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Systems Modeling and Economic Analysis of Photovoltaic (PV) Powered Water Pumping Brackish Water Desalination for Agriculture

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SYSTEMS MODELING AND ECONOMIC ANALYSIS OF PHOTOVOLTAIC (PV)

POWERED WATER PUMPING AND BRACKISH WATER DESALINATION

FOR AGRICULTURE

by

Michael Jones

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Approved:

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ABSTRACT

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by

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Utah State University, 2015

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Global growing demand for agricultural production has put increased pressure on freshwater resources in various global locations. Many areas have saline groundwater resources which have not been utilized for agriculture due to the economics associated with water pumping and desalination. Limited availability to electricity and high operational costs of diesel generators are major obstacles to utilization of these resources. Reduced costs associated with large-scale renewable energy have renewed interest in understanding the potential impacts of developing distributed photovoltaic (PV) powered water pumping and desalination systems for agriculture. In order to determine the economic feasibility of solar-powered water pumping and desalination for agriculture, an engineering system model that performs hourly simulations of direct-coupled PV pumping and desalination systems by integrating environmental resource data and industrial component performance data was developed. Optimization algorithms were created to identify the best membrane type, control method and reverse osmosis system configuration for a given set of locational parameters. Economic analysis shows that PV-powered systems are more economical than diesel-powered systems for water pumping, with water desalination costs for PV- and diesel-powered systems being comparable. Grid-powered systems are able to pump and desalinate water for a lower cost than PV or diesel for all cases evaluated. A sensitivity analysis is performed to generalize results for different input parameters and illustrate the impact of input variables on water unit costs. Several case studies in the Jordan Valley were evaluated to illustrate the economic viability of solar-based systems with simulation results including a direct comparison to diesel- and grid-connected alternatives. Results indicate that under fair environmental conditions and irrigating greenhouse vegetables, the PV-, diesel-, and grid-powered systems produce favorable internal rates of return of 40%, 84%, and 248%, respectively. Under poor environmental conditions and less profitable crops the PV-, diesel-, and grid-powered systems all result in negative internal rates of return, illustrating the need for optimal location and crop selection for system implementation.

(80 pages)

PUBLIC ABSTRACT

The objective of this study was to determine the economic viability of solar-powered water pumping and desalination systems for agriculture. Growing global demand for agricultural production has put increased pressure on limited freshwater resources in various locations around the word. Many areas have low-quality groundwater resources that have not been utilized for agriculture due to limited availability to electricity, high operational costs of diesel generators and the economics associated with water pumping and processing. Reverse osmosis is a desalination technology that removes salts and other minerals from low-quality water, making it fit for drinking or irrigation. Reduced costs associated with large-scale renewable energy has renewed interest in understanding the potential impact of developing solar powered water pumping and desalination systems for agriculture, allowing access to the untouched groundwater resources. In order to determine the economic feasibility of solar-powered water pumping and desalination for agriculture, an engineering systems model that performs hourly simulations of solar-powered pumping and desalination systems was developed. Optimization algorithms were integrated to identify the best membrane type, control method, and reverse osmosis system configuration for a given set of locational parameters. Economic analysis showed that PV-powered systems are more economical than diesel-powered systems for water pumping, with water desalination costs for PV and diesel powered systems being comparable. Grid-powered systems were able to pump and desalinate water for a lower cost than PV or diesel for all cases evaluated. Several case studies in the Jordan Valley were evaluated to illustrate the economics of solar-, diesel-, and grid-powered systems. Results indicated that for favorable environmental conditions and the use of greenhouse vegetables the PV-, diesel-, and grid-powered systems produced internal rates of return of 40%, 84%, and 248%, respectively. Under poor environmental conditions and growing less profitable crops the PV-, diesel-, and grid-powered systems all resulted in negative internal rates of return, illustrating the need for optimal location and crop selection for system implementation.

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Michael A. Jones

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A	Membrane Permeability Coefficient
a	Crop Salt Tolerance Threshold
A_{desal}	Annualized Desalination System Cost
$A_{power\ sys}$	Anualized Power System Cost
$A_{pumping}$	Annualized Pumping System Cost
A_{pipe}	Cross-Sectional Area of Pipe
B	Membrane Salt Permeability Coefficient
b	Crop Yield Slope
C_c	RO Brine Concentration
C_f	RO Feed water Concentration
cf_i	Net Cash Flow for Year i
C_p	RO Permeate Concentration
EC_e	Electrical Conductivity of Soil Paste
EC_w	Electrical Conductivity of Irrigation Water
$E_{desalination}$	Annual Energy Consumed by the Desalination System
EHE	Equivalent Hydraulic Energy for Pumping
$E_{pumping}$	Annual Energy Consumed by the Pumping System
f	Darcy Friction Factor
FF	Fouling Factor
f_{PD}	Positive Displacement Pump Frequency
g	Acceleration due to Gravity
h_{static}	Static Pumping Head

H_T	Total Pumping Head
k_f	Dynamic Pumping Head Coefficient
K_L	Minor Losses
k_{PD}	Positive Displacement Pump Fluid Displacement per Revolution
L	Pumping Distance
P_c	RO Concentrate Pressure
P_f	RO Feed water Pressure
pf_{avg}	Polarization Factor
P_p	RO Permeate Pressure
P_{PD}	Positive Displacement Pump Electrical Power
p_{PD}	Positive Displacement Pump Pressure
Q_c	RO Concentrate Flowrate
Q_f	RO Feed water Flowrate
Q_p	RO Permeate Flowrate
Q_{PD}	Positive Displacement Pump Flowrate
S_e	Surface Area of Membrane
T	Water Temperature
TCF	Temperature Correction Factor
TDS	Total Dissolved Solids
$V_{permeate}$	Volume of Permeate Produced Annually
X	Salinity Concentration Factor
Y_{rel}	Relative Crop Yield (percent)

Greek:

$\Delta\bar{P}$	Average Pressure Differential Across Membrane

ΔP_{fc}	Pressure Drop from the Feed to Concentrate Sides of Element
Δt	Simulation Time-step
$\overline{\Delta\pi}$	Average Difference in Osmotic Pressure across Membrane
η_{motor}	Motor Efficiency
η_{PD}	Mechanical Efficiency of Positive Displacement Pump
π_c	Osmotic Pressure of RO Concentrate
π_f	Osmotic Pressure of RO Feed water
π_p	Osmotic Pressure of RO Permeate

CHAPTER 1

INTRODUCTION

Water scarcity is a growing problem in many areas of the world, with increasing pressure from growth in global population [1,2]. The majority of global freshwater consumption, 70%, is currently used for agriculture [3]. Irrigation with brackish water from marginal-quality aquifers is largely practiced in Middle Eastern countries, but is limited by a variety of drawbacks such as lower crop yields and limited crop selection [4-6]. Desalination is one method of increasing the availability of freshwater in these water-scarce areas, and providing opportunities for growing high-value crops. Desalination in agriculture has not been widely adopted primarily due to the economics associated with the procurement and operation of systems and limited access to electricity. However, some countries have successfully utilized desalination for agriculture. More than 200 desalination plants ranging in size from 100 to 5,000 m^3 day^{-1} were installed for agricultural use in Spain between 1995 and 2000 [7]. Unexpected challenges such as exhaustion of groundwater resources and uncontrolled brine discharges impacted the private operation of the systems. The majority of these systems have since been replaced with larger, public desalination plants, and are still used for agriculture [7]. Farms in Southern Jordan have recently been investing in diesel based desalination systems for the production of high-value crops such as bananas. High diesel fuel prices and limited access to the grid in rural areas make photovoltaic (PV)-powered water pumping and desalination systems a promising alternative.

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

PV-powered water pumping and desalination systems have both been researched independently and have proven to be technically feasible. PV water pumping systems have been commercialized and have proven to operate successfully with minimal attendance in various environments. In Jordan, PV-powered groundwater pumping systems were shown to be more economically favorable than diesel generator powered systems for equivalent hydraulic energy below 2.1 million $m^4 year^{-1}$ [21]. The equivalent hydraulic energy is the product of the volume pumped and the total dynamic head at which it is pumped, resulting in units of m^4. Due to a variety of advancements including decreases in PV costs and development of inverters specifically tailored for solar pumping, PV-powered water pumps are expected to be economically viable over a wide range of locations and pumping scenarios. This study develops a comprehensive evaluation of medium to large-scale, variable speed, PV pumping and desalination systems. Hourly simulations over the course of a year are used to evaluate system performance. Optimal system configurations are determined by simulating a wide range of system architectures, including three types of power supplies, four inverter configurations, four membrane types, two RO system recovery rates, and energy recovery device options. Agricultural factors such as crop salt tolerance, water requirements, yields and net profits are used to identify crops most suitable for desalination in agriculture. An economic analysis is performed to determine water unit pumping and desalination costs, return on investment, internal rate of return, payback periods, and total lifetime costs. A sensitivity analysis is used to make the results applicable to other locations and input parameters. Several case studies are evaluated in order to illustrate the economic viability of PV, generator and grid powered water pumping and desalination systems for agriculture in Jordan and Palestine.

CHAPTER 2

METHODS

System optimization of PV water pumping and desalination systems is performed through the development of sub-process models integrated into a system model. Sub-process models include various PV configurations, inverters, control systems, pumps, RO elements and agricultural systems. The system modeling presented is used to analyze the energy efficiency, performance and cost-effectiveness of different system configurations and control strategies. Detailed descriptions of the sub-process models are presented in the following sections. Hourly PV performance is modeled using HOMER [22] and the remainder of the system modeling, optimization and economic evaluation is performed in MATLAB. This study is focused on medium-scale pumping and RO systems, with PV array sizes ranging from 15-120 kW.

2.1 System Architecture and Optimization

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

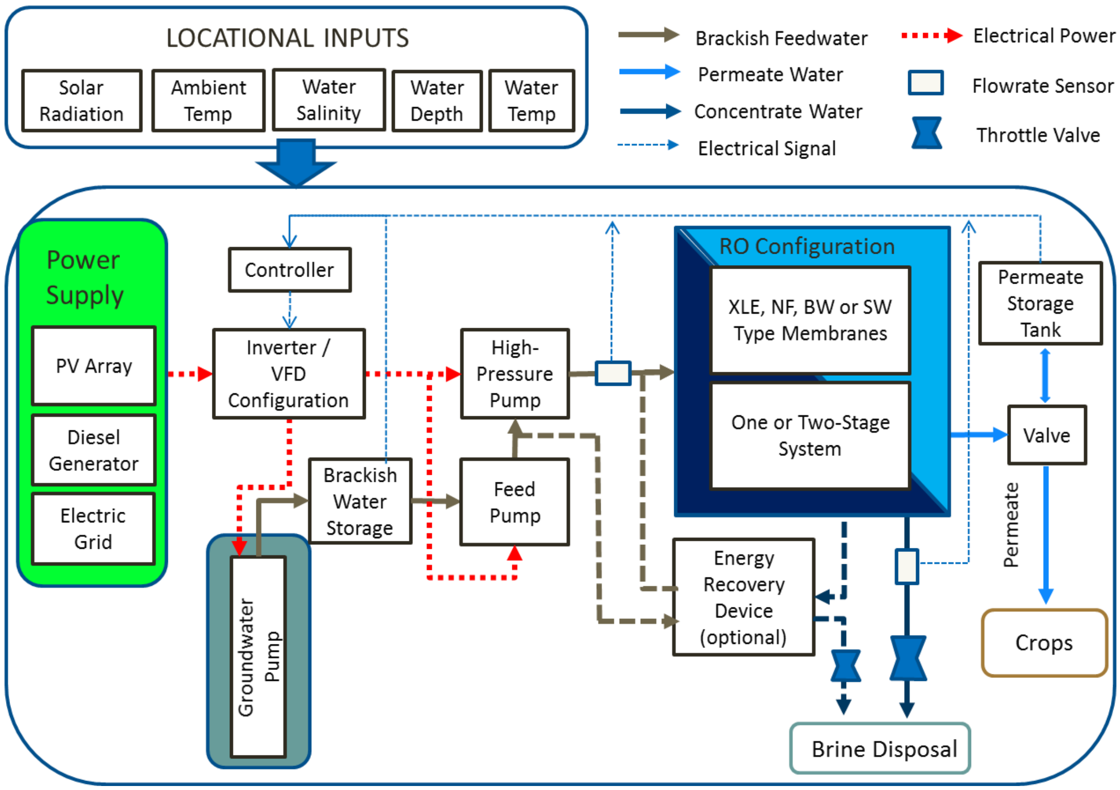

Figure 1. Modeling architecture illustrating the various configurations and required geographically specific data. Viable pathways include various energy sources, inverter or variable frequency drive (VFD) configurations, membrane types, membrane configurations and energy recovery devices. Membrane type options include extra low energy, nanofiltration, brackish water, and seawater elements.

