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Final Report

Techno-economic Evaluation of BWRO Systems for Brackish Water Desalination in the Jordan Valley

by:

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Acronyms and Abbreviations

ADS: Arab Development Society

BOOT: Build-Own-Operate-Transfer

BWRO: Brackish Water Reverse Osmosis

COPSCO: Consolidated Palestinian Company

CMWU: Coastal Municipal Water Utility

DEEP: The Desalination Economic Evaluation Program

DR: Discount Rate

EC: Electrical Conductivities (µS/cm)

ED: Electro Dialyses

EMS: Electromechanical Services

GES: Global Environmental Services

IAEA: International Atomic Energy Agency

IR: Interest Rate

MCM: Million Cubic Meters

MEDRC: Middle East Desalination Centre

µS: Micro Siemens

NIS: Israeli New Shekel

NPV: Net Present Value

PARC: The Palestinian Agriculture Relief Committee

PCBS: Palestinian Central Bureau of Statistics

PPM : Part Per Million

PV: Photovoltaic

PWA: Palestinian Water Authority

Kwh: Kilo Watt Hour

RES: Reneweble Energy Sources

RO : Reverse Osmosis

TDS: Total dissolved solid (mg/L)

TWC: Total water cost

UPC: Unit product cost ($/m^3)

Abstract

Due to the brackish water nature of ground and limited access to fresh water resources, few Brackish Water Reverse Osmosis (BWRO) desalination plants were constructed in the Jordan Valley. Two BWRO units, one in Marj Na'aja (1320 m^3/d) and the second in Al-Zubeidat (10 m^3/d) were taken as case studies. The aim of this study is to evaluate the techno-economic feasibility of these water treatment facilities, with focus on factors affecting the unit cost of desalinated water and coupling solar photovoltaic (PV) to BWRO desalination unit. The study also aimed to formulate guidelines for desalination in The Jordan Valley. For these purposes the Desalination Economic Evaluation Program (DEEP) was used to redesign and analyze the collected data.

The analysis results prevailed that the unit product cost (UPC) of Marj Na'aja BWRO unit is \$0.245 /m^3 and is capable of producing water in the range of \$0.21-\$6.54 /m^3, depending on the plant size, power source and cost. The cost breakdown results of Marj Na'ja unit showed that energy, material, labor, and capital costs account for 64%, 4%, 20% and 12% of the total costs, respectively.

Furthermore, the results analysis indicated a water production cost of \$0.423/m^3 if Marj Na'aja unit was powered by solar PV cells instead of electricity. On the other hand, the economic analysis of the smaller BWRO unit of Al- Zubiedat powered by PV cells showed that the UPC is \$5.09/m^3. This indicates that the UPC of the small scale BWRO desalination units are higher than the larger ones. In addition, the analysis results showed a higher cost factors for energy and labor costs of the electrically powered Marj Na'aja BWRO unit compared to the solar powered scenario. However, capital and labor costs were representing the highest two cost factors for Marj Na'aja unit when powered by PV cells. On the other hand, for Al- Zubiedat BWRO unit material and labor costs were forming the highest cost factors.

Finally, the outputs and the collected results from the economic analyses, costs breakdown and sensitivity analysis were employed to formulate guidelines for BWRO desalination in the Jordan

valley. The suggested guidelines focused on the economics of BWRO desalination, and on the best practices to be applied in order to reduce the production costs of fresh water from desalination.

Contents

List of tables

List of figures

1 Introduction

1.1 Background

Palestine suffers from water shortage problem, not contributed to unavailability of water resources, but because of the occupation's dominance and restrictions on the natural water resources. This consequently limits the access of Palestinians to these resources. The major natural water resources in Palestine namely are; Mountain aquifer (the Western, the North –Eastern, and the Eastern aquifer basin) in West Bank, Coastal aquifer in Gaza and the Jordan River. Palestinian Water Authority (PWA) recognizes this issue, and started to look for unconventional water resources, in order to fulfil the gap between the water supply and the water consumption. One of these resources is desalination of saline and brackish water, especially in Gaza strip, where a significant rise in salinity level was observed in the coastal aquifer wells as a result of continuous over pumping, according to the PWA's annual water status report, 2011. Moreover, brackish ground water wells have been detected in the Jordan Valley. Recently, desalination using Reverse Osmosis (RO) technology has been adopted by PWA strategies (2012-2017). Though, it has been implemented on a small scale only, with total capacity ~ 2-3 MCM/ year.

RO technology is based on pressurizing saline water across a membrane which allows only the passage of fresh water and retains salts. In other words, increasing the brine concentration on one side and producing fresh water on the other. Advances over the last decades have dramatically reduced the energy costs associated with RO desalination technology. However, desalination is still an energy intensive process (Mistry et al., 2011), where, energy use per unit of water in RO plants increases as the input water quality deteriorates. Furthermore, experience with desalination technology still relatively new in Palestine. Therefore, there is a need for a deep understanding of the costs associated with implementing RO technology, with the Jordan Valley is chosen as the case study. This requires studying the effects of applying various power sources for RO desalination plants. This will empower the comparison of different number of design options on a reliable basis with common assumptions and by applying different scenarios. This research also intends to study the effect of different parameter (e.g. feed salinity, electricity cost, interest rate, etc.) on the unit cost of desalinated water. Moreover, there is a need for development of guidelines for desalination in the Jordan Valley that defines the best practices to be applied to reduce the cost of producing fresh water from desalination for agricultural and domestic uses in the Jordan Valley area. Therefore, the outputs and the results obtained from this study will be employed to formulate guidelines for BWRO desalination in the Jordan valley.

1.2 Description of Study Area

1.2.1 Location and population

The Jordan Valley is part of the Jordan Rift, which is a long depression of the earth's crust that extends from Turkey in the north to the Red Sea in the south, passing through Syria, Lebanon, Jordan and Palestine (Da'as and Walraevens, 2013). The Jordan Valley area, which is located in the eastern part of The West Bank, is well known for its fertile productive soil. The Jordan Valley area is about 1,611,723 dunams, representing 28.8 % of the total area of the West Bank, of which 87.5 % of this area is located in Area C[1](Yael, 2011).

Jericho and Al Aghwar area, the most representative area of the Jordan Valley, is located in the central-southern part of the Jordan Valley, to the west of the Jordan River and northwest of the Dead Sea. It is bounded by Wadi Nuwei'meh and Wadi Marrar to the north and south, respectively; the Jordan River forms the eastern boundary and the Jordan Rift Fault is the western boundary (Da'as and Walraevens, 2013). The findings of Palestinian central bureau of statistics (PCBS) showed that the total population of Jericho & Al Aghwar governorate was 49,390 capita in 2013.

[1] Based in the agreements signed between occupation and the Palestine, the West Bank is divided into Areas A, B, and C. Where, Area A was transferred to the complete control of the Palestinian Authority; Area B is under Israeli control in security matters and Palestinian control in civilian matters; and Area C, which comprises 60 % of the land area of the West Bank, under complete Israeli occupation.

1.2.2 Climatic condition and rainfall

The climate of Jericho and Al Aghwar area is classified as arid. The recorded annual mean temperature was 24.2 °C and the annual mean of maximum air temperature reached 31.0 °C for 2008. Whereas, the annual mean of minimum air temperature was 17.9 °C in Jericho Station in 2008 (PCBS, 2009). The data of Jericho Meteorological station in 2008 indicated that the quantities of rainfall reached about 118.8 mm in Jericho Station. According to the PCBS, Jericho had the highest annual mean of evaporation as it approached 2,342 mm. The data of 2008 shown that the annual mean of quantity of evaporation increased in July to 308.9 mm in Jericho Station (PCBS, 2009). The annual mean sunshine duration for Jericho Station in 2008 was 8.9 hour\day, while the mean wind speed was 7.1 Km/hr., while the recorded mean annual atmospheric pressure was 1,036.9 mbar (PCBS, 2009).

1.2.3 Water resources and salinity

Water is being provided to Jericho mainly by 'Ein AL Sultan water spring, through the public water network established in 1955 by Jericho Municipality (Jericho municipal Council, 2011). The average rate of water pumped from 'Ein AL Sultan spring is around 650 m^3/ hr. The spring water is being distributed in specific quantities among the public water network (ARIJ, 2012). Figure 1 shows the allocation of 'Ein AL Sultan spring quotas, where water is used mainly for domestic and agricultural uses (Palestinian Hydrology Group, 2011). It can be noticed from Table 1 that the amount of water consumed in Jericho city in 2009 was equivalent to 169,280 m^3/month. Therefore, the rate of water consumption per capita in Jericho found to be around 225 L/day (ARIJ, 2012b).

In addition, there are four public harvesting reservoirs in the city; the combined capacity of which reached 4,500 m^3 (Jericho Municipal Council, 2011).

Furthermore, the price of water in Jericho is the least among Palestine because of the low pumping cost of the water available from 'Ein AL Sultan spring; where water selling price is only 1.4 NIS/m^3 (0.41 \$/m^3) (Jericho Municipal Council, 2011). Another water resource in the Jordan Valley is Al 'Auja spring, which is one of the main springs in Palestine; with estimated rate of discharge being considered more than 10 million cubic meters per year, (ARIJ, 2012a). The spring's discharge primarily depends on the quantity of rainwater, meaning the discharge declines if the amount of rains decreases. Moreover, the spring is susceptible to 'drying out', which used to happen infrequently but has in recent years become a more frequent phenomenon. Also, the spring dried out as a result of the Israeli Mekerot Company over extracting water from the aquifer once the spring water started to flow. Al 'Auja town receives water from the privately owned Israeli company 'Mekerot' (ARIJ, 2012b). The average rate of water supply per capita in Al 'Auja town is around 174 liters per day, with the quantity of water supplied to Al 'Auja in 2011 being estimated at 18,250 m^3/ month (GVC & FAO, 2015).

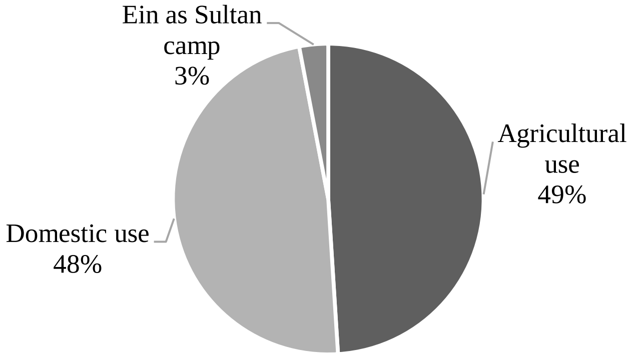

Figure 1: Distribution of 'Ein AL Sultan spring water quotas, 2009, (Palestinian Hydrology Group, 2011)

While, the specified quantities of water used for agriculture, reach farmers through agricultural channels at particular time periods. For agricultural uses, most of farmers depend on agricultural wells, PWA give license to operate these wells, around 162 agricultural wells located in the Jordan Valley with total abstraction capacity that reaches 16.631 MCM/year (PWA, 2013). Categorization of the wells capacity is listed in Table 1 below, assuming the operation time is 18 hour operation a day.

Table 1: Agricultural wells categorization source (PWA, 2013)

Categorization of licensed abstraction (m^3/hr)	No of wells
Less than 10	42
10-20	32
20-30	24
30-40	9
40-50	5

Based on Areej report in 1995, the geology of the Jordan Valley is characterized by the Jordan rift valley deposits which are mainly consisted of Marl and Pleistocene alluvial formations. Jericho and Al Aghwar lies on top of two sub-basins of Eastern Aquifer. The chemical composition of such soils causes a high mineral content (e.g. Na, Ca, K, and Mg) in the ground water wells and springs. Many studies proofed that the shallow aquifer of the Jordan Valley is more saline than any of the other aquifers. This is partially contributed to the chemical composition of groundwater in the Rift which depends on the mixing ratio between the natural precipitation and the brines or with their diluted equivalents (Moller, 2007). Based on Moller study, brines flushed from sediments and from adjacent sedimentary rocks, which host entrapped brines from the precursors of the Dead Sea formed during the late stages of Lake Lisan leads to high rise in salinity in springs located along the northwestern shore of the Dead Sea. Fresh water flushes out these residual brines as a result of the continuous falling of the sea level, (Moller et al., 2006). Moreover, the total reliance on groundwater that is fed from the Quaternary and Mountain Aquifers of the Eastern Basin leaded to overexploitation of various well fields. This resulted in yield drops from various wells as well as salinization of the resource (Da’as and Walraevens, 2013 and Areej, 1995).

Moreover, the return flow of brackish water from irrigation has an effect on ground water salinity (agricultural pollution) (Da’as and Walraevens, 2013). Additional factor affecting the ground water quality in Jordan Valley is the seepage of untreated water to groundwater wells and springs (Maan Development Center, 2010). Da’as and Walraevens study revealed that the groundwater salinity and the ion contents are increasing towards the east and with increasing depth. Ground water quality in the Jordan Valley is described in Figure 2.

