SUSTAINABILITY ANALYSIS OF PV-POWERED ELECTRODIALYSIS DESALINATION FOR SAFE DRINKING WATER IN THE GAZA STRIP

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Abstract

In this paper we discuss the need, systems design, and environmental sustainability analysis of a photovoltaic-powered electrodialysis reversal (PV-EDR) brackish water desalination (BWD) plant for producing potable water in the Gaza Strip. Such systems can provide access to safe drinking water in this region, where sustained overabstraction has caused 96% of groundwater to become unfit for direct human consumption. The focus of our work is on analyzing the potential of PV-EDR BWD as a more environmentally sustainable alternative to on-grid reverse osmosis (OG-RO) BWD systems; which is currently the most prevalent type of desalination technology in the region. Our analysis is based on the design of a PV-EDR BWD system capable of producing 10 m$^3$ potable water per day at a TDS of 400 mg/L from a water source with an average TDS of 2600 mg/L. For this system, an analytical simulation model predicted a specific energy consumption of 0.82 kWh/m$^3$ for desalination, 1.199 kWh/m$^3$ for pumping, production rate of 0.917 m$^3$/h, and a recovery ratio of 0.91. Based on these results, we conducted a preliminary study of the most significant environmental burdens of the PV-EDR BWD system in relation to existing OG-RO BWD systems. Our results show that the designed PV-EDR BWD system reduces the carbon footprint of use-phase energy consumption as well as environmental burdens of groundwater abstraction. However, environmental burdens from factors such as, land use due to PV-panels and ecological impacts from untreated brine discharge need to be mitigated if PV-EDR BWD systems are scaled to meet a significant portion of the demand for potable water in the future.
I. INTRODUCTION

The Gaza Strip is a narrow stretch of land measuring 365 square kilometers bordered by Israel, Egypt, and the Mediterranean Sea. The total population of the Gaza Strip is 1.88 million, making it one of the most population dense regions in the world (5,151 people/km²) [1]. The only source for groundwater in the region is the coastal aquifer which has a sustainable yield of 55 million cubic meters (MCM) per year [2]. It is estimated that 200 MCM of water is drawn from this aquifer annually in the year 2016, with the water demand expected to rise to 260 MCM/year by the year 2020 [3]. The sustained overabstraction of water has resulted in significant intrusion of sea water and untreated sewage. The major water quality problems are high salinity and high nitrate concentration. The chloride (Cl) concentration ranges between 600-2000 parts per million (ppm) inland and 2000-10,000 ppm near coastal regions. The nitrate (NO₃) concentration is in the range of 50-600 ppm in most parts of the Gaza Strip. Consequently, an estimated 96% of groundwater exceeds the World Health Organization (WHO) guidelines for safe drinking water and is unfit for direct human consumption [4,5].

II. STATUS OF BRACKISH WATER DESALINATION PLANTS IN THE GAZA STRIP

Brackish and sea water desalination are among the most viable means for providing access to clean drinking water in the region [2, 3, 6]. More than 90% of the people living in Gaza rely on water from desalination plants for drinking purposes [7]. The number of operational brackish desalination plants in the Gaza Strip has been on the rise with 154 operational water desalination plants as of 2015. The total production capacity of these plants amounts to 13,128 m³/day in summer and 8,656 m³/day in winter [8]. Almost all of these plants use on-grid reverse osmosis (OG-RO) for desalting feed water [9].

Most BWD plants in the Gaza Strip are powered using electricity from the distribution grid. However, the supply of electricity is severely constrained in the region. The peak electricity demand in the Gaza Strip as of 2011 was 350 MW while the capacity for supply was at 242 MW. This shortfall will significantly increase in the near future as the expected peak demand by the end of the year 2020 is 550 MW [10]. The operational electricity demand from water and waste-water facilities itself is expected to rise to 90 MW in the next four years from 35 MW in the year 2015 [11]. Emissions resulting from fossil fuel-based primary energy production are also becoming a significant concern [12]. These challenges motivate the need for research on renewable energy powered BWD in the Gaza Strip.