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

2.1.1 Power Systems

Three power systems are modeled and evaluated in this study: PV arrays, diesel generators and the electric grid. The baseline solar panel used in this study is a Sharp 245-Watt module. This is a widely used, low cost module that is representative of other solar panels on the market. Using PV module specifications and location-specific TMY3 solar insolation data, HOMER, a computer model capable of simulating renewable micro-grids, was used to simulate an hourly power production profile for a single PV module. The hourly power production profile was scaled in order to satisfy the energy demands of the system and determine the optimal PV array size. Simulation results displaying the daily power produced by a PV array and the corresponding water production profile are illustrated in Figure 2. The PV powered systems evaluated in this study do not include large battery banks. Instead, the operating rate of the system is adjusted to match the amount of power available from the PV system. Two different configurations are considered for the PV system: 1) a shared PV array for both pumping and desalination systems and 2) independent PV arrays for the pumping and desalination systems.

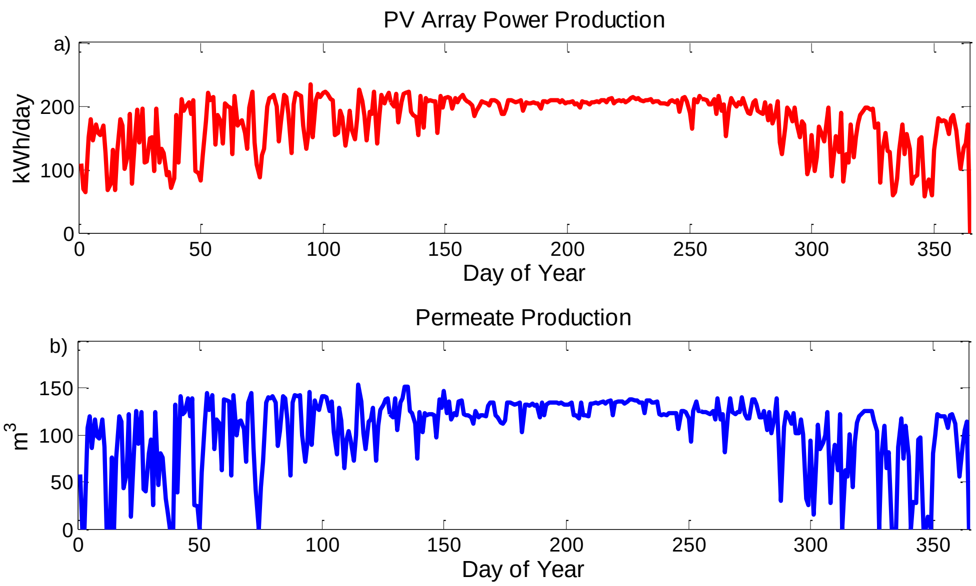

Figure 2. a) Simulations results for daily PV array power production and b) simulation results for daily permeate production

Kohler diesel generators ranging from 10-60 kW were modeled as an alternative power supply. The generator was modeled based on manufacturer data, specifically, fuel consumption as a function of the electrical load. A grid connected system is also evaluated for comparison, where the grid electricity price is defined as an input parameter. Unlike PV powered systems, diesel and grid powered systems are assumed to operate on demand.

Wind power has previously been investigated in the Jordan area and results indicated that very few areas in Jordan have sufficient wind resources to compete with solar power [10]. For this reason, wind power is not included in this study.

2.1.2 Control Strategies and Inverter Configurations

An inverter is required for DC systems to convert the DC power from the PV array to AC power for the pumping and desalination systems. For PV pumping and desalination systems operating on a variable power supply, such as solar, the inverter frequency is used to control motor operating speed. A controller is used to operate each system at the frequency which will lead to maximum system efficiency and reliability. The control system is used to allocate power to the pumping and desalination subsystems based on solar irradiation intensity, pumping head, water level in the storage tanks, brackish water salinity and water requirements. The modeled system includes four different inverter configurations and control strategies for PV powered systems: 1) separate operation of both systems with one power supply and a single inverter, 2) separate operation of both systems with one power supply, a variable frequency pumping system and a fixed speed desalination system, 3) independent power supplies and variable frequency inverters for the pumping and desalination systems and 4) an integrated solar water pumping and desalination system. A custom control system, inverters, and a small battery backup system may be necessary to avoid sudden power and speed fluctuations in the desalination system. Maximum power point tracking (MPPT) is also incorporated into the system in order to operate the PV array at the most efficient point. For diesel and grid powered systems, a simple control system is required to operate the system at desired times in order to meet demand. These systems operate at a fixed rate and inverters are not required.

2.1.3 Groundwater Pumps

Grundfos SP-series groundwater supply pumps are modeled in this work. Grundfos has a wide selection of dependable groundwater pumps and all of the essential performance data for modeling pump performance at various frequencies was obtained from the manufacturer. Pump curves ranging from 30-60 Hz are obtained from pump performance data and are represented in the model by a second-order polynomial. A pumping system curve based on input parameters such as static head and a coefficient for frictional losses is generated using Equations 1 and 2 [23]:

$$H_T = h_{static} + k_f Q^2 \tag{1}$$

$$k_f = \frac{f\left(\frac{L}{D}\right) + \sum K_L}{2gA_{pipe}^2} \tag{2}$$

where h_{static} is the water depth, k_f is the coefficient for frictional losses, f is the Darcy friction factor, L is the length of the pipe, D is the pipe diameter, K_L terms are minor losses, g is acceleration due to gravity, and A is the cross-sectional area of the pipe. The intersection points between the pump curves and the system curve are used to determine the system performance at various frequencies. A second-order polynomial is used to approximate performance between these intersection points. The power available to the pump is used to determine the operating speed, flow-rate and pumping head at any given time. Pump prices were obtained from the 2014 Grundfos product price list [24].

2.1.4 High-Pressure Pumps

Danfoss APP series and Cat pumps are modeled in this work for the desalination system high-pressure pump. Both brands offer high-efficiency, corrosion-resistant pumps designed for desalination systems. A positive-displacement pump for the desalination system is modeled using a motor efficiency curve and constant mechanical efficiency estimated from manufacturer datasheets. The flowrate is proportional to the frequency and the displacement per revolution is obtained from pump datasheets. Curves representing the motor efficiency as a function of the percent of rated load were used to model the pump motor. Manufacturers typically only provide motor efficiency curves at the standard frequency of 50 or 60 Hz. However, motors controlled by a VFD have been shown to have similar efficiencies at lower frequencies, and can be accurately represented using the efficiency curve at the standard frequency [25]. Individual motors may have higher or lower efficiencies at lower frequencies compared to the efficiency curve, but on average the efficiency curve at the standard frequency is assumed to accurately represent the operation of the motor [25]. To minimize cavitation, the system requires a low-pressure feed pump. Feed pumps have a much lower power consumption compared to the high-pressure pump, and are modeled using a constant efficiency.

2.1.5 Reverse Osmosis and Nanofiltration Elements

Reverse osmosis technology uses applied pressure and a semi-permeable membrane to remove salts and other particles from water, as shown in Figure 3.

Only a small portion of the salts and particles are able to pass through the membrane, producing a high-quality product water, also called permeate. A brine, also called concentrate, line is used to flush the salts and particles away from the membranes. Multiple reverse osmosis elements can be used in series in order to recover larger portions of the feed water as permeate, as shown in Figure 4.

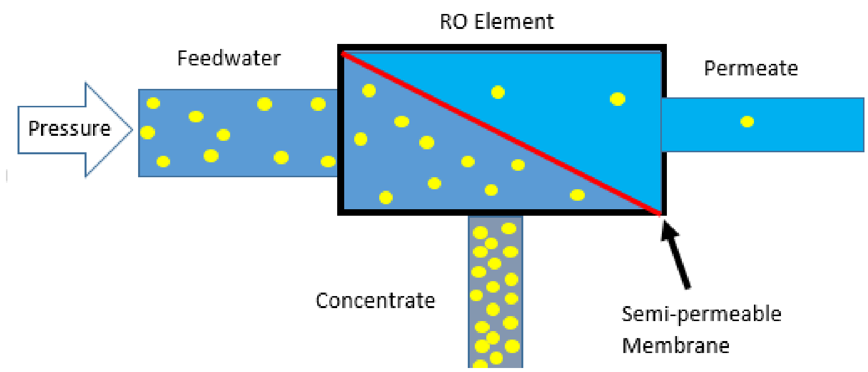

Figure 3. Schematic of RO operating principle

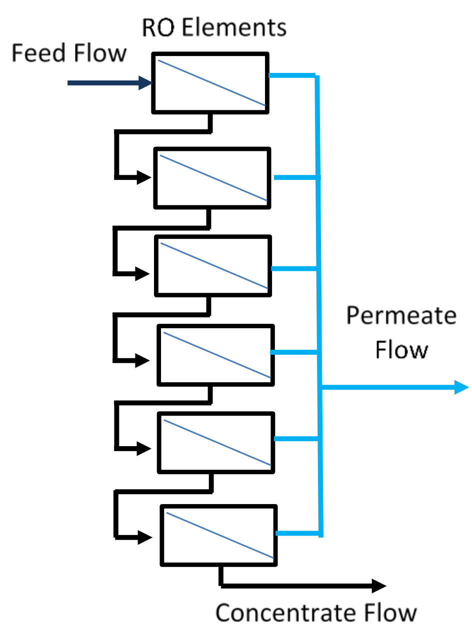

Figure 4. Flow diagram for multiple RO elements in series

Many different membrane types are available and each has different characteristics. Extra low energy (XLE), nanofiltration (NF), brackish water (BW) and seawater (SW) type membrane elements were evaluated and compared in this work. Specifically, this study included the evaluation of the following Filmtec elements: XLE-440, NF90-400, BW30-440i and SW30XLE-440i. RO or nanofiltration (NF) element performance is modeled using the equations outlined by Bilton [15] and Dow [26], which are contained in Table 1. Membrane-specific parameters such as the membrane area, water permeability coefficient and salt diffusion coefficient were obtained from the membrane datasheets or solved for using DOW's Reverse Osmosis System Analysis (ROSA) software [27]. Provided with the feed water salinity, flowrate pressure, temperature, membrane characteristics, membrane configuration, system recovery rate and a given feed pressure, the remaining permeate and concentrate flowrates, pressures and salinity levels are determined on an element-by-element basis, by solving Equations 4 – 13 simultaneously. The system pressure is then adjusted iteratively until the desired system recovery rate was achieved. All of the systems modeled are assumed to operate at a fixed system recovery rate by using an automated control system.

The variables used in Table 1 are defined as follows: Q_f is the feed water flowrate, Q_p is the permeate flowrate, Q_c is the concentrate flowrate, P_f is the feed water pressure, P_c is the concentrate pressure, P_p is the permeate pressure, C_f is the concentration of the feed water, C_p is the concentration of the permeate water, C_c is the concentration of the concentrate, π_f is the osmotic pressure of the feed water, π_p is the osmotic pressure of the permeate, π_c is the osmotic pressure of the

Table 1. Equations for Reverse Osmosis Element Performance Modeling

Permeate flowrate	$Q_p = A\ S_e\ TCF\ FF\ (\Delta\bar{P} - \overline{\Delta\pi})$	(3)
Pressure differential	$\Delta\bar{P} = P_f - \frac{\Delta P_{fc}}{2} - P_p$	(4)
Single element concentrate side pressure drop	$\Delta P_{fc} = 0.0756\left(\frac{Q_c + Q_f}{2}\right)^{1.7}$	(5)
Concentrate pressure	$P_c = P_f - \Delta P_{fc}$	(6)
Osmotic pressure differential	$\overline{\Delta\pi} = pf_{avg}\frac{\pi_f + \pi_c}{2} - \pi_p$	(7)
Permeate salt concentration	$C_p = \frac{\left(B\ S_e\ pf_{avg}\ TCF\left(\frac{C_f + C_c}{2}\right)\right)}{Q_p}$	(8)
Conservation of water	$Q_f = Q_c + Q_p$	(9)
Conservation of salt	$Q_f\ C_f = Q_c\ C_c + Q_p\ C_p$	(10)
Osmotic pressure of feed water	$\pi_f = \frac{(0.002654\ (T + 273)C_f)}{1000 - \frac{C_f}{1000}}$	(11)
Osmotic pressure of concentrate	$\pi_c = \frac{(0.002654\ (T + 273)C_c)}{1000 - \frac{C_c}{1000}}$	(12)
Temperature correction factor	$TCF = EXP\left[3020\left(\frac{1}{298} - \frac{1}{273 - T}\right)\right]\ if\ T < 25$ $TCF = EXP\left[2640\left(\frac{1}{298} - \frac{1}{273 - T}\right)\right]\ if\ T < 25$	(13)

concentrate, A is the membrane permeability coefficient, B is the membrane salt permeability coefficient, S_e is the membrane element area, TCF is the temperature correction factor, FF is the membrane fouling factor, $\Delta\bar{P}$ is the average pressure differential across the membrane, $\Delta\bar{\pi}$ is the average difference in osmotic pressure across the membrane, ΔP_{fc} is the pressure drop from the feed to concentrate sides of a single element, pf_{avg} is the average polarization factor and T is the feed water temperature (°C). This modeling method allows performance to be modeled for a wide variety of water supplies, membrane types and RO element configurations.

