Feasibility and Design of Solar-Powered Electrodialysis Systems for Agriculture Applications

by

Jacob N. Easley

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Author . . . .
Department of Mechanical Engineering
May 13, 2022

Certified by . . . .
Amos G. Winter V
Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by . . . .
Nicolas Hadjiconstantinou
Chairman, Department Committee on Graduate Theses

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Abstract

This paper presents photovoltaic-powered electrodialysis reversal (PV-EDR) as a promising desalination technology for agricultural applications in the Middle East and North Africa (MENA). Water scarcity in MENA has led to reliance on brackish water for irrigation of crops. Irrigating crops with high salinity water causes a host of problems including decreased yield and soil degradation. Current solutions are water and energy intensive, leading to overextraction of renewable water resources as well as overreliance on fossil fuels for electricity, which is expensive. Market research in MENA and interviews conducted with farmers in Jordan led to the conclusion that energy cost is the most significant issue facing small-scale desalination systems for agriculture in MENA. PV-EDR is chosen as an ideal desalination architecture to meet the needs of farmers by reducing energy costs compared to on-grid reverse osmosis (RO) systems that are currently employed in MENA. Time-variant (TV) operational theory for PV-EDR is presented, which allows for desalination production to match the available solar irradiance throughout a day, leading to decreased power system sizing and further cost savings. TV-PV-EDR can be integrated with water- and energy-efficient drip irrigation systems in order to tailor desalination production to crop water demand throughout a season. Given a case study in Jordan, a TV-PV-EDR system is designed and compared to current benchmark RO systems in relation to capital cost, energy cost, and total lifetime cost. TV-PV-EDR was found to be less expensive and more energy efficient than RO systems over its lifetime despite having a larger capital cost. TV-PV-EDR has the potential to provide a mechanism through which more energy-efficient, higher recovery desalination for agriculture can be achieved.

Thesis Supervisor: Amos G. Winter V
Title: Associate Professor of Mechanical Engineering

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Chapter 1

Introduction

The Middle East and North Africa (MENA) face a food and water security problem, exacerbated by population growth and climate change. MENA is the most water scarce region in the world, with access to only 1.4% of the world's renewable fresh water despite having 6.3% of the world's population [1]. This is especially problematic for its agriculture sector, which accounts for 85% of the water use in MENA [2]. Increased water consumption and depleted freshwater resources have driven users to rely on brackish groundwater for agriculture [3]. Using high salinity irrigation water poses several problems for sustainable agriculture. Crop selection becomes limited as certain crops cannot be irrigated with salty water, including many of the high value vegetable crops typically grown in MENA [4, 5]. Salinity-sensitive crops exhibit decreases in the quality and quantity of yield when irrigated with high salinity water. Additionally, irrigating with high salinity water degrades soil quality over time, leading to further drops in productivity and yield, with the high salinity soil requiring time and money to reclaim [4, 6]. These issues are especially problematic for developing economies, which rely heavily on domestic agriculture for both food security and economic growth [7–10]. Political conflict, lack of economic resources, and poor governance make large-scale structural change in MENA's agricultural sector difficult [7, 11, 12]. Farmers in these countries are left to their own methods to address water quality and quantity issues, which often take the form of energy and water intensive solutions. New solutions and policies are needed to incentivize environmentally friendly, low-energy, water-efficient technologies for water treatment and irrigation. Addressing water quality issues puts less stress on water resources, increases crop yields and productivity, and preserves soil health while boosting local and national economies.

There has been success in the past at combatting water scarcity and quality issues through the implementation of water desalination and widespread water policy changes. Spain, for instance, allocates 22% of its total desalination capacity toward agriculture, more than any other country in the world [13]. Spain's desalination infrastructure in the 20th century was mostly comprised of small-scale systems having a production range between 100 and 5000 m3/day [13]. In the 2000s, Spain transitioned to large-scale seawater desalination systems ($>$ 100,000 m3/day) because the increased number of small-scale inland desalination systems was contributing to groundwater aquifer exhaustion and brine discharge issues [13]. Today, most people rely on these large public desalination plants for their water needs as they have shown to be more economical and less inconvenient than small-scale, privately owned systems which require capital and maintenance [13].

Israel is another example of a water scarce country whose water landscape has seen rapid change over the course of a few decades through the installation of large-scale seawater desalination plants, wastewater treatment, and shifts to high value irrigated crops [14]. Moreover, Israel's widespread adoption of drip irrigation has contributed to its 1600% increase in crop productivity in the past 65 years [15].

Both Spain and Israel's success relied on large-scale national desalination systems. However, large-scale change is difficult for many areas of MENA where water conflict, politics, and scarce resources hinder cooperative efforts to change water policy and invest in water infrastructure at a large scale. Much of MENA also has limited access to seawater and the distribution networks required to transport water over large distances. Thus, farmers often have no choice but to rely on small-scale inland desalination to combat salinity issues. Despite the advantages—economic and otherwise—of large-scale desalination systems, small-scale desalination systems will be an essential component of water and food security for the foreseeable future. Therefore, efforts are needed to improve upon existing systems by providing high recovery, energy efficient, renewably powered desalination and irrigation systems for small-scale brackish water applications.

Small-scale brackish water desalination for irrigation is practiced to some extent in MENA. However, current desalination solutions pose a few economic and environmental concerns. Desalination is energy intensive and requires large amounts of grid electricity and diesel, which are becoming more expensive and volatile in price [16]. High consumption of grid electricity is also problematic as it relies heavily on fossil fuels. Because of this, renewable energy systems are desirable for desalination, but high energy requirements—and, thus, large capital costs associated with installing renewable energy systems—prove to be a barrier to widespread adoption. Current systems, often reverse osmosis (RO), output large volumes of high salinity waste brine, which is toxic to local ecosystems and expensive to dispose of properly [17,18]. Desalination for agriculture could become more sustainable and economically feasible by implementing more energy efficient, higher recovery desalination systems.

Though not as widespread as RO, electrodialysis reversal (EDR) is more energy and water efficient than RO for many brackish water applications and could be a good candidate for agriculture applications. Additionally, drip irrigation, a micro-irrigation technology that delivers water directly to the root zone of the crop, has the potential to decrease the amount of water required for irrigation, thus further decreasing the size and energy requirements of desalination systems. Under correct practices, drip irrigation can reduce the amount of water lost to deep percolation and runoff by 20 to 76% while increasing water productivity by 15% [19].