The Gaza Strip is particularly suitable for solar energy harvesting as the annual global horizontal irradiation (GHI) is 2100 kWh/m² in the northern half of Gaza and 2200 kWh/m² in the southern half [13]. Consequently, PV and solar-thermal powered BWD systems have the potential to be cost competitive for producing potable water. A 10 m³/day PV-RO BWD plant was successfully tested in Az Zubeidat village in the West Bank region [14]. The specific energy consumption of this plant was reported as 2.3 kWh/m³ for feed water with a total dissolved solids (TDS) of 2680 mg/L. The life cycle cost of producing water was 3.17 $/m³ with a battery bank and 2.33 $/m³ without batteries. The design and simulation-based evaluation of a 2.0 m³/hour PV-RO BWD plant at Al Maleh village is described by Mahmoud [15]. At a feed water TDS of 3382.06 mg/L, the unit has a specific energy consumption of 2.0 kWh/m³. The system used a total of 162 PV modules, each rated for 55 Wp (Watt peak) to ensure 5.0 hours of operation. A battery storage of 27.5 kWh was also built in to supply 1.5 days’ worth of backup power. A three-stage solar thermal desalination system based on evaporative distillation was designed and experimentally
characterized by Al-Azhar University in the Gaza Strip [16]. The highest monthly production for this system was between 0.204–0.085 m$^3$/day. In our literature review, we did not find any previous work that developed ED or PV-ED BWD systems for the Gaza Strip.

In the next sections, we discuss design goals and local constraints for selecting system specifications of a prototype PV-EDR BWD plant that is being installed at Al-Saada in the Gaza Strip. An analytical model based on our previous work [17] is used for estimating the specific energy consumption of potable water production for this design. These estimates are used for comparing the environmental sustainability of PV-EDR BWD against existing OG-RO BWD plants in the region. Based on the results from this analysis, we make the case for PV-EDR BWD as a more environmentally sustainable alternative to existing OG-RO BWD plants for potable water production in the Gaza Strip. We begin this discussion by providing a brief introduction to the electrodialysis desalination process.

III. PHOTOVOLTAIC-POWERED ELECTRODIALYSIS FOR BRACKISH WATER DESALINATION

3.1 Description of the electrodialysis process

In the electrodialysis (ED) process, saline water is pumped through a stack of ion exchange membranes (Fig. 1). By applying an electric potential across the stack (at the anode and cathode), anions are pulled toward the anode and cations toward the cathode. The ED stack consists of alternating pairs of ion exchange membranes. Anion exchange membranes (AEM) only allow anions to pass through, while cation exchange membranes (CEM) only pass cations. As anions move towards the anode due to the electric potential, they are blocked by the CEM and remain in the concentrate stream. Similarly, cations moving toward the cathode are blocked when they reach the first AEM. In a commercial ED stack, there are multiple alternating CEM and AEM pairs, resulting in alternating compartments of diluted and concentrated saline flow. If the potential applied to the ED stack is reversed at set time intervals it prevents excessive buildup of salt residue on the AEMs and CEMs. This process effectively switches the diluate and concentrate streams and is termed as electrodialysis reversal (EDR).

![Figure 1: Schematic diagram illustrating an electrodialysis stack](image-url)
3.2 Photovoltaic-Powered electrodialysis

PV-ED is an attractive alternative to OG-ED in places with copious solar irradiance throughout the year [18]. Lundstrom [19] conducted one of the first studies of PV-ED and concluded that it is a viable alternative to gasoline-powered ED systems in remote locations when fuel costs approach $2.30 per gallon. Since then, several previous studies [20-25] have looked at modeling and experimentally validating PV-ED BWD systems. The benefits resulting from coupling PV with ED BWD include, (a) ability to operate in remote locations that are not connected to the grid [20, 22], (b) reduction in emissions to air resulting from fossil fuel-based primary energy production [26], and (c) an overall decrease in operational expense [27]. However, the capital cost for PV-ED BWD systems is greater than OG-ED BWD systems due to the need for additional components such as, batteries, inverters, charge controllers, and PV panels.

3.3 Photovoltaic-Powered electrodialysis reversal desalination for the Gaza Strip

PV-EDR BWD is an attractive technology for producing potable water in the Gaza Strip due to the following advantages.

- For the salinity ranges common in the Gaza Strip, ED BWD has a significant energetic advantage over RO systems. At a TDS of 1000 mg/L ED BWD only requires 28.6% of the energy used to desalinate water by RO systems. This factor is 86.3% at a TDS of 4000 mg/L [25].

- ED BWD also has an advantage over RO desalination in terms of the both operational and capital expenses in this salinity range. The break-even point for the two systems is approximately 5000 mg/L, below which ED is more economical [25]. This difference in cost-effectiveness will reduce when comparing PV-EDR BWD systems to OG-RO systems due to the additional costs for panels and batteries. However, production costs for PV-EDR BWD systems are expected to be more economical than conventional grid mix over the next decade [26].