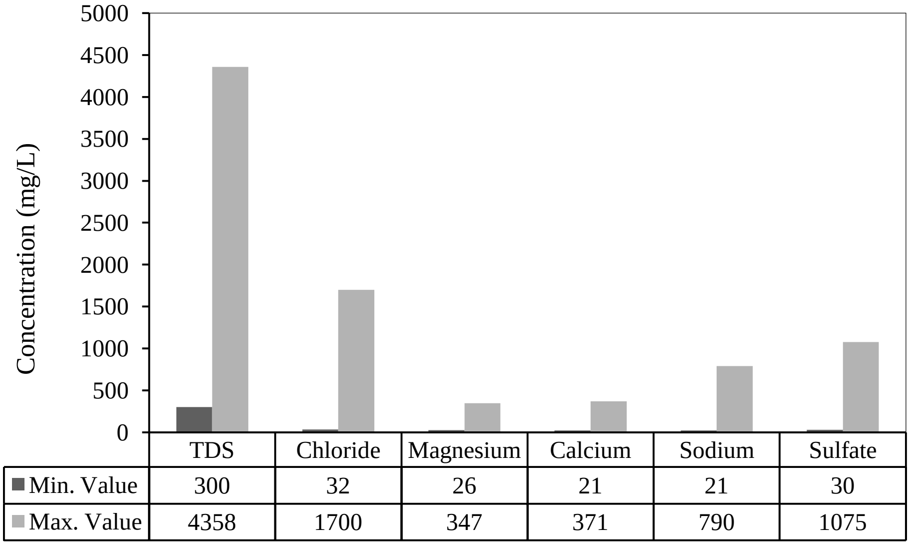

Figure 2: Ground water quality in the Jordan Valley (Da’as and Walraevens, 2013)

Jordan Valley water wells quality is monitored by PWA. Water well analysis has shown that most of agricultural wells are of deteriorated quality, and salinity is the major issue of the wells quality. Maximum salinity level expressed in electrical conductivity (EC) recorded in 2012 was 6,870 µs/cm, where the minimum was 358 µs/cm (PWA, 2013). The quality deterioration heading to east and northern east of Jericho and Tubas districts affected by the salinity of the Jordan Valley aquifer (Marie and Vengosh, 2001). The following table represents saline water locations in the Jordan Valley, quantities and salinity values.

Table 2: Saline water resources in the Jordan Valley

Source	Quantity (million m^3/yr)	Salinity as TDS (mg/L)
Al Fashkha	80-100	5000
Al Maleh	1	3000
Jericho,Alojah,Alzbeidat,Marj na'ja and Marj gazal	5	1500-3500

The largest cultivated agricultural area is located in the Jordan Valley and constitutes 52% of the total irrigated land in the West Bank. Besides, the Jordan Valley is described as fertile productive region, which is correspond 52% of the total irrigated land in the West Bank and known as the food basket of Palestine where citrus, bananas, date palms, vegetables and field crops are grown all over the year, (Da'as and Walraevens, 2013). Since precipitation rate in the Jordan Valley is low, and potential evaporation is high (2200 mm/year), rain fed farming is not feasible in the region, pressure is rising on ground water wells and springs exploitation. However, groundwater quality is deteriorated mainly due to high chloride concentration and, to the elevated concentrations of sulfate and nitrate in some boreholes, which may restrict the use of groundwater, especially for agricultural purposes, according to Da'as and Walraevens, 2013.

1.3 BWRO desalination plants in Palestine

The first BWRO desalination plant in Palestine was built in 1991 in Dir El-Balah (Gaza). It was constructed by the Electromechanical Services (EMS), a subsidiary of the Israeli makorot, with a capacity of 45 m^3/h (Al sheikh et al., 2003). Since then, many small and large scale plants were operated especially in Gaza, where the salinity levels are very high (TDS more than 2200 mg/L) (Abuhabib et al., 2012). There are seven desalination plants distributed over Gaza, six for brackish water and one for sea water, that are operated by Coastal Municipal Water Utilities (CMWU) (Mogeir et al., 2013).

In West Bank, there are four small scale brackish water desalination plants located in the Jordan Valley, namely are: Al- Zubeidat plant, Marj Na'jaa plant, The Palestinian Agriculture Relief

Committee (PARC) desalination pilot project, and Consolidated Palestinian Company (COPSCO) desalination unit. This study will focus on Al- Zubeidat and Marj Na'ja BWRO desalination plants.

1.4 Technical performance and operational conditions of BRWO desalination plants in the Jordan Valley

1.4.1 Marj Na'jah BWRO desalination unit

Project location and description

The desalination unit was installed in Marj Na'aja village which is located to the Northern part of the Jordan Valley (32° 10′ 56.74 N, 35° 10′ 28.33 E) and about 40 km far from Jericho (Figure 3) (Nofal, I., 2015). The main economic activity in the village is the agriculture. However, this activity is facing many problems like, low land quality, water salinity, low productivity of crops and low Fruit quality. The cropping pattern in the study area is mainly vegetables and some date palm and field crops. The total cultivated lands equal 111.3 hectare in which 93% of it is cultivated by vegetables. According to MoA, wealthy farmers had shifted from growing vegetables to another soil and water salinity resistance crops such as date palm trees (Abuhaija, 2015).There are 6 wells in Marj Na'aja village that were used for irrigation all of these wells are suffering from salinity problem at different levels. The MoA suggested to solve the salinity problem through a constructing a pilot RO unit at Marj Na'aja (well No 19-17/020), where salinity level varies between 4500-5000 ppm. The detailed budget needed to construct the unit defined by MoA and the donor agencies for each item are presented in Table 3 below.

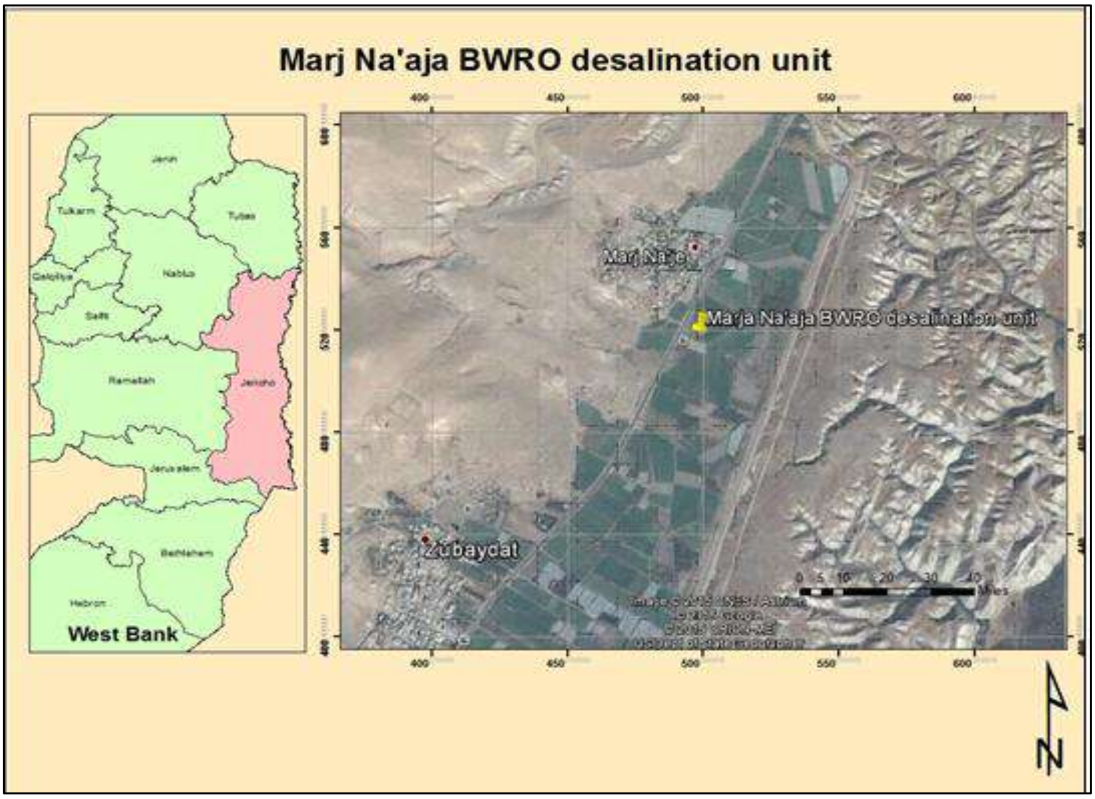

Figure 3: Location of Marj Na'aja RO unit

Technical and operational conditions

The capacity of Marj Na'ja RO unit is between 60-75 m^3/hr. at the inlet, producing 50 m^3 of permeate water per hour, with salinity levels between 600 and 1000 ppm. Construction of two tanks with capacity of 150 m^3, and 250 m^3 was also proposed; the first tank needed for the collection of saline water from the well before being pumped to the RO unit, and the second one for the collection of the desalinated water from the RO to be pumped later directly for irrigation use. The pre-filtration step consisted of two stages, namely are, sand filtration with backwash and cartridge filter.

Blending desalinated with brackish water was applied to increase mainly calcium and magnesium content. The unit produce 1320 m^3 of fresh water/d (60 m^3/d after blending × 22 pumping hours). The output of brine solution is 420 m^3/d (20 m^3 of brine solution generated for each 75 m^3 enter the unit). The generated brine is discharged through a pipeline into the Jordan River. The main indicative site data in addition to technical performance of Marj Na’aja BWRO desalination plant are summarized in Table 4.

Table 3: The budget needed for the construction of Marj Na’aja Ro unit (MoA)

Item	Suggested Budget ($)	Donor
RO unit	100,000	Arab Organization for Agriculture development (AOAD)
RO infrastructure	4,000	Local Villagers
Saline water collection tank	8,000	United Nation Development Program (UNDP)
Desalinized water collection tank	9,000	United Nation Development Program (UNDP)
Saline water pumping booster	3,000	United Nation Development Program (UNDP)
Braine water line	3,500	Dutch Project
Well rehabilitation	3,500	Red Cross (RC)
Desalinized water conveying line	1,000	JICA
Desalinized water pumping booster	7,000	Local Villagers (this amount needed on yearly bases
RO operation and maintenance	1,2 00	Local Villagers (this amount needed on yearly bases)

Table 4: Technical performance and operational condition of Marj Na’aja BWRO desalination unit (Abuhaija, 2015)

Permeate flow:	50.00 m^3/hr	Raw water flow:	71.7 m^3/hr
HP Pump flow:	66.7 m^3/hr	Blended flow:	55.0- 60.0 m^3/hr
Feed pressure:	14.5 bar	Permeate recovery:	75.0 %
Feed water Temperature:	30.0 °C	Blending ratio:	9.1 %
Feed water pH:	7.7	Element age:	3.0 years
Chemical dose, ppm (100%):	0.0 H_2SO_4	Flux decline % per year :	7.0
		Fouling factor:	0.80
		Salt passage increase, %/yr:	10.0
Average flux rate:	24.9 L/m^2.hr		

Stage	Perm. Flow	Flow/Vessel feed		Flux	Beta	Conc. &Throt. pressure		Element type	Elem. No.	Array
	m^3/hr	m^3/hr	m^3/hr	l/m^2.hr		bar	bar			
1-1	39.5	11.1	4.5	29.5	1.17	13.6	0.0	CPA3	36	6x6
1-2	10.5	9.1	5.6	15.8	1.05	12.0	0.0	ESPA2	18	3x6

	Raw water		Feed water		Permeate		Concentrate	
Ion	mg/L	meq/L	mg/L	meq/L	mg/L	meq/L	mg/L	meq/L
Ca	344.9	17.2	344.9	17.2	34.956	1.7	1367.5	68.2
Mg	410.7	33.8	410.7	33.8	41.627	3.4	1628.5	134.0
Na	447.6	19.5	447.6	19.5	62.821	2.7	1717.4	74.7
K	48.0	1.2	48.0	1.2	7.316	0.2	182.3	4.7
NH_4	0.5	0.0	0.5	0.0	0.076	0.0	1.9	0.1
Ba	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
Sr	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
CO_3	0.6	0.0	0.8	0.0	0.055	0.0	3.0	0.1
HCO_3	274.0	4.5	299.2	4.5	36.696	0.6	1157.8	19.0
SO_4	598.0	12.5	598.0	12.5	57.705	1.2	2381.0	49.6
Cl	1914.0	54.0	1914.0	54.0	216.343	6.1	7516.3	212.0
F	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
NO_3	47.0	0.8	47.0	0.8	11.433	0.2	164.4	2.7
B	0.00		0.00		0.000		0.00	
SiO_2	0.0		0.0		0.00		0.0	
CO_2	22.05		9.83		10.94		9.83	
TDS	4085.2		4110.6		469.0		16120.0	
pH	7.2		7.7		6.7		8.1	

Table 5 illustrates the capital cost, the annual running costs and the cost of desalinated water produced by Marj Na'aja BWRO unit. These data were provided by the MoA, (Abuhaija, 2015).

