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Feasibility and design of solar-powered electrodialysis reversal desalination systems for agricultural applications in the Middle East and North Africa

Jacob N. Easley [a,*], Samer Talozi [b], Amos G. Winter V. [a]

[a] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, United States
[b] Civil Engineering Department, Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110, Jordan

HIGHLIGHTS

- Current methods to desalinate irrigation water in the Middle East and North Africa (MENA) are expensive and energy intensive.
- Photovoltaic-powered electrodialysis reversal (PV-EDR) was chosen as an improved desalination method to be deployed in MENA.
- A time-variant scheme for EDR is proposed wherein flow rate and stack voltage are varied based on available solar irradiance.
- The levelized cost of water ($/m^3) of TV-PV-EDR was found to be 24% less than current RO systems despite a higher CAPEX.

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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 was chosen as an improved 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. A novel time-variant (TV) operational approach is presented for continuous PV-EDR wherein flow rate and EDR stack voltage are varied based on the available solar irradiance such that desalination power matches available solar power throughout a day. This results in a variable product salinity throughout the day, but the presence of large water reservoirs on MENA farms ensures that irrigation water is adequately mixed before being sent to crops. The TV approach enables low-energy, continuous, solar-powered desalination without the need for batteries. Given a case study in Jordan, a TV-PV-EDR system was conceptually designed and compared to current benchmark RO systems in relation to capital cost, energy cost, and total lifetime cost via a theoretical techno-economic analysis. TV-PV-EDR was found to have a levelized cost of water ($/m^3) that is 24 % less than current RO systems 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.

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

* Corresponding author.
E-mail address: jeasl@mit.edu (J.N. Easley).

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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 m^3/day [13]. In the 2000s, Spain transitioned to large-scale seawater desalination systems (>100,000 m^3/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 economic and environmental concerns. Desalination is energy intensive and requires large amounts of grid electricity or 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 [19]. 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 % [20].

This paper focuses on codifying the market needs and design theory for a photovoltaic-powered electrodialysis reversal (PV-EDR) system for irrigation. The current market space around the need for desalination and irrigation in MENA is investigated in order to develop design requirements. From these design requirements, EDR is chosen to be the most viable solution path to meet the needs of MENA farmers. 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 and operate a system to meet the given design requirements. The utility of this design theory is then demonstrated by conceptually designing and sizing a system for a case study farm in Jordan and quantifying its benefit compared to existing technology.

2. User needs and design requirements for desalination for agriculture in MENA

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 by the authors through literature review about 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 then 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 the Food and Agriculture Organization of the United Nations (FAO) and World Bank food and agriculture databases [5,21].

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 a 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 [22]. 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 [23,24].

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.

2.1. Market research and design requirements

The design requirements in Table 1 were elucidated through aforementioned market research in MENA and interviews with farmers and lead users in Jordan. The five primary factors that influence the selection of these design requirements are discussed in the subsequent subsections.

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 [22,25,26]. For small-scale brackish water desalination in Jordan, the value of desalinated water outweighs the cost of desalination for high-value vegetable crops [22]. 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 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. [4] and could benefit from desalination. The most sensitive of these crops require an irrigation water salinity of 400–700 ppm in order to achieve maximum yield [27]. The salinity requirements of these crops thus drive product salinity requirements of desalination systems.

Lead 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 [28].

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 (Table 3) [24,29–41].

Table 1
Design requirements for desalination system for agriculture.

Design requirement	Value
Production capacity	20–75 m^3/h
Feed salinity	1500–6000 ppm
Product salinity	400–700 ppm
Recovery ratio	≥70 %
Energy source	Solar and grid
OPEX/energy cost	< current RO systems
LCOW	≤ current RO systems
CAPEX	minimized but > current RO systems is acceptable

Table 2
Five most popular crops in each of the 11 most water-stressed countries in MENA [5].

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

Lead users in Jordan stated that their RO systems comprise the majority of the total energy cost of their farms [29,42–46]. 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 makes it an ideal location to implement solar energy systems [47]. 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 [21]. 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 [28,42–46,48–52]. 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 total lifetime cost. 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

Table 3
Percentage of irrigation performed with groundwater in the 11 most water-stressed countries in MENA [24,29–39].

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 %

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 [53]. 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 [28,46,54]. 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 [22]. 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 [55]. During farm visits in Jordan, the size range of the farms that incorporated desalination was 3.2 ha to 200 ha [44,46]. The production rate of individual desalination systems found in Jordan ranged from 25 m^3/h to 75 m^3/h [28,42–46]. Farms that required more desalinated water incorporated multiple 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 for 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 [28,42–46]. 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.

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 for irrigation is then presented.

3.1. Design choices for a 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 [19]. 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 renewables.

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 [18,19]. EDR has further energetic benefits compared to RO when higher product salinities are desired [19]. 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]. 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. 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/h), the capital cost benefits of batch EDR outweigh the energy drawbacks, making it a more cost-effective solution compared to continuous EDR [56]. However, these benefits are less pronounced for large flow rates, making continuous EDR much more common. Flow rates of 20 m^3/h to 75 m^3/h are desired for irrigation purposes, much larger than the 1 m^3/h production rate where batch operation is considered the most cost-effective [56]. Continuous EDR is thus chosen in this study to be the ideal system for agriculture applications because of its energetic benefits and common use for larger flow rate systems.