This paper focuses on codifying the market needs and design theory for an integrated photovoltaic-powered electrodialysis reversal (PV-EDR) and drip irrigation system. The market need for small-scale desalination for agriculture applications in MENA is first reviewed. From market research findings, EDR is identified to be an ideal candidate given its higher water recovery and lower energy consumption compared to traditional RO systems for brackish water desalination. Design requirements are presented based on market research on agricultural systems in MENA including interviews with farmers in Jordan. Given these design requirements, this study goes on to articulate the parametric design theory for an EDR system for irrigation applications with the goal of presenting how one might practically design an integrated system to meet the given design requirements. A time-variant operational mode of EDR with solar energy is presented that allows water production to match available solar irradiance, which decreases the size requirement of the solar system. The integration of desalination and drip irrigation is further discussed, specifically focused on how one might consider the operation of a system in which the water production rate of a desalination system and the water demand of an irrigation system are different. The energetics and water-savings benefits of irrigation scheduling is also discussed as it pertains to desalination. The utility of this design theory is then demonstrated by designing and sizing a system for a case study in Jordan. The performance metrics of this system are compared to benchmark RO systems in Jordan by comparing capital cost, energy cost, levelized cost of water (LCOW), and specific energy consumption (SEC).

Chapter 2

User Needs and Design Requirements for Desalination for Agriculture

While desalination for agriculture has been adopted in various parts of the world including MENA, current systems do not meet the needs of farmers. This conclusion was made through literature review in the MENA region, exploration of existing desalination systems in MENA, and interviews with farmers in Jordan to elucidate user needs and evaluate how well current systems meet those needs. Insights from MENA market research and field work in Jordan were used to develop a list of design requirements for desalination for irrigation applications.

An initial market review of the agricultural landscape in MENA was helpful in evaluating the factors that most affect the economic feasibility of desalination for agriculture. The 11 most water-stressed countries in MENA were identified, and information was gathered for each regarding income level, agriculture contribution to GDP, land resources, renewable surface water and groundwater resources, cropping patterns, electricity access, and irrigation practices. This information was largely collected from Food and Agriculture Organization (FAO) and World Bank food and agriculture databases [5, 20].

While this market context contributes to a high-level view of the MENA region, it is also important to understand how individual farmers perceive and address issues related to water quality and scarcity. To gain this additional perspective, the authors traveled to Jordan to conduct interviews with local farmers. While each country in MENA faces unique challenges, the findings from field work in Jordan are indicative of MENA at large because of the similarities in agricultural practices found in most MENA countries regarding crop selection and irrigation patterns. Jordan was chosen as the ideal beachhead market for introducing improved desalination systems for agriculture because of the extent to which it has already addressed water quality and scarcity issues through investment in desalination and drip irrigation. Small-scale brackish water desalination is already in practice in Jordan, which makes it an ideal location to speak with farmers about the improvements that could be made to current systems [21]. Additionally, employing water saving technologies such as drip irrigation contributes to the economic feasibility of desalination as it leads to smaller and less expensive desalination systems. Drip irrigation is being adopted at a rapid pace in MENA, so it is advantageous to conduct interviews in Jordan where drip irrigation adoption already accounts for 81% of all irrigation [22, 23].

In Jordan, the authors visited 11 farms, ranging in size from 3.2 ha to 200 ha. Six of the farms employed desalination—all of which were RO systems powered by grid electricity—with an additional farm planning to invest in an RO system within the next year. The farmers in Jordan who had desalination systems were considered lead users for this market study. These farmers spoke about the tradeoffs they considered when purchasing desalination systems as well as how investing in desalination had affected their irrigation practices and yield. They also provided insight as to their sensitivity to different costs associated with their systems in addition to the biggest problems and pain points they face with their current systems. Farmers who did not have desalination systems spoke about their perception of desalination and what problems might be solved or created by the addition of such systems. They also discussed their perceived risks and barriers to adopting the technology.

Conducting market research and identifying user needs led to the identification of five primary factors that affect the feasibility of integrating desalination with irrigation: crop selection, energy, irrigation water quality, farm size, and cost. The next section discusses each of these factors and how they contribute to the development of

Country	Popular Crops
Algeria	Potato, Wheat, Watermelon, Onion, Tomato
Bahrain	Date, Tomato, Pumpkin, Cucumber, Eggplant
Jordan	Tomato, Cucumber, Potato, Olive, Watermelon
Kuwait	Tomato, Date, Cucumber, Potato, Eggplant
Libya	Potato, Watermelon, Tomato, Onion, Date
Morocco	Sugar beet, Wheat, Potato, Olive, Tomato
Oman	Date, Tomato, Sorghum, Cucumber, Melon
Qatar	Tomato, Date, Pumpkin, Eggplant, Pepper
Tunisia	Olive, Tomato, Wheat, Barley, Potato
UAE	Date, Cucumber, Tomato, Eggplant, Onion
Yemen	Mango, Sorghum, Onion, Potato, Grape

Table 2.1: Five most popular crops in each of the 11 most water-stressed countries in MENA [5].

design requirements.

2.1 MENA Market Research and Interviews in Jordan

2.1.1 Crop Selection

Desalination's feasibility for agriculture is affected by crop selection because different crops respond differently to irrigation water quality. It has been found that desalination is most economically feasible for salt-sensitive crops with high value added from low salinity irrigation water [21, 24, 25]. For small-scale brackish water desalination in Jordan, the value of desalinated water outweighs the cost of desalination for high-value vegetable crops [21]. High-value vegetable and tree crops require less water and provide higher profit margins than cereal crops, which tend to be more tolerant to salinity. Table 2.1 shows the most popular crops for the 11 most water scarce countries in MENA [5]. Of the crops listed, 63% are considered "Sensitive" or "Moderately Sensitive" to salinity according to a compilation of crop salinity sensitivities from Hanson et al. and could benefit from desalination [4].

Country	Use of Groundwater for Irrigation, as Percent of Total
Algeria	65%
Bahrain	90%
Jordan	53%
Kuwait	76%
Libya	99%
Morocco	47%
Oman	100%
Qatar	93%
Tunisia	60%
UAE	100%
Yemen	67%

Table 2.2: Percentage of irrigation performed with groundwater in the 11 most water-stressed countries in MENA [23, 27–37].

Leads users in Jordan discussed how crop selection affected their decision to invest in desalination. Crops that generally have stable market demand and prices are most lucrative to farmers; these crops generally are sensitive to salinity. An example of this is banana cultivation in Jordan. Its high demand and price throughout the year justify the cost of investing in desalination for many farmers [26].

Most high-value, water-productive crops in MENA are sensitive or moderately sensitive to salinity. The salinity requirements of these crops thus drive product salinity requirements of desalination systems.

2.1.2 Energy

Energy often constitutes the majority of the lifetime cost of a desalination system. Lowering energy requirements and subsequently energy cost is a key factor in increasing the economic feasibility of desalination for agriculture. Desalinating brackish water requires less energy than desalinating seawater because of its lower salinity. Brackish water in MENA is often found in groundwater aquifers, which farmers in MENA rely on heavily as shown in Table 2.2 [23, 27–39].