- A significant concern for BWD plants in a water stressed region such as the Gaza Strip is the need to maximize recovery ratio. ED-based desalination has an advantage over RO systems as they can operate at a recovery ratio of 85–95% in salinity ranges of 1000-4000 mg/L [25].

- Several regions in the Gaza Strip lack access to reliable grid-based power. Currently, a maximum of 4 hours of electricity is supplied per day in the winter & summer months due to high power demand. In spring & fall, a maximum of 8 hours of electricity is supplied per day [28]. The shortfall in electricity production in the region is also expected to rise to 550 MW by the end of the year 2020 [10]. These limitations and the high levels of solar irradiation (average GHI >=2100 kWh/m² [13]) make PV-EDR BWD a cost competitive alternative for potable water production in the region.

IV. DESIGN REQUIREMENTS AND SPECIFICATIONS OF THE PV-EDR BWD SYSTEM

This section discusses design requirements and specifications of a prototype PV-EDR BWD system that is being constructed for potable water production in the Gaza Strip. Ten potential locations were initially
selected based on discussions with our collaborators from the Coastal Municipalities Water Utility (CMWU), the Palestinian Water Authorities (PWA), the Water, Sanitation, and Hygiene (WASH) section of the United Nations Children’s Emergency Fund (UNICEF) office in Palestine, and the United States Agency for International Development (USAID) West Bank/Gaza mission. The most favorable location for all the stakeholders involved a legal well, ideally operated by CMWU for ease of operation and maintenance. All ten sites were evaluated based on multiple parameters, including feed water characteristics, available unshaded land area, potential beneficiaries, public access to desalination plant, existing infrastructure in the site, ability for comparative benchmarking, availability of technical operators, time of operation, and overall safety. The most favorable location from the evaluation was the Al-Saada well in Khan Younis. This site also houses an OG-RO BWD plant that supplies desalinated water to the municipal network. The design requirements for the PV-EDR BWD system based on location-specific needs in Khan Younis are listed below.

- **Production capacity:** The system is expected to serve 1000–1500 people every day. The Sphere handbook on minimum standards in water supply, sanitation and hygiene recommends 7.5–15 liters per person per day (lpcd) for meeting basic water needs [29]. In this paper, we use a target production of 10 lpcd, meaning the system should produce 10–15 m³/day of potable water.

- **Hours of operation:** For ensuring safety and security, the system is required to be continually monitored by a technician while it is in operation. Based on the availability of the technician at the Al-Saada well, the upper limit of operation was set at 12 hours.

- **Water quality:** The water quality report for the groundwater well which feeds the PV-EDR BWD plant indicates a TDS variation of 2213–2480 ppm between the years 2013–2016. The quality parameters for produced water are set according to the World Health Organization (WHO) guidelines for potable drinking water [30]. The WHO guidelines to not explicitly specify a guideline for TDS. This is chosen to be less than 500 ppm based on taste requirements [31].

- **Cost of water production:** The target cost of producing potable water should be close to 3 NIS/m³ (0.6 $/m³). This estimate is based on a study conducted by Al-Ghuraiz [32] which surveyed the ability of people in the Gaza Strip to pay for drinking water.

V. ESTIMATION OF PERFORMANCE PARAMETERS FOR THE PV-EDR BWD SYSTEM

An analytical model of the electrodialysis process based on our previous work [17] was used to estimate the performance of an EDR system that met the listed design requirements. The factors that were input into the model include:

- **Membrane parameters:**
  - Stack manufacturer: Hangzhou Iontech
  - Membrane series: Ionsep-MC
  - Membrane width: 34.29 cm
  - Membrane length: 138.5 cm
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- Total membrane area: 23.7458 m²
- Number of cell pairs: 50

- Stack parameters:
  - Spacer thickness: 1mm
  - Applied voltage: 40V

- Stream parameters:
  - Feed Concentration: 2600 mg/L
  - Feed ion characteristics: \( NO_3^- \) 292 ppm; \( Cl^- \) 873 ppm; \( SO_4^- \) 203; \( Ca^{++} \) 99 ppm; \( Mg^{++} \) 90 ppm; \( F^- \) 1.1 ppm; \( K^+ \) 6 ppm; \( Na^+ \) 566 ppm;
  - Product Concentration: 400 mg/L
  - Recovery rate: 91%
  - Flow Rate: 4.2 m³/h in diluate and concentrate stream

Based on these inputs, the specific energy consumption of the system is estimated to be 2.019 kWh/m³. In this, 0.82 kWh/m³ is used by the electrodialysis stack and 1.199 kWh/m³ is used by the pumping system. The model also predicted a run time of 10.9 hours to produce 10 m³ of product water. Based on these estimates, we compare the environmental impact of the PV-EDR BWD system against existing OG-RO BWD plants in the Gaza Strip. Ideally, this comparison would involve similar sized BWD systems. However, due to unavailability of data on small-scale OG-RO BWD systems in Gaza, we compare the PV-EDR BWD system with six existing large-scale OG-RO BWD plants in the region.