3.1.3. Considerations for PV-EDR operation

One of the seemingly difficult attributes of utilizing a solar system 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 a desalination system 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. Battery storage could be utilized to capture this energy, but the high cost and maintenance requirements of large batteries often become a barrier to entry for end users.

He et al. [57] previously developed a time-variant operational scheme for EDR wherein system flow rate and EDR stack voltage are adaptively controlled depending on the available solar energy, allowing for the desalination power profile to better match the solar profile and facilitating a smaller and less expensive EDR stack and power system compared to static EDR operation. This work, however, only pertained to batch systems operating at small flow rates (<1 m^3/h).

A new time-variant scheme can be developed for continuous EDR systems with larger flow rates, which has not been done previously to the authors' knowledge. However, adjusting flow rate of a continuous EDR system inevitably changes its product salinity because of physical limits placed on the stack current given a certain flow rate. Thus, product salinity will be higher than nominal when flow rate is higher than nominal and vice versa. This would normally be unacceptable for drinking water applications, but it can work well for agriculture applications as the system would be operated in such a way that this variable salinity water is blended over the course of a day in a water storage pond to reach its target salinity. In this way, a continuous EDR system operating in a time-variant mode can sync water production to the solar irradiance profile, leading to a reduction in size and cost of solar panels.

3.2. Parametric design theory for time-variant, continuous PV-EDR operation

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

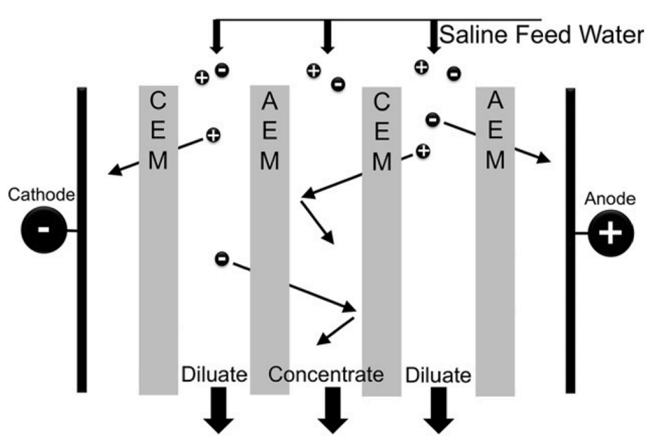

Fig. 1. Electrodialysis reversal (EDR) process. Saline feed water enters a stack of alternating anion exchange membranes (AEMs) and cation exchange membranes (CEMs). An electric field is applied across the stack at the anode and cathode. Cations are attracted to the cathode and pass through the CEM, 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. The "reversal" denotation of EDR comes from the ability to reverse its voltage polarity, causing the concentrate and diluate streams to switch. Figure reproduced from Wright and Winter [58].

Wright et al. [58] previously modeled the operation of EDR using an electrical circuit model. He et al. [59] used this modeling theory to develop time-variant flow- and voltage- control batch EDR. To model an EDR system, a single cell pair is considered (Fig. 2). The molar concentration is given as C. Superscripts denote the bulk concentration, AEM surface concentration, and CEM surface concentration as C^b, C^{AEM}, and C^{CEM}, respectively. Subscripts denote the diluate and concentrate concentrations as C_d and C_c, respectively. A second subscript y denotes the channel segment along the flow path. i represents the current through each segment while L represents the length of flow path. h denotes the channel gap between two membranes. The desalination rate in an EDR stack segment is given as

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

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

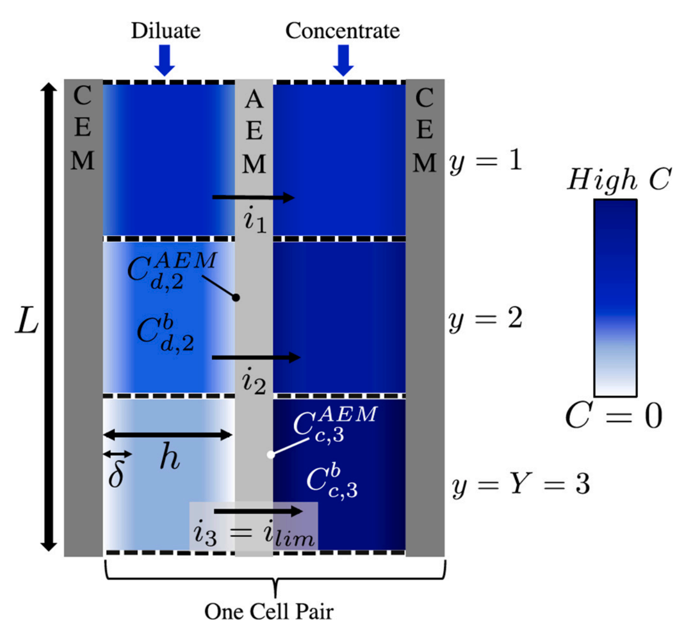

Fig. 2. Model diagram of a single cell pair of an EDR system. Figure reproduced from Wright and Winter [58]. The molar concentration is given as C. Superscripts denote the bulk concentration, AEM surface concentration, and CEM surface concentration as C^b, C^{AEM}, and C^{CEM}, respectively. Subscripts denote the diluate and concentrate concentrations as C_d and C_c, respectively. A second subscript y denotes the channel segment along the flow path. i represents the current through each segment while L represents the length of flow path. h denotes the channel gap between two membranes.