Table 5: The capital cost, the operational running cost and the cost of desalted water, (Abuhaija, 2015)

Total cost	
Fixed cost	**160000 $**
RO unit	100000 $
Storage tanks ,Pumping units, brine line	60000 $
Running cost	**65929 $**
Electricity	1.2 KW/m^3 or 0.13 \$/m^3
Antiscalant	1 liter / 1320 m^3 (1 liter = 3 $)
Cotton filters	500$ every 6 months
General maintenance	100 $/month
Cost of produced desalted water	**0.346 \$/m^3**

1.4.2 Al- Zubeidat BWRO desalination unit

Project location and description

Al-Zubeidat village in Jericho Governorate located about 35.4 km north of Jericho City and bordered by the Jordan River to the east, Marj Na'aja village to the north, Tubas city to the west, and Marj al Ghazal village to the south (Figure 4). The agricultural area in Al- Zubeidat is about 3,944 dunums in which 877.5 dunums are cultivated by vegetables. There are three groundwater wells located in Al-Zubiedat and used for agricultural purposes (ARIJ, 2012[a]).

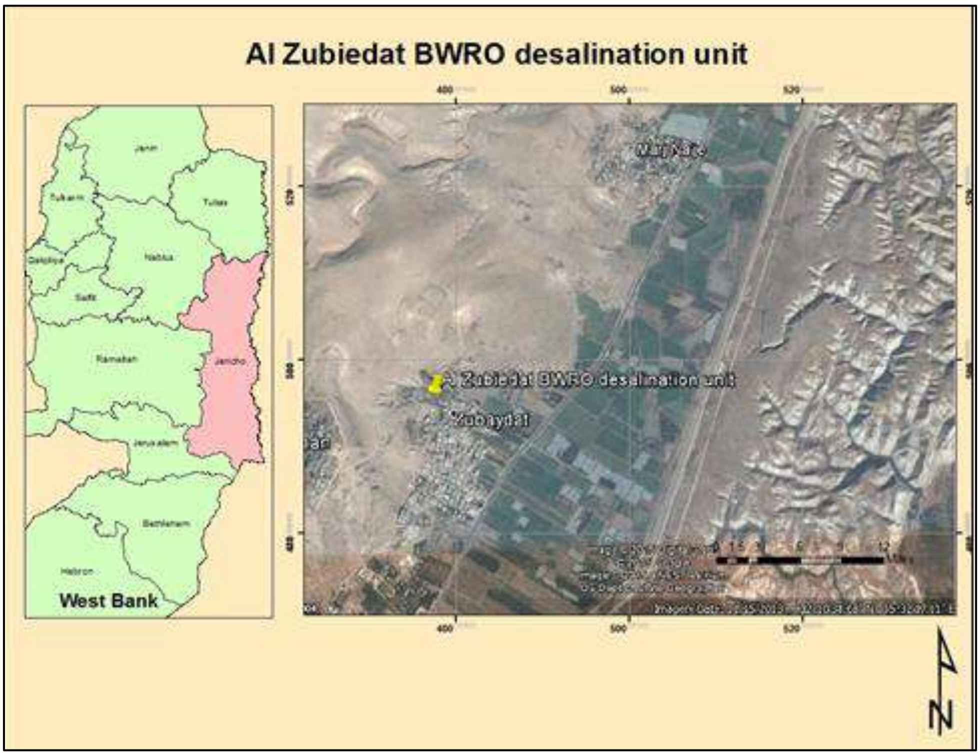

Figure 4: Location of Al-Zubeidat BWRO desalination unit

Technical and operational performance

The BWRO desalination unit of Al- Zubaidat has been implemented by Al-Najah University in cooperation with the Global Environmental Services (GES) under the supervision of PWA and was funded by Middle East Desalination Centre (MEDRC), (Bsharat, 2014). In the desalination unit of

Al-Zubeidat, raw water is pumped from a local groundwater well in the village to a 200 m^3 storage tank before being pumped to the desalination unit (Yousef, 2013).

Al- Zubeidat project is a typical RO unit powered by a PV power plant of 28 solar modules providing an average 5 kw/hr. The RO process proceeded by a pre-filtration step consisted of two stages, the multi-media filtration and the cartridge filters. Two columns of multimedia filter were installed (16 inch dia. × 65 inch length, each) to remove suspended and colloidal solids. While, two cartridge filters were installed (4 inch dia. × 20 inch length) for the purpose of providing additional support against the passage of clay, silt or other chemical impurities. The RO Membrane used in the project is spiral wound type (4 inch dia. × 40 inch length), the active area of one membrane element is about 7.2 m^2(Yousef, 2013). The unit contained three vessels that were connected in series, each vessel comprises of two RO membranes connected also in series, meaning that six RO membranes were installed in the project of Al-Zubeidat. An antiscalant storage tank with a 100 liter capacity with auxiliary dosing pump for injecting the antiscalant directly to the feeding water pipe.

The unit produces 10 m^3 of desalinated water/day (1.538 m^3/h×6.5 h/day) that is used for domestic consumption by nearby houses in the village. The desalinated water is blended with saline raw water at (2:1) ratio. The generated brine is discharged to the Agricultural network; however, small scale pilot of salt drying beds has been tested in the site (Baharat, 2014).

Results of Yousef study showed that; 28 PV modules were installed on the roof of the brackish water tank in two arrays; the front array consists of 12 PV modules and the rear of 16 PV modules (Yousef, 2013) and (Bsharat, 2014). The main indicative site data as well as technical performance of Al- Zubeidat BWRO desalination plant are summarized in Table 6 below.

Moreover, according to Yousef, 2013, the total capital cost of AL- Zubeidat BWRO desalination unit was about 58,000$. The detailed estimation of the capital and the operational cost performed by Yousef, 2013, is illustrated in Table 7.

Table 6: The technical performance and operational condition of Al- Zubeidat BWRO desalination unit, (Yousef, 2013)

Permeate flow:	1.53 m^3/hr	Raw water flow:	2.36 m^3/hr
HP Pump flow:	3 m^3/hr		
Feed pressure:	10.75 bar	Permeate recovery:	65.0 %
Feed water Temperature:	25.0˚C (81 F)	Blending ratio:	9.1 %
Feed water pH:	7.6		
Chemical dose, ppm (100%):	0.00 H_2SO_4		
Power	1.68 kW		
Specific energy	1.09 kWh/m^3		
Average flux rate:	35.28 L/m^2.hr	Feed type:	Well Water (SDI<3)

	Raw/ Feed water		Permeate		Concentrate	
Ion	mg/L	meq/L	mg/L	meq/L	mg/L	meq/L
Ca	200	10.00	3.61	0.09	564.00	14.10
Mg	146	12.17	2.48	0.21	411.00	34.25
Na	483	21.00	15.64	0.68	1351.30	58.75
K	13.1	0.34	2.48	0.06	32.80	0.84
NH_4	0	0.00	0	0.00	0.00	0.00
Ba	0	0.00	0	0.00	0.00	0.00
Sr	0	0.00	0	0.00	0.00	0.00
CO_3	1.82	0.06	0	0.00	12.84	0.43
HCO_3	305	5.00	0	0.00	871.40	14.29
SO_4	187.7	3.91	2.38	0.05	522.90	10.89
Cl	1200	34.29	26.6	0.76	3379.00	96.54
F	0	0.00	0	0.00	0.00	0.00
NO_3	36	0.58	10.42	0.17	83.50	1.35
B	0.85	-	0.37	-	0.63	-
SiO_2	21.6	-	0.37	-	61.01	-
CO_2	7.8	-	8.2	-	12.80	-
TDS	2593.7	-	77.3	-	7259.70	-
pH	7.6	-	6.7	-	8.06	-

Table 7: Capital and operational costs of Al-Zubeidat BWRO desalination unit (Yousef, 2013)

Component	Quantity	Unit price ($)	Life time year	Total price ($)
PV module (185 W)	5180 WP	1/Wp	20	5180
Batteries (2V/875 Ah)	24	437.5	10	10500
Charge Controller (2.5 kW)	2	1500	20	3000
Inverter (3.6 kW)	3	2100	20	6300
Installation Material	---	---	20	1000
Installation (electrical & mechanical) Cost	---	---	---	2000
Transfer pump	1	2400	20	2400
High pressure pump	1	3500	20	3500
Anti-scaling pump	1	1000	20	1000
Multimedia filter	2	1100	5	2200
Cartridge filter	2	600	5	1200
RO membrane vessel	3	3500	5	10500
Piping, valves, gages	1	3900	20	3900
Electric control panel	1	1200	20	1200
Instrument control panel	1	2000	20	2000
Cleaning system	1	1500	20	1500
Steel structure (epoxy coated)	1	1400	20	1400
Total capital cost of the system ($)				**58780**
O & M cost $/year				3527
Replacement of cartridge filter replacement ($/yr.)				1200
Replacement of multimedia filter ($/yr.)				2200
Replacement of RO ($ every three years)				10500
Replacement of battery ($ every three years)				10500
Salvage Value ($/yr.)				5878
Annual running cost ($/year)				**33805**
Cost of produced water ($/m^3)				**3.17**

1.5 Problem definition

Due to the fact that the occupation controls the major water resources, the available natural water resources are already overexploited and water quality is threatened. Therefore, looking for unconventional water resources such as desalination of brackish water or seawater can be used to fulfil the gap. Recently, desalination using RO technology has been adopted by PWA strategies. Though, it has been implemented on a small scale only, with total capacity ~ 2-3 MCM/Y (PWA, 2011). This amount is provided through small scale desalination units that belong to 100 private water suppliers, in addition to one public sea water desalination plant and around six public brackish water desalination plants operated by CMWU and Municipal Departments (PWA, 2011).

The Jordan Valley, in particular is facing limited accessibility to water resources and quality deterioration challenges, due to the continuous rising in annual demand for agricultural, and over extraction of groundwater wells. All of these factors led to the increase in salinity levels ~1000 – 10000 ppm according to Bsharat, 2014.

Therefore, four small scale brackish water desalination plants are located in the Jordan Valley. However, brackish groundwater desalination via RO is an energy intensive process, thus relatively costly, especially if powered by purchased electricity. In Palestine, only few studies focused on analyzing the economic feasibility of the desalination facilities located in the Jordan Valley area. The most recent one was conducted by Basharat, 2014. Thus, additional studies are needed to conduct a comparison between applying different energy sources to RO desalination plants, especially solar energy, and there economic implications. It's also essential to study the unit cost of the desalinated water and the effect of different parameter (e.g. feed salinity, electricity cost, interest rate, etc.) on the unit cost of desalinated water. Moreover, there is a need for developing a strategy for desalination in the Jordan Valley that define the best practices to be applied to reduce the cost of producing fresh water from desalination for agricultural and domestic uses in the Jordan Valley area.

1.6 Research questions and objectives

1.6.1 Research Questions

- What are the key considerations in BWRO desalination projects in the Jordan Valley to define the best practices to be applied to reduce the cost of desalination?
- What are the effects of applying various sources of power (electricity and solar energy) in RO desalination plants on the unit cost of desalinated water?
- What are the factors that affect the unit cost of desalinated water in the Jordan Valley?

1.6.2 Research Objectives

This research aims to highlight the applicability of RO desalination systems to overcome the water issues in the Jordan Valley. Consequently, this research is intended to evaluate cost and performance of various sources of power (electricity and solar energy) in order to enable an effective comparison of different alternatives Moreover, this research intends to study the effect of different parameter (e.g. feed salinity, electricity cost, interest rate, etc.) on the unit cost of desalinated water. Also, it aims to investigate the opportunity of applying RO desalination of the brackish water resources in the Jordan Valley (on a larger scale).

Besides, the research aims to use the findings from the economic analysis to formulate guidelines for BWRO desalination in the Jordan Valley. This key guidelines focus on the economics of BWRO desalination, and on the best practices to be applied to reduce the cost of producing fresh water from desalination in the Jordan Valley area.

1.7 Methodology

As a first step, the research highlights the current water and energy issues in the Jordan Valley. Field data was collected by a comprehensive survey, as a form of personal interviews with RO plants operator. Then, the collected field data was analyzed, in order to precisely evaluate the economic performance of existing RO desalination plant in Jordan Valley.

In the evaluation process, local data and assumptions from pervious literature were used. The cost data include site-specific feed intake, pretreatment, post-treatment, site development and concentrate treatment costs, RO replacement, water transport costs, etc.

In order to perform the cost comparison, the Desalination Economic Evaluation Program (DEEP) was used. DEEP is a tool freely available and developed by the international atomic energy agency. DEEP was used to evaluate the performance and the cost of various water and power co-generation configurations. The results were used to hold a comparison of a large number of design options and scenarios on a consistent basis with common assumptions.