Lead users in Jordan stated that their RO systems comprise the majority of the total energy cost of their farms [27, 40–44]. Almost every lead user pinpointed energy cost as the most significant pain point of their current desalination system. The farmers least worried about energy costs were ones who employed solar systems to offset some of their energy costs.

MENA's high solar irradiance make it an ideal location to implement solar energy systems [45]. Despite its potential for solar energy, each of the 11 countries listed in Table 2 attribute the majority of their electricity generation to oil, gas, and coal sources, with 9 of the 11 attributing over 95% of their electricity generation to these sources [20]. Given the abundance of solar irradiance in MENA, solar energy will be one of the most important energy assets to MENA as electricity prices rise and become more volatile. Farmers in Jordan listed cost as the primary barrier to solar energy adoption [26, 40–44, 46–50]. However, many of the farmers who had purchased solar arrays paid them off within three years because of the energy cost savings. One farmer stated that their solar system was "the best investment [they] have ever made."

Energy is important to consider when designing a desalination system because of its large contribution to the total lifetime cost of a system. Employing solar energy provides an avenue by which the energy costs of desalination can be decreased. It is important, then, that solar-powered desalination systems perform comparably or better than current on-grid systems in order to incentivize their use.

2.1.3 Irrigation Water Quality

Understanding what constitutes ideal water composition for crops is essential to the design of an improved desalination system for agriculture. While desalination is able to decrease the salinity of water, it is not able to remove all harmful substances in water. For example, boron, which is toxic to many crops, is difficult to remove via desalination [4]. Pre-treatment and post-treatment are often required to remove harmful constituents such as boron, suspended solids, or bacteria. Additionally, while monovalent ions such as Na^{+} and Cl^{-} inhibit healthy plant growth, the presence of divalent ions such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} are essential to healthy plant growth [51]. Conventional RO systems remove monovalent and divalent ions alike, so farmers are often required to blend desalinated water with some volume of feed water or install fertigation systems to introduce these nutrients back into the irrigation water [26, 44, 52]. In Jordan, blending or fertigation was often used to bring water salinity back up to around 500 ppm.

Irrigation water chemistry affects desalination design because of the added expense of implementing fertigation systems to introduce ions and nutrients back into the water. Finding less expensive methods to ensure ideal water chemistry can help make desalination more affordable.

2.1.4 Farm Size

Farm size affects desalination system design by setting constraints on both the production capacity and cost of a system. Smallholder farmers with less than 1 ha of land often do not have access to the capital required to purchase desalination systems. This is compounded by the economies of scale of desalination wherein the levelized cost of desalinated water becomes less for larger production rates [21]. While the majority of farm holdings in MENA are less than 1 ha, larger farm holdings constitute the majority of cultivated land area in MENA [53]. During farm visits in Jordan, the size range of the farms that incorporated desalination was 3.2 ha to 200 ha [42, 44]. The production rate of individual desalination systems found in Jordan ranged from 25 m3/hr to 75 m3/hr [26, 40–44]. Farms that required more desalinated water incorporated multiple of these systems in parallel to meet their total water requirement. Farmers with less land said that the cost of desalination was the biggest barrier to adoption. Similar trends were found regarding solar systems.

Farm size is an important indicator of economic feasibility of desalination because it determines both production rate and sensitivity to capital cost in both desalination systems and solar systems. While desalination can be profitable over its lifetime for a large range of farm sizes, smaller farms are more sensitive to the short-term impacts of purchasing a system.

2.1.5 Cost

Though employing desalination for agriculture can in many cases be profitable when considering the total lifetime cost of a system, the immediate effects of capital and operating costs significantly inform farmers' perceptions of the risks and tradeoffs of investing in desalination. An important insight gained from field work in Jordan was that farmers are more sensitive to energy and operating costs of desalination systems than capital cost. Every lead user interviewed stated that energy and maintenance costs were the biggest pain points of their current systems [26, 40–44]. Some farmers went as far as to say that capital cost was not a concern at all; they were able to acquire the capital necessary to make large purchases by selling equipment or portions of land or by taking out loans. Instead, monthly electricity cost and the frequency at which they were required to replace RO membranes were much larger concerns. Farmers with the most land were the least concerned with capital costs as they had access to the most capital, but farmers of smaller plots of land also understood the financial benefits of investing in solar power or desalination.

Cost, of course, directly influences economic feasibility. The need to reduce energy costs instead of minimizing capital costs is an important insight that greatly influences what type of system architecture and operational mode is economically feasible for farmers. It is important for an improved system to have reduced energy costs compared to current systems while maintaining a comparable or better lifetime cost.

2.2 Design Requirements

Market research on MENA in addition to field work in Jordan was used to elucidate a set of design requirements for desalination systems for agriculture.

1. Production Capacity: 20-75 m^3/hr
2. Feed Salinity: 1500 – 6000 ppm
3. Product Salinity: 300 – 700 ppm

4. Recovery Ratio: $\geq 70\%$

5. Energy Source: Solar and Grid

6. OPEX/Energy Cost: $<$ current RO systems

7. CAPEX: $>$ current RO systems

8. LCOW: $\leq$ current RO systems

These design requirements were elucidated from both a high-level view of MENA as well as a ground-level view through the lens of Jordan. Production capacity was considered largely based on the distribution of farm sizes in MENA and the typical system capacities found in Jordan. Feed salinity was taken as the typical salinity of brackish groundwater, which MENA relies on heavily for agriculture. Product salinity is dependent on crop selection, so a range of typical salinities is listed; priority should be placed on decreasing the cost of introducing nutrients back into the irrigation water. High water recovery ratio is desired and should be comparable to or better than current systems. An improved desalination system should be able to operate on solar power because of its energetic benefits as well as the need to shift to renewable energy. Energy costs should be less than current systems running on grid electricity, and employing solar energy is expected to bring additional cost savings. While capital cost should ideally be minimized, farmers listed energy costs as much higher of a priority. The levelized cost of water (LCOW) is the total lifetime cost of a system per cubic meter of water produced. Minimizing LCOW accounts for both capital expenditures (CAPEX) and operating expenditures (OPEX) and ensures that the total lifetime cost of an improved system is less than current systems even if its CAPEX is higher.

Chapter 3

Desalination System Selection and Design Theory

The following section presents the design theory for an improved desalination system architecture and operational mode given the design requirements derived in the previous section. It is found that continuous EDR best fits these design requirements and that operating this system in a time-variant scheme allows for cost-effective use of solar power. Governing theory that informs the design of a continuous PV-EDR system with drip irrigation is then presented. The first knowledge contribution develops time-variant operation of continuous EDR as a cost-effective method for utilizing solar energy for desalination. The second knowledge contribution focuses on design considerations when integrating desalination and irrigation, namely how one might consider tailoring desalinated water production to crop water demand.