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 a given stack segment, ϕ is the current leakage factor, I_y is the current in a given stack segment, z is the ion charge number, F is Faraday's constant, A_y is the area of a given 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 Eq. (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 decrease in $|\frac{dC^b_{d,y}}{dt}|$, which corresponds to less desalination. Increasing I_y leads to an increase in $|\frac{dC^b_{d,y}}{dt}|$, 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 Eq. (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 to how much current can be applied to the stack. This limiting current density $i^{+,-}_{lim}$ is calculated as

$$i^{+,-}_{lim} = \frac{C^b_d zFk}{t^{AEM,CEM} - t_{+,-}}, \tag{2}$$

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

$$k = \frac{ShD_{aq}}{d_h}, \tag{3}$$

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

$$Sh = 0.29Re_d^{0.5}Sc^{0.33}, \tag{4}$$

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

$$Re_d = \frac{\rho_{aq}u_{ch}d_h}{\mu}, \tag{5}$$

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 Eqs. (2) to (5), it can be concluded that the limiting current density i_{lim} scales with the flow rate Q_d as

$$i_{lim} \propto \sqrt{Q_d}. \tag{6}$$

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 Eq. (6). An important insight from this relationship is that a change in system flow rate will cause a change in product salinity because of the nonlinear current scaling. This means that both the flow rate and product salinity of a time-variant continuous EDR system will change over the course of a day depending on the available solar power.

To illustrate this design theory in practice, a system was conceptually designed for a case study in Jordan based on the design requirements outlined in Section 2:

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

In order to design an EDR system for this case study, Eq. (1), along with additional EDR modeling theory from Wright et al. [58], was used to build a system sizing tool for continuous EDR. Inputs into this system sizing tool include feed salinity, desired product salinity, production rate, recovery ratio, and the fraction of limiting current density at which the system will operate. Given these inputs and a set of flow spacer properties, this tool calculates desalination rate, power consumption, and pressure drop for a given arrangement of EDR stacks of a certain number of cell pairs. By changing the number of stacks in series and number of cell pairs in each stack, one can design a system that meets the target salt cut. For high flow rates, multiple lines of stacks can be put in parallel.

Because of the large range of flow rates considered for this design, a single pump is not adequate for efficient time-variant operation as most pumps are sized for efficient operation only within a small range of flow rates. In applications where a large range of flow rates is considered, multiple pumps of varying size are typically selected so that efficient operation can be ensured for the entire flow rate range. For this application, three pumps (small, medium, and large) are independently sized for different operating points within the flow rate range considered. Only a single pump will be operating at a time depending on the flow rate corresponding to the given power availability.

To meet the target production rate of 40 m^3/h and product salinity of 550 ppm, a network of stacks was sized that contained two parallel lines of five stacks each, with each stack containing 530 cell pairs. This system had a total pressure drop of 0.97 bar and a total power consumption of 11.5 kW, yielding an SEC of 0.57 kWh/m^3.

Given this baseline EDR system, the water production and energy consumption of a time-variant PV-EDR system was found by taking hourly solar irradiance data for a typical day in Jordan [60]. This solar irradiance data, along with a solar panel area, yields an hourly power allowance for the desalination system.

The degree to which this available solar energy affects product flow rate and product salinity of the aforementioned system is shown in Fig. 3. This is found by considering a range of flow rate inputs for the system architecture previously designed. The system sizing tool calculates the required power and the product salinity. As available power increases, flow rate increases via an increase in pumping power. For this given flow rate increase, applied stack current may only increase by the square root of the flow rate increase as shown in Eq. (6); thus, the product salinity must increase. 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 data in Fig. 3 was used as a look up table to calculate the hourly product flow rate and salinity given the hourly power allowance for the desalination system derived from the aforementioned solar irradiance data for Jordan. Thus, the total volume of product water was calculated by integrating the flow rate over the course of a day. The final salinity of the blended product water was calculated as a weighted average of the product salinity over the course of the day. The hourly power allowance was integrated over the course of a day to determine the total amount of energy required for a day of desalination. The total water production and resultant salinity for the day were 480 m^3 and 545 ppm, respectively. The total energy required for a day's worth of desalination was 290 kWh.

Fig. 4 visually depicts how a system of this size operates over the

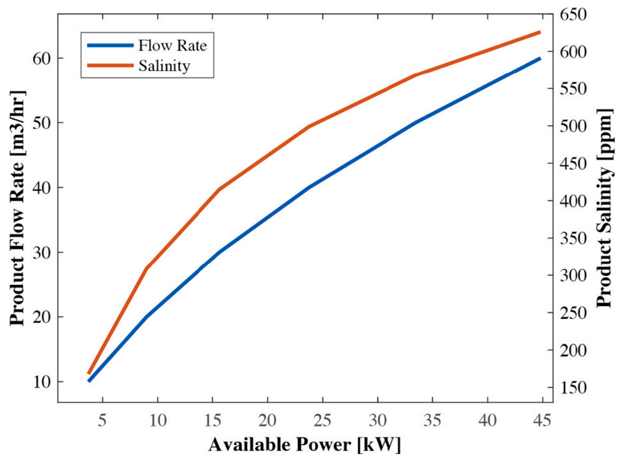

Fig. 3. Behavior of a continuous EDR system at variable power. As the available power increases, flow rate through the EDR stack increases via an increase in pumping power. Applied stack current may only increase by the square root of the flow rate increase (Eq. (6)). This change in flow rate and current result in a certain product salinity. For a set stack design and configuration, an increase in available power yields a higher product salinity.