VI. ENVIRONMENTAL SUSTAINABILITY-BASED COMPARISON OF OG-RO AND PV-EDR BWD FOR POTABLE WATER PRODUCTION

While desalination of brackish water has potential to improve access to clean drinking water, it also results in increased energy demand and environmental impacts. Previous studies that looked at life cycle assessment (LCA) of reverse osmosis desalination found that electricity consumption during use is the most dominant source for environmental impacts from BWD plants [33]. Apart from energy consumption, factors that are of significant concern are, land requirement for the desalination plant, ground water depletion, and brine disposal [34]. In this section, we analyze the environmental impacts of the PV-EDR BWD system by benchmarking it against OG-RO BWD systems in Gaza on the factors listed above. OG-RO BWD systems are chosen as they are the currently the most prevalent technology for desalting brackish water sources for producing potable water in the Gaza Strip.

6.1 Environmental impact of use-phase energy consumption

To quantify the environmental impact of use-phase energy consumption, we compare the specific carbon footprint of product water for existing OG-RO BWD systems in Gaza with the proposed PV-EDR system. Here, specific carbon footprint is defined as the kilogram equivalent CO₂ emissions resulting from the energy consumed for producing a 1 m³ of product water. Equations 1 and 2 describe the calculation of specific carbon footprint (SCF_{use}) that is used for benchmarking OG-RO and PV-EDR BWD.
Here, $SE_{desal}$ is the specific energy of the desalination plant measured in kWh/m$^3$. $CI_i$ is the equivalent carbon intensity of the $i^{th}$ energy source used and is measured in kg eq. CO$_2$/kWh. $f_i$ is the fraction of the total energy supplied by the $i^{th}$ energy source. $M$ is the total number of energy sources available.

Table 1: (Top) IPCC 2013 Global Warming Potentials (GWP) for a 100-year time horizon [37]. (Bottom) Calculation of global warming potential (GWP) for energy sources available for desalination systems in the Gaza Strip. Specific fuel consumption for the diesel generator is based on the study conducted by Jakhrani et al. [38]. Emissions from the diesel generator are calculated using emission factors provided by the US EPA for distillate no.2 [35].

<table>
<thead>
<tr>
<th>Emission type</th>
<th>GWP 100 year</th>
</tr>
</thead>
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<tr>
<td>Carbon dioxide (CO$_2$)</td>
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</tr>
<tr>
<td>Methane (CH$_4$)</td>
<td>34</td>
</tr>
<tr>
<td>Nitrous oxide (N$_2$O)</td>
<td>298</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy source</th>
<th>L/kWh</th>
<th>kg CO$_2$/kWh</th>
<th>kg CH$_4$/kWh</th>
<th>kg N$_2$O/kWh</th>
<th>CI (kg eq. CO$_2$/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 kW standby diesel generator</td>
<td>$6.5 \times 10^{-1}$</td>
<td>1.753178</td>
<td>7.211897</td>
<td>1.373695</td>
<td>1.759724</td>
</tr>
<tr>
<td>Electricity at point of</td>
<td>n/a</td>
<td>7.629542</td>
<td>1.109766</td>
<td>9.95626</td>
<td>7.629575 \times 10^{-1}</td>
</tr>
<tr>
<td>consumption in Israel [36]</td>
<td></td>
<td>$\times 10^{-1}$</td>
<td>$\times 10^{-1}$</td>
<td>$\times 10^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

Equation 3 illustrates the calculation of $CI$. Here, $e_j$ is the kilograms of the $j^{th}$ greenhouse gas emitted per kWh of electricity produced. $G_j^{100}$ is the IPCC 2013 Global Warming Potential (GWP) of the $j^{th}$ greenhouse gas over a 100-year time horizon [35]. These values are shown in Table 1 (Top). $N$ is the total number of greenhouse gases considered.