2.1.6 RO System Configurations

A key design consideration for RO system design is the appropriate system recovery rate. Based on the feed water quality, the RO or NF system recovery rate must be carefully selected and controlled to avoid fouling or scaling on the membranes. The recovery rate is the percentage of system feed water that passes through the membranes and becomes product water, also called permeate. Pre-treatment can reduce scaling or fouling potential and increase the potential recovery rate. However, a recovery rate that is too high may still result in fouling or damage to the membranes. A single-stage BWRO system with 6 elements in series can typically only recover up to 55% of the feed water as permeate. For this reason, two-stage systems with a 2:1 staging ratio are commonly used in traditional BW desalination and can achieve recovery rates of approximately 75% [28]. Two-stage systems typically use either an inter-stage booster pump or hydraulic turbocharger to increase the feed pressure to the second stage and balance the recovery rates for each stage. A flow diagram for a two-stage RO system is illustrated in Figure 5. Both one and two-stage systems are evaluated in this study.

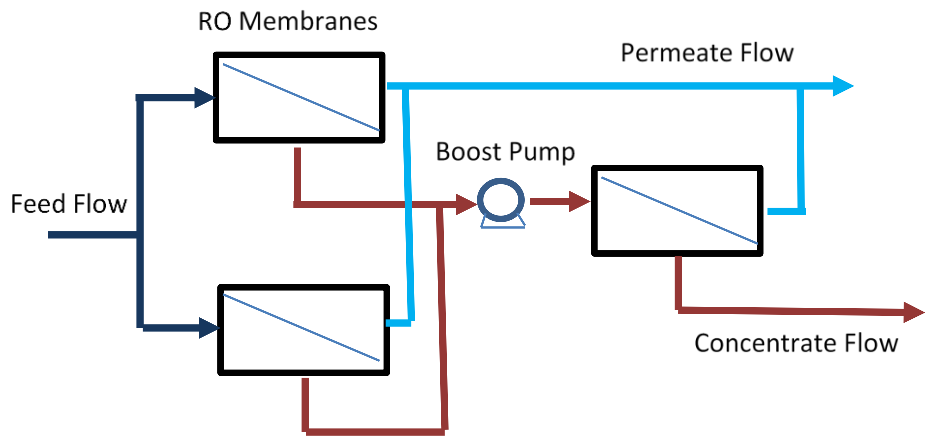

Figure 5. Flow diagram for a two-stage RO system

2.1.7 Energy Recovery Devices

In simple reverse osmosis systems without energy recovery, a large amount of energy is wasted through the pressurized brine stream, which is rejected. Energy recovery devices are used to transfer energy from the high-pressure brine stream to the low-pressure feed stream of the desalination system. This can significantly decrease the amount of power required by the high-pressure pump. The high-pressure pump can then be downsized, resulting in additional savings on equipment costs. Energy recovery devices are often used in seawater reverse osmosis (SWRO) systems and have also been shown to be economical in many brackish water reverse osmosis (BWRO) systems [29]. Many different energy recovery devices are currently available from a variety of manufacturers. Rotary pressure exchangers and hydraulic turbocharger type energy recovery devices were included in the model. In rotary pressure exchangers, such as the PX devices developed by Energy Recovery Inc. [30] or the iSave developed by Danfoss [31], the pressurized brine comes in direct contact with the low-pressure feed stream. A small amount of mixing occurs, increasing the salinity of the feed water, but the energy is transferred to the feed stream at a very high efficiency. The brine stream is at a lower pressure than the feed water stream, and some pressure losses occur across the pressure exchanger, so a circulation pump must be used to compensate for the difference. A flow diagram for a system with a pressure exchanger energy recovery device is shown in Figure 6. Hydraulic turbochargers operate by installing a hydraulic turbine on the concentrate stream, and transferring the mechanical energy generated to the feed stream via another rotor. A flow diagram for a system incorporating a hydraulic turbocharger is included in Figure 7. It is important to note that most energy recovery devices currently on the market were designed for fixed speed operation, and should only be applied to fixed speed RO systems. However, the iSave incorporates an integrated pressure exchanger and positive displacement circulation pump, which can be used to control the membrane recovery rate. This system, in principle, can be used on variable speed PV systems with a more advanced control algorithm. Schematics illustrating how these energy recovery devices are incorporated into the system are contained in the supplementary materials.

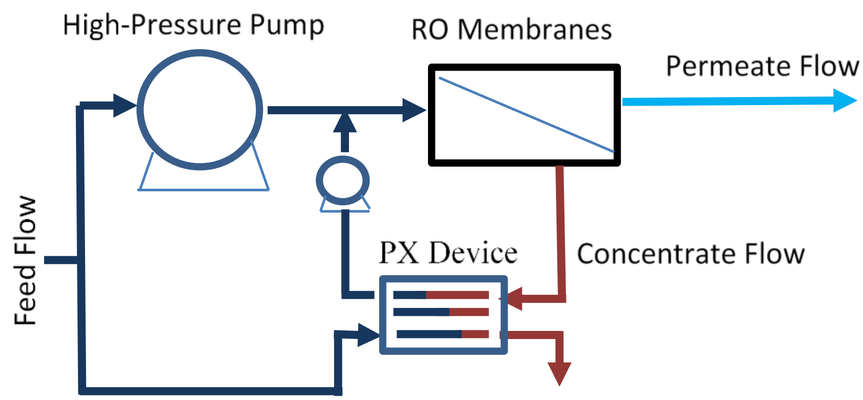

Figure 6. Flow diagram for a RO system with a pressure exchanger

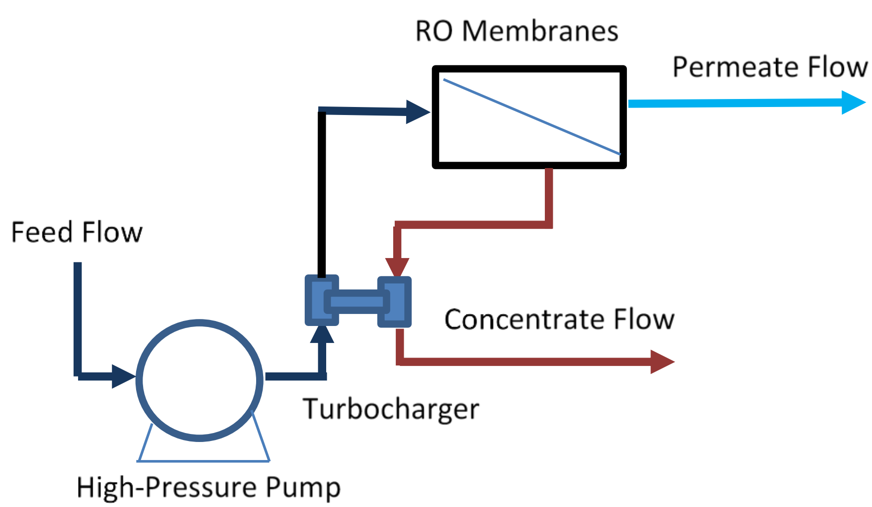

Figure 7. Flow diagram for a RO system with a hydraulic turbocharger

2.1.8 Agriculture System

The feasibility of integrating desalinated water into agriculture systems requires understanding of the agricultural economics. Water produced through desalination is more expensive compared to conventional water resources and requires use of high valued cropping systems where the local resources are favorable [32]. Major factors influencing the economics of desalination for agriculture include the salt tolerance, seasonal water requirements and net profits for each crop type.

Many methods and types of software programs exist for modeling crop water requirements. One common method is recommended by the United Nations Food and Agriculture Organization (FAO), which utilizes climatic data, reference crop evapo-transpiration, crop factors, and field conditions to determine the seasonal water requirements for a specific crop and location [33]. These methods can be complex and require many inputs including crop-specific parameters, climate data, soil quality, irrigation methods and farming practices. In this study, a simplified approach was taken. Average crop yields, seasonal water requirements, and net profits per hectare of farmland were obtained from existing research specific to the locations evaluated. These seasonal water requirements can be found in Figure C.1 of Appendix C.

The impact of soil salinity on relative crop yield is modeled using a piecewise function, as shown in Figure 8 [34]. This function is defined using two crop-specific parameters: the salt tolerance threshold (a) and the yield slope (b). Relative crop yield is unaffected below the salt tolerance threshold, resulting in 100% of the expected yield. At soil salinity concentrations above the salt tolerance threshold, the crop yield begins to decrease at a constant rate defined by the yield slope. The soil salt concentration is measured by the electrical conductivity (EC_e) of a saturated paste taken from the root zone, measured in dS m^{-1}. This is a generally accepted soil salinity measurement, and values for the salt tolerance threshold and yield slope have already been determined for common crops. The relative crop yield beyond the salt tolerance threshold can be estimated using Equation 14 [34]:

$$Y_{rel} = 100 - b(EC_e - a) \tag{14}$$

where a is the salinity threshold, b is the yield slope and EC_e is the electrical conductivity of the soil paste.

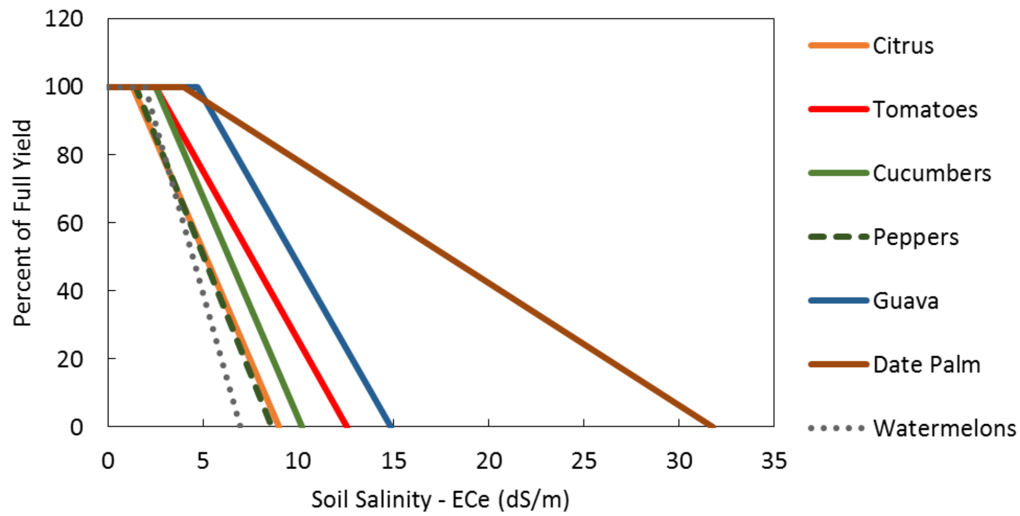

Figure 8. Effect of soil salinity (ECe), measured by electrical conductivity, on relative yields for various crops [35].

The salinity of the soil can be related to the salinity of the irrigation water by means of a concentration factor X, shown in Equation 15. A concentration factor of 1.5 is assumed used for this study, corresponding to a typical leaching fraction used in agricultural systems. Electrical conductivity can be then converted to ppm by using Equation 16 [35].

$$EC_e = X\,(EC_w) \tag{15}$$

$$640\ EC_e = TDS \tag{16}$$

2.2 Economic Analysis

The economic analysis for this work is performed using an annualized life cycle cost method. Current system capital and operating and maintenance (O&M) costs were obtained from manufacturers, distributors and existing research. The following sections explain how costs are modeled on a component level and the key economic indicators which are used to compare and evaluate system designs.

2.2.1 System Cost Modeling

The system cost model includes capital, operating and maintenance costs for all aspects of the pumping and desalination systems, including the power systems (PV, diesel generators, or grid), control systems, groundwater pumping system, desalination system and water storage tanks. The PV power supply costs are calculated using a baseline cost of \$2.50 W^{-1}, which includes the PV modules, wiring, structure, site preparation and installation [36]. For PV systems, control system costs include a controller, inverters, small backup or auxiliary batteries and, for some cases, a solar charge controller. The PV power supply assumed to be maintenance free. The capital costs for diesel generators were determined based on prices obtained from distributors, with an additional cost of 10% for installation. Operational costs due to diesel fuel, generator maintenance or grid electricity costs are also included. For diesel or grid powered systems, costs include a simple controller and an optional variable frequency drive for the integrated pumping and desalination system configuration. Groundwater pumping system costs include a submersible well pump, piping system, a groundwater storage tank, installation and maintenance. The RO system capital cost is calculated on a component level, incorporating costs for pumps, membranes, RO structure, filtration and treatment systems, energy recovery devices, storage tanks, instrumentation, engineering and installation. O&M costs for the desalination system include treatment chemicals, brine disposal, water taxes, labor, and maintenance. A comprehensive list of all cost assumptions used in the modeling work is included in Table A.1 of Appendix A.

2.2.2 Economic Evaluation

Primary economic indicators such as the water unit desalination cost (WUDC), water unit pumping cost (WUPC), and total water unit cost (TWUC) were used to evaluate and optimize the design of the system. These metrics also allow the work to be directly compared to previous research. The water unit desalination cost (US$/$m^3$) is calculated by dividing the annualized desalination system cost, which includes capital and operating expenses, by the annual permeate production. The water unit pumping cost (US$/$m^4$) is calculated by dividing the annualized pumping system cost, which also includes capital and operating expenses, by the annual equivalent hydraulic energy. This allows costs and energy requirements for pumping systems with different well depths and flowrates to be compared. The total water unit cost (US$/$m^3$) is the annualized cost of both the pumping and desalination systems divided by the annual permeate production. Financial results such as the net present value (NPV), return on investment (ROI), internal rate of return (IRR) and payback period were used to evaluate the entire water pumping, desalination and farming scenario in each case study presented. The equations for calculating each of the indicators mentioned are included in Table 2.