course of a day under constant operation or variable flow rate and product water salinity. In the constant power operational scheme, flow rate and salinity are constant throughout the day, and much potential solar energy is lost during the middle of the day. A total of 360 m^3 of water is produced and stored. In time-variant operation, the desalination system is allowed to operate at higher power levels, leading to higher flow rates and higher salinities. Conversely, during low irradiance hours, production rate and salinity are lower. A total of 480 m^3 of water is produced throughout the day as more of the available solar energy is captured. For applications such as drinking water desalination, this changing salinity would pose issues as consumers would receive water of different salinity depending on what time of day they receive water. Desalination for irrigation, however, provides an opportunity to take advantage of this time-variant scheme without facing the negative consequences associated with changing product water salinity.

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 [61]. From a practical perspective, a system can be designed such that the product salinity associated with the maximum flow rate is still within an acceptable range for crops. Furthermore, farmers in MENA typically incorporate intermediate reservoirs to store water in before delivering it to the crops. These reservoirs allow for variable salinity water to be mixed over the course of a day to reach a constant salinity before being delivered to

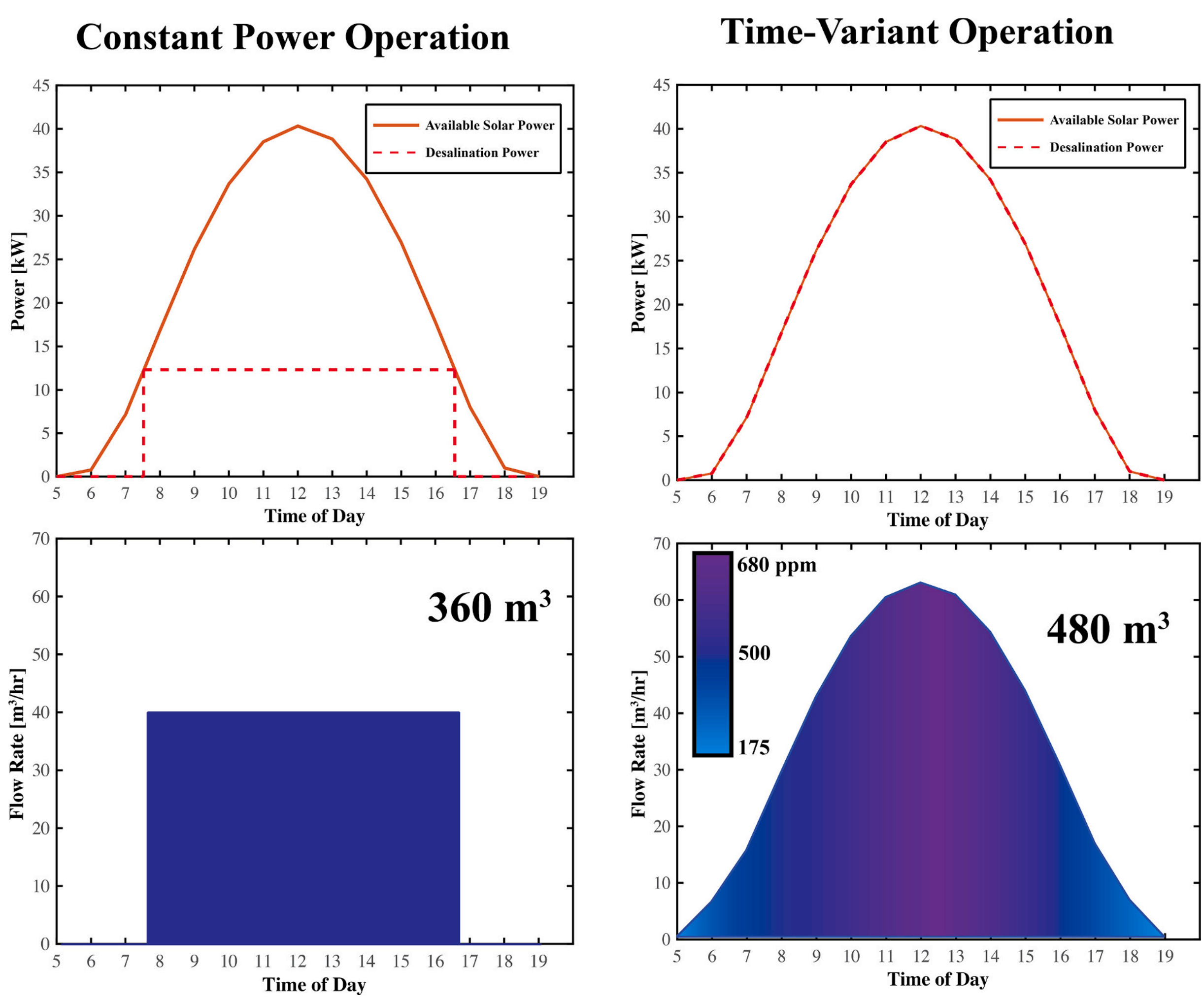

Fig. 4. Time-variant operation throughout a day of desalination. In the constant power operational scheme, flow rate and salinity are constant throughout the day, and much potential solar energy is lost during the middle of the day. In time-variant operation, the desalination system is allowed to operate at higher power levels, leading to higher flow rates and higher salinities. More water is produced throughout the day as more of the available solar energy is captured.

crops. This is especially true for reservoirs that are much larger than a day's worth of irrigation water.