6.1.1 Existing large-scale OG-RO BWD plants in the Gaza Strip - For existing OG-RO BWD plants in the Gaza strip, the primary source of energy is electricity supplied by the municipal grid. Most plants also use diesel-powered standby generators to operate the plant during loss of grid power. Therefore, the specific carbon footprint of an OG-RO BWD is driven by the actual mix of the used power sources.
To calculate SCF\textsubscript{use} for existing OG-RO BWD plants, data on hourly capacity and energy consumption published by Mogheir et al. \cite{39} was used to estimate SE\textsubscript{desal}. The equivalent carbon intensity (CI) for grid-based electricity consumption in Gaza is assumed to be equal to that of Israel due to unavailability of direct data. This assumption is based on the fact that Gaza imports most of its electricity from Israel \cite{10}. CI from electricity production using the diesel-powered standby generator is estimated based on data available for a 5kW diesel generator. The specific fuel consumption for this generator is based on the study conducted by Jakhrani et al. \cite{38}. Emissions from the diesel generator are calculated using emission factors provided by the US EPA for distillate no.2 \cite{35}. Table 1 (Bottom) illustrates these data. The last column in Table 1 represents CI for the two energy sources. Since the actual mix of power sources (\(f_i\)) and thus the values for \(f\textsubscript{diesel}, f\textsubscript{elec}\) are not known, SCF\textsubscript{use} is plotted for \(f\textsubscript{diesel}\) varying from 0–1. Figure 2 (a) shows the SCF\textsubscript{use} for six existing OG-RO BWD plants operating in the Gaza. As seen in Fig. 2 (a), SCF\textsubscript{use} increases with an increase in power is supplied from the diesel-powered standby generator. The desalination plant at Al-Saada has the least SCF\textsubscript{use} varying between 0.5722–1.3198 kg eq. CO\textsubscript{2}/m\textsuperscript{3} depending on the percentage of power supplied by the diesel generator. The maximum SCF\textsubscript{use} (1.5259–3.5194 kg eq. CO\textsubscript{2}/m\textsuperscript{3}) is seen at the Al-Balad desalination plant. Apart from CO\textsubscript{2} emissions, combustion of fossil fuels also generates pollutants such as carbon monoxide, sulfur dioxide, hydrocarbons compounds, and particulate matter. Quantifying these emissions requires more detailed inventory information about these energy sources and is not within the scope of the current analysis.

![Figure 2](image-url)  

**Figure 2:** (a) Variation of specific carbon footprint due to energy consumption (kg eq. CO\textsubscript{2}/m\textsuperscript{3}) with fraction of power supplied by the diesel-powered standby generator (\(f\textsubscript{diesel}\)) for existing OG-RO BWD plants in Gaza. The TDS of the feed water is shown in the legend. Please note that the line for the Al-Bureij plant is not visible at it overlaps with the values for the Al-Salam desalination plant. (b) Variation of SCF\textsubscript{use} for the PV-EDR BWD system with fraction of total energy supplied by the electricity grid (\(f\textsubscript{elec}\)) and diesel generator (\(f\textsubscript{diesel}\)). The values for SCF\textsubscript{use} are represented using color. The fraction contribution remaining after summing the contributions of grid electricity and the diesel generator is supplied by PV. Constant lines of \(f\textsubscript{PV}\) are also shown.
maximum value of SCF\textsubscript{PV}. The minimum value of SCF\textsubscript{EDR} system is split as, 20% from grid electricity, 10% from diesel generator, and 70% from PV. As an example, the point (0.2, 0.58) on this figure implies that the total energy used by the PV system is 58% from diesel generator, 42% from grid electricity, and 0% from brackish water desalination system. Another study by Dominguez-Ramos et al. [41] estimated the carbon intensity of power generation from multicrystalline-Si PV modules for Spanish plants at 0.033 kg eq. CO\textsubscript{2}/kWh. A mean annual in-plane irradiation of 1,825 kWh/m\textsuperscript{2}-year was assumed. The average annual global horizontal irradiance in Gaza (\textgtrsim 2100 kWh/m\textsuperscript{2} year [13]) is more than the two cases. Therefore, the actual CI for the PV modules installed in Gaza is expected to be lower than the current estimate. For this study, 0.04907 kg eq. CO\textsubscript{2}/kWh is chosen as it represents a more conservative estimate. The specific energy intensity of the PV-EDR system at Al-Saada is 2.019 kWh/m\textsuperscript{3}, computed using the MATLAB\textsuperscript{6} model described in the previous section. While this value is at the upper end of the specific energies intensity reported for OG-RO BWD plants in Gaza (0.75–2 kWh/m\textsuperscript{3}) [39], it should be noted that smaller capacity BWD plants for potable water production (1–5 m\textsuperscript{3}/h) tend to have greater specific energy intensities than large-scale plants [14, 15]. Figure 2 (b), plots SCF\textsubscript{use} for the PV-EDR system with varying values of f\textsubscript{elec} and f\textsubscript{diesel}. The value of f\textsubscript{PV} can be calculated based on the other two fractions. As an example, the point (0.2, 0.1) on this figure implies that the total energy used by the PV-EDR BWD system is split as, 20% from grid electricity, 10% from the diesel generator, and 70% from PV. The minimum value of SCF\textsubscript{use} for the PV-EDR systems is 0.0991 kg eq. CO\textsubscript{2}/m\textsuperscript{3} when f\textsubscript{PV} =1. The maximum value of SCF\textsubscript{use} is 3.5529 kg eq. CO\textsubscript{2}/m\textsuperscript{3} when f\textsubscript{diesel} =1. Table 2 compares the SCF\textsubscript{use} for the