The variables used in Table 2 are defined as follows: $A_{power\ sys}$ is the annualized cost of the power supply (including equipment, operation and maintenance costs), $A_{pumping}$ is the annualized cost of the pumping system, A_{desal} is the annualized cost of the desalination system, *COE* is the cost of energy for the given power system, *EHE* is the annual equivalent hydraulic energy of the pumping system, *WUPC* is the water unit pumping cost, *WUDC* is the water unit desalination cost, *TWUC* is the overall water unit cost, $V_{permeate}$ is the annual volume of permeate produced, $E_{pumping}$ is the annual energy used by the pumping system, $E_{desalination}$ is the annual energy used by the desalination system, cf_n is the net cash flow during the nth year of the system operation, *investment* is the negative initial cost of the system, and r is the rate where the present value of the cash flow equals the initial investment. This method of economic evaluation gives results on the economics of individual subsystems and the system as a whole.

Table 2. Equations for Economic Analysis

Equivalent hydraulic energy (m^4)	$EHE = \sum Q_f \, \Delta t \, H_T$	(17)
Cost of energy (US$/kWh)	$COE = \frac{A_{power\ sys}}{E_{pumping} + E_{desalination}}$	(18)
Water unit pumping cost (US$/ m^4)	$WUPC_{m4} = \frac{(A_{pumping} + COE\ (E_{pumping}))}{EHE}$	(19)
Water unit pumping cost (US$/$m^3$ permeate)	$WUPC_{m3} = \frac{(A_{pumping} + COE\ (E_{pumping}))}{V_{permeate}}$	(20)
Water unit desalination cost (US$/$m^3$)	$WUDC_{m3} = \frac{(A_{desal} + COE\ (E_{pumping}))}{V_{permeate}}$	(21)
Overall water unit cost (US$/$m^3$)	$TWUC_{m3} = WUDC_{m3} + WUPC_{m3}$	(22)
Payback period (years)	$Payback = \frac{PW_{total\ system\ cost}}{A_{system\ profits}}$	(23)
Return on investment (%)	$ROI = \frac{Return - Investment}{Investement}$	(24)
Internal rate of return (%)	$\frac{cf_1}{1+r} + \frac{cf_2}{(1+r)^2} + \cdots + \frac{cf_n}{(1+r)^n} + Investment = 0$	(25)

CHAPTER 3

RESULTS AND DISCUSSION

Simulations were performed using the methods presented in order to evaluate and optimize system designs. Sensitivity analysis was performed in order to illustrate the impact of environmental conditions and system costs on the total water unit cost. Several case studies including water pumping, desalination and agricultural evaluation for locations in the Jordan Valley are then presented.

3.1 Pumping and Desalination System Evaluation

Pumping and desalination system performance and cost are significantly affected by the system design. The optimal power supply, membrane type and system configuration for RO systems can vary based on the feed water quality, groundwater depth, required permeate quality, water demand and cost of energy. The developed model was used to identify optimal system configurations for different scenarios based on the water unit costs, specific energy consumption and permeate quality. Results are presented for water salinities ranging from 1500 to 7500 ppm, water depths ranging from 30 to 120 m and PV array sizes ranging from 15 to over 100 kW. In these simulations, the PV powered system produces the maximum amount of permeate possible and operation is not limited by the water demand or permeate water storage tank size.

3.1.1 System Capacity and Power Supply Evaluation

PV-, diesel-, and electric grid-powered systems are all included as viable options for power production in the model. The PV-powered system is only operated during daylight hours, when there is sufficient power available to operate the system. Solar irradiation is simulated using TMY3 data for Amman, Jordan. The modeling results shown in Figure 9a indicate that water unit desalination costs are very similar for PV- and diesel-powered systems. Error bars are used to illustrate simulation results using minimum and maximum expected costs for PV systems, diesel fuel and grid electricity. The results in Figure 9b illustrate that PV-powered systems are able to pump water at a lower cost than diesel systems for most cases. As expected, if access to the electric grid is available, then a grid-powered system is the most viable option for both water pumping and desalination.

System capacity also has a significant impact on the water unit pumping and desalination costs. Simulations were performed with PV arrays ranging from 15 to 116 kW and appropriately sized pumping and desalination systems. Diesel and grid powered systems were sized and operated in order to produce the same amount of annual permeate water as the PV system. Nanofiltration elements, a water depth of 60 m, and a feed water salinity of 4500 ppm were used in this simulation. The results in Figure 9 show that increasing the PV system size from 15 to 33 kW significantly reduces both the water unit desalination and pumping costs. Further system size increases result in more gradual water unit cost reductions. Similar cost reductions due to increased system size were also observed for the diesel and grid powered systems. Interest rate is a major factor influencing the overall cost of PV pumping and desalination systems due to the high upfront cost of the PV array and higher RO equipment costs compared to diesel or grid. Although PV-powered systems provide electricity at a lower cost than diesel generators, diesel-powered systems can often produce the same amount of permeate per day by using smaller pumps and fewer membranes and operating the system up to 24 hours per day, depending on the seasonal water requirements. In most cases, this allows the diesel and grid-powered pumping and desalination system size to be reduced, resulting in lower equipment costs compared to PV powered systems.

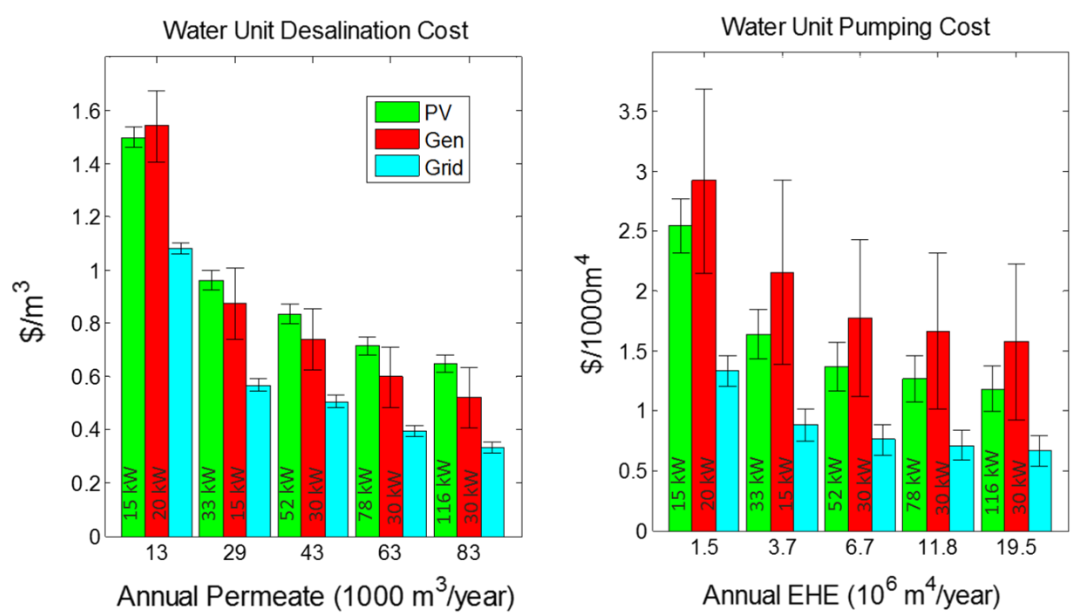

Figure 9. a) Effect of system size and power supply on water unit desalination cost (WUDC) and b) effect of system size and power supply on water unit pumping cost (WUPC) for a feed water salinity of 4500 ppm and a water depth of 60 meters using nanofiltration elements. PV array and generator ratings are indicated on each bar. Error bars illustrate high and low values based on the following costs: installed PV prices of $2.00, $2.50 and $3.00/Watt, diesel fuel prices of $0.48, $0.95 and $1.43/liter, and grid electricity prices of $0.09, $0.12 and $0.15/kWh.

3.1.2 Inverter Configuration Evaluation

The modeling work included the evaluation of 4 different inverter configurations and control strategies, as detailed in the methods section. Simulations were performed using a solar radiation data from Jordan, nanofiltration elements, a two-stage configuration and no energy recovery. A water depth of 60 meters was used for results presented in Figure 10a, and a water salinity of 4500 ppm was used for results presented in Figure 10b. As shown in Figure 10, the independent systems configuration and the integrated system configuration resulted in very comparable, low water unit costs. The integrated system configuration requires a more advanced control system in order to match the flowrates of the groundwater pump and the high-pressure pump. The integrated system also has cost savings resulting from eliminating the need for a groundwater storage tank, and the groundwater pumping system operation is not limited by a full or empty groundwater storage tank. However, if pretreatment is required then the independent systems configuration is more advantageous because it allows chemical dosing in the groundwater storage tank.

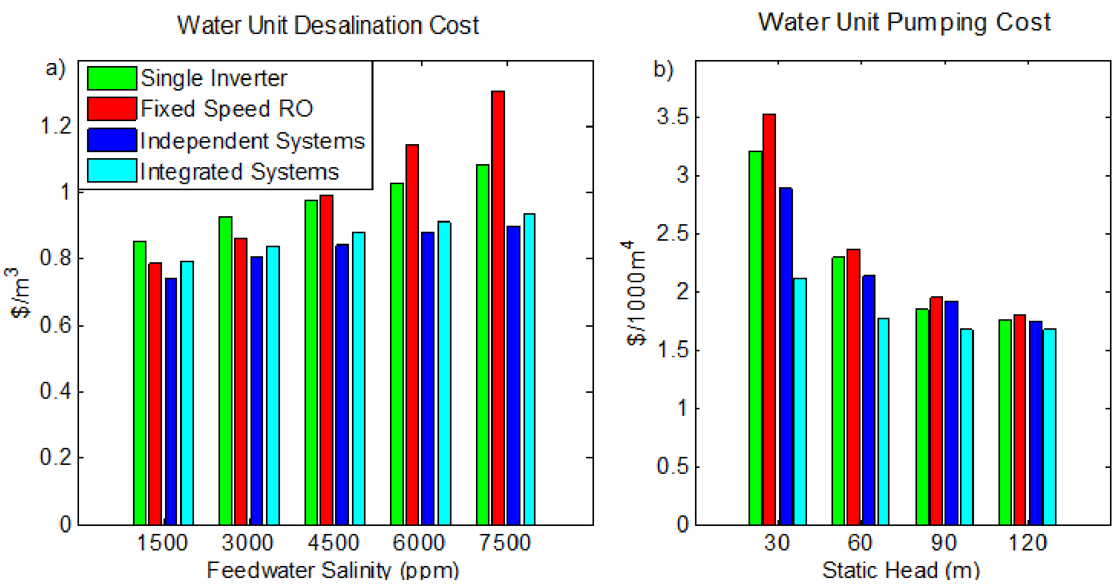

Figure 10. a) Effect of inverter configuration and water salinity on water unit desalination cost, b) effect of system inverter configuration and water depth on water unit pumping cost. The following inverter configurations were evaluated: 1) a single inverter system, 2) a dual inverter system with a fixed speed desalination system 3) completely independent, variable frequency pumping and desalination systems 4) an integrated solar water pumping and desalination system with two variable frequency inverters.

3.1.3 Membrane Type Evaluation

The following membrane element types were evaluated in this study: extra low energy, nanofiltration, brackish water and seawater elements. Each membrane has different water and salt permeability properties, and therefore has different energy requirements and permeate quality. The water unit desalination cost, specific energy consumption and permeate quality of permeate water for each type of membrane are shown in Figure 11. These results are based on simulations using solar radiation data for Jordan, an integrated system inverter configuration, a two-stage configuration and no energy recovery. As expected, the extra low energy and nanofiltration elements have lower desalination cost and specific energy consumption because they are operated at a lower pressure and are designed for lower salinity feed water. However, these elements also have lower salt rejection and produce a lower quality permeate when compared to brackish water or seawater elements. Therefore, the feed water salinity and salt tolerance of the crops must be taken into account when selecting the element type. Extra-low energy elements show promising results. However, XLE elements are designed for very low salinity feed water, and performance at higher salinity feed water needs to be validated before full-scale system implementation. The optimal membrane type is dependent on the feed water salinity and the permeate quality requirements. Nanofiltration elements may be the most cost effective for mildly salt sensitive crops or locations with low salinity feed water, but BW elements may be required for very salt sensitive crops or high salinity feed water.