3.1 Design Choices for Desalination System for Irrigation

3.1.1 Selection of Desalination Process: RO vs. EDR

RO and EDR are the two most common brackish water desalination processes. While RO accounts for 80% of brackish water desalination, EDR only accounts for 8%

despite studies showing that EDR is more energy efficient for certain brackish water conditions [54]. In the RO process, feed water is pressurized to overcome its osmotic pressure and pass through a semi-permeable membrane. In EDR, a voltage is applied to a stack of ion-exchange membranes to separate dissolved ions in water and pass them through these membranes into a waste stream. RO and EDR are similar in that they are both capable of operating at a range of size scales, feed salinities, and product salinities. Both can also be powered by multiple energy sources including grid electricity and renewable sources. EDR has several advantages, however, that make it the ideal candidate for brackish water agriculture applications. For low feed salinities ($<$ 5000 ppm), EDR is more energy efficient than RO [18, 54]. EDR has further energetic benefits when higher product salinities are desired [54]. This is especially relevant to the irrigation case where the product salinity is significantly higher than the salinity targeted for drinking water applications. EDR also requires less maintenance than RO as its membranes are stronger and less prone to clogging and fouling [18]. An added benefit to EDR for irrigation water is the ability to selectively tune ion removal [55, 56]. Monovalent ions such as Na^+ and Cl^-, which are harmful to plant growth, can be removed while divalent ions that are essential to healthy plant growth such Ca^{2+}, Mg^{2+}, and $SO_4{}^{2-}$ can remain. EDR does tend to have a higher capital cost than RO. However, its energetic benefits, decreased maintenance needs, and propensity for selective ion removal could make it the ideal technology to be paired with irrigation given the design requirements of lower energy costs and lower LCOW. For these reasons, EDR is considered for the remainder of this paper.

3.1.2 EDR Operational Mode

EDR traditionally operates in either a continuous mode or a batch mode. In continuous EDR operation, feed water reaches its target salinity at the end of a single pass through an EDR stack or network of stacks. In batch EDR operation, a fixed volume of water—a batch—is stored in a tank and is circulated through an EDR stack multiple times until the target salinity is reached. Batch EDR is less energy efficient than continuous EDR because of the continuous mixing of newly recirculated lower salinity water with pre-recirculated higher salinity water in the batch recirculation tank throughout a batch. Batch EDR also requires higher flow rates—and thus, more pumping energy—than continuous EDR for a set production rate because of the need to recirculate water multiple times. A benefit of batch EDR is that it requires much less membrane area—and thus, less capital cost—than continuous EDR as water is recirculated through the stack multiple times. For very small production rates (< 1 m^3/hr), the capital cost benefits of batch EDR outweigh the energy drawbacks, making it a more cost-effective solution compared to continuous EDR. However, these benefits are less pronounced for large flow rates, making continuous EDR much more common. Based on the design requirements, flow rates of 20 m^3/hr to 75 m^3/hr are desired–much larger than the 1 m^3/hr production rate where batch operation is considered the most cost-effective. Continuous EDR is chosen in this study to be the ideal system for agricultural applications because of its energetic benefits and common use for larger flow rate systems.

3.1.3 Considerations for PV-EDR Operation

There is an urgent need for renewable energy solutions because of rising electricity costs and overreliance on fossil fuels. MENA's high solar energy potential make solar power a viable solution for renewably powered desalination and irrigation. One of the primary barriers to solar power adoption is its high capital cost. Therefore, it is important that solar power schemes are operated in an energy-efficient manner to reduce the number of solar panels needed, especially for an energy intensive process such as desalination. One of the seemingly difficult attributes of solar systems is that its power level fluctuates through a day or week depending on cloud cover and time of year, which makes it difficult for the operation of systems at a constant power level. To operate a photovoltaic-powered electrodialysis reversal (PV-EDR) system designed for a specific flow rate at a specific power level requires either an oversized solar system to account for low irradiance periods of the day or an oversized EDR system so that enough water can be desalinated during the few hours where solar energy is at its highest. In both cases, solar energy is inevitably wasted during the middle of the day when solar irradiance is at its highest, making the PV-EDR system more expensive. An EDR system could instead operate in a time-variant manner where pump power and stack power are adjusted depending on the available solar energy. In turn, flow rate and product salinity will change as pump power and stack power are changed. This could allow for an EDR system to better match a fluctuating solar irradiance profile by increasing flow rate during high irradiance points and decreasing it during low irradiance points. The product salinity, however, could not remain constant because of physical limitations placed on the stack current given a certain flow rate as is discussed in the proceeding section. Product salinity will be higher than nominal when flow rate is higher than nominal and vice versa. The system would be operated in such a way that this variable salinity water is blended over the course of a day to reach its target salinity. In this way, a continuous EDR system operating in a time-variant mode can tune water production to the solar irradiance profile, leading to a reduction in size and cost of solar panels.

3.2 Parametric Design Theory for Continuous PV-EDR Operation with Drip Irrigation

3.2.1 Time-Variant PV-EDR Governing Theory

Electrodialysis reversal is a desalination process that removes ions using an applied electric field and ion exchange membranes. In an EDR stack, shown in Fig. 3-1, high salinity water flows through the inlet of a stack composed of alternating anion exchange membranes (AEMs) and cation exchange membranes (CEMs), which allow the passing of anions and cations, respectively. When an electric field is applied, anions are drawn toward the anode, and cations are drawn toward the cathode. Anions and cations then pass through the AEMs and CEMs, respectively, leaving behind alternating channels of diluate and high salinity concentrate streams that exit the stack. Diluate water is stored in a product tank or reservoir, and concentrate

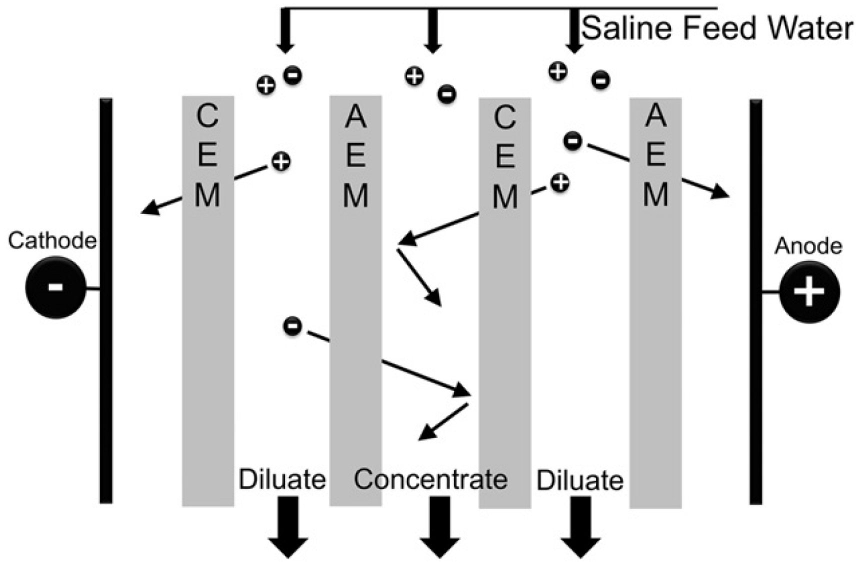

Figure 3-1: Electrodialysis reversal (EDR) process. Saline feed water enters a stack of alternating anion exchange membranes (AEMs) and cation exchange membranes (CEMs). An electric field is applied across the stack at the anode and cathode. Cations are attracted to the cathode and pass through the CEM, and anions are attracted to the anode and pass through the AEM. Alternating concentrate and diluate channels are formed over the length of the stack. Figure reproduced from Wright and Winter (2014) [18].

is disposed. EDR stacks are often comprised of dozens or even hundreds of these alternating AEM-CEM cell pairs.