In this study, three scenarios were analyzed economically. The first case was analyzed by taking the present situation in Marj Na’aja BWRO unit as the base case. The second scenario was to analyze the option of coupling solar energy to the BWRO unit in Marj Na’aja. And the third scenario was the small scale Al- Zubiedat BWRO unit- powered by PV. Besides, sensitivity analyses were carried out by changing several important parameters that could potentially have a major influence on the UPC. Those parameters are plant water capacity, electricity cost, interest rate, plant availability, feed water salinity, and feed water temperature. These analyses will be carried out to permit deep understanding of possible trends in the cost of desalinated water as the mentioned factors change. The common approach is to choose a base case scenario of input values and to change one factor, while holding all other input variables constant.

The obtained results will be employed to develop guidelines for desalination in the Jordan Valley. The guidelines will focus on improving the development and management of desalinated water in the Jordan Valley, and providing principles that link resource management to the specific water-using sectors. The main objectives of developing the guidelines are to: guide governmental agencies and private sector investments towards desalination projects, to improve economic assessment and management of water desalination, and to highlight the topics that need further research to improve desalination. The first step in formatting the guidelines is to make investigations and deep understanding of study area, and define water challenges and key issues. Then, by relaying on the results obtained from the economic analysis, cost breakdowns and sensitivity analysis, approaches and guidelines will be developed. These guidelines are intended to improve technical and economic performance of BWRO desalination units, and to introduce the best practices to reduce the cost of desalination in the Jordan Valley.

2 Literature Review

2.1 Desalination technologies

The most worldwide used desalination processes are membrane technology using RO. About 59.85% the total global desalination capacity produced by RO, besides to three forms of thermal separation, namely are; multistage Flash desalination (MSF), Multiple-Effect Evaporation (MEE), Multiple-Effect Evaporation with thermal vapor compression and Mechanical Vapor Compression (MVC). However, only RO processes are considered in Palestine for both brackish water and seawater desalination due to the vital advantages provided by the RO technology, such as, it's lower cost, it's compact size, simplicity of operation, high salt rejection, higher recovery ratio and lower environmental impact, even more, the removal of inorganic and organic matter, bacteria and viruses (Greenlee et al., 2009), (Karagiannis et al., 2008), and (Zhou and Tol, 2005).

2.2 Basics of RO desalination technology

RO is a form of highly pressurized filtration by using a semi permeable membrane that allows water to pass through from the high pressure side to the low pressure one, but retains salts, generating fresh water and a concentrated brine solution on the high-pressure side of the membrane (Al-Karaghouli and Kazmerski, 2013). Figure 5 presents a schematic diagram of a typical RO desalination unit.

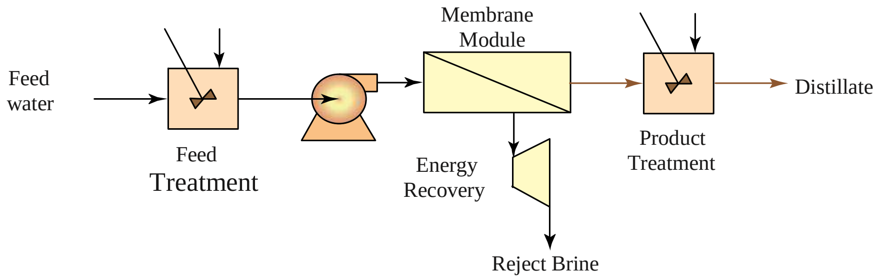

Figure 5: Scheme of a typical RO desalination unit, (El-Dessouky and Ettouney, 2002)

The conventional RO desalination plant consists of four major processes, namely are: pre-treatment, pressurization, separation, and post treatment (stabilization) (Al-Karaghouli and Kazmerski, 2012). The pretreatment of feed-water includes filtration, sterilization, and addition of chemicals to prevent scaling and biofouling of the membrane (Al-Karaghouli and Kazmerski, 2012). During the pressurization processes, the pressure of the pretreated feed water is increases normally to a proper operating pressure, which is suitable for the feed water salinity and the membrane.

The high-pressure pump produces the pressure needed to force the water to pass through the membrane. The pressure ranges from 17 to 27 bars for brackish water and between 55 and 82 bars for seawater. While, in the separation step; the membranes prevent the passage of dissolved salts but allowing the desalinated product water to pass through (Al-Karaghouli and Kazmerski, 2012). As the water passes through the membrane, the salt concentration in the remaining brine solution increases. In BWRO systems, the brine stream varies significantly, between 15 - 30% of the RO feed stream (Drak and adato, 2014). The semi- permeable membranes have different configurations. The most two of the commercially successful configurations are; spiral-wound module and hollow-fiber module. In both configurations, module elements are serially connected in pressure vessels (up to seven in spiral-wound modules and up to two in hollow-fiber modules).

The post treatment unit goals are to achieve degasification (i.e. hydrogen sulfide) and pH adjustment (Al-Karaghouli and Kazmerski, 2012). The installed capacity of RO system ranges between 0.1 m^3/day (for marine and house hold applications) up to 395,000 m^3/day (for commercial applications) (El-Dessouky and Ettouney, 2002), (ESCWA water development report 3, 2009), (Al-Sofi et al., 1995), (Zhang et al., 2005), and (Al-Karaghouli and Kazmerski, 2013).

2.3 Economics of desalination

The cost of an RO desalination plant includes two main elements: the capital and the annual operating costs (Zhou and Tol, 2005). The operating cost, is not only defined by the cost of energy consumed to power the desalination plant which is subject to rise and fall in energy prices (Zhou and Tol, 2005) and (Frioui and Oumeddour, 2008), but also includes other costs such as labor, chemicals, membrane replacement, spare parts, and insurance costs. On the other hand, the capital cost, includes direct and indirect costs. Direct capital costs include the purchase cost of main equipments (e.g., high pressure pumps) and auxiliary parts, land cost, and engineering cost, etc. (Ghaffour et al., 2013). Indirect capital costs include elements such as freight and insurance, construction, and overhead (Ghaffour et al., 2013). The normalized total desalinated water cost (TWC) in a specific plant is equal to the sum of the capital costs, amortized over the plant's life, and the annual operating costs divided by the average annual production of desalinated water in that plant, according to (Ghaffour et al., 2013) and (Zhou and Tol, 2005).

2.3.1 Factors affecting the desalination cost

Unit water production cost is influenced by different design and operational variables including; plant capacity, salinity and quality of feed water, specific site conditions and characteristics, skilled labor, energy cost, plant life, plant availability and amortization (El-Dessouky and Ettouney, 2002).

2.3.2 Components of desalination economics

The capital cost

Capital cost covers all initials costs. These costs can be calculated with average value 15-50% (Wilf et al., 2007) or 30-45% (Moch and Moch, 2003). The capital cost includes the purchase cost of major and auxiliary equipment, land, construction, management overheads, and contingency costs etc., El-Dessouky and Ettouney, 2002, reported the following as elements of capital cost:

1. Land: the cost of land may vary widely, from zero to a sum depending on the site characteristics and condition. Government-owned plants normally have zero charges.
2. Well construction: According to recent estimates, an average well construction cost indicated to be around $650 per meter depth (El-Dessouky and Ettouney, 2002). While, in Palestine well construction costs ranges between 177- 348 $/m depth according to PWA.
3. Process equipment: including; processing equipment, instrumentation and controls, pipes and valves, pumps, process cleaning systems, as well as pre- treatment and post-treatment equipment. Such equipment's considered to be expensive, and their cost according to El-Dessouky and Ettouney, 2002, depends on the type of technology and capacity.
4. Membranes: the cost of membrane modules depends on plant capacity, and ranges from $500 to $1,000 per 50-100 m^3/d modules (El-Dessouky and Ettouney, 2002).
5. Auxiliary equipment: such as, open intakes or wells, transmission piping, storage tanks, generators and transformers, pumps, pipes and valves (El-Dessouky and Ettouney, 2002).
6. Building construction: this cost might vary from $100 to $1,000/$m^2$; depending on the building type. Such buildings could include a control room, laboratory, offices and workshops (El-Dessouky and Ettouney, 2002).

Indirect capital costs

The elements of indirect cost are expressed normally as percentages of total direct capital cost. According to El-Dessouky and Ettouney, 2002, the indirect cost elements are;

1. Freight and insurance: typically equal to 5% of the total direct costs (El-Dessouky and Ettouney, 2002).
2. Construction overhead: construction overhead costs are about 15% of direct material and labor costs, and also include fringe benefits, labor burden, field supervision, construction

equipment, temporary facilities, contractor's profit and miscellaneous expenses (El-Dessouky and Ettouney, 2002).

3. Contingency costs: generally repreresnts 10% of the total direct costs (El-Dessouky and Ettouney, 2002).
4. Owner's costs: This cost is about 10% of direct material and labor costs, including engineering and legal fees (El-Dessouky and Ettouney, 2002).

Annual operating costs

El-Dessouky and Ettouney, 2002, defined the annual operating costs as expenditures that is incurred after plant commissioning and during operation, and these costs include:

1. Energy: In BWRO, energy represents about 10% of the total cost owing to a lower operating pressure. Where, capital costs and O&M costs from 65% and 25%, respectively (Wilf, 2007). The specific electricity consumption is considered the key criterion for the RO layout, which should be as low as possible. Meaning that; the recovery ratio must be kept as high as possible and the accompanying feed water pressure as low as possible. Electricity cost may vary over the range of $0.04–0.09/kWh (Al-Karaghouli and Kazmerski, 2012) and (El-Dessouky and Ettouney, 2002).
2. Labor costs: are site-specific and depend highly on plant ownership (i.e., public or private) (El-Dessouky and Ettouney, 2002).
3. Membrane replacement: membrane replacement rate may vary between 5% per year for membranes treating brackish water when incorporated with a proper operation and pretreatment systems to 20% per year for membranes treating seawater (El-Dessouky and Ettouney, 2002).
4. Maintenance and spare parts: this cost normally less than 2% of the total capital cost on an annual basis (El-Dessouky and Ettouney, 2002).
5. Insurance: is about 0.5% of the total capital cost (El-Dessouky and Ettouney, 2002).

6. Amortization or fixed charges: it accounts for annual interest payments for direct and indirect capital costs. It is obtained commonly, by multiplying these costs by an amortization (annuity) factor, which is given by (Lameia, 2008):

$$a = \frac{i \times (1+i)^n}{(1+i)^n - 1} \qquad (1)$$

Where, i is the discount (annual interest) rate and ranges between 5-10 % and n is the economic plant life. The annual cost of capital can then be calculated by multiplying the investment cost with the annuity factor (a). To convert this to a unit cost, it is further divided by annual output of the plant, according to Lameia, 2008, assumed 90% of capacity.

7. Chemical: the chemicals regularly used to clean desalination plants include sulfuric acid, caustic soda, various antiscalants and chlorine. Chemical cost may be affected by availability of close manufacturing plants and by global market prices (El-Dessouky and Ettouney, 2002). Moreover, chemical treatment depends highly on the top brine temperature and feed salinity. Table 8 provides estimates for the unit cost of the most common chemicals used in RO desalination, dosing rates and specific rates per unit.

Table 8: Estimated chemical costs and dosing rates (El-Dessouky and Ettouney, 2002)

Chemical	Unit cost $/kg	Dosing rate g/m^3	Specific cost $/m^3
Sulfuric acid	0.504	0.242	0.0122
Caustic soda	0.701	0.140	0.0098
Antiscalant	1.9	0.050	0.0095
Chlorine	0.482	0.040	0.00193

Unit product cost for the RO process depends on capacity. Recent data for existing small RO units, such as the one in Cyprus, reveal unit product costs of \$0.83/m^3 for a capacity of 40,000 m^3/d and \$1.22/m^3 for 20,000 m^3/d (El-Dessouky and Ettouney, 2002). Costs for future RO plants are mainly dependent on local factors such as energy costs, interest rate, qualified labor, and quality of intake water (Lameia, 2008).

In Table 9, costs percentage of various components for desalination of brackish water was illustrated. It can be easily found that fixed costs are the major factor, and costs associated with membrane replacement, maintenance are relatively small. These costs depend very much on the status of technology and may be further reduced with evolving of the technology, however, will not have significant impact on the overall cost of desalination. Due to improved membrane technology recently, costs of RO desalinated water production have decreased. For brackish water (less than 10,000 ppm), it has been suggested that RO is the most economic method of water desalination. The water production cost of large capacity BWRO plants (40,000 - 46,000 m^3/day) range from \$0.26 to \$0.54 /m^3, for medium capacity plants (20 - 1,200 m^3/day) the cost range from \$0.78–\$1.33 /m^3, and for very small BWRO (few m^3/day) the cost range from \$0.56 –\$12.99 /m^3 (Al-Karaghouli and Kazmerski, 2013).