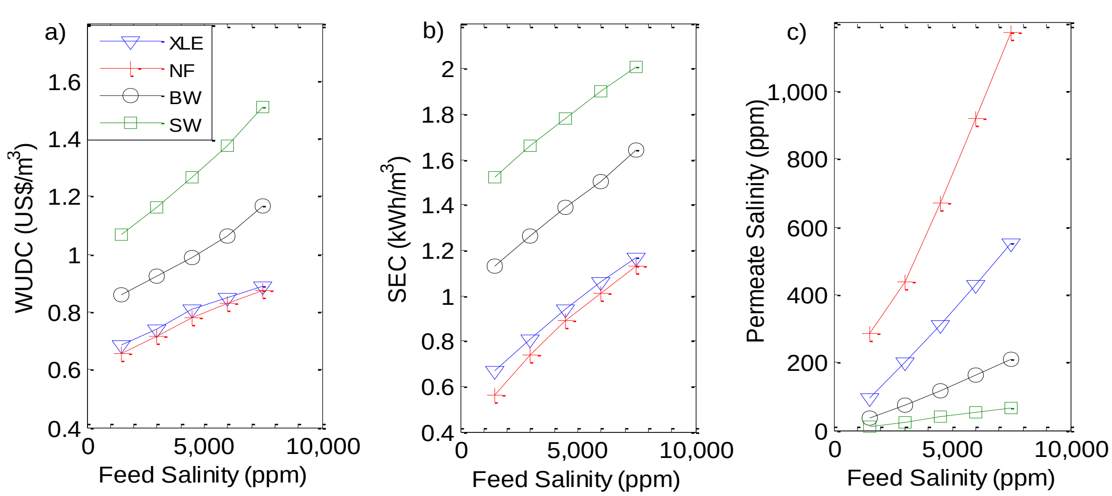

Figure 11. Effect of salinity on a) water unit desalination cost (WUDC), b) specific energy consumption (SEC), and c) permeate salinity for extra low energy, nanofiltration, brackish water and seawater elements.

3.1.4 Energy Recovery and Two-Stage Systems

Single-stage desalination systems were compared to two-stage systems and systems incorporating a pressure exchanger type energy recovery device. Simulations were performed using solar radiation data from Jordan, nanofiltration elements and an integrated system inverter configuration. A water depth of 60 meters was used for results presented in Figure 12a, and a water salinity of 4500 ppm was used for results presented in Figure 12b. As shown in Figure 12, both systems with energy recovery and two-stage systems were shown to be more economical than traditional single-stage desalination systems. Energy recovery devices were shown to be more economical than two-stage systems only for systems operating at high pressure due to higher salinity feed water (such as seawater, which has a salinity of approximately 32,000 ppm) or the use of BW or SW elements. Two-stage systems were shown to be the most economical for all of the situations considered in this study. However, in cases where a two-stage system cannot be used due to a limited recovery rate based on scaling or fouling potential of the feed water, a system with an energy recovery device is the most cost effective solution.

3.2 Sensitivity Analysis

Many of the factors which affect the economic viability of solar powered pumping and desalination can vary significantly based on geographic location. Capital costs, operating costs and interest rates can also change dramatically over time and vary by location. In order to make the study beneficial for different site

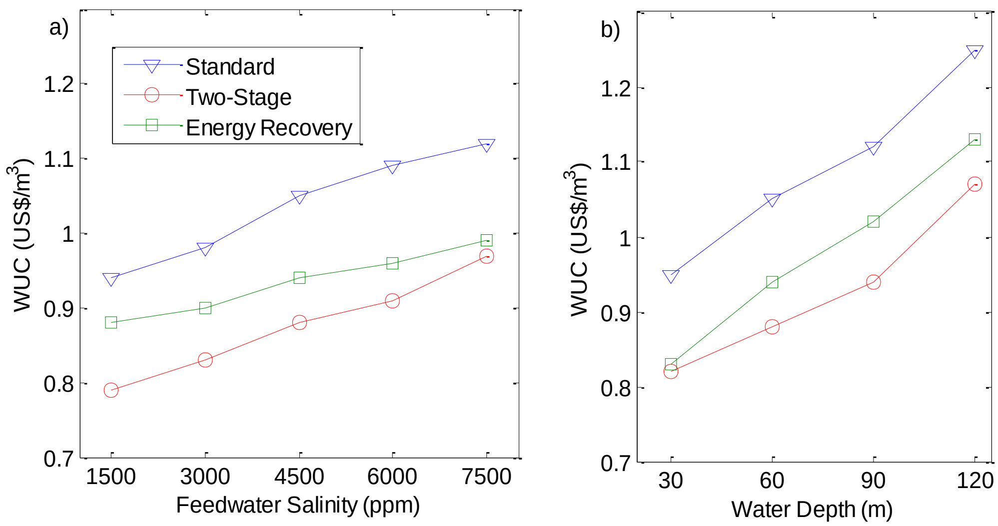

Figure 12. Comparison of overall water unit cost (WUC) resulting from using a standard single stage system configuration, a two-stage system and a single stage system with a pressure exchanger type energy recovery device

criteria, a detailed sensitivity analysis was performed to generalize results for different input parameters and also illustrate the impact of different variables on the total water unit cost. Results presented in Figure 13 show the variability in the total water unit cost when using a range of lower limit, baseline and upper limit values expected in locations where this system may be implemented, and also includes a 95% confidence interval based on a 2-tailed distribution [37]. Lower limit, baseline and upper limit values for the most influential parameters are as follows: interest rates of 0, 8 and 16%, groundwater depths of 30, 60, and 120 meters, irradiation values of 4.5, 5.7, and 6.8 kWh/m^2/day, and feed water salinities of 1500, 4500, and 7500 ppm. Other values used in the analysis can be obtained from Table B.1 of Appendix B. Results from an additional analysis using the same baseline values +/- 20% can be found in Table B.2. As expected, the substantial impact of irradiation, water depth and salinity indicate that the location for PV pumping and desalination systems must be chosen strategically. The interest rate sensitivity has the largest impact due to the large capital costs of PV systems and the large range of available interest rates, varying from 0% for subsidized projects to very high interest rates in some developing countries.

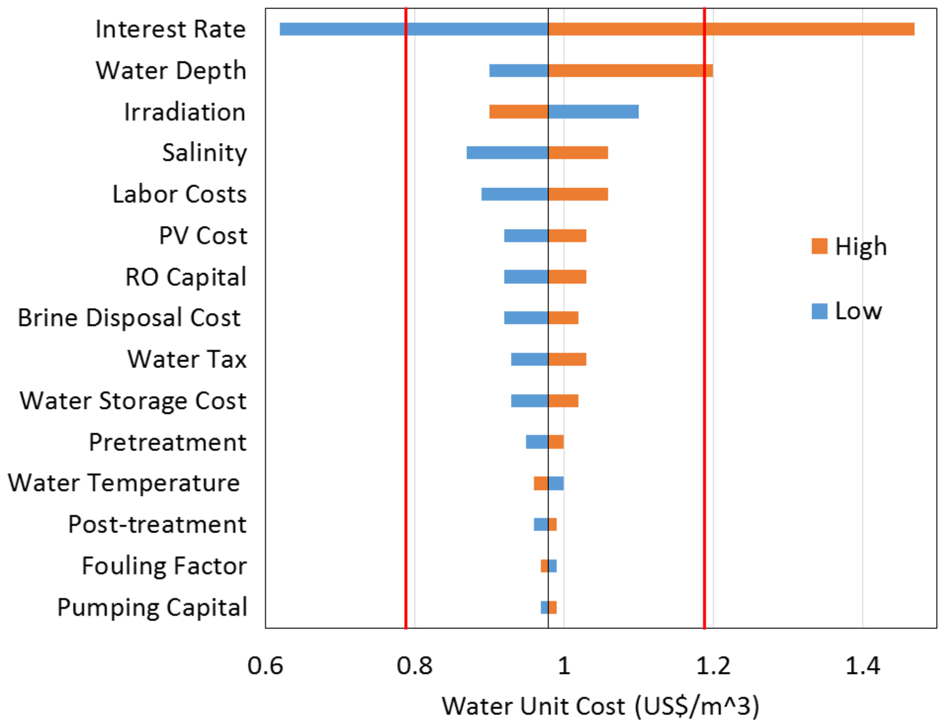

Figure 13. Sensitivity analysis results illustrating the impact of locational parameters and system costs on the total water unit cost

In the previous sections, an ideal match between the water production and water demand was assumed. In most agricultural applications, if water demands are not met for an extended period then yields will be severely affected. The system may be oversized to ensure that the peak demand is met during summer months.

During other seasons, the system may not be operating at full capacity because the demand is met and water storage tanks are full. When the system is only used to produce 75% of the annual capacity, the water unit cost increases linearly from $0.98/m^3 to $1.37/m^3. When the system only produces 50% of the annual capacity, the water unit cost increases to $1.75/m^3. This indicates that poor matching between the water supply and demand can severely reduce the economic viability of PV powered water pumping and desalination systems.

3.3 Case Study: Jordan Valley

Three regions on the eastern bank of the Jordan Valley were selected for case study evaluations. Water related parameters for each case study were selected based on data collected from over 250 wells in the Jordan Valley. The southern portion of the Jordan valley is characterized by a large number of wells with depths between 30 and 90 meters and low salinity, below 2,000 ppm. The central and northern regions of the Jordan Valley typically have deeper wells, ranging from 60 to several hundred meters deep with water salinity below 4,000 ppm. The reported water temperatures in all three regions range from 20 to 26 degrees Celsius. The three case studies are intended to survey the Jordan Valley with the specific locations selected based on evaluating an optimistic scenario in the southern region, a baseline scenario in the central region and a pessimistic scenario in the northern region. Water depths of 32, 78 and 80 m, salinity values of 1560, 2240 and 3580 ppm were used in the Southern, Central, and Northern Jordan Valley case studies respectively.

Bananas, greenhouse vegetables, and citrus fruits are all commonly grown in the Jordan Valley. Existing research on the average net profits, seasonal water requirements, and farm sizes for each of these crops was used for the case study economics and water consumption requirements [38]. In past studies, the use of desalinated water for agriculture was reported to result in lower crop water and fertilizer requirements, as well as increased yields compared to crops grown with marginal quality, untreated groundwater [7]. For this reason, the average water requirements have been reduced by 20% and the net profits have been increased by 20% from the reported averages for the following case studies, due to irrigation with desalinated water. An interest rate of 10% and a system lifetime of 20 years were used for the case studies. Other model input parameters and economic results for each case study are presented in Table 3. Greenhouse vegetables were shown to have the highest ratio of profits to water requirements, and were used for the optimistic case study in the Southern Jordan Valley. Bananas are very profitable but also have very large water requirements, and were used for the Central Jordan Valley case study as a baseline scenario. Citrus fruits represent a very poor crop choice, with low profits and high water requirements, and are included in the Northern Jordan Valley case study. Solar irradiation was represented using hourly TMY3 data from the nearby cities of Amman and Irbid [39].

The location-specific data and crop assumptions were used as inputs to the developed model. An optimization routine was used to determine the best membrane type, inverter configuration and RO system configuration for each case study. Optimal PV powered system architectures for all three case studies included nanofiltration elements, an integrated system inverter configuration and two-stage systems without energy recovery. The PV array size was optimized by increasing the PV array size until the demand was met. The case study in the Southern Jordan Valley required only a 43 kW PV array, the Central Jordan Valley case study required a 69 kW PV array and the Northern Jordan Valley case study required a 45 kW PV array. Differences in array size are primarily impacted by the water requirements and secondarily impacted by the water resource characteristics in the case studies presented.

The first case study confirms that greenhouse vegetables are a good candidate for desalination in agriculture, due to the relatively high profits and low water requirements. The shallow groundwater depth and low salinity in the Southern Jordan Valley also contribute to a low water unit cost. However, the water demand for vegetables is not well matched to the supply produced, resulting in many periods where the system is not operating. Overall the system is still profitable with an internal rate of return of 40%. The location for the second case study has fairly typical groundwater depth and salinity for the Jordan Valley. The case study shows that while bananas produce very high revenues; the extremely high water demands require a large and expensive pumping and desalination system. The water demands for bananas also require system oversizing to meet the peak demand in summer. This system results in very minimal returns with an internal rate of return of 8%. As expected, the third case study illustrates the effect of poor crop choice and poor location, and results in a very unprofitable system. Additional information about the three case studies performed, including system design, parameters and additional results, can be found in Table D.1-3 of Appendix D.

Table 3. Locational parameters, crop information and economical results for case studies evaluating the economic viability of pumping and desalination systems for agriculture.