Wright (2018) previously modeled the operation of EDR using an electrical circuit model [57]. He et al. (2020) used this modeling theory to develop time-variant operational theory of batch EDR through flow rate and voltage control [58]. He et al. found that one can maximize daily water production by adaptively controlling flow rate and voltage given a variable power source, which can facilitate a smaller and less expensive EDR stack and power system compared to static EDR operation [58]. Although He's work focused on batch EDR, similar principles can be applied toward continuous EDR.

To model an EDR system, a stack is discretized into a set of subsequent segments, represented by the subscript y. The desalination rate in an EDR stack segment is given as

$$\frac{dC^b_{d,y}}{dt} = \frac{1}{NV^{cell}_y}[Q_d(C^b_{d,y-1} - C^b_{d,y}) - \frac{N\phi I_y}{zF} + \frac{NA_y D^{AEM}(C^{AEM}_{c,y} - C^{AEM}_{d,y})}{l^{AEM}} + \frac{NA_y D^{CEM}(C^{CEM}_{c,y} - C^{CEM}_{d,y})}{l^{CEM}}] \tag{3.1}$$

where $\frac{dC^b_{d,y}}{dt}$ is the rate of change of the diluate bulk concentration in a stack segment, N is the number of cell pairs, V^{cell}_y is the volume of water contained in one cell pair segment, Q_d is the product flow rate, $C^b_{d,y-1}$ is the diluate bulk concentration in the previous stack segment, $C^b_{d,y}$ is the diluate bulk concentration in the current stack segment, ϕ is the current leakage factor, I_y is the current in the current stack segment, z is the ion charge number, F is Faraday's constant, A_y is the area of the current segment, D^{AEM} and D^{CEM} are the diffusion coefficients of the solute in the AEMs and CEMs, respectively, l^{AEM} and l^{CEM} are the thicknesses of the AEMs and CEMs, respectively, and $C^{AEM}_{c,y}$, $C^{AEM}_{d,y}$, $C^{CEM}_{c,y}$, and $C^{CEM}_{d,y}$ are the concentrations of the diluate and concentrate streams at the interface with adjacent AEMs and CEMs in a segment. From Equation (3.1), it is seen that a negative $\frac{dC^b_{d,y}}{dt}$ corresponds to a decreasing diluate stream salinity. The higher in magnitude this number is, the higher the degree of desalination. For a given stack arrangement, both product flow rate Q_d and the applied current I_y can be adjusted to affect desalination rate. With all else constant, increasing Q_d leads to an increase in $\frac{dC^b_{d,y}}{dt}$, which corresponds to less desalination. Increasing I_y leads to a decrease $\frac{dC^b_{d,y}}{dt}$, which corresponds to an increased rate of desalination. This makes intuitive sense as well; increasing flow rate means that the water has less residence time in the stack and, thus, less time to desalinate. Increasing the current increases the electric potential applied across the stack, which promotes further ion separation.

Given Equation (3.1), one could posit that during high irradiance hours, an increase in Q_d could be accompanied by the required increase in I_y needed to maintain a constant $\frac{dC^b_{d,y}}{dt}$. However, given a certain flow rate there is a physical limit as to how much current can be applied to the stack. This limiting current density $i^{+,-}_{lim}$ is calculated as

$$i_{lim}^{+,-} = \frac{C_d^b zFk}{t^{AEM,CEM} - t_{+,-}} \tag{3.2}$$

where $t^{AEM,CEM}$ is the transport number of the counterion in the AEM or CEM membrane (usually assumed to be 1), $t_{+,-}$ is the transport number of the cations or anions in the bulk solution, respectively, and k is the boundary-layer mass transfer coefficient given by

$$k = \frac{ShD_{aq}}{d_h} \tag{3.3}$$

where Sh is the Sherwood number, D_{aq} is the diffusion coefficient of the aqueous solution, and d_h is the hydraulic diameter. The Sherwood number is given by

$$Sh = 0.29Re_d^{0.5}Sc^{0.33} \tag{3.4}$$

where Re_d is the Reynolds number and Sc is the Schmidt number. The Reynolds number is given by

$$Re_d = \frac{\rho_{aq}u_{ch}d_h}{\mu} \tag{3.5}$$

where ρ_{aq} is the density of the aqueous solution, u_{ch} is the channel velocity of the fluid, and μ is the dynamic viscosity. The channel velocity u_{ch} is directly proportional to the flow rate given some flow channel area. From Equations (3.2) to (3.5), it can be concluded that the limiting current density i_{lim} scales with the flow rate Q_d as

$$i_{lim} \propto \sqrt{Q_d} \tag{3.6}$$

As such, for an increase in system flow rate, the amount by which applied current can be increased is limited because of the nonlinear scaling shown in Equation (3.6). Therefore, adjusting system flow rate in a continuous system leads to a product salinity setpoint that is different than the initial target.