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. Thus, this operational scheme for agriculture presents a unique opportunity to overcome limitations that might otherwise prevent adoption or feasibility of time-variant continuous EDR.

4. PV-EDR system comparison

4.1. System design and simulation

This section presents a cost and performance comparison of the time-variant PV-EDR system discussed in the previous section and current benchmark RO systems in Jordan. However, it is also useful to compare the time-variant strategy to other EDR cases, namely PV-EDR with battery storage and grid-powered EDR in order to see what advantages time-variant PV-EDR presents over other possible EDR variants:

1. **Time-Variant, Photovoltaic-Powered Electrodialysis Reversal (TV-PV-EDR):** This scheme consists of the baseline EDR system operated with a solar power system without batteries (Fig. 4). The production rate is varied throughout the day based on the time-variant theory discussed in Section 3. Three pumps of varying size are used in parallel for each line because of the wide range of flow rates considered for this scheme. This allows for each pump to efficiently operate in a narrow range of flow rates instead of one pump operating very inefficiently across the entire range of flow rates.
2. **Photovoltaic-powered Electrodialysis Reversal with Batteries (Battery-PV-EDR):** As mentioned previously, solar systems containing batteries can be undesirable because of added cost and maintenance requirements; however, this system is included here for comparative purposes. This scheme consists of the baseline 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 the baseline 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. Both a high pressure pump and a low pressure feed pump are considered for this system in order to facilitate feed blending. This benchmark system is based on RO system parameters from systems seen in Jordan in addition to information found on commercially available RO systems.

Using the same solar irradiance profile as was used for the TV-PV-EDR system discussed in Section 3, the water production and energy consumption of Battery-PV-EDR was found on an hourly basis. The system was allowed to operate at the constant power level of the baseline EDR system throughout the day, with any available solar energy above this power level being stored in a battery. This stored energy was used to produce additional water at the constant power level during low irradiance hours. The daily water production and product salinity were 481 m^3 and 499 ppm, respectively. The required battery capacity was found to be 99 kWh while the total energy required for a day's worth of desalination was 297 kWh.

The water production and energy consumption of Grid-EDR was found by considering desalination production with the baseline EDR system for 12 h–the same amount of time the two PV-EDR systems were able to operate given the solar irradiance profile. The daily water production and product salinity were 481 m^3 and 499 ppm, respectively. The total energy required for a day's worth of desalination was 296 kWh.

The water production and energy consumption of Grid-RO was found by considering commercially available RO systems as well as current RO systems in Jordan [28,42–46,48–52,62]. This system consisted of six parallel lines each containing four RO membrane cartridges. A pumping power of 34 kW was used to calculate the energy consumption of RO for 12 h of desalination. This desalinated water was mixed with additional feed water such that the target flow rate and product salinity were met. The daily water production and product salinity were 480 m^3 and 550 ppm, respectively. The total energy required for a day's worth of desalination was 403 kWh.

4.2. Cost and performance comparison

This system comparison uses CAPEX, OPEX, LCOW, and SEC as the primary performance metrics. CAPEX, given by *CC*, is calculated by

$$CC = C_{mem} + C_{spacers} + C_{elec} + C_{pump} + C_{solar}, \tag{7}$$

where C_{mem} is the cost of ion-exchange membranes, $C_{spacers}$ is the cost of flow spacers, C_{pump} is the cost of the pumps, and C_{solar} is the cost of the solar system. OPEX, given by *OC*, is calculated per cubic meter by

$$OC = c_{energy} + c_{chem} + c_{maintain}, \tag{8}$$

where c_{energy} is the specific cost of electricity [$/$m^3$], c_{chem} is the specific cost of chemicals [$/$m^3$], and $c_{maintain}$ is the specific cost of maintenance [$/$m^3$]. LCOW is calculated by

$$LCOW = \frac{CC + C_{replace}}{V_{water}} + OC, \tag{9}$$

where $C_{replace}$ is the replacement cost of components of the system's lifetime and V_{water} is the total volume of water produced over the system's lifetime. SEC is calculated by

$$SEC = E_{desal}/V_{water}, \tag{10}$$

where E_{desal} is the total energy required to desalinate.

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 considers the total lifetime cost of a system.

For this study, CAPEX consists of the following items shown in Table 4. EDR membranes, electrodes, and spacers are priced based on wholesale suppliers [64,65]. RO membranes are priced based on suppliers and the cost Jordanian farmers pay for replacement membrane cartridges [28,42–46,48–52]. The power system components—solar system and battery—are also priced based on common supplier pricing and cost data collected in Jordan [42,43,46,66,67].

Pump cost was calculated using supplier sizing tools and pricing from Grundfos [70]. For TV-PV-EDR, three pumps were selected. The flow

Table 4
Items included in CAPEX. Items marked with “X” for each system are included in that system's CAPEX.

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		

rate range was separated into three distinct sub-ranges, and a pump was selected for each one by inputting flow rate and pressure requirements into Grundfos' pump sizing tool. The flow rate, pressure, efficiency, and power were found for various operating points of these three pumps. For each of the other three cases, a single pump was selected. The efficiency and power was found for a single operating flow rate and pressure. All of these 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 are the most important in 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 [68]. The chemical and maintenance costs listed are common values for EDR and RO [69].

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 5 and 6, respectively.