		Case 1	Case 2	Case 3
	Crop	Greenhouse Vegetables *	Bananas	Citrus**
Locational Parameters	Net revenue ($/Ha/year)	9000	15000	1500
	Annual water requirement (m^3/Ha/year)	4040	12000	8080
	Area (Ha)	10	4	4
	Water depth (m)	32	78	80
	Water salinity (ppm)	1568	2240	3584
	Water temperature (°C)	23	24	20
PV Results	Total capital cost (US$)	252146	332335	256023
	Annual operating cost (US$)	15152	16609	14471
	Water unit pumping cost (US$/1000m^4)	3.3	2.5	2.74
	Water unit desalination cost (US$/m^3)	0.89	0.87	1.14
	Overall water unit cost (US$/m^3)	1.12	1.26	1.52
	Net present value	385077	37081	-328805
	Internal rate of return	**40%**	**8%**	**-182%**
	Return on investment	**101%**	**8%**	**-87%**
Diesel Generator Results	Total capital cost (US$)	138684	153909	141461
	Annual operating cost (US$)	26054	31638	25769
	Water unit pumping cost (US$/1000m^4)	2.72	2.26	2.52
	Water unit desalination cost (US$/m^3)	0.78	0.75	1.03
	Overall water unit cost (US$/m^3)	1.06	1.12	1.45
	Net present value	405727	84555	-309954
	Internal rate of return	**84%**	**8%**	**-189%**
	Return on investment	**113%**	**21%**	**-189%**

Grid Powered Results	Total capital cost (US$)	102284	105389	105421
	Annual operating cost (US$)	17045	19635	16847
	Water unit pumping cost (US$/1000m^4)	1.49	1.17	1.35
	Water unit desalination cost (US$/m^3)	0.57	0.53	0.77
	Overall water unit cost (US$/m^3)	0.72	0.72	1
	Net present value	518825	238261	-197950
	Internal rate of return	**248%**	**22%**	**-187%**
	Return on investment	**210%**	**87%**	**-80%**
	*Greenhouse vegetables consist of tomato, cucumber, melon, hot and sweet pepper, eggplant, bean, **Citrus consists of clementine, mandarin and other oranges, lemon, pomelos			

The selected case studies are intended to demonstrate the capabilities of the assembled model while illustrating the potential impact of PV-RO systems. Many previous PV-RO systems have been dependent on large energy storage systems, and have had limited application due to small system sizes. Advances in control strategies, power management, PV technologies, and membrane longevity have facilitated the evaluation of PV-RO systems that are directly coupled. Results from the case studies above illustrate the importance of crop selection and the impact of the water resource on the economics of the system.

CHAPTER 4

CONCLUSIONS

In this study, models were successfully developed in order to evaluate PV pumping and desalination system performance. Simulations were performed under various environmental conditions in order to determine the optimal inverter configuration, membrane type, desalination system configuration and power supply for different scenarios. The cost of PV-powered water pumping and desalination has been greatly reduced compared to previous research due to the use of larger system sizes, system optimization and low-energy membranes. High value crops were investigated for the case study area of interest and relative crop yields due to soil sensitivity were modeled. PV and diesel generator powered pumping and desalination systems were found to be comparable in cost and performance for most situations, but grid powered systems are clearly more cost effective in all cases. The use of PV water pumping and desalination for agriculture was found to be profitable only for crops with high returns, fairly low water requirements, and ideal locations with shallow groundwater depths, low salinity feed water and high solar irradiation.

CHAPTER 5

FUTURE WORK

Recommendations for future work include a more detailed evaluation of crop water requirements, yields and values for various global locations.. Control algorithms must also be developed for variable speed desalination systems in order to avoid rapid fluctuations in flow and pressure which result in damage to membranes. Hybrid PV- and diesel-powered systems may present a more cost-effective solution in situations where the water demand is not well matched to the PV system water production.

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APPENDICES

Appendix A. Cost Estimations

Table A.1. Summary of equipment and operating cost values used in the study

Subsystem	Component	Cost ($)	Notes	Component Lifetime (years)
Power Supply - PV	Installed PV Array	$2.50/Watt	Includes module, wiring, structure, installation	25
Power Supply - Generator	Generator	$13000,$15000,$18000,$20000,$21000	Kohler 10,20,30,40,60 kW	10
	Diesel Fuel	$0.95/l	-	-
	Maintenance	3% of Generator Cost		
Power Supply - Grid	Grid Electricity	$0.12/kWh	-	-
PV Power Distribution System	V/f Inverters or VFD	$2500, $4500, $6500, $8000, $11000	20,30,40,60,75+ kW	10
	Auxiliary Batteries (PV)	$2,000	24V, 415 Ah, 4 battery bank	5
	Controller and Programming	$500, $2000, $4000	Fixed-speed system, Variable-speed system, Integrated variable-speed system	25
	MPPT Charge Controller (PV only)	$182/kW	-	25
Groundwater Pumping System	Groundwater Pump	$7360, $7280, $9350, $9520	Grundfos 475S400-5-B, 300S400-10, 230S400-13, 150S400-23	10
	Pipe	$5/m, $13/m	For 3" or 6" Diameter Piping	10
	GW Installation	20% of Pump and piping cost	-	-
	GW Storage Tank	$50/m^3, $100/m^3, $200/m^3	For low cost (SRPE) medium cost (plastic crates) high cost (fiberglass tank)	25
	GW System Maintenance	3% of pumping equipment cost	-	-
	Water Tax	$0.00, $0.03, $0.04, $0.05, $0.10/m^3 feed water	No tax, low-use tax, high-use tax, Jordan	-

RO/NF System	High Pressure Pump	$1300/m3h	Positive Displacement CATPUMPS or Danfoss APP	25
	HPP Motor	$2500, $3700, $4800, $5800, $8000, $10000	For 20, 30, 40, 50, 60, 70 kW Weg Motors	15
	Low Pressure Pump	$3,000		10
	PX Energy Recovery Devices	$10000,-$32000	PX 30S - PX 180	25
	iSave ERD	$26000, 55000	Danfoss iSave 21 and 40	
	Circulation Pump	$3,000		25
	RO/NF Membrane	$600 each		5
	Pressure Vessel	$600 each		
	RO Structure, pipes, fittings	$6000+1500*N_vessels		
	Multimedia Filter	$10,000	Optional	
	Dosing Pump	$2,500	For pre-treatment or post-treatment	
	Permeate Storage Tank	$50/m^3, $100/m^3, $200/m^3	For low cost (SRPE/corrugated metal) medium cost (plastic crates) high cost (fiberglass tank)	
	System Container	$3,000		25
	RO Engineering	5% of RO Equipment Cost		-
	RO Installation	15% of RO Equipment Cost		-
	RO Instrumentation	10% of RO Equipment Cost		-
	Brine Disposal	$0.03/m^3, $0.20/m^3, $0.33/m^3, $0.50/m^3	Cost per m^3 of brine for surface reject, sewer, deep-well injection, evaporation pond	-

	Pre-treatment	$0.00/m^3, $0.015/m^3, $0.03/m^3	Cost per m^3 of feed water for no pre-treatment, mild pre-treatment, normal pre-treatment	-
	Post-treatment	$0.00/m^3, $0.01/m^3, $0.02/m^3	Cost per m^3 of permeate-water for no post-treatment, mild post-treatment, normal post-treatment	-
	Annual Labor	$5,000	Automated System	-
	Annual HPP Mainentance	$500, $1000, $100	Centrifugal, Cat pumps, Danfoss	-
	Annual RO Spare Parts and Maintenance	3% of RO equipment cost		-

Appendix B. Sensitivity Analysis Parameters

Table B.1. Summary of variable values and results from a sensitivity analysis using lower limit, baseline, and upper limit values.

Variable:	Units	Variable Values			Water Unit Cost			Percent Change		
		Low	Base	High	Low	Base	High	Low	Base	High
Pumping Capital	$	9974	12468	14962	0.97	0.98	0.99	-1.0	0.0	1.0
Pumping O&M	$/year	3314	3475	3635	0.97	0.98	0.99	-1.0	0.0	1.0
Fouling Factor		0.8	0.9	1	0.99	0.98	0.97	1.0	0.0	-1.0
Post-treatment	$/m^3 perm	0	0.01	0.02	0.97	0.98	0.99	-1.0	0.0	1.0
Water Temperature	C	15	20	25	1	0.98	0.96	2.0	0.0	-2.0
Pretreatment	$/m^3 feed	0	0.015	0.03	0.95	0.98	1	-3.1	0.0	2.0
Water Storage Cost	$/m^3 capacity	50	100	150	0.93	0.98	1.02	-5.1	3.0	4.1
Water Tax	$/m^3 feed	0	0.05	0.1	0.93	0.98	1.03	-5.1	0.0	5.1
Brine Disposal Cost	$/m^3 brine	0.03	0.2	0.33	0.92	0.98	1.02	-6.1	0.0	4.1
RO Capital	$	119470	149338	179206	0.92	0.98	1.03	-6.1	0.0	5.1
PV Cost	$/Watt	2	2.5	3	0.92	0.98	1.03	-6.1	0.0	5.1
RO O&M	$/year	14177	17721	21265	0.91	0.98	1.04	-7.1	0.0	6.1
Labor Costs	$/year	5000	10000	15000	0.89	0.98	1.06	-9.2	0.0	8.2
Salinity	ppm	1500	4500	7500	0.87	0.98	1.06	-11.2	0.0	8.2
Irradiation	kWh/m^2/day	4.56	5.7	6.84	1.1	0.98	0.9	12.2	0.0	-8.2
Water Depth	m	30	60	120	0.9	0.98	1.2	-8.2	0.0	22.4
Interest Rate	%	0	8	16	0.62	0.98	1.47	-36.7	4.0	50.0

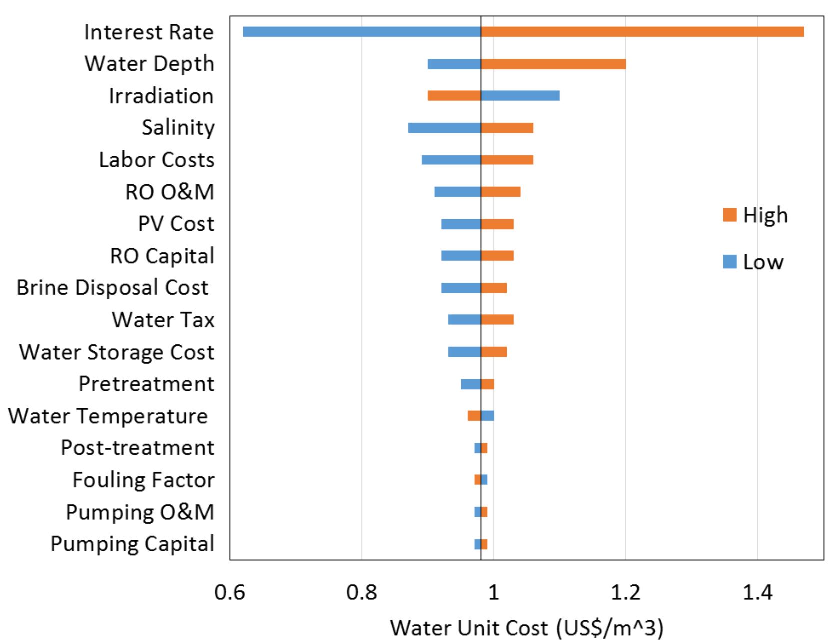

Figure B.1. Results from a sensitivity analysis using lower limit, baseline, and upper limit values to evaluate water unit costs.

Table B.2. Summary of variable values and results from a sensitivity analysis using baseline values +/- 20%.

		Variable Values			WUC Values			Percent Change		
Variable:	Units	Low	Base	High	-20%	Base	+20%	Low	Base	High
Brine Disposal Cost	$/m^3 brine	0.16	0.2	0.24	0.975	0.98	0.985	-0.5	0.0	0.5
Pretreatment	$/m^3 feed	0.012	0.015	0.018	0.974	0.98	0.986	-0.6	0.0	0.6
Pumping O&M		3314	3475	3635	0.97	0.98	0.99	-1.0	0.0	1.0
Pumping Capital	$	9974	12468	14962	0.97	0.98	0.99	-1.0	0.0	1.0
Water Temperature	C	16	20	24	0.99	0.98	0.97	1.0	0.0	-1.0
Water Tax	$/m^3 feed	0.04	0.05	0.06	0.97	0.98	0.99	-1.0	0.0	1.0
Fouling Factor		0.72	0.9	1.08	1	0.98	0.97	2.0	0.0	-1.0
Water Storage Cost	$/m^3 capacity	80	100	120	0.97	0.98	1	-1.0	0.0	2.0
Salinity	ppm	3600	4500	5400	0.96	0.98	1.01	-2.0	0.0	3.1
Water Depth	m	48	60	72	0.95	0.98	1.01	-3.1	0.0	3.1
Labor Costs	$/year	8000	10000	12000	0.96	0.98	1.02	-2.0	0.0	4.1
RO Capital	$	119470	149338	179206	0.92	0.98	1.03	-6.1	0.0	5.1
PV Cost	$/Watt	2	2.5	3	0.92	0.98	1.03	-6.1	0.0	5.1
RO O&M		14177	17721	21265	0.91	0.98	1.04	-7.1	0.0	6.1
Interest Rate	%	6.4	8	9.6	0.92	0.98	1.05	-6.1	4.0	7.1
Irradiation	MJ/m^3 day	4.56	5.7	6.84	1.1	0.98	0.9	12.2	0.0	-8.2

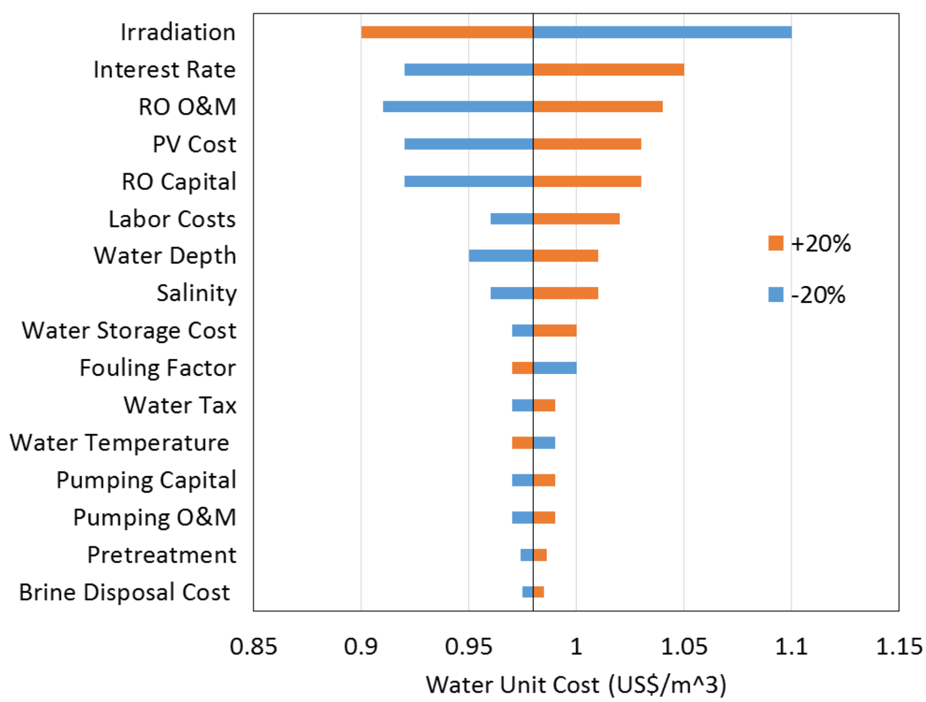

Figure B.2. Results from a sensitivity analysis using lower limit, baseline, and upper limit values to evaluate water unit costs.