Table 9: Percent Distribution of Cost Factors (Miller, 2003)

Factor	Brackish water (%)
Fixed costs	54
Electric power	11
Labor	9
Membrane replacement	7
Maintenance	9
Consumables (chemicals)	10

2.4 Comparison with similar studies

For verification of the economic analysis results, the obtained results were compared with other similar studies conducted in Palestine and with studies from different countries. Tables 10 and 11 highlights the results obtained from previous researches. Generally, it can be concluded that UPC results of BWRO units in the Jordan Valley of this study shows acceptable agreement. Furthermore, the comparison of specific power consumption also shows an acceptable agreement with other results from previous studies. The small differences are mainly contributed to the differences in the source and the cost of electrical power and the deriving pressures. It may also referred to the use of different assumptions for UPC estimations.

Table 10: Techno-economic condition of BWRO desalination plants in Gaza, Palestine (Mogeir, 2013)

Plant name	Location	Construction date	Cost (US$)	Capacity (m^3/h)	Production (m^3/day)	Recovery rate %	Energy consumption (kWh)	UPC (US$/$m^3$)
Al-Balad	Deir El-Balah	1991	650,000	60	420	75	120	0.72
Al-Sharqia	Khanyounis	1997	500,000	55	440	70	60	0.31
Al-Saada	Khanyounis	1998	250,000	80	640	70	60	0.34
Al-Bureij	Al-Bureij	2009	NA	60	480	83	60	0.28
Al-Nuwairi	B. Suhaila – Khanyounis	2010	NA	50	400	75	60	0.34
Al-Salam	Rafah	2010	NA	60	480	80	60	0.27

Table 11: Economic evaluation results of RO plants in different countries obtained from previous studies (El-Ghonemy, 2012)

	Plant-1	Plant-2	Plant-3	Plant-4	Plant-5	Plant-6	Plant-7	Plant-8
Location	Hurgada, Egypt	Sharm, Egypt	El-Tor, Egypt	Safaga, Egypt	Hurgada, Egypt	Al-jouf KSA	Sadous Riyadh, KSA	India
Construction year	2002	2002	2002	2002	2002	2000	1995	2009
Capacity (m^3/day)	4800	3500	2000	500	250	50	15	50
KWh/m^3	The energy consumption rate could reach about 11 KWh/m^3 for the smallest RO plant, and decreases to about 8 KWh/m^3 for the bigger plants					3	4.675	1.58
Unit cost	1.28$/$m^3$	1.73$/$m^3$	1.85$/$m^3$	2.46$/$m^3$	2.7$/$m^3$	2 $/$m^3$	Not mentioned	6100 IDR/m^3
Feed water intake	SW, Surface	SW, Well:	SW, Well:	SW, Well:	SW, Well:	BW, Well,	BW, Well	BW, Well

TDS (mg/L) intake	43,000	43,000	47,000	49,000	47,000	2000	5888	3850
Power source	Public electricity	Public electricity	Public electricity	Public electricity	Public electricity	Public electricity	PV-RO	Public electricity

2.5 Coupling Renewable Energy Sources (RES) with RO desalination system

The use of RES to power desalination technologies is promising for remote regions, where the connection to the public electrical grid is not feasible, and water scarcity is severe (Al-Karaghouli and Kazmerski, 2013). Several solar, wind, and geothermal or hybrid solar/wind desalination plants have been installed worldwide; most of them are a small-capacity-demonstration projects. The cost of water produced from desalination units coupled with renewable energy resources depends very much on the cost of energy produced from these resources. Regardless of the free cost of renewable energy, the capital cost of renewable energy systems is still very high; consequently the produced water cost is also high. However, with further technology development of renewable energy, the capital cost is expected to be reduced (Al-Karaghouli and Kazmerski, 2013).

RO desalination coupled with solar energy

Solar energy can be converted either to thermal energy using solar stills or solar thermal collection systems or to electrical energy that is can be produced from solar photovoltaic (PV) conversion or solar thermal power (Al-Karaghouli and Kazmerski, 2013). A schematic diagram of RO coupled with solar PV system is presented in Figure 6 below. PV- powered RO plants are considered one of the most promising systems of renewable-energy-powered desalination, especially when used in remote areas. In general, investment cost is relatively high in PV powered RO system which results in high water production cost. According to Al-Karaghouli and Kazmerski, 2013, the reported cost of BWRO system powered by PV with capacities less than 100 m^3, ranges from \$6.5 to \$9.1 /m^3.

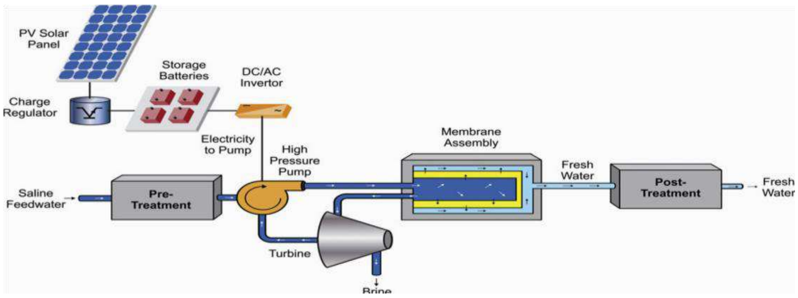

Figure 6: Schematic diagram of PV/RO system (Al-Karaghouli and Kazmerski, 2013)

RO desalination coupled with wind energy

The principle of generating energy from wind is by the use of wind turbines that convert air movement into rotational energy to produce mechanical power or drive a generator to produce electrical power (Karaghouli and Kazmerski, 2013). A large number of medium (1000 to 2500 m^3/day) and small (less than 100 m^3/day) wind powered RO systems have been designed and tested in different parts of the world. The water production cost of the medium-size systems range from 1.8 to 5.2 US$/$m^3$. For small size systems, water production cost range from $3.9 to $9.1 /$m^3$ (Karaghouli and Kazmerski, 2013).

RO desalination coupled with geothermal energy

Geothermal energy uses the heat energy beneath the earth's surface. In general, earth's temperature fluctuates widely, and geothermal energy is usable for a wide range of temperatures variation, from room temperature to over 150 ºC (Karaghouli and Kazmerski, 2013). The main advantage of geothermal energy is that thermal storage is unnecessary. Geothermal reservoirs are generally classified as being either low temperature (less than150 ºC) or high temperature (higher than 150 ºC), and energy from the earth is usually extracted with ground heat exchangers. Economics of renewable energy coupled desalination. From previous experience of different projects, it is estimated that a geothermal source with a temperature of 801 to 100 ºC can produce fresh water at a cost of $2 to $2.8 /$m^3$ (Karaghouli and Kazmerski, 2013).

2.6 Environmental impacts of desalination

The main environmental impacts commonly associated with water desalination are; gas emission resulting from energy consumption, generation of concentrated brine, and discharge of chemicals used in the pretreatment step (Karaghouli and Kazmerski, 2013).

All desalination technologies are energy intensive processes that result in the emission of a huge amount of greenhouse gases that include CO, CO_2, NO, NO_2, and SO_2. The amount of CO_2 is estimated to be 25 kg/m^3 of product water (Lattemann and Hopner, 2008) and (Dawoud, AlMulla, 2012). The use of renewable energy resources is an excellent solution to overcome such emissions.

Concentrate is the by-product of desalination. It is generally a liquid substance with very high concentration. The salinity of the brine discharged from RO plants is about 100% higher than the seawater salinity (Karaghouli and Kazmerski, 2013).

2.7 The Desalination Economic Evaluation Program (DEEP 5.1)

DEEP is a free software packages, developed for the International Atomic Energy Agency (IAEA) and used to estimate the general competitiveness of various energy sources and desalination technologies. By employing a very simple model, DEEP can be used to estimate costs for various desalination technologies and cost of different power and water configuration (El-Dessouky and Ettouney, 2002). DEEP is based on a hybrid Microsoft Excel spreadsheet and Visual Basic methodology, and is suitable for economic evaluations and screening analyses of various desalination and energy source options (Al-Karaghouli and Kazmerski, 2012). The program allows designers and decision makers to evaluate performance and cost estimates of various desalination and power configurations. It includes simplified models of different desalination options including; MSF, MED, RO, and hybrid systems, and even more different power options including nuclear, fossil, and renewable sources. Furthermore, cogeneration of electricity and water, as well as water-only plants, can be modeled and evaluated. The program as well enables a side-by-side comparison of a number of design alternatives, which helps to identify the most feasible options for water and power production at a specific location (El-Dessouky and Ettouney, 2002) and (Al-Karaghouli and Kazmerski, 2012).

There are two types of input data required by DEEP software, namely are, Technical input parameter (for example, feed water temperature and salinity, maximum design pressure, fouling factor, average flux, etc.), and the economic parameter (for example, labor salary, chemical cost for pre and post treatment, life time, etc.), (see appendix 2-A). The required input data include the plant configuration, power and water capacities, and various basic performance and costing data. The effect of salinity and temperature on recovery ratio and required feed water pressure both considered within DEEP model. Also, current cost and performance data have been incorporated within the model (El-Dessouky and Ettouney, 2002). The output of DEEP includes the levelized cost of water and power (defined as $/m^3 or $/kWh), breakdowns of cost components, energy consumption for each selected option. Specific power plants can be modeled by adjusting input data such as design power, power cycle parameters and costs.

The spreadsheet serves three important goals; enabling side-by-side comparison of a large number of design alternatives on a consistent basis with common assumptions, enabling quick identification of the most feasible options for providing specified quantities of desalinated water and/or power at a given location and it provides cost estimation of desalinated water and power as a function of quantity and site-specific parameters, such as temperatures and salinity (El-Dessouky and Ettouney, 2002) and (Al-Karaghouli and Kazmerski, 2012).

2.7.1 **DEEP model Description**

The flow chart for RO model in DEEP software is shown in Figure 7 below.

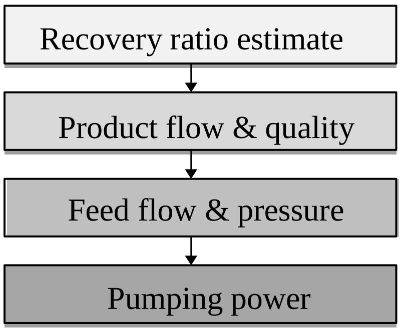

Figure 7: Flow chart for RO performance model in DEEP (IAEA, 2006)

Here, the system recovery ratio can be specified either by the user or can be estimated by DEEP, as follows (IAEA, 2006):

$R = 1 – C. S_f$ (2)

Where, S_f refers to the feed salinity in ppm and CNS is a constant and can be defined as in equation 3 below (IAEA, 2006):

$C = 1.15e^{-3}/P_{max}$ (3)

Where, P_{max} refers to the maximum design pressure of the membrane in bars. It is essential to keep in mind that as feed salinity becomes small, the recovery ratio approaches unity and as it approaches the numerical equivalent of maximum membrane pressure (in millibars), recovery approaches zero, as would be expected in practice (IAEA, 2006).

For permeate salinity and feed pressure, feed temperature and salinity correction factors are taken into account and have been verified against commercial design data. Feed pressure (P_f) can be calculated as follows (IAEA, 2006):

$$P_f = \Delta P_d + P_{osm} + \Delta P_l \qquad (4)$$

And ΔP_d can be calculated by the following equation (IAEA, 2006):

$$\Delta P_d = (\varphi d / \varphi n).\ \Delta P_n.\ c_t.\ c_s.\ c_f \qquad (5)$$

Where, $P_{osm:}$ is the average osmotic pressure across the system;

ΔP_l: is the corresponding pressure loss;

Δp_d and $\varphi_{d:}$ are the design net driving pressure and flux;

Δp_n and $\varphi_{n\,:}$ are the nominal net driving pressure and flux;

and c_t, c_s and c_f : are correction factors related to temperature, salinity and fouling, respectively. On the other hand, equation 8 can be used to calculate permeate salinity ($\mathbf{S_p}$) (IAEA, 2006):

$$S_p = (1\text{-}r_m).\ S_f.\ \varphi_n / \varphi_d.\ c'_r.\ c'_t \qquad (6)$$

Where, $\mathbf{S_f}$ is the feed salinity; and $\mathbf{c'_r}$ and $\mathbf{c'_t}$ are correction factors related to recovery and temperature, respectively, and $\mathbf{r_m}$ refers to the membrane salt reject fraction. The calculation of energy recovery ($Q_{er)}$, is given by equation 9 below (IAEA, 2006):

$$Q_{er} = (1\text{-}r_m).\ \xi_{er}\ Q_{hp} \qquad (7)$$

Where, ξ_{er} is the energy recovery efficiency and Q_{hp} is the available high pumping power (IAEA, 2006).

3 Economic analysis of BWRO desalination plants in the Jordan Valley

3.1 Economic assumptions

Preparation of reliable and consistent input is important for obtaining reliable results with DEEP. The variables that were employed in DEEP are either 'expected input' by the user or 'default data' (these can be modified) or 'part of the model' data that should not usually be changed. Desalination cost data were collected from a wide variety of sources including field surveys, reports, and published journals. The main economic parameters used for the analysis were defined in Table 12[2].