The results from this system cost comparison are shown in Table 7. As expected, 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. 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. While operating the system at higher flow rates does increase the SEC, operation at lower flow rates greatly decreases SEC.

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.

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, a novel time-variant operational scheme 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 and energy savings in both the EDR system and power system compared to solar-powered systems operating at constant power. For irrigation, TV-PV-EDR can be implemented with large water reservoirs acting as energy buffers. This allows for water produced at variable salinities throughout a day to be adequately mixed during storage before being sent to the crops. Current irrigation practices in MENA already include the use of large water reservoirs, so this architecture would pose minimal change to current practices.

The integration of desalination and drip irrigation also presents 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. Since the production rate of TV-PV-EDR is also closely related to solar irradiance, it can be closely tailored to crop water demand. To account for daily differences in water production and crop water demand, an energy buffer is needed, which can be in the form of the water reservoirs discussed earlier.

It was found through a theoretical techno-economic analysis that the lifetime cost of TV-PV-EDR is less than alternatives including benchmark RO systems found in Jordan. Energy and operating costs of a TV-PV-EDR system 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. It is possible that even more cost savings might 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 at lower power throughout a longer period of the day. Implementing time-variant theory would then decrease the necessary size of those batteries. Future work will include determining whether or not the benefits of such a configuration outweigh the added complexity and maintenance requirements. Additionally, many farms employing solar systems often

Table 5
CAPEX cost metrics for EDR and RO system cost comparison.

Item	Lifetime [yr]	Unit cost [$]	Units
ED membranes	10	43 [63,64]	$\$/m^2$
RO membranes	5	630 [28,42–46,48–52]	$/cartridge
Electrodes	10	2000 [63,65]	$\$/m^2$
Spacers	10	3 [63,64]	$\$/m^2$
Solar array	20	1.5 [42,43,46]	$/W
Battery storage	10	293 [66,67]	$/kWh

Table 6
OPEX cost metrics for EDR and RO system cost comparison.

Item	EDR	RO
Energy [$/kWh]	0.11 [68]	0.11 [68]
Chemicals [$\$/m^3$]	0.01 [69]	0.03 [69]
Maintenance	0.011 [69]	0.018 [69]

Table 7
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	Battery-PV-EDR	Grid-EDR	Grid-RO
CAPEX [$]	$215,361	$235,578	$144,659	$32,735
OPEX [$\$/m^3$]	$0.02	$0.02	$0.09	$0.14
LCOW [$\$/m^3$]	$0.136	$0.141	$0.171	$0.178
SEC [kWh/m^3]	0.60	0.62	0.62	0.84

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 h each day.

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 conduct 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.

This novel TV-PV-EDR operational scheme addresses the energy and water challenges faced by farmers in MENA. Utilizing desalinated water for irrigation increases crop yields and promotes soil health and longevity. Operating PV-EDR in a time-variant manner allows for effective use of solar energy for desalination. This decreases the energy cost and environmental impact of using grid energy for desalination. Time-variant PV-EDR makes small-scale, high recovery desalination more accessible to farmers, which can boost local economies and strengthen the agriculture sector over time.

Future work could include piloting a time-variant PV-EDR system in Jordan. To this end, the time-variant theory discussed here would be formulated into a controller that can be tested experimentally with lab-scale systems. Design optimizations would be run with this control theory to evaluate system cost and performance to a higher fidelity. Further benefit can be added by employing ion-selective membranes with EDR. 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. These membranes tend to be more expensive, so a tradeoff exists.

Limitations of this theoretical 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. Additionally, this techno-economic analysis was performed assuming a single water chemistry. In reality, different sources of water have different contaminants and may require more or less pre- and post-treatment depending on the contaminants. Water testing will always be important to determine the suitability of EDR or other treatment options. For example, dealing with different ions or elevated salinity levels may require more acid dosing in a system to prevent scaling and fouling of membranes, which may negatively impact water recovery or performance. This study assumes that complications from additional contaminants would be similar for both EDR and conventional systems such as RO; therefore, the authors decided that considering a single water chemistry was sufficient for this comparative analysis. However, additional analyses should be performed for case studies where water salinity is higher. An EDR system would require more energy input and more membranes to handle added salinity. There may be a point where the benefits of EDR do not outweigh the added cost for treating high salinity feed streams. Another important aspect of a real-world system is the handling of waste streams. The EDR system would need a dedicated brine management system designed to process this waste stream.

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. Each of these considerations leads to cost and energy savings when implementing TV-PV-EDR over current systems.

This work provides value to the academic community by elucidating the design requirements for desalination for agriculture as well as developing time-variant operational theory for low-cost, low-energy desalination. Practically, this work provides insight for engineers to be able to design desalination systems for agriculture. This work also addresses the needs of farmers in MENA by providing low-energy solutions for producing desalinated water for irrigation, promoting crop yield and soil health.