Appendix C. Crop Water Requirement Profiles

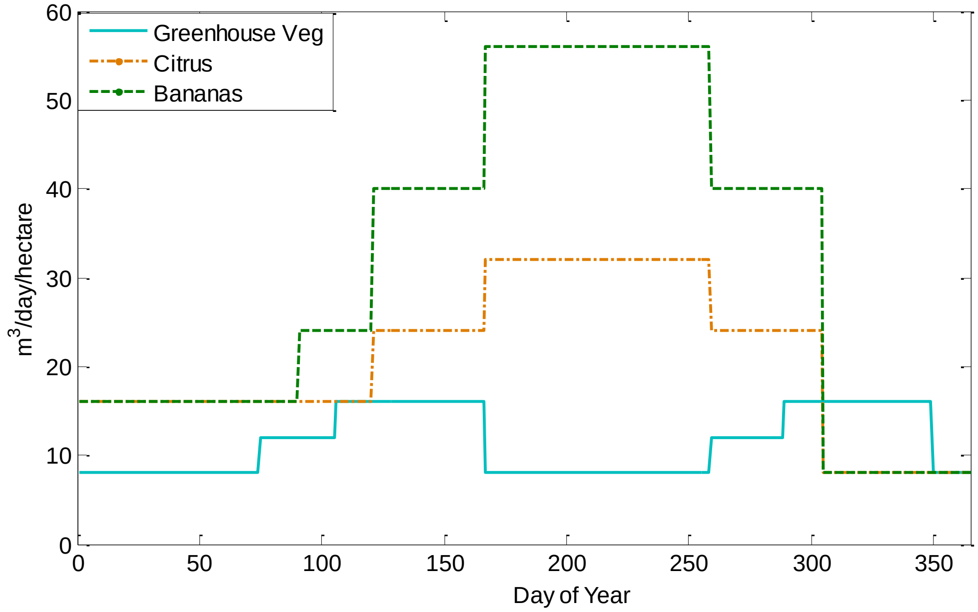

Figure C.1. Seasonal water requirements for several crops evaluated in the Jordan Valley case studies.

Appendix D. Simulation Results for Case Studies

Table D.1. System design, parameters and results for case study #1.

PV System		Diesel Generator System		Grid System	
Inverter configuration	4	Inverter configuration	4	Inverter configuration	4
Membrane Selection	2	Membrane Selection	2	Membrane Selection	2
Membrane Recovery Config	2	Membrane Recovery Config	2	Membrane Recovery Config	2
Energy Recovery Config	1	Energy Recovery Config	1	Energy Recovery Config	1
PV selection	1	PV selection	1	PV selection	1
Brine disposal method	3	Brine disposal method	3	Brine disposal method	3
Pretreatment method	2	Pretreatment method	2	Pretreatment method	2
Annual Permeate Flow (m^3/year)	40050	Annual Permeate Flow (m^3/year)	40050	Annual Permeate Flow (m^3/year)	40050
Annual Permeate Req (m^3/year)	41400	Annual Permeate Req (m^3/year)	41400	Annual Permeate Req (m^3/year)	41400
Annual EHE (m^4/year)	2825126	Annual EHE (m^4/year)	4137199	Annual EHE (m^4/year)	4137199
Salinity TDS(mg/l)	1568	Salinity TDS(mg/l)	1568	Salinity TDS(mg/l)	1568
Static head (m)	32	Static head (m)	76.88	Static head (m)	76.88
Diesel Price (US$/l)	0.95	Diesel Price (US$/l)	0.95	Diesel Price (US$/l)	0.95
System Lifetime (years)	20	System Lifetime (years)	20	System Lifetime (years)	20
Interest Rate (%)	0.1	Interest Rate (%)	0.1	Interest Rate (%)	0.1
WUPC ($/m^4 feed)	3.3	WUPC ($/m^4 feed)	2.72	WUPC ($/m^4 feed)	1.49
WUPC ($/m^3 perm)	0.23	WUPC ($/m^3 perm)	0.28	WUPC ($/m^3 perm)	0.15
WUDC ($/m^3 perm)	0.89	WUDC ($/m^3 perm)	0.78	WUDC ($/m^3 perm)	0.57
WUC($/m^3 perm)	1.12	WUC($/m^3 perm)	1.06	WUC($/m^3 perm)	0.72
COE ($/kWh)	0.42	COE ($/kWh)	0.43	COE ($/kWh)	0.14
COE power ($/kWh)	0.37	COE power ($/kWh)	0.4	COE power ($/kWh)	0.12
COE inv ($/kWh)	0.04	COE inv ($/kWh)	0.03	COE inv ($/kWh)	0.02
Capital overall ($)	252146	Capital overall ($)	138684	Capital overall ($)	102284

System O&M ($/year)	15152	System O&M ($/year)	26054	System O&M ($/year)	17045
Net Present Cost ($)	381143	Net Present Cost ($)	360493	Net Present Cost ($)	247396
Net Present Value ($)	385077	Net Present Value ($)	405727	Net Present Value ($)	518825
ROI (%)	101	ROI (%)	113	ROI (%)	210
IRR (%)	40	IRR (%)	84	IRR (%)	248
Farm payback period (years)	3	Farm payback period (years)	2	Farm payback period (years)	1
SEC pump (kWh/m^4)	0.0049	SEC pump (kWh/m^4)	0.0042	SEC pump (kWh/m^4)	0.0042
SEC desal (kWh/m^3)	0.56	SEC desal (kWh/m^3)	0.45	SEC desal (kWh/m^3)	0.45
GW Pump Cost (US$)	7360	GW Pump Cost (US$)	7360	GW Pump Cost (US$)	7360
GW Pipe Cost (US$)	676	GW Pipe Cost (US$)	1259	GW Pipe Cost (US$)	1259
GW Installation	1607	GW Installation	1724	GW Installation	1724
GW storage tank_cost (US$)	0	GW storage tank_cost (US$)	0	GW storage tank_cost (US$)	0
GW System Capital (US$)	9643	GW System Capital (US$)	10343	GW System Capital (US$)	10343
GW O&M	2476	GW O&M	2518	GW O&M	2518
GW pump selection	1	GW pump selection	1	GW pump selection	1
GWP scale factor	0.235554	GWP scale factor	1.00771	GWP scale factor	1.00771
High-pressure Pump Cost (US$)	45075	High-pressure Pump Cost (US$)	31163	High-pressure Pump Cost (US$)	31163
Low-pressure Pump Cost (US$)	3000	Low-pressure Pump Cost (US$)	3000	Low-pressure Pump Cost (US$)	3000
Number of Modules	1	Number of Modules	1	Number of Modules	1
Number of Membranes	21	Number of Membranes	21	Number of Membranes	21
Membrane Capital (US$)	12600	Membrane Capital (US$)	12600	Membrane Capital (US$)	12600
Pressure Vessel Capital (US$)	2100	Pressure Vessel Capital (US$)	2100	Pressure Vessel Capital (US$)	2100
Fittings Cost (US$)	700	Fittings Cost (US$)	700	Fittings Cost (US$)	700
RO Pipe Cost (US$)	700	RO Pipe Cost (US$)	700	RO Pipe Cost (US$)	700
RO structure cost (US$)	8500	RO structure cost (US$)	8500	RO structure cost (US$)	8500

Auxiliary pumps cost (US$)	3000	Auxiliary pumps cost (US$)	3000	Auxiliary pumps cost (US$)	3000
Multimedia Filter Cost (US$)	0	Multimedia Filter Cost (US$)	0	Multimedia Filter Cost (US$)	0
Pretreatment equipment cost (US$)	2500	Pretreatment equipment cost (US$)	2500	Pretreatment equipment cost (US$)	2500
Desal Storage Tank Cost (US$)	16000	Desal Storage Tank Cost (US$)	16000	Desal Storage Tank Cost (US$)	0
Container Cost (US$)	3000	Container Cost (US$)	3000	Container Cost (US$)	3000
Energy Recovery Cost (US$)	0	Energy Recovery Cost (US$)	0	Energy Recovery Cost (US$)	0
RO Engineering (US$)	4859	RO Engineering (US$)	4163	RO Engineering (US$)	3363
RO Installation (US$)	14576	RO Installation (US$)	12489	RO Installation (US$)	10089
RO Instrumentation (US$)	9718	RO Instrumentation (US$)	8326	RO Instrumentation (US$)	6726
RO System Capital (US$)	126328	RO System Capital (US$)	108241	RO System Capital (US$)	87441
Pretreatment Chemical Cost (US$/year)	802	Pretreatment Chemical Cost (US$/year)	801	Pretreatment Chemical Cost (US$/year)	801
Brine_disposal_cost (US$/year)	401	Brine_disposal_cost (US$/year)	400	Brine_disposal_cost (US$/year)	400
RO Labor (US$/year)	5000	RO Labor (US$/year)	5000	RO Labor (US$/year)	5000
RO O&M (US$/year)	11230	RO O&M (US$/year)	10618	RO O&M (US$/year)	10138
Array Rating (kW)	43	Gen Rating (kW)	20	Grid Electricity Cost (US$/kWh)	0.12
PV Capital (US$)	106575	Gen Capital (US$)	13600	Grid extension cost (US$/km)	100000
PV O&M	1066	Annual Gen O&M (US$)	12713.89	Grid extension distance (US$)	0
PV O&M (US$/year)	1066	VFD Capital (US$)	6500	Grid Extension Capital (US$)	0
Power Distriubtion Capital (US$)	9600	VFD O&M	203.786		
Power Distribution O&M	380	Annual GWP Fuel Cost (US$)	5743.589		

		Annual DP Fuel Cost (US$)	5946.416		
		Yearly Gen EHE	4137199		
		Yearly Gen Permeate	40049.72		

Table D.2. System design, parameters and results for case study #2.