Table 12: The major economic assumptions

Parameter	Parameter	References
Discount rate (DR), %	5 %	(Bouhelal et al., 2004)
Interest rate (IR),%	6 %	(Mahmoud and Ibrik, 2006) and El-Dessouky and Ettouney, 2002)
Plant life (years)	30	El-Dessouky and Ettouney, 2002)
Plant availability (%)	95	Enrique, 2012 and Wittholz, et al. (2008)
Labor cost ($/m^3)	0.005	El-Dessouky and Ettouney, 2002)

The calculations of the Unit Product Cost of water (UPC) using DEEP were based on simplified models and correlations. The main share of capital costs refers to construction costs. While, the operating costs are divided into; energy costs and operation & maintenance costs (staff costs, insurance costs and material costs which consist of spare parts costs, chemicals for pre- and post-treatment, and membrane replacement costs). UPC is the sum of the amortized capital cost and the operating costs.

In this study, three scenarios were studied and evaluated economically. The First case was taking the present situation in Marj Na'aja BWRO unit as the base case. The second case was, coupling solar energy to power the BWRO unit in Marj Na'aja instead of electricity. The reason behind

[2] Costs related to water transportation and distributions are excluded.

choosing solar energy rather than other renewable energy resources is that the Jordan valley is well known high solar energy potential, (Mahmoud and Ibrik, 2006). The third case was the small scale BWRO unit of Al – Zubiedat, powered by PV.

3.2 Economics of desalination: Main results from DEEP

3.2.1 Case 1: Marj Na'aja BWRO unit powered by a conventional energy sources- present situation

DEEP software was used for calculating the unit water cost and the total annual cost of BWRO unit of Marj Na'aja. Table 13 presents in details the cost analysis results. The UPC is found to be 0.245$/m^3, this value is lower than the value given by Abu-Alhaija, 2015, which is $ 0.346 /m^3. However, the calculated UPC value is in agreement with the value estimated by Karagiannis and Soldatos, 2008, with UPC value ranged between $0.26-$1.33/m^3 for brackish water desalination. Miller, 2003; and Sethi, 2007 also have found that the UPC ranges between $0.10/m^3 - $1.00/m^3. Whereas, the UPC of Marj Na'aja BWRO is lower than the cost trends for BWRO desalination units provided by Jaber and Ahmed, 2004. They reported that for BWRO units with capacity range between 20-1200 m^3/d, the cost may vary from $0.78- $1.23/m^3. This shows the variation in the reported UPC values in literature The estimated UPC is less than the water selling price in The Jordan Valley which is around $0.41 /m^3, this indicate that applying RO technology for brackish water desalination is a feasible option.

It is also noticed, that Marj Na'aja BWRO exhibits a low capital costs, (12 % of the total cost, see cost break down results, Figure 8). This is contributed to the lower operating pressures required for the low salinity feed, therefore, equipment costs are low. The highest percentage in the cost breakdown is energy cost (64%). This value is high if compared to the value given by Wilf, 2007, which was 10 %. The difference could be contributed to the higher price of the purchased electricity in Palestine ($ 0.156 /kWh) compared to other countries ($ 0.04 - $0.09 /kWh, Ettounay et al., 2002). If the cost of electricity decreases, from \$ 0.15 /kWh to \$ 0.1/kWh, the UPC will be decreased potentially by 23 %, see Figure 11 (more details in section 3.4.1). However, it has been reported, that the power cost of typical brackish water RO represents only 11% of the total cost, and the largest costs are fixed costs at 54% (Miller, 2003). Labor costs for Marj Na'aja BWRO unit present 20 % of the total cost. The costs associated to the material including chemical used pre-treatment and replacement of the RO are relatively small, the average cost is \$0.01 /m^3 and about 4 % of the total cost. Pretreatment costs normally can represent a significant portion of the capital cost. However, the use of media filtration pretreatment in Marj Na'aja unit lowered these costs.

Table 13: Main cost results of case 1: Marj Na'aja BWRO unit powered by electricity

Capital Costs of Desalination Plant				
	RO	Total (M\$)	Specific (\$/m^3 d)	Share
Construction Cost	0.17	0.17	130	59%
Intermediate loop cost	-	-	-	0%
Backup Heat Source	-	-	-	0%
Infall/Outfall costs	0.09	0.09	66	30%
Water plant owners cost	0.02	0.01	6	3%
Water plant contingency cost	0.02	0.02	14	6%
Interest during Construction	0.01	0.01	4	2%
Total Capital Costs		0.291	220	
Annualized Capital Costs				
Sp. Annualized Cap Costs			**0.03**	\$/m^3

Operating Costs of Desalination Plant				
	RO	Total (M\$)	Specific (\$/m^3)	Share
Energy Costs				
Heat cost		-	-	0%
Backup heat cost		-	-	0%
Electricity cost	0.0	0.0	0.00	0%
Purchased electricity cost	0.1	0.1	0.16	73%
Total Energy Costs	0.0	0.0	0.16	73%
Operation and Maintenance Costs			-	0%
Management cost	-	-	-	0%
Labor cost	0.02	0.02	0.05	22%
Material cost	0.003	0.003	0.01	3%
Insurance cost	0.001	0.001	0.00	1%
Total O&M cost	0.03	0.03	0.06	27%
Total Operating Costs	0.1	0.1	**0.22**	
Total annual cost			**0.11**	**M\$**
Water production cost			0.245	\$/m^3
Water Transport costs			-	\$/m^3

Total water cost	**0.245**	**$/m^3**

3.2.2 Case 2: Marj Na'aja BWRO unit powered by the solar PV cells

Small capacities RO plants with simple designs powered by solar PV cells as energy sources can effectively provide fresh water to remote and rural communities. In this section, the economic feasibility of powering Marj Na'aja BWRO desalination unit with solar PV cells instead of the conventional energy sources was investigated, in order to reduce the cost of energy and then investigate if the UPC will be reduced.

In order to define the capital cost of installing the PV system, an estimation of the system size and components were performed referring to previous studies and field data. For more details about the PV system design and cost estimation see appendix 2-B (table 19-20). The estimated PV installation cost was added to the RO unit capital cost, while the cost of purchased electricity was eliminated, since the required power for the operation of the plant will be generated from the PV system.

The resulted installation cost of the PV system found to be $230,651,8. Under case 2, the capital cost percentage increased up to 76% of the total cost compared to 12% of case 1, see figures 8 and 9.

The UPC of the desalinated water by Marj Na'aja unit coupled with PV cells became $0.423/m^3. This UPC found to be relatively high when compared to the first case despite the reduction in energy costs. Yet again this is attributed to the high equipment and installation costs of the PV cells. All main cost analysis findings are illustrated in Table 14.

Table 14: Main cost results of case 2: Marj Na'aja BWRO unit powered by solar PV panels

Capital Costs of Desalination Plant				
	RO	Total (M$)	Specific ($/m^3 d)	Share
Construction Cost	1.90	1.90	1,441.35	81%
Intermediate loop cost	-	-	-	0%
Backup Heat Source	-	-	-	0%
Infall/Outfall costs	-	0.09	66	4%
Water plant owners cost	0.10	0.10	72	4%
Water plant contingency cost	0.20	0.20	151	9%
Interest during Construction	0.07	0.07	49	3%
Total Capital Costs		2.35	1780	
Annualized Capital Costs		0.15		
Sp. Annualized Cap Costs			**0.32**	$/m^3

Operating Costs of Desalination Plant				
	RO	Total (M$)	Specific ($/m^3)	Share
Energy Costs				
Heat cost		-	-	0%
Backup heat cost		-	-	0%
Electricity cost	-	-	-	0%
Purchased electricity cost	-	-	-	0%
Total Energy Costs	-	-	-	0%
Operation and Maintenance Costs			-	0%
Management cost	-	-	-	0%
Labor cost	0.03	0.03	0.07	69%
Material cost	0.003	0.003	0.01	7%
Insurance cost	0.01	0.01	0.02	24%
Total O&M cost	0.05	0.05	0.10	100%
Total Operating Costs		0.05	**0.10**	

Total annual cost	**0.19**	**M$**
Water production cost	0.423	$/m^3
Water Transport costs	-	$/m^3
Total water cost	**0.423**	**$/m^3**

3.2.3 Case 3: Al – Zubeidat BWRO unit powered by a PV solar system

The capital costs data of Al Zubeidat BWRO unit obtained from Yousef, 2013 were modified according to the assumed life time of the unit (30 years), the costs calculation are presented in details in appendix 2-C (Table 21). After that, the small scale BWRO desalination unit in Al-Zubeidat was economically analyzed. The results in Table 15 show that the UPC is \$5.094 /m^3. This value is highest among the three cases. The reason behind this value is the very small capacity of the unit powered by PV cells. Al-Al-Karaghouli and Kazmerski, 2013, reported cost of a PV-powered BWRO system with capacity less than 100m^3, ranges from \$6.5 to \$9.1 /m^3. The variation between the estimated UPC of Al-Zubeidat and the UPC values obtained from Al- Karaghouli and Kazmerski study could be referred to the use of different assumption for the economic calculations and the unit construction year. The UPC value obtained by DEEP is higher than the estimated value by Yousef, 2013 which was \$3.17/m^3.

Furthermore, the UPC results of this case are significantly higher compared to case 2. This mainly results from the significant difference of both plants feed capacities, as explained later in section 3.4.2.

Table 15: Main cost results of case 3: Al- Zubeidat BWRO desalination unit powered by solar PV panel

Capital Costs of Desalination Plant				
	RO	Total (M$)	Specific ($/m^3 d)	Share
Construction Cost	0	0	17,705	84%
Intermediate loop cost	-	-	-	0%
Backup Heat Source	-	-	-	0%
Infall/Outfall costs	-	0.00	66	0%
Water plant owners cost	0.01	0.01	885	4%
Water plant contingency cost	0.02	0.02	1,859	9%
Interest during Construction	0.01	0.01	605	3%
Total Capital Costs	0.21	0.21	21120	
Annualized Capital Costs		0.01		
Sp. Annualized Cap Costs			**3.95**	$/^{m3}

Operating Costs of Desalination Plant				
	RO	Total (M$)	Specific ($/m^3)	Share
Energy Costs				
Heat cost		-	-	0%
Backup heat cost		-	-	0%
Electricity cost	0.00	0.00	0.00	0%
Purchased electricity cost	-	-	-	0%
Total Energy Costs	0.00	0.00	0.00	0%
Operation and Maintenance Costs			-	0%
Management cost	-	-	-	0%
Labor cost	0.001	0.001	0.14	13%
Material cost	0.003	0.003	0.70	62%
Insurance cost	0.001	0.001	0.29	26%
Total O&M cost		0.004	1.14	100%
Total Operating Costs		0.004	**1.14**	

Total annual cost	**0.02**	**M$**
Water production cost	5.094	$/m^3
Water Transport costs	-	$/m^3
Total water cost	**5.094**	**$/m^3**

3.3 Cost break downs

The cost breakdowns of the three cases are represented in Figures 8, 9, and 10. The results show that cost factors distribution for electrically driven BWRO units is different from solar energy driven units, see Figures 8 and 9. Energy and labor costs represent the highest two cost components for electrically powered BWRO unit of Marj Na'aja. While, capital and labor costs are representing the highest two components for the solar powered case.

Furthermore, it is noticed that the cost distribution for large scale plant is different from the small ones. Material and labor cost are the highest costs component for the small scale BWRO unit of Al-Zubiedat, see Figure 10. These results are in agreement with the findings of Al-Karaghouli and Kazmerski, Table 16, which represent the cost breakdown electricity powered RO and renewable energy driven RO. It can be clearly noticed that for renewable energy coupled RO system, the capital costs are the highest and the energy costs are the lowest.