Using the model presented in Wright (2018), one can observe the change in product salinity given a variable flow rate when operating at a set fraction of limiting current

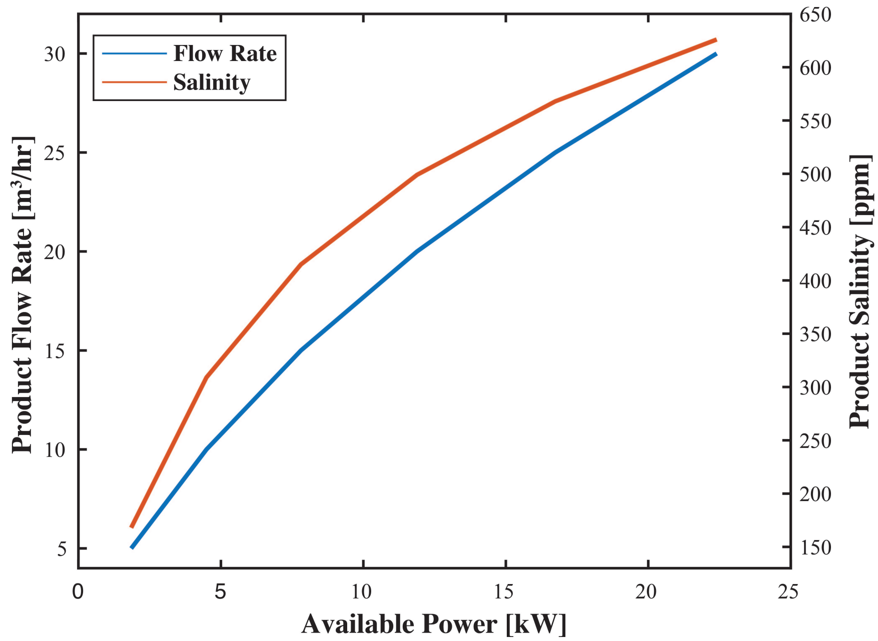

Figure 3-2: Behavior of EDR system at variable power. As the available power increases, flow rate through the EDR stack increases. A subsequent increase in current through the stack is allowed based on the theory from Wright et al. (2018) [57]. This change in flow rate and current result in a certain product salinity. For a set stack design and configuration, an increase in available power yields a higher product salinity.

density. Using this model, a continuous EDR system was designed for a feed salinity of 2000 ppm, a product salinity of 500 ppm, and a flow rate of 20 m^3/hr. Figure 3-2 shows the change in product flow rate and product salinity given a change in available power. When more power is available, the flow rate is increased followed by an increase in product salinity. Conversely, when less power is available, the system operates at a lower product flow rate with a product salinity lower than the initial setpoint.

The potential risk associated with this time-variant operational mode is that since product salinity changes throughout the day depending on available solar power, crops would be given lower salinity water in the morning or evening and higher salinity water in the middle of the day. However, many crops are resilient when faced with small changes in irrigation water quality and quantity, especially considering that the system can be designed such that the average salinity seen by the crops over the course of a day will be the nominal target salinity [59]. Furthermore, farmers typically incorporate intermediate reservoirs or tanks to store water in before it is delivered to the crops. In Jordan, these intermediate reservoirs are often larger than a day's worth of irrigation water. In these cases, it is likely that sufficient mixing of the water could occur prior to irrigation such that the water delivered to the crops will be of a constant salinity.

From a design theory perspective, this time-variant operational mode allows for a continuous PV-EDR system to be operated at a variable flow rate depending on the available solar energy. Using this theory to better tailor desalination production with solar irradiance decreases the size requirement of solar panels and energy storage.

3.2.2 Irrigation Scheduling

An equally important piece to consider when designing an EDR system for irrigation is the irrigation system itself and how one might operate the two subsystems together. While farm tours in Jordan suggest that current desalination systems are largely uncoupled to irrigation systems due to the presence of large intermediate water storage, an improved desalination system could achieve further water and energy savings by considering this interplay. Time-variant operation of PV-EDR allows one to tailor water production to crop water demand over some time horizon by considering how both desalination production rate and crop water demand change over the course of a week or season.

The interaction between a desalination system and an irrigation system is nontrivial because they operate at different time scales and production/consumption rates. Desalinated water is produced continuously throughout a day with variable production rate depending on solar irradiance. Individual irrigation events can be relatively short in duration though high in flow rate. An added interaction is the difference in volume between daily desalination production and crop water consumption.

Crop water demand is closely coupled to crop evapotranspiration ET_c, which is the total amount of water released from the soil and crop leaves in a day. ET_c can be calculated using the Penman-Monteith equation with crop coefficients and relies on daily weather parameters such as solar irradiance, number of sun hours, temperature, relative humidity, and wind speed. Using an irrigation controller or scheduler that accounts for ET_c could lead to water and energy savings as studies show that many farmers do not have access to tools that allow them to effectively calculate their crop water demand, instead relying on observations to irrigate which can be prone to human error and lead to overwatering of crops [60].

Time-variant PV-EDR has the added benefit that its production rate is closely linked to the solar irradiance. This is advantageous for irrigation as crop water demand is also linked to solar irradiance via ET_c. Figure 3-3 shows the correlation between ET_c and solar irradiance for a simulated season of tomato growth in Jordan using a drip irrigation system model developed by Grant et al. [61]. One can see that ET_c is strongly correlated with solar irradiance over the course of a season. While this correlation is evident on a seasonal time scale, there is less correlation on a daily time scale. To account for this difference, an energy buffer is required either in the form of product water storage or batteries to better match water production with crop water demand. Many farmers have large water storage reservoirs that could be used as an energy buffer in this case.

Additional energetic benefits could be gleaned by optimizing field layout and irrigation scheduling to better utilize the available solar power. Previous work has shown that low-energy, low activation pressure drip emitters can cut hydraulic energy requirements by 43% compared to conventional emitters [62]. Integration of drip irrigation scheduling with time-variant PV-EDR would yield more energy- and water-efficient agriculture that results in higher yield.

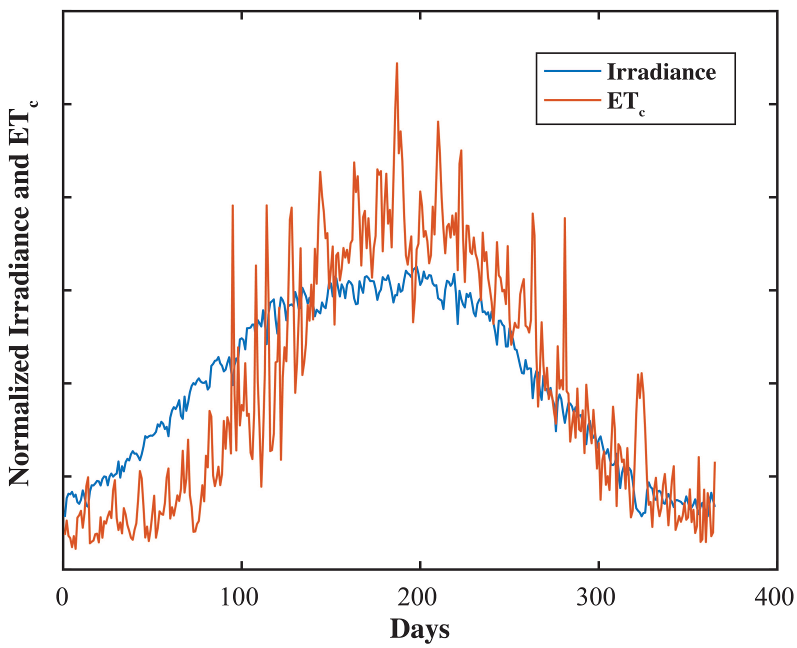

Figure 3-3: Comparison of solar irradiance and crop evapotranspiration (ET_c) over the course of a season of tomato growth in Jordan. Solar irradiance and ET_c correlate well on a seasonal or month time scale but correlate less well on a daily or weekly time scale. For a desalination system whose production rate is closely related to solar irradiance, water production will match crop demand well over the course of a season, but an energy buffer is needed on a daily and weekly time scale to account for differences between water production and crop water demand.