PV		Diesel Generator System		Grid System	
Inverter configuration	4	Inverter configuration	4	Inverter configuration	4
Membrane Selection	2	Membrane Selection	2	Membrane Selection	2
Membrane Recovery Config	2	Membrane Recovery Config	2	Membrane Recovery Config	2
Energy Recovery Config	1	Energy Recovery Config	1	Energy Recovery Config	1
PV selection	1	PV selection	1	PV selection	1
Brine disposal method	3	Brine disposal method	3	Brine disposal method	3
Pretreatment method	2	Pretreatment method	2	Pretreatment method	2
Annual Permeate Flow (m^3/year)	44124	Annual Permeate Flow (m^3/year)	44124	Annual Permeate Flow (m^3/year)	44124
Annual Permeate Req (m^3/year)	45920	Annual Permeate Req (m^3/year)	45920	Annual Permeate Req (m^3/year)	45920
Annual EHE (m^4/year)	6960367	Annual EHE (m^4/year)	7295152	Annual EHE (m^4/year)	7295152
Salinity TDS(mg/l)	2240	Salinity TDS(mg/l)	2240	Salinity TDS(mg/l)	2240
Static head (m)	78	Static head (m)	122.88	Static head (m)	122.88
Diesel Price (US$/l)	0.95	Diesel Price (US$/l)	0.95	Diesel Price (US$/l)	0.95
System Lifetime (years)	20	System Lifetime (years)	20	System Lifetime (years)	20
Interest Rate (%)	0.1	Interest Rate (%)	0.1	Interest Rate (%)	0.1
WUPC ($/m^4 feed)	2.5	WUPC ($/m^4 feed)	2.26	WUPC ($/m^4 feed)	1.17
WUPC ($/m^3 perm)	0.39	WUPC ($/m^3 perm)	0.37	WUPC ($/m^3 perm)	0.19
WUDC ($/m^3 perm)	0.87	WUDC ($/m^3 perm)	0.75	WUDC ($/m^3 perm)	0.53
WUC($/m^3 perm)	1.26	WUC($/m^3 perm)	1.12	WUC($/m^3 perm)	0.72

COE ($/kWh)	0.4	COE ($/kWh)	0.39	COE ($/kWh)	0.13
COE power ($/kWh)	0.37	COE power ($/kWh)	0.36	COE power ($/kWh)	0.12
COE inv ($/kWh)	0.03	COE inv ($/kWh)	0.02	COE inv ($/kWh)	0.01
Capital overall ($)	332335	Capital overall ($)	153909	Capital overall ($)	105389
System O&M ($/year)	16609	System O&M ($/year)	31638	System O&M ($/year)	19635
Net Present Cost ($)	473732	Net Present Cost ($)	423259	Net Present Cost ($)	272552
Net Present Value ($)	37081	Net Present Value ($)	87555	Net Present Value ($)	238261
ROI (%)	8	ROI (%)	21	ROI (%)	87
IRR (%)	8	IRR (%)	8	IRR (%)	22
Farm payback period (years)	8	Farm payback period (years)	5	Farm payback period (years)	3
SEC pump (kWh/m^4)	0.0047	SEC pump (kWh/m^4)	0.0042	SEC pump (kWh/m^4)	0.0042
SEC desal (kWh/m^3)	0.61	SEC desal (kWh/m^3)	0.5	SEC desal (kWh/m^3)	0.5
GW Pump Cost (US$)	9350	GW Pump Cost (US$)	9350	GW Pump Cost (US$)	9350
GW Pipe Cost (US$)	1274	GW Pipe Cost (US$)	1857	GW Pipe Cost (US$)	1857
GW Installation	2125	GW Installation	2241	GW Installation	2241
GW storage tank_cost (US$)	0	GW storage tank_cost (US$)	0	GW storage tank_cost (US$)	0
GW System Capital (US$)	12749	GW System Capital (US$)	13448	GW System Capital (US$)	13448
GW O&M	2861	GW O&M	2903	GW O&M	2903
GW pump selection	3	GW pump selection	3	GW pump selection	3
GWP scale factor	0.478269	GWP scale factor	6.890568	GWP scale factor	6.890568
High-pressure Pump Cost (US$)	45075	High-pressure Pump Cost (US$)	31163	High-pressure Pump Cost (US$)	31163
Low-pressure Pump Cost (US$)	3000	Low-pressure Pump Cost (US$)	3000	Low-pressure Pump Cost (US$)	3000
Number of Modules	1	Number of Modules	1	Number of Modules	1
Number of Membranes	21	Number of Membranes	21	Number of Membranes	21
Membrane Capital (US$)	12600	Membrane Capital (US$)	12600	Membrane Capital (US$)	12600
Pressure Vessel Capital (US$)	2100	Pressure Vessel Capital (US$)	2100	Pressure Vessel Capital (US$)	2100

Fittings Cost (US$)	700	Fittings Cost (US$)	700	Fittings Cost (US$)	700
RO Pipe Cost (US$)	700	RO Pipe Cost (US$)	700	RO Pipe Cost (US$)	700
RO structure cost (US$)	8500	RO structure cost (US$)	8500	RO structure cost (US$)	8500
Auxiliary pumps cost (US$)	3000	Auxiliary pumps cost (US$)	3000	Auxiliary pumps cost (US$)	3000
Multimedia Filter Cost (US$)	0	Multimedia Filter Cost (US$)	0	Multimedia Filter Cost (US$)	0
Pretreatment equipment cost (US$)	2500	Pretreatment equipment cost (US$)	2500	Pretreatment equipment cost (US$)	2500
Desal Storage Tank Cost (US$)	22400	Desal Storage Tank Cost (US$)	22400	Desal Storage Tank Cost (US$)	0
Container Cost (US$)	3000	Container Cost (US$)	3000	Container Cost (US$)	3000
Energy Recovery Cost (US$)	0	Energy Recovery Cost (US$)	0	Energy Recovery Cost (US$)	0
RO Engineering (US$)	5179	RO Engineering (US$)	4483	RO Engineering (US$)	3363
RO Installation (US$)	15536	RO Installation (US$)	13449	RO Installation (US$)	10089
RO Instrumentation (US$)	10358	RO Instrumentation (US$)	8966	RO Instrumentation (US$)	6726
RO System Capital (US$)	134648	RO System Capital (US$)	116561	RO System Capital (US$)	87441
Pretreatment Chemical Cost (US$/year)	883	Pretreatment Chemical Cost (US$/year)	882	Pretreatment Chemical Cost (US$/year)	882
Brine_disposal_cost (US$/year)	442	Brine_disposal_cost (US$/year)	441	Brine_disposal_cost (US$/year)	441
RO Labor (US$/year)	5000	RO Labor (US$/year)	5000	RO Labor (US$/year)	5000
RO O&M (US$/year)	11544	RO O&M (US$/year)	10932	RO O&M (US$/year)	10260
Array Rating (kW)	69	Gen Rating (kW)	30	Grid Electricity Cost (US$/kWh)	0.12
PV Capital (US$)	173337	Gen Capital (US$)	15400	Grid extension cost (US$/km)	100000
PV O&M	1733	Annual Gen O&M (US$)	17508.46	Grid extension distance (US$)	0
PV O&M (US$/year)	1733	VFD Capital (US$)	8500	Grid Extension Capital (US$)	0

Power Distriubtion Capital (US$)	11600	VFD O&M	294.3575		
Power Distribution O&M	470	Annual GWP Fuel Cost (US$)	9523.876		
		Annual DP Fuel Cost (US$)	6825.185		
		Yearly Gen EHE	7295152		
		Yearly Gen Permeate	44124		

Table D.3. System design, parameters and results for case study #3.

PV System		Diesel Generator System		Grid System	
Inverter configuration	4	Inverter configuration	4	Inverter configuration	4
Membrane Selection	2	Membrane Selection	2	Membrane Selection	2
Membrane Recovery Config	2	Membrane Recovery Config	2	Membrane Recovery Config	2
Energy Recovery Config	1	Energy Recovery Config	1	Energy Recovery Config	1
PV selection	1	PV selection	1	PV selection	1
Brine disposal method	3	Brine disposal method	3	Brine disposal method	3
Pretreatment method	2	Pretreatment method	2	Pretreatment method	2
Annual Permeate Flow (m^3/year)	29199	Annual Permeate Flow (m^3/year)	29199	Annual Permeate Flow (m^3/year)	29199
Annual Permeate Req (m^3/year)	30240	Annual Permeate Req (m^3/year)	30240	Annual Permeate Req (m^3/year)	30240
Annual EHE (m^4/year)	4104414	Annual EHE (m^4/year)	4906301	Annual EHE (m^4/year)	4906301
Salinity TDS(mg/l)	3584	Salinity TDS(mg/l)	3584	Salinity TDS(mg/l)	3584
Static head (m)	80	Static head (m)	124.88	Static head (m)	124.88
Diesel Price (US$/l)	0.95	Diesel Price (US$/l)	0.95	Diesel Price (US$/l)	0.95
System Lifetime (years)	20	System Lifetime (years)	20	System Lifetime (years)	20
Interest Rate (%)	0.1	Interest Rate (%)	0.1	Interest Rate (%)	0.1

WUPC ($/m^4 feed)	2.74	WUPC ($/m^4 feed)	2.52	WUPC ($/m^4 feed)	1.35
WUPC ($/m^3 perm)	0.38	WUPC ($/m^3 perm)	0.42	WUPC ($/m^3 perm)	0.23
WUDC ($/m^3 perm)	1.14	WUDC ($/m^3 perm)	1.03	WUDC ($/m^3 perm)	0.77
WUC($/m^3 perm)	1.52	WUC($/m^3 perm)	1.45	WUC($/m^3 perm)	1
COE ($/kWh)	0.41	COE ($/kWh)	0.41	COE ($/kWh)	0.14
COE power ($/kWh)	0.37	COE power ($/kWh)	0.38	COE power ($/kWh)	0.12
COE inv ($/kWh)	0.04	COE inv ($/kWh)	0.03	COE inv ($/kWh)	0.02
Capital overall ($)	256023	Capital overall ($)	141461	Capital overall ($)	105421
System O&M ($/year)	14471	System O&M ($/year)	25769	System O&M ($/year)	16847
Net Present Cost ($)	379220	Net Present Cost ($)	360850	Net Present Cost ($)	248846
Net Present Value ($)	-328805	Net Present Value ($)	-309954	Net Present Value ($)	-197950
ROI (%)	-87	ROI (%)	-86	ROI (%)	-80
IRR (%)	-182	IRR (%)	-189	IRR (%)	-187
Farm payback period (years)	-30	Farm payback period (years)	-7	Farm payback period (years)	-10
SEC pump (kWh/m^4)	0.0045	SEC pump (kWh/m^4)	0.0042	SEC pump (kWh/m^4)	0.0042
SEC desal (kWh/m^3)	0.67	SEC desal (kWh/m^3)	0.63	SEC desal (kWh/m^3)	0.63
GW Pump Cost (US$)	9350	GW Pump Cost (US$)	9350	GW Pump Cost (US$)	9350
GW Pipe Cost (US$)	1300	GW Pipe Cost (US$)	1883	GW Pipe Cost (US$)	1883
GW Installation	2130	GW Installation	2247	GW Installation	2247
GW storage tank_cost (US$)	0	GW storage tank_cost (US$)	0	GW storage tank_cost (US$)	0
GW System Capital (US$)	12780	GW System Capital (US$)	13480	GW System Capital (US$)	13480
GW O&M	2167	GW O&M	2208	GW O&M	2208
GW pump selection	3	GW pump selection	3	GW pump selection	3
GWP scale factor	0.483208	GWP scale factor	0.483208	GWP scale factor	0.483208
High-pressure Pump Cost (US$)	45075	High-pressure Pump Cost (US$)	31163	High-pressure Pump Cost (US$)	31163
Low-pressure Pump Cost (US$)	3000	Low-pressure Pump Cost (US$)	3000	Low-pressure Pump Cost (US$)	3000

Number of Modules	1	Number of Modules	1	Number of Modules	1
Number of Membranes	21	Number of Membranes	21	Number of Membranes	21
Membrane Capital (US$)	12600	Membrane Capital (US$)	12600	Membrane Capital (US$)	12600
Pressure Vessel Capital (US$)	2100	Pressure Vessel Capital (US$)	2100	Pressure Vessel Capital (US$)	2100
Fittings Cost (US$)	700	Fittings Cost (US$)	700	Fittings Cost (US$)	700
RO Pipe Cost (US$)	700	RO Pipe Cost (US$)	700	RO Pipe Cost (US$)	700
RO structure cost (US$)	8500	RO structure cost (US$)	8500	RO structure cost (US$)	8500
Auxiliary pumps cost (US$)	3000	Auxiliary pumps cost (US$)	3000	Auxiliary pumps cost (US$)	3000
Multimedia Filter Cost (US$)	0	Multimedia Filter Cost (US$)	0	Multimedia Filter Cost (US$)	0
Pretreatment equipment cost (US$)	2500	Pretreatment equipment cost (US$)	2500	Pretreatment equipment cost (US$)	2500
Desal Storage Tank Cost (US$)	12800	Desal Storage Tank Cost (US$)	12800	Desal Storage Tank Cost (US$)	0
Container Cost (US$)	3000	Container Cost (US$)	3000	Container Cost (US$)	3000
Energy Recovery Cost (US$)	0	Energy Recovery Cost (US$)	0	Energy Recovery Cost (US$)	0
RO Engineering (US$)	4699	RO Engineering (US$)	4003	RO Engineering (US$)	3363
RO Installation (US$)	14096	RO Installation (US$)	12009	RO Installation (US$)	10089
RO Instrumentation (US$)	9398	RO Instrumentation (US$)	8006	RO Instrumentation (US$)	6726
RO System Capital (US$)	122168	RO System Capital (US$)	104081	RO System Capital (US$)	87441
Pretreatment Chemical Cost (US$/year)	585	Pretreatment Chemical Cost (US$/year)	584	Pretreatment Chemical Cost (US$/year)	584
Brine_disposal_cost (US$/year)	293	Brine_disposal_cost (US$/year)	292	Brine_disposal_cost (US$/year)	292
RO Labor (US$/year)	5000	RO Labor (US$/year)	5000	RO Labor (US$/year)	5000
RO O&M (US$/year)	10809	RO O&M (US$/year)	10197	RO O&M (US$/year)	9813
Array Rating (kW)	45	Gen Rating (kW)	30	Grid Electricity Cost (US$/kWh)	0.12

PV Capital (US$)	111475	Gen Capital (US$)	15400	Grid extension cost (US$/km)	100000
PV O&M	1115	Annual Gen O&M (US$)	13069.59	Grid extension distance (US$)	0
PV O&M (US$/year)	1115	VFD Capital (US$)	8500	Grid Extension Capital (US$)	0
Power Distriubtion Capital (US$)	9600	VFD O&M	294.3575		
Power Distribution O&M	380	Annual GWP Fuel Cost (US$)	6296.883		
		Annual DP Fuel Cost (US$)	5613.302		
		Yearly Gen EHE	4906301		
		Yearly Gen Permeate	29198.96		