CRediT authorship contribution statement

Jacob N. Easley: Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Amos G. Winter V:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Samer Talozi:** Methodology, Resources, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Farzaneh Roudi-Fahimi, Liz Creel, Roger-Mark De Souza, The Role of Population in Demand for Fresh Water. Technical Report, 2000.
[2] Hani Sewilam, Peter Nasr, in: Desalinated Water for Food Production in the Arab Region, 2017, pp. 59–81.
[3] Ahmed Rashad Khater, Intensive Groundwater Use in the Middle East and North Africa Management of Water Resources in Bahrain View Project Groundwater Protection in the Arab Region View Project. Technical Report, 2018.
[4] Blaine R. Hanson, Stephen R. Grattan, Allan Fulton, Agricultural Salinity and Drainage. Technical Report, 2006.
[5] Food and Agriculture Organization, FAOSTAT Crop and Livestock Products, 2020.
[6] J.D. Oster, I. Shainberg, I.P. Abrol, Reclamation of Salt-Affected Soils. Technical Report, 1999.
[7] Alejandro Nin Pratt, Hoda El-Enbaby, Jose Luis Figueroa, Hagar Eldidi, Clemens Breisinger, Agriculture and Economic Transformation in the Middle East and North Africa: A Review of the Past With Lessons for the Future. Technical Report, IFPRI, 2018.