6.1.2 PV-EDR brackish water desalination system - For calculating the SCF\textsubscript{use} of the PV-EDR system, the carbon intensity of electricity production from multicrystalline-Si PV modules is taken as 0.04907 kg eq. CO\textsubscript{2}/kWh [40]. This estimate excludes installation, operation, maintenance, and end-of-life phase of the PV modules. Additionally, the PV modules are assumed to be produced with Chinese electricity mix and installed at an irradiation of 1700 kWh/m\textsuperscript{2}-year. Another study by Dominguez-Ramos et al. [41] estimated the carbon intensity of power generation from multicrystalline-Si PV modules for Spanish plants at 0.033 kg eq. CO\textsubscript{2}/kWh. A mean annual in-plane irradiation of 1,825 kWh/m\textsuperscript{2}-year was assumed. The average annual global horizontal irradiance in Gaza (\textgtrsim 2100 kWh/m\textsuperscript{2} year [13]) is more than the two cases. Therefore, the actual CI for the PV modules installed in Gaza is expected to be lower than the current estimate. For this study, 0.04907 kg eq. CO\textsubscript{2}/kWh is chosen as it represents a more conservative estimate. The specific energy intensity of the PV-EDR system at Al-Saada is 2.019 kWh/m\textsuperscript{3}, computed using the MATLAB\textsuperscript{6} model described in the previous section. While this value is at the upper end of the specific energies intensity reported for OG-RO BWD plants in Gaza (0.75–2 kWh/m\textsuperscript{3}) [39], it should be noted that smaller capacity BWD plants for potable water production (1–5 m\textsuperscript{3}/h) tend to have greater specific energy intensities than large-scale plants [14, 15]. Figure 2 (b), plots SCF\textsubscript{use} for the PV-EDR system with varying values of f\textsubscript{elec} and f\textsubscript{diesel}. The value of f\textsubscript{PV} can be calculated based on the other two fractions. As an example, the point (0.2, 0.1) on this figure implies that the total energy used by the PV-EDR BWD system is split as, 20% from grid electricity, 10% from the diesel generator, and 70% from PV. The minimum value of SCF\textsubscript{use} for the PV-EDR systems is 0.0991 kg eq. CO\textsubscript{2}/m\textsuperscript{3} when f\textsubscript{PV} =1. The maximum value of SCF\textsubscript{use} is 3.5529 kg eq. CO\textsubscript{2}/m\textsuperscript{3} when f\textsubscript{diesel} =1. Table 2 compares the SCF\textsubscript{use} for the

![Graph](image-url)
OG-RO BWD plant and the PV-EDR BWD at the Al-Saada well. As seen, in the best-case scenario, the PV-EDR BWD system is able to achieve more than an 80% reduction in SCF<sub>use</sub> compared to the OG-RO BWD plant at Al-Saada. Other previous work on estimating the carbon footprint of PV-ED based BWD have reported similar gains [26]. Therefore, PV-EDR BWD has a strong potential for mitigating carbon dioxide emissions resulting from energy used to desalinate water for potable use in Gaza.

Table 2: Minimum and maximum estimates for SCF<sub>use</sub> for the PV-EDR and OG-RO BWD plants at the Al-Saada well.