Chapter 4

PV-EDR System Cost Comparison

This section presents a cost and performance comparison of time-variant PV-EDR and current benchmark RO systems in Jordan. The design theory from Section 3 along with the model partially presented in Section 4 from Wright et al. (2018) are used to characterize the design and performance of the EDR systems investigated in this section [57]. The benchmark system is based on RO system parameters from systems seen in Jordan in addition to information found on commercially available RO systems. The following case study parameters represent a typical system one might see in Jordan:

- Location: Jordan
- Production Rate: 40 m^3/hr
- Feed Salinity: 2000 ppm
- Product Salinity: 550 ppm
- Recovery Ratio: 70%
- Lifetime: 20 years

In order to effectively compare the cost and performance of EDR and benchmark RO systems, it is helpful to consider four characteristic systems:

1. **Time-Variant, Photovoltaic-Powered Electrodialysis Reversal (TV-PV-EDR):** This scheme consists of a continuous EDR system operated with a solar power system without batteries. The production rate is varied throughout the day based on the time-variant theory discussed in Section 3.

2. **Photovoltaic-powered Electrodialysis Reversal with Batteries (Battery-PV-EDR):** This scheme consists of a continuous EDR system operated with a solar power system with batteries. The system is operated at a constant power such that the flow rate and product salinity are constant. Any available solar power above this constant power threshold is stored in batteries so that desalination can continue at times of low irradiance.

3. **On-Grid Electrodialysis Reversal (Grid-EDR):** This scheme consists of a continuous EDR system operated with grid electricity. The system is operated at a constant power level such that the flow rate and product salinity are constant.

4. **On-Grid Reverse Osmosis (Grid-RO):** This scheme consists of an RO system operated with grid electricity. Product water at 80 ppm is blended with some portion of feed water to bring the final salinity to 550 ppm.

TV-PV-EDR has been the focus of much of this paper; however, it is also useful to compare this strategy to other EDR cases, namely Battery-PV-EDR and Grid-EDR. While TV-PV-EDR presents many advantages over Grid-RO, it is helpful to see what advantages it presents over other possible EDR variants. Additionally, many farms employing solar systems often have grid electricity access as well. This could present an opportune operational strategy wherein a TV-PV-EDR scheme operates during daylight hours while a Grid-EDR scheme operates at night in order to maximize water production. This could then be compared to a Grid-RO system that operates for 24 hours each day. Considering Battery-PV-EDR is also of interest as battery storage is another strategy that can be used to capture extra solar energy during the day. Batteries, however, are expensive, so a tradeoff exists. Previous work has performed system design optimizations to size a batch PV-EDR system that employs time-variant theory while also incorporating batteries [63–65]. Taking advantage of both time-variant operation and the benefits of employing a battery as an energy buffer can greatly decrease the necessary battery capacity and decrease the overall cost of a system. A similar optimization could be performed for continuous EDR.

The EDR characteristic system strategies studied here use the same base EDR system architecture. This system was sized using Wright's modeling theory and consists of two lines and five stages, each with 530 cell pairs. The TV-PV-EDR system required 226 m^2 of solar array area to produce the target volume of water while the Battery-PV-EDR system required 230 m^2. The benchmark RO system consisted of 6 tubes each containing four RO membrane cartridges.

This system comparison uses CAPEX, OPEX, LCOW, and SEC as the primary performance metrics. From the design requirements, OPEX, which includes energy cost, is the parameter of primary importance to farmers. However, while farmers are more sensitive to OPEX than CAPEX, it is important that the LCOW of a TV-PV-EDR system is comparable or less than that of benchmark RO systems as it provides insight into the total lifetime cost of a system.

For this study, CAPEX consists of the following items shown in Table 4.1. EDR membranes, electrodes, and spacers are priced based on wholesale suppliers [66, 67]. RO membranes are priced based on suppliers and the cost Jordanian farmers pay for replacement membrane cartridges [26, 40–44, 46–50]. The power system components—solar system and battery—are also priced based on common supplier pricing and cost data collected in Jordan [40, 41, 44, 63, 68].

Pump cost was calculated using supplier sizing tools and pricing from Grundfos [69]. For TV-PV-EDR, the pumping system consists of three pumps in parallel for each line, consisting of a small, medium, and large pump to account for the variable flow rate during operation. Each of the other three cases were sized for a single pump at a constant operating point. Pumps were sized using Grundfos' sizing tool, and power data and pricing were obtained from the Grundfos catalog.

This study assumes that the items listed in Table 4.1 are the most important in

Item	TV-PV-EDR	Battery-PV-EDR	Grid-EDR	Grid-RO
Membranes	X	X	X	X
Electrodes	X	X	X	
Spacers	X	X	X	
Pump	X	X	X	X
Solar System	X	X		
Batteries		X		

Table 4.1: Items included in CAPEX. Items marked with "X" for each system are included in that system's CAPEX.

Item	Lifetime [yr]	Unit Cost [$]	Units
ED Membranes	10	43 [65, 67]	$/m^2$
RO Membranes	5	630 [26, 40–44, 46–50]	$/cartridge
Electrodes	10	2000 [65, 66]	$/m^2$
Spacers	10	3 [65, 67]	$/m^2$
Solar Array	20	1.5 [40, 41, 44]	$/W
Battery Storage	10	293 [63, 68]	$/kWh

Table 4.2: CAPEX cost metrics for EDR and RO system cost comparison.

comparing the CAPEX of an EDR and RO system. In reality, other components such as filtration, electronics, and hydraulics will also contribute to the capital cost of a system, but it is assumed that the cost of these additional components will be similar across similarly sized EDR and RO systems, so they are excluded from this comparison.

For this study, OPEX consists energy, chemicals, and maintenance costs. Electricity costs were taken from the most recent energy census in Jordan [70]. The chemical and maintenance costs listed are common values for EDR and RO [71].

The replacement costs of components are not included in the reported OPEX of the system but are included in the total lifecycle cost of the system. This was done because component replacements happen at varying time scales, often on the order of years. While replacement costs were important to farmers in Jordan, monthly recurring expenditures were of more importance. CAPEX and OPEX cost metrics are shown in Tables 4.2 and 4.3, respectively.