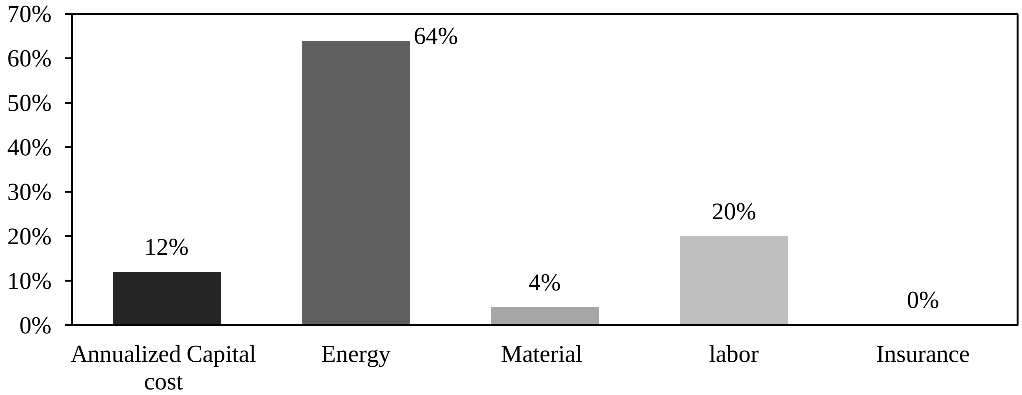

Figure 8: Cost break down for Marj Na'aja BWRO desalination unit powered by electricity

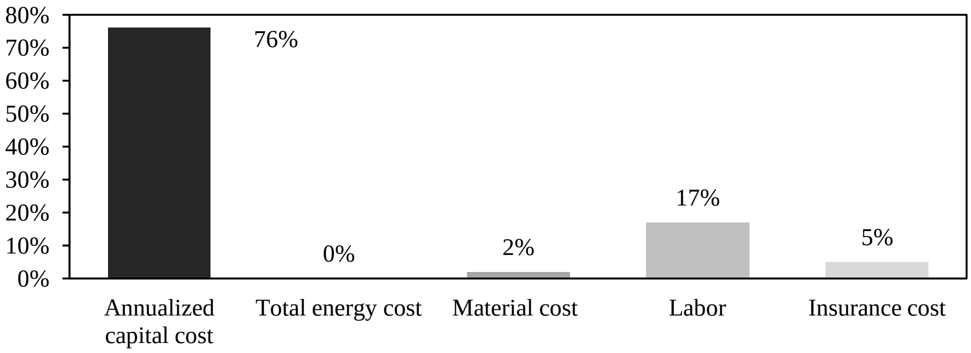

Figure 9: Cost break down for case 2: Marj Na'aja BWRO desalination unit powered by PV

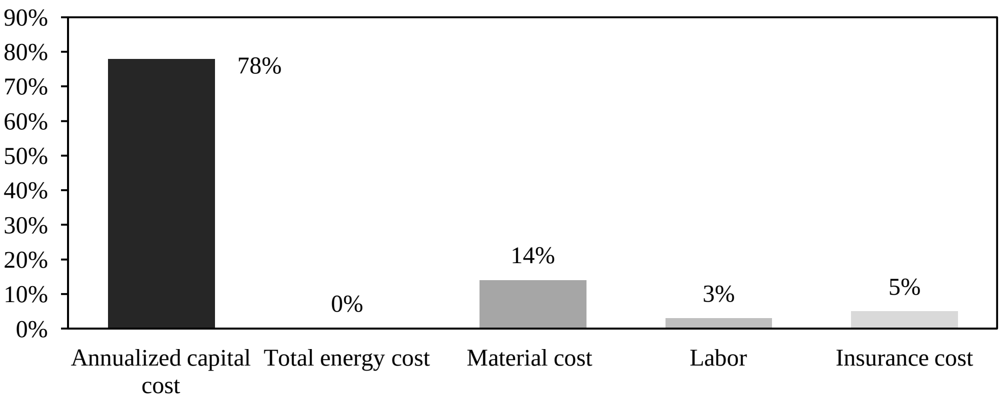

Figure 10: Cost break down for case 3: Al- Zubiedat BWRO desalination unit powered by PV

Table 16: Distribution of costs for conventional and renewable energy powered RO desalination system (Al-Karaghouli and Kazmerski, 2011)

Type of process	Capital costs (%)	Operational costs (%)	Energy costs (%)
Conventional (RO)	22 – 27	14 – 15	59 – 63
Renewable	30 – 90	10 – 30	0 -10

3.4 Sensitivity analysis for Marj Na'aja BWRO desalination plant

Sensitivity analyses were also conducted with variations in several important parameters that could potentially have a major influence on the UPC. Among the parameters that were varied for these analyses are plant water capacity, purchased electricity cost, interest rate, plant availability, feed water salinity, and feed water temperature. These analyses were carried out to permit the understanding of possible trends in the cost of desalinated water as the mentioned factors changed.

3.4.1 Effect of purchased electricity cost on UPC

The effect of the cost of purchased electricity consumed by pumps and other components in the BWRO on UPC was studied. The results obtained from the analysis were presented in Figure 11. The analysis shows that increasing the electricity price from \$0.08 up to \$0.10 per kWh will increase the UPC by about 13%.

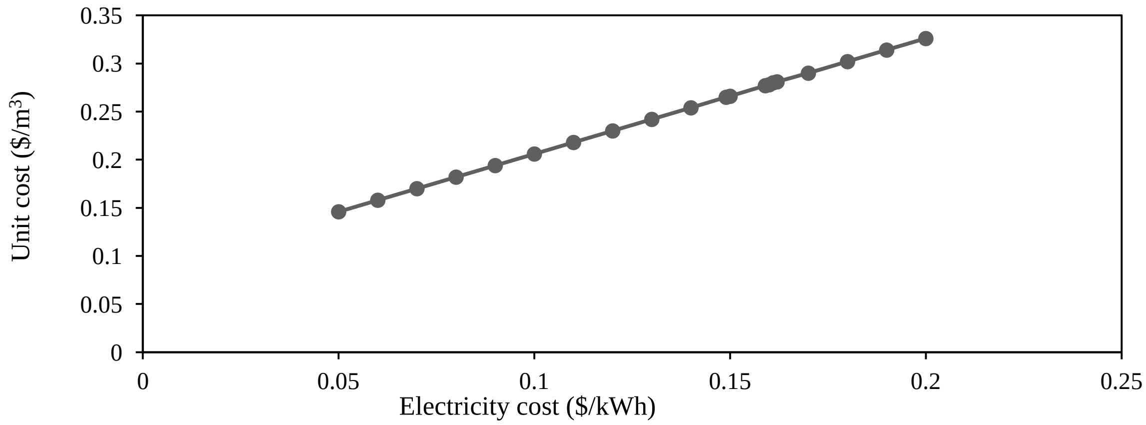

Figure 11: Effect of purchased electricity cost on UPC

3.4.2 Effect of water capacity on UPC

The sensitivity of UPC to the specific capacity of water plant was established and represented in Figure 12. The trend shows the decrease on UPC as the water capacity of the plant increases. It was found that UPC decreased by 6 %, when the plant capacity increased from 1320 m^3 to 2000 m^3.

Moreover, the effect of smaller plant capacities on UPC is major represented by the steep slope of the curve at the start (Figure 12). For example, if the plant capacity is increased from 100 m^3/d up to 200 m^3/d the decrease on UPC is about 38 %. Economy of the scale of RO unit has been studied by previous researches including Poullikkas, 2001. It was reported that plant capital cost and UPC decrease significantly as a function of capacity for plants smaller than 12,000 m^3/d for BWRO. The effect of economy of scale was not great for plants exceeding this range.

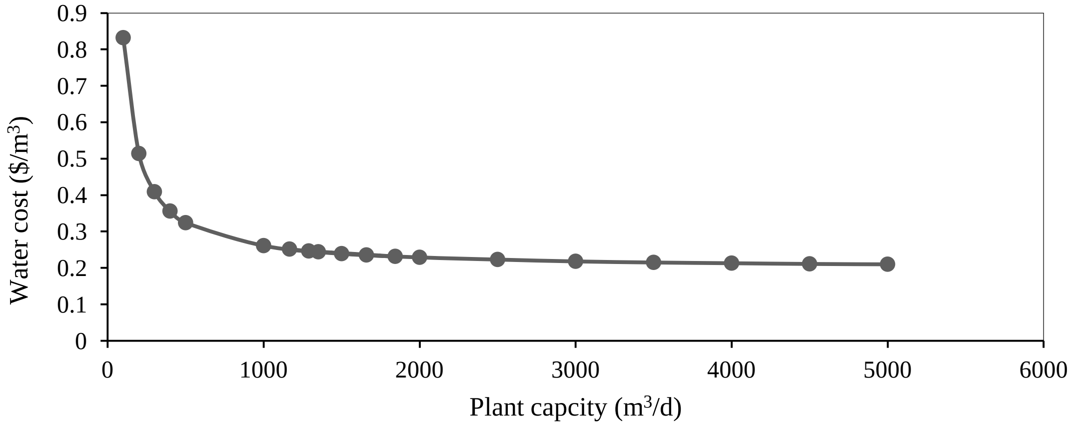

Figure 12: Effect of the water capacity of the units on UPC

3.4.3 Effect of Interest Rate (IR) on UPC

Figure 13 shows the effect of IR on water cost for the different cases. The resulted trends indicate that UPC is increased slightly by increasing the interest rate; where, the increase in UPC was about 1 % when the IR increased from 0.06 up to 0.07. These results agree with Al-Karaghouli, and Kazmerski, findings. According to them, IR usually has a large effect when the desalination plant has a high construction cost and high construction time, such as in the case of nuclear and fossil fuel desalination. This factor should have a minor effect in RO water desalination (Al-Karaghouli, and Kazmerski, 2012).

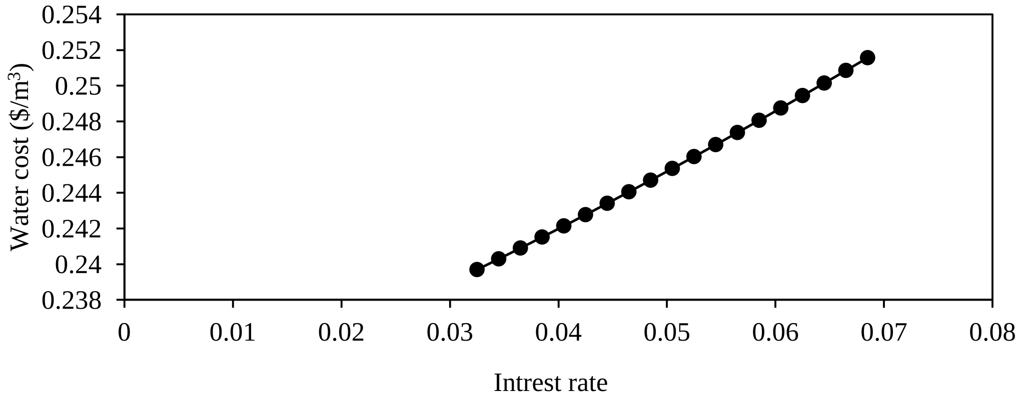

Figure 13: Effect of IR on UPC

3.4.4 Effect of plant availability on UPC

The potential annual capacity under "normal" conditions for each plant is considered to be 346 day per year, thus, 95% time availability, (Lapuente, 2012). The effect of plant availability on UPC was studied and illustrated in Figure 14. The analysis implies that UPC will increase as the plant availability decreases. However, this increase is minimal, for example, when the plant availability decreases from 95% to 90%, the UPC will be increased about 1.2%.

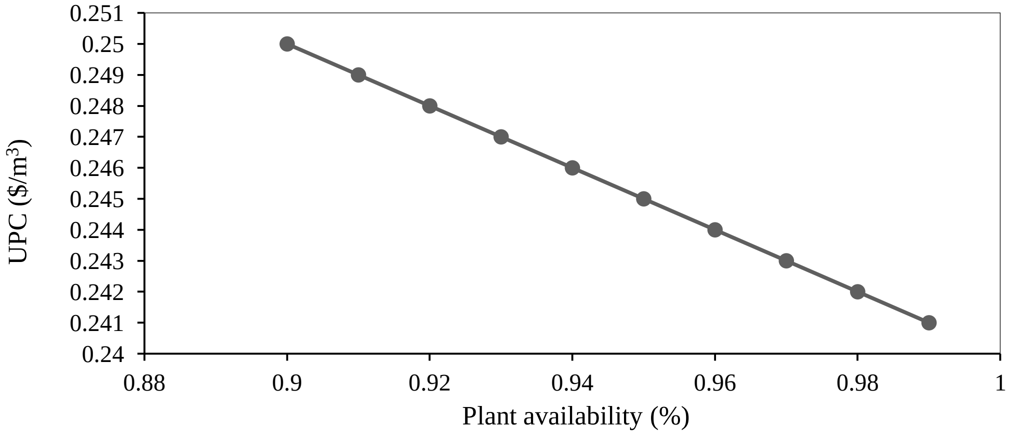

Figure 14: Effect of plant availability on UPC

3.4.5 Effect of feed water salinity (TDS) on UPC

TDS in the intake water might increase over than 4500 mg/L at Marj Na'aja unit due seasonal variation. The effect of the variation in feed water salinity on UPC was investigated, since higher feed water salinity increases the required pumping (feed) pressure. Consequently, it will increase the power consumption and UPC. The salinity variations also have an effect on the recovery ratio, desalinated water quality, feed water flow, brine flow, and brine salinity. The effect of feed water salinity on the above mentioned parameters was described in Table 17 below. Moreover, the effect of salinity on UPC and power consumption was plotted in Figure 15.