<table>
<thead>
<tr>
<th></th>
<th>f&lt;sub&gt;PV&lt;/sub&gt;</th>
<th>f&lt;sub&gt;elec&lt;/sub&gt;</th>
<th>f&lt;sub&gt;diesel&lt;/sub&gt;</th>
<th>SCF&lt;sub&gt;use&lt;/sub&gt;</th>
</tr>
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<tbody>
<tr>
<td>PV-EDR BWD</td>
<td>1</td>
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<td>0.0991</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3.5529</td>
</tr>
<tr>
<td>OG-RO BWD</td>
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<td>0</td>
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</tr>
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<td></td>
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<td>0</td>
<td>1</td>
<td>1.3198</td>
</tr>
</tbody>
</table>

6.2 Groundwater depletion

Overabstraction of groundwater is causing significant long-term damages to the coastal aquifer [3]. Even so, it is estimated that close to 4 MCM of brackish water is abstracted every year by existing BWD plants in the Gaza Strip [8]. The most viable long term strategy for improving the water sustainability in the region is transitioning to large capacity sea-water desalination facilities [42]. In the near-term it is expected that BWD plants will continue to be utilized for potable water production in the region. To compare the relative merits of OG-RO and PV-EDR BWD, we have to estimate the efficiencies of groundwater utilization by the two technologies. In our discussions, this efficiency is calculated in terms of the recovery ratio—which is the ratio of product water to feed water. Assessment of six large scale OG-RO BWD plants in the Gaza Strip indicated that the recovery ratio ranges between 0.70–0.83 [39]. Increasing the recovery ratio of such BWD plants can reduce groundwater abstraction while meeting the same demand for potable water. An added advantage of increasing recovery ratio is that it lowers the volume and hence the costs associated with brine management and disposal. In this respect, ED BWD is more favorable than RO BWD as recovery rates as high as 0.85-0.94 can be realized [43]. A potential method to account for the difference in recovery ratio between the two technologies is by adjusting the calculation of SCF<sub>use</sub> to account for the respective recovery ratio. This measurement is shown in Equation 4.

\[
SCF_{use}^{in} = \frac{SCF_{use}}{r}
\]

Here, SCF<sub>use</sub><sup>in</sup> is the kilogram equivalent of carbon dioxide emissions from energy use for desalinating 1 cubic meter of water input into the system. \( r \) is the recovery ratio of the BWD plant. This equation helps us to account for the trade-offs between SCF<sub>use</sub> and \( r \) while operating the BWD plant. For example, if a RO BWD plant is run at a lower recovery ratio, it consumes lesser electricity and consequently lowers its SCF<sub>use</sub>. However, this mode of operation results in additional abstraction of ground water that is unaccounted for in the calculation of SCF<sub>use</sub>. Alternatively, SCF<sub>use</sub><sup>in</sup> allows us to account for this groundwater depletion by focusing on the emissions per cubic meter of groundwater abstracted to meet a fixed demand.
Figure 3 (a) and (b) plot $SCF_{in \ use}^0$ for the six large-scale OG-RO BWD plants in Gaza as well as the PV-EDR BWD prototype. As seen, the plant at the Al-Saada well has an $SCF_{in \ use}^0$ ranging from 0.8210–1.8854 kg eq. CO$_2$/m$^3$. The higher recovery ratio of ED desalination is reflected by the fact that minimum $SCF_{in \ use}^0$ for the PV-EDR BWD at the Al-Saada well (0.1089 kg eq. CO$_2$/m$^3$) is almost 87% lower than the OG-RO BWD plant at the same facility.

6.3 Land use

The amount of land occupied by BWD systems for potable water is of significant concern in densely populated areas such as the Gaza Strip. Small-scale systems need to be located close to the target users as it does not make economic sense to pipe the produced water through large distances. When comparing the land use due to similarly sized OG and PV-powered BWD systems, the most significant difference arises due to additional land used by photovoltaic (PV) panels. The PV-EDR BWD system will consist of 24 Access 72 cell modules, each 0.315 kW$_{peak}$ and 1.93 m$^2$. Therefore, the total land used due to PV-modules (46.32 m$^2$) translates to 4.632 m$^2$ of land used per cubic meter of produced water. A potential solution to mitigate the effects of additional land used by the PV modules is to mount them on existing rooftops.

