study is focused on medium-scale pumping and RO systems, with PV array sizes ranging from 15 to 120 kW.

2.1. System architecture

The general system design includes a power supply (PV, grid or diesel generator), power distribution system (consisting of a controller and inverters or variable frequency drives), groundwater pump, desalination system, water storage tanks, and instrumentation. The general system design and modeling architecture is illustrated in Fig. 1.

Foundational inputs for the modeling work include location-specific parameters such as available solar resource, ambient temperature, seasonal crop water requirements, and feed water composition, depth, and temperature. Performance data provided by various manufacturers is used to model the PV array, submersible ground water pump, high-pressure pump, RO or NF elements, and energy recovery devices. The simulation produces an hourly desalinated water production profile, including water distributed to crops and water storage tank levels. The results of the hourly simulations, as well as component costs are used to perform an economic assessment and calculate key economic indicators. The economic indicators and water production profile are used to determine an optimal system architecture.

2.1.1. Power systems

Three power systems are modeled and evaluated in this study: PV arrays, diesel generators, and the electric grid. The baseline solar panel used in this study is a Sharp 245 W module. This is a widely used, low cost module that is representative of other solar panels on the market. Using PV module specifications and location-specific solar insolation data, HOMER is used to simulate an hourly power production profile for a single PV module. HOMER first calculates the incident solar radiation based on the provided horizontal radiation data, latitude, time of year, time of day, and the orientation of the PV array. HOMER then calculates the PV cell temperature and the PV cell power output on an hourly basis [21]. The hourly power production profile is then scaled in order to satisfy the energy demands of the system and determine the optimal PV array size. The PV-powered systems evaluated in this study do not include large battery banks. As a result, the system will shut down when there is not sufficient power to maintain the RO system's minimum flow rate and pressure requirements. This is expected to occur overnight and during low sunlight conditions. The operation of the system is adjusted to match the amount of power available from the PV system. Two different configurations are considered for the PV system: 1) a shared PV array for both pumping and desalination systems and 2) independent PV arrays for the pumping and desalination systems.

Alternative power systems are modeled and include diesel generator and grid electricity. Kohler diesel generators ranging from 10 to 60 kW