The results from this system cost comparison are shown in Table 4.4. As expected,

Item	EDR	RO
Energy [$/kWh]	0.11 [70]	0.11 [70]
Chemicals [$/m^3]	0.01 [71]	0.03 [71]
Maintenance	0.011 [71]	0.018 [71]

Table 4.3: OPEX cost metrics for EDR and RO system cost comparison.

all EDR scenarios perform better than RO in terms of OPEX, namely energy costs. This energy savings leads to a smaller LCOW compared to Grid-RO despite the stark difference in capital investment required for EDR compared to RO. LCOW is the lowest for TV-PV-EDR. The initial investment of a solar system leads to lower lifetime cost compared to paying for grid electricity each month. Battery-PV-EDR, though having a smaller LCOW than Grid-EDR, has a greater LCOW than TV-PV-EDR because of the cost associated with purchasing a large energy buffer. However, as mentioned before this cost could go down by incorporating time-variant operation in a system with batteries to decrease the overall size of the batteries. The SEC of each EDR case is less than that of Grid-RO with TV-PV-EDR having the lowest SEC out of the three EDR cases. This is because of the nonlinear relationship between available power and flow rate shown in Fig. 3-2. While operating the system at higher flow rates does increase the SEC, operation at lower flow rates greatly decreases SEC.

	TV-PV-EDR	**Battery-PV-EDR**	**Grid-EDR**	**Grid-RO**
CAPEX [$]	$157,135	$177,352	$86,433	$29,209
OPEX [$/m^3]	$0.02	$0.02	$0.09	$0.14
LCOW [$/m^3]	$0.102	$0.107	$0.138	$0.170
SEC [kWh/m^3]	0.60	0.62	0.62	0.81

Table 4.4: Cost comparison results for TV-PV-EDR, Battery-PV-EDR, Grid-EDR, and Grid-RO systems. TV-PV-EDR is found to have the lowest LCOW while Grid-RO has the lowest capital cost. TV-PV-EDR also has a lower SEC than all other cases.

TV-PV-EDR meets the design requirements discussed in this paper. It also performs the best in terms of LCOW and OPEX compared to each of the other scenarios. Each of the EDR cases does have a high capital cost associated with it compared to

Grid-RO, but the energy savings associated with EDR make it less expensive over its lifetime than Grid-RO.

Chapter 5

Discussion

The need for energy- and water-efficient desalination was found through market research in MENA and interviews in Jordan. These interviews led to insights into the factors that influence economic feasibility of small-scale brackish water desalination for agriculture applications. Design requirements for an improved desalination system were derived based on this market research. An important insight elucidated from field work in Jordan is that farmers are much more sensitive to operating costs than capital costs. This insight motivates EDR as the opportune desalination process for agriculture applications because of its energy savings compared to RO for low feed salinities.

EDR was presented as the ideal desalination process to satisfy the derived design requirements. For PV-EDR systems, time-variant operational theory was presented that allows EDR to operate at variable flow rate and salinity depending on available power in order to better capture the available solar energy throughout a day. TV-PV-EDR facilitates cost savings in both the EDR system and power system compared to solar-powered systems operating at constant power as systems do not need to be oversized in order to meet production targets.

The integration of desalination and irrigation was presented as an additional area of energy and water savings. Crop water demand is dependent on crop evapotranspiration, a parameter calculated by solar irradiance amongst other things. Crop water demand calculated via crop evapotranspiration follows solar irradiance closely on a seasonal time scale; however, this correlation is weaker on a daily or weekly scale. Since the production rate of TV-PV-EDR is closely related to solar irradiance, it can be more closely tailored to crop water demand, which also relies on solar irradiance. To account for daily differences in water production and crop water demand, an energy buffer is needed. TV-PV-EDR can be implemented with large water reservoirs acting as energy buffers. This has the added benefit that water produced at variable salinity levels can be adequately mixed during storage before being sent to the crops. Current irrigation practices already include the use of large water reservoirs, so this architecture would pose minimal change to current practices.

It was found that the lifetime cost of TV-PV-EDR is less than alternatives including benchmark RO systems found in Jordan. Energy and operating costs of TV-PV-EDR systems are smaller compared to RO because of its increased energy efficiency in addition to cost savings from investing in solar energy. The capital cost of EDR was found to be more than that of benchmark RO systems; however, farmers emphasized a much stronger sensitivity to operating costs than capital cost. These results show that farmers can gain significant cost savings by switching to EDR even if they continue to operate it with grid electricity. Further cost savings are seen when implementing solar power. Even more cost savings may be achieved by implementing time-variant theory in a solar-powered system with batteries. Operating in a time-variant mode with batteries would allow the system to gain benefits from both time-variance and batteries. Implementing batteries would allow the system to operate at more efficient operating points as it could operate over a longer period of the day. Implementing time-variant theory would decrease the size of batteries, ultimately lowering cost.

This work adds value to the academic community by elucidating the conditions under which desalination for irrigation can be economically feasible in addition to developing time-variant theory that can allow for continuous EDR to operate with solar energy more effectively. Practically, this study presents the baseline engineering design principles to enable engineers to choose appropriate subsystems and build further design optimizations for more specific case studies and system architectures.

It also sets the foundation for future pilot systems to be designed and tested.

Future work includes piloting a time-variant PV-EDR system in Jordan. To this end, the time-variant theory discussed here will be formulated into a controller that can be tested experimentally with lab-scale systems. Design optimizations will be run with this control theory to evaluate system cost and performance to a higher fidelity.

Limitations of this study include the use of a specific case study in Jordan. Though many of these results can be generalized to MENA and other areas of the world, similar steps should be taken when designing systems for specific contexts. This study also assumes that the main drivers of desalination system cost are membranes, pumps, solar systems, batteries, and energy costs. Future studies could focus on performing a more in-depth cost analysis of EDR for this context.

Chapter 6

Conclusions

This paper defines design requirements for a desalination system for agriculture applications. From market research in MENA and field work in Jordan, it was determined that EDR best meets the needs of farmers because of its energy savings, high water recovery, ability to tune water chemistry to meet crop needs, and ability to effectively operate using solar energy. PV-EDR systems can take advantage of time-variant operational theory wherein variable flow rate is commanded based on the available solar irradiance such that desalination production can better match the solar irradiance profile throughout a day, leading to power system cost savings. TV-PV-EDR can be integrated with drip irrigation by considering how desalination production can be tailored to crop water demand through the use of an energy buffer such as a water reservoir.

Future work consists of further development of time-variant theory for continuous EDR systems, culminating in a full-scale pilot system in Jordan. The primary research question in time-variant theory development is evaluating how one might optimize EDR system design and operation for the lowest LCOW and OPEX. This control architecture should be tested at a smaller scale and demonstrated in field testing. This controller should then be implemented on an agriculture size scale. I also recommend that further work focus on desalination system integration with drip irrigation systems. Irrigation scheduling can be implemented in a controller alongside TV-PV-EDR control.

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