6.4 Brine disposal

Brine generated from BWDs can cause adverse impacts on the local ecosystem if they are improperly discharged. Of the 154 BWD plants in the Gaza Strip, 130 plants route brine to the municipal sewer network, 2 plants discharge brine directly to the Mediterranean Sea, and 20 plants use other means of disposal [8]. Improper disposal of brine into channels or surface pits can adversely impact the surrounding ecology and contaminate groundwater aquifers [7]. Disposal of brine to the sea (which is often warmer, more saline, and often contains elevated levels of Chlorine and trace metals) adversely affects local marine life [44]. Previous studies have reported that impact assessment of brine disposal is not properly integrated into previous life cycle assessment studies of desalination [33]. Environmental assessments of BWD plants often report the volume and the TDS of the brine generated as an indicator for environmental impact of brine disposal.

ED BWD generates a lower volume of brine than RO BWD as they operate at higher recovery ratios. Consequently, for a given input salinity, the brine produced by ED BWD is of higher TDS. Based on a recovery ratio of 0.91 and an input TDS of 2600 mg/L, and output product water TDS of 400 mg/L, the PV-EDR BWD at Al-Saada will produce 0.09 m$^3$ of brine at a TDS of 22,622 mg/L per cubic meter of produced water. The produced brine will be disposed through the municipal sewerage system. An alternate solution is to dispose the brine to the sea. While the produced brine is of lower TDS than the Eastern Mediterranean Sea (38600ppm [45]), the chemical composition of the produced brine needs to be analyzed to evaluate the impacts of disposing it into the seawater.

6.5 Suitability of PV-EDR BWD for potable water production in the Gaza Strip

Based on the preliminary comparison PV-EDR BWD and OG-RO BWD, we can conclude that the former technology has the potential to mitigate environmental impact of BWD resulting from (a) use-phase energy consumption and (b) groundwater abstraction in the Gaza Strip. However, factors such as, (a) land use due to PV-panels and (b) ecological impacts from untreated brine discharge, need to be investigated further to reduce the environmental burdens. While this paper presents a preliminary analysis comparing
PV-EDR to OG-RO BWD, a life cycle assessment (LCA) is required for a more accurate quantification of benefits. Nonetheless, the results from this study make a strong case for PV-EDR BWD to become a more sustainable alternative for potable water production in the Gaza Strip.

VII. FUTURE WORK

The PV-EDR BWD system discussed in this paper will be installed at the Al Saada well in Khan Younis by June 2017. Our future work will focus on experimentally evaluating the performance of this system. Data gathered from these studies will help us refine the previously developed analytical models and improve their predictive accuracy. We will also focus on optimizing the PV-EDR system for specific energy consumption, recovery ratio, and life cycle cost in the future. To better understand the sustainability potential of PV-EDR systems in the Gaza context, we will perform an in-depth comparative life cycle assessment (LCA) that looks at cradle-to-grave environmental impacts for PV-EDR and OG-RO BWD systems. Another potential area of research is mitigating the environmental impact of brine created from BWD systems. We will analyze the potential of technologies such as solar and wind-assisted evaporation to further concentrate the produced brine so that they can be reused in industrial applications.

VIII. CONCLUSIONS

In this paper, we discuss the potential for photovoltaic-powered electrodialysis reversal (PV-EDR) brackish water desalination (BWD) systems to be a viable alternative for producing potable water in the Gaza Strip. The design requirements for a PV-EDR system operating at the Al-Saada well in Khan Younis is discussed. The system produces 10 m$^3$ of potable water in a run time of 10.9 hours at a TDS of 400 mg/L. The specific energy consumption and the recovery ratio for this system is analytically estimated to be 2.019 kWh/m$^3$ and 0.91 respectively. Based on these estimates, we conduct a preliminary environmental sustainability analysis of the PV-EDR BWD system in relation to existing large-scale OG-RO BWD systems. We discuss environmental burdens resulting from (a) energy consumption during use, (b) groundwater abstraction, (c) land use, and (d) brine disposal. Our analysis shows that PV-EDR systems have the potential to reduce the carbon footprint of potable water production to 0.0991 kg eq. CO$_2$ per cubic meter of produced water. This represents a significant reduction compared to the existing OG-RO plant at the Al-Saada well. The designed PV-EDR system also has the potential to reduce environmental impacts of groundwater abstraction as it operates at higher recovery ratio (0.91) compared to existing RO BWD systems in the region (0.79-0.83). These advantages indicate that PV-EDR based brackish water desalination can be a more sustainable alternative to on-grid RO systems for potable water production. Therefore, PV-EDR offers a promising, scalable, and innovative solution for water-energy scarce contexts, such as the Gaza Strip. Our future work will focus on conducting an in-depth life cycle analysis to better compare these two alternatives.

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