[8] M. Syrquin, Patterns of structural change, in: Handbook of Development Economics Volume I, 1988.
[9] Christopher B. Barrett, Michael R. Carter, C.Peter Timmer, A century-long perspective on agricultural development, American Journal of Agricultural Economics volume 92 (Apr 2010) 447–468.
[10] Bruce F. Johnston, John W. Mellor, American Economic Association The Role of Agriculture in Economic Development. Technical Report 4, 1961.
[11] Nadim Khouri, Clemens Breisinger, 2016 Global Food Policy Report: Regional Developments. Technical Report, 2016.
[12] Tarik M. Yousef, Development, Growth and Policy Reform in the Middle East and North Africa Since 1950. Technical Report, 2004.
[13] Domingo Zarzo, Elena Campos, Patricia Terrero, Spanish experience in desalination for agriculture, Desalin. Water Treat. 51 (1-3) (2013) 53–66.
[14] Philippe Marin, Shimon Tal, Joshua Yeres, Klas Ringskog, Water Management in Israel Key Innovations and Lessons Learned for Water-Scarce Countries. Technical Report, 2017.
[15] Alon Tal, Rethinking the Sustainability of Israel's Irrigation Practices in the Drylands, Mar 2016.
[16] Catherine Clifford, How Higher and More Volatile Energy Prices Will Affect the Move to Clean Energy, Mar 2022.
[17] Argyris Panagopoulos, Katherine Joanne Haralambous, M. Loizidou, Desalination Brine Disposal Methods and Treatment Technologies - A Review, Nov 2019.
[18] Natasha C. Wright, Amos G. Winter, Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India, Desalination 352 (Nov 2014) 82–91.
[19] Sohum K. Patel, P. Maarten Biesheuvel, Menachem Elimelech, Energy consumption of brackish water desalination: identifying the sweet spots for electrodialysis and reverse osmosis, ACS ES&TEng. 1 (5) (May 2021) 851–864.
[20] J. Jägermeyr, D. Gerten, J. Heinke, S. Schaphoff, M. Kummu, W. Lucht, Water savings potentials of irrigation systems: global simulation of processes and linkages, Hydrol. Earth Syst. Sci. 19 (7) (Jul 2015) 3073–3091.
[21] World Bank, World Bank Global Electrification Database, 2022.
[22] Tala H. Qtaishat, Emad K. Al-Karablieh, Amer Z. Salman, Mohammad A. Tabieh, Hussain F. Al-Qudah, Nayef Seder, Economic analysis of brackish-water desalination used for irrigation in the Jordan Valley, Desalin. Water Treat. 72 (Apr 2017) 13–21.
[23] Coherent Market Insights, MENA Drip Irrigation Systems Market Analysis, Aug 2020.
[24] Food and Agriculture Organization, AQUASTAT: Country Profile Jordan, 2012.
[25] Avigail Kaner, Effi Tripler, Efrat Hadas, Alon Ben-Gal, Feasibility of desalination as an alternative to irrigation with water high in salts, Desalination 416 (Aug 2017) 122–128.
[26] Mohammad Tabieh, Emad Al-Karablieh, Amer Salman, Hussein Al-Qudah, Ahmad Al-Rimawi, Tala Qtaishat, Farmers' ability to pay for irrigation water in the Jordan Valley, J. Water Resour. Prot. 07 (15) (2015) 1157–1173.
[27] Stephen R. Grattan, Irrigation Water Salinity and Crop Production, 2002.
[28] Yazeed Jawazneh, Personal Conversation With Mr. Yazeed Jawazneh, Jordanian Farmer, Mar 2022.
[29] AGRIDEV, Agriculture-périmètres irrigués. Technical Report, 2009.
[30] Gov't of Tunisia, Rapport d'investissement par pays Tunisie. High-level Conference on Water for Agriculture and Energy in Africa: The Challenges of Climate Change. Technical Report, Sirte, Libyan Arab Jamhiriya, Dec 2008.
[31] Food and Agriculture Organization, AQUASTAT: Country Profile Morocco, 2005.
[32] Food and Agriculture Organization, AQUASTAT: Country Profile Algeria, 2005.
[33] Food and Agriculture Organization, AQUASTAT: Country Profile Libyan Arab Jamahiriya, 2006.
[34] Food and Agriculture Organization, AQUASTAT: Country Profile Bahrain, 2009.
[35] Food and Agriculture Organization, AQUASTAT: Country Profile Yemen, 2013.
[36] Food and Agriculture Organization, AQUASTAT: Country Profile UAE, 2013.
[37] Food and Agriculture Organization, AQUASTAT: Country Profile Oman, 2013.
[38] Food and Agriculture Organization, AQUASTAT: Country Profile Kuwait, 2013.
[39] Food and Agriculture Organization, AQUASTAT: Country Profile Qatar, 2013.
[40] IGRAC, The Global Groundwater Information System (GGIS), 2022.
[41] Efrat Farber, Avner Vengosh, Ittai Gavrieli, Amer Marie, Thomas D. Bullen, Bernhard Mayer, Amir Polak, Uri Shavit, The geochemistry of groundwater resources in the Jordan Valley: the impact of the Rift Valley brines, Appl. Geochem. 22 (3) (Mar 2007) 494–514.
[42] Yahya Al Mugerbi, Personal Conversational With Yahya Al Mugerbi, Jordanian Farmer, Mar 2022.
[43] Rami Hamaydeh, Personal Conversation With Rami Hamaydeh, Jordanian Farmer, Mar 2022.
[44] Talal Al Farhan, Personal Conversation With Talal Al Farhan, Jordanian Farmer, Mar 2022.
[45] Ahmad Al Adwan, Personal Conversation With Ahmad Al Adwan, Jordanian Farmer, Mar 2022.
[46] Al-Waer Family, Personal Conversation With Al-Waer Family, Jordanian Farmers, Mar 2022.
[47] IFC World Bank Group, The Potential of Renewable Energy in MENA. Technical Report, 2012.
[48] Maher Al Adwan, Personal Conversation With Maher Al Adwan, Jordanian Farmer, Mar 2022.
[49] Ahmad Hafez Al-Shobaki, Personal Conversation With Ahmad Hafez Al-Shobaki, Jordanian Farmer, Mar 2022.
[50] Ahmad Mohammad Al-Shobaki, Personal Conversation With Ahmad Mohammad Al-Shobaki, Jordanian Farmer, Mar 2022.
[51] Saeed Al-Shobaki, Personal Conversation With Saeed Al-Shobaki, Jordanian Farmer, Mar 2022.
[52] Salameh Al Sarhan, Personal Conversation With Salameh Al Sarhan, Jordanian Farmer, Mar 2022.
[53] U. Yermiyahu, A. Tal, A. Ben-Gal, A. Bar-Tal, J. Tarchitzky, O. Lahav, Environmental Science: Rethinking Desalinated Water Quality and Agriculture, Nov 2007.
[54] Rajesha Kumar, Mansour Ahmed, G. Bhadrachari, Jibu P. Thomas, Desalination for agriculture: water quality and plant chemistry, technologies and challenges, Water Sci. Technol. Water Supply 18 (5) (Oct 2018) 1505–1517.
[55] OECD/FAO, OECD-FAO Agricultural Outlook 2018-2027: Farm Size Distribution in Selected MENA Countries, 1996-2003, 2018.
[56] Natasha Wright, Design of Cost-Optimized Village-Scale Electrodialysis Systems for Brackish Water Desalination, Massachusetts Institute of Technology, Cambridge, 2018.
[57] Wei He, Anne-Claire Le Henaff, Susan Amrose, Tonio Buonassisi, Ian Marius Peters, Amos G. Winter, Voltage-and Flow-Controlled Electrodialysis Batch Operation: Flexible and Optimized Brackish Water Desalination. Technical Report, 2020.
[58] Natasha C. Wright, Sahil R. Shah, Susan E. Amrose, Amos G. Winter, A robust model of brackish water electrodialysis desalination with experimental comparison at different size scales, Desalination 443 (Oct 2018) 27–43.
[59] Wei He, Anne-Claire Le Henaff, Susan Amrose, Tonio Buonassisi, Ian Marius Peters, Amos G. Winter, Voltage-and Flow-Controlled Electrodialysis Batch Operation: Flexible and Optimized Brackish Water Desalination, 2021.
[60] ASHRAE, IWEC2 Weather Files for International Locations, 2022.
[61] Pasquale Steduto, Theodore C. Hsiao, Elias Fereres, Dirk Raes, Crop Yield Response to Water. Technical Report, Food and Agriculture Organization, 2012.
[62] Lenntech Water Treatment Solutions, Lennro Series: Brackish Water Reverse Osmosis Systems, 2018.
[63] Sahil R. Shah, Natasha C. Wright, Patrick A. Nepsky, Amos G. Winter, Cost-optimal design of a batch electrodialysis system for domestic desalination of brackish groundwater, Desalination 443 (Oct 2018) 198–211.
[64] Weihai Cortec International Tade Co. Ltd, Plastic Spacer for RO Membrane Rolling, 2015.
[65] Platinized Titanium Anode, 2014.
[66] Grace Connors, Predictive Time-Variant Photovoltaic Electrodialysis Reversal: A Novel Design Optimization using Predictive Machine Learning and Control Theory, Massachusetts Institute of Technology, Cambridge, 2021. PhD thesis.
[67] Modernize Home Services, Solar Panel Installation Costs, May 2022.
[68] The Hashemite Kingdom of Jordan National Electric Power Company, NEPCO Annual Report 2020. Technical Report, 2021.
[69] José Medina, Feasibility of Water Desalination for Agriculture. Technical Report, Food and Agriculture Organization, Rome, 2004.
[70] Grundfos, Inline Multistage Centrifugal Pumps. https://product-selection.grundfos.com/ae/products/cr-cre-cri-crie-crn-crne-crt-crte/cr?tab=models, 2022.