Table 17: Effect of feed water salinity on UPC

TDS	UPC	Power consumption	Recovery ratio	Fresh water quality	Feed flow	Feed water pressure	Brine flow	Brine TDS
mg/L	$/m^3	kWh/m^3	%	mg/L	m^3/d	bar	m^3/d	mg/L
2000	0.227	0.9	85	25	1561	14	241	12957
3000	0.234	0.94	77	27	1718	14.1	398	12957
4000	0.24	0.99	69	29	1910	14.2	590	12957
4500	0.245	1.02	65	30	2022	14.2	702	12957
5000	0.25	1.05	61	31	2150	14.3	830	12957
6000	0.26	1.11	54	32	2459	14.3	1139	12957
7000	0.273	1.2	46	34	2871	14.4	1551	12957
8000	0.29	1.31	38	36	3451	14.5	2131	12957
9000	0.316	1.47	31	37	4323	14.6	3003	12957
10000	0.356	1.73	23	39	5785	14.7	4465	12957
11000	0.435	2.24	15	41	8741	14.7	7421	12957

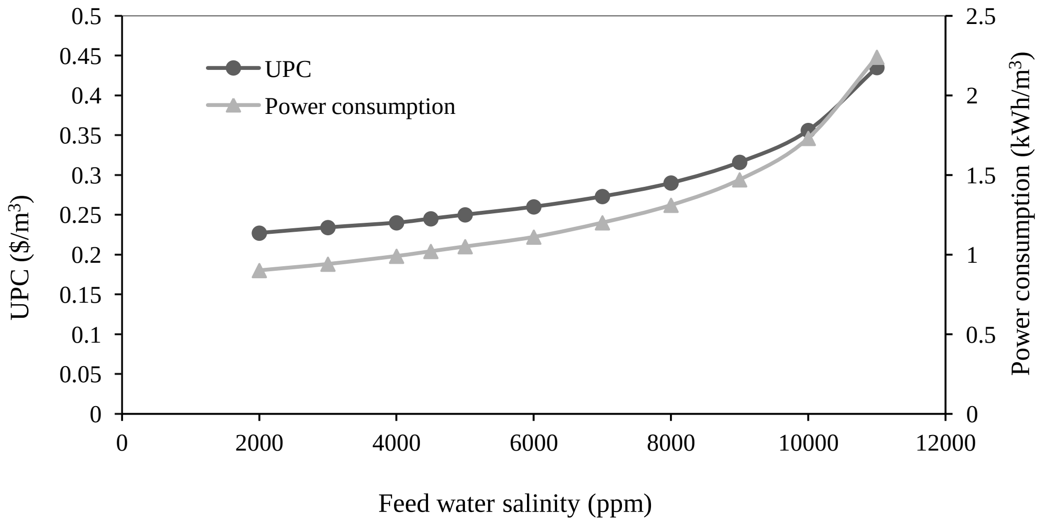

Figure 15: The effect of feed water salinity on UPC and power consumption

It can be noticed from Table 17 and Figure 15 that, when TDS increased, the UPC, the required pressure, the power consumption and the brine flow also increased. Conversely, it will decrease the recovery ratio and then the desalinated water quality. For instance, if TDS increases from 4,500 ppm up to 6,000 ppm, this will increase the UPC, power consumption, and feed pump pressure slightly by 6.1 %, 9.1 %, and 0.7 %, respectively. Then, the recovery ratio, and the desalinated water quality will decrease by 17 % and 6.6 %, respectively. These findings indicate that the seasonal feed water salinity has a minor effect on the UPC and greater effect on the desalinated water quality.

3.4.6 Effect of feed water temperature on UPC

Al-Karaghouli, and Kazmerski findings indicate that with higher feed temperatures, the salt passage increases, flux also increases, and then lower operating pressure is required. On the other hand, for lower temperatures salt passage decreases (reducing the TDS in the product water), whereas operating pressures increase (Al-Karaghouli, and Kazmerski, 2012). When operating pressures do not increase, then the amount of permeate or product water is reduced.

Commonly, RO systems are designed for raw water temperatures of 25 - 30 °C. A temperature range between 34 °C and 20°C is used to investigate the variation of temperature on UPC, power consumption and on RO system performance. The analysis outcomes are represented in Table 18 and Figure 16. The displayed results indicate that, when temperature decreases from 30 °C to 25 °C, the UPC increased marginally by 4.4%, power consumption increased by 6.8 %, and feed pressure increased by 10.5 %, whereas the desalinated water quality improved by 13.3%.

Table 18: Effect of feed water temperature on UPC and RO performance

Temperature	UPC	Power consumption	Recovery ratio	Fresh water quality	Feed flow	Feed water pressure	Brine flow	Brine TDS
°C	$/m^3	kWh/m^3	%	mg/L	m^3/d	bar	m^3/d	mg/L
34	0.238	0.97	65	33	2022	15.9	702	12957
33	0.24	0.98	65	32	2022	16.2	702	12957
32	0.242	0.99	65	31	2022	16.5	702	12957
31	0.243	1.00	65	31	2022	16.8	702	12957
30	0.245	1.02	65	30	2022	17.1	702	12957
29	0.247	1.03	65	29	2022	17.4	702	12957
28	0.249	1.04	65	29	2022	17.8	702	12957
27	0.251	1.06	65	27	2022	18.1	702	12957
26	0.254	1.07	65	27	2022	18.5	702	12957
25	0.256	1.09	65	26	2022	18.9	702	12957
24	0.258	1.1	65	25	2022	19.4	702	12957
23	0.261	1.12	65	24	2022	19.8	702	12957
22	0.264	1.14	65	24	2022	20.3	702	12957
21	0.267	1.15	65	23	2022	20.8	702	12957
20	0.27	1.17	65	22	2022	21.3	702	12957

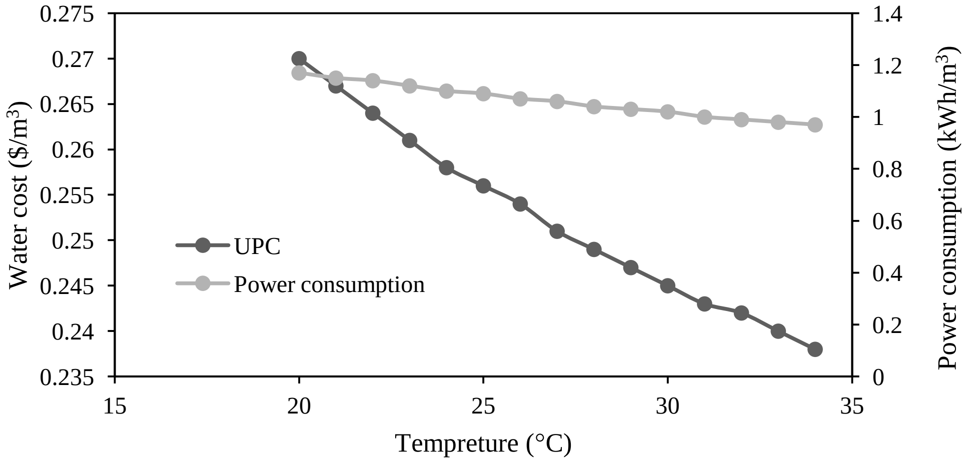

Figure 16: Effect of feed water temperature on UPC and power consumption

4 Guidelines for BWRO desalination in the Jordan Valley

The outputs and the results obtained from the economic analyses, cost breakdowns, and sensitivity analysis were employed to formulate guidelines for BWRO desalination in the Jordan valley. This section will focus on the economics of BWRO desalination, and on the best practices to be applied to reduce the cost of producing fresh water from desalination in the Jordan Valley area.

4.1 Key development and challenges in water sector in the Jordan Valley

1. Groundwater is being overexploited and groundwater quality is deteriorating. At the same time, domestic and agricultural demands are increasing. Therefore, employment of non-conventional water resources is essential to overcome these challenges.
2. Desalination, in general, is energy intensive and hence a costly option to consider. Capital costs and initial investments are also high depending on the technology used, site conditions and other factors.
3. Power plants for energy generation to derive large-scale RO desalination are not available.
4. Experience in desalination technology in Palestine is relatively new.
5. Negative environmental impacts accompanied by desalination projects, and these impact will need mitigation measures to reduce their effect.

4.2 Key considerations

4.2.1 Feed water source, quality and plant location

- The source of water affects the design and implementation of the RO desalination plant including the operation pressure, energy consumption, brine generation, location and the scale of the plant, etc. Feed water location and water demand significantly affect desalination costs. Preferably, the implemented desalination projects need to optimize costs by matching both demand and supply within close proximity of each other. These contexts should be taken into account in the strategy.

4.2.2 Costs and benefits of BWRO desalination

- Based on the output from the economic analysis. RO desalination technology is strongly recommended and considered as a strategic alternative to overcome the water shortage and water quality deterioration problems. Because of the advantages provided by the RO technology, such as, it's lower cost if compared to other technologies, its compact size, simplicity of operation, high salt rejection, higher recovery ratio and lower environmental impact.
- Desalinated water cost is affordable. Currently the average water selling price is about $0.41/m^3 of the municipal water in the Jordan valley, this value may vary depending on the locality and the source of water. Whereas, the estimated cost desalinated brackish water found to be $0.245/m^3 in Marj Na'aja BWRO desalination unit, which is competitive to the municipality water price. This cost may vary depending on plant capacity, purchased electricity cost, interest rate, availability of the plant, feed water salinity, and feed water temperature (as discussed in section 3.4). These factors should be optimized to reduce UPC.
- According to table 2, More than 100 MCM/year of brackish water are located in the Jordan Valley area. However, only about 0.5 MCM/year is being desalinated by the BWRO desalination units. Larger scale unit should be implemented in the Jordan Valley. According to PWA national strategy for water and water for Palestine, 2013, there is a large desalination project planned downstream from the Fashka Springs, with a scheduled production capacity of at least 22 MCM /year by 2022.

4.2.3 The linkage between energy consumption and desalination cost

- Energy cost is the key cost element in electrically powered BWRO plants, accounting for more than 50% of the total product cost. This reason behind such high value is the high price of the purchased electricity in Palestine ($ 0.156 /kWh) when compared to other countries.
- Substantial reductions in the cost of producing desalinated water will require substantial reductions in energy or capital costs, since, energy and capital costs are the two largest components of UPC.
- There are small developments but have a significant effectiveness that can be applied for membrane technologies which will reduce the required energy for desalination. This in turn will offer significant reductions on UPC. So choosing the technical characteristics of the system components is a vital decision.
- Mixing the produced desalinated water with brackish water is a strategic option, that is used in BWRO units to re mineralized the desalinated water, therefore this eliminates the cost of chemical used for pretreatment.

4.2.4 Coupling renewable energy BWRO desalination projects

- The use of renewable energy sources to power BWRO desalination technologies is promising for remote areas in the Jordan Valley. Several solar, geothermal, biomass, or nuclear power could be coupled to BWRO units in the study area to reduce energy cost.
- Solar powered BWRO units are preferred rather than other renewable energy resources, since the Jordan valley is well known high solar energy potential. Besides, the Jordan Valley area has a low wind energy potential which makes the application of wind energy converters an unfeasible option. However, applying of various renewable energy sources (e.g., biomass, geothermal, etc.,) in the Jordan Valley need further investigations.

- BWRO plants with simple design powered by solar PV cells as energy sources can effectively provide fresh water to remote and rural communities, at affordable costs. The cost of water produced from desalination units coupled with renewable energy resources depends very much on the cost of energy produced from these resources, and on the required energy to operate the system.
- The option of combining power plant for energy generation to a large-scale desalination plants should be investigated**.**

4.2.5 Economy of scale

- The cost of the small scale BWRO desalination units is higher than the larger ones. The estimated UPC found to be between \$0.514-\$6.54 /m^3 for desalination plant with capacity ranges between 10- 200 m^3, while for capacity ranges between 300-5000, the estimated UPC was between \$0.409-\$0.21/m^3.
- Constructing centralized BWRO desalination units for a clustered of brackish water wells is a feasible option, to minimize the high operational cost of the small scale units.
- There is a significant difference between the implementation of small and large scale desalination projects in terms of complexity, design and financing requirements. The implementation of small-scale BWRO desalination projects require the use of predesigned package plants, while large-scale plants typically require custom designed for each project.

4.2.6 Public acceptance

- Desalination is a relatively new concept to the water users in the Jordan Valley area. So public and stakeholders should be informed appropriately about desalination to allow constructive and effective participation in decisions and consultations related to the new desalination projects. Public acceptance is already included within the environmental approval and licensing processes but needs to be accompanied with practical communication initiatives to educate the public and stakeholders effectively.

- Many approaches could be followed to achieve public awareness and acceptance, including; facilitating public access to information on water desalination, distribution information brochures on desalination at events and conferences, and incorporation desalination within water use awareness campaigns.

4.2.7 Implementation of BWRO projects

- Desalination projects require effective planning, implementation, operation and maintenance. To ensure success implementation of the mentioned arrangements many factors should be considered including: proper planning approaches, proficient operations and maintenance schedules, access to robust and reliable technology, comprehensive national standards and guidelines, and facilitate public acceptance.
- Trusted and capable water institutions are required to successfully plan, implement, operate and maintain BWRO desalination projects.

4.2.8 Development of skills and local capacity

- Since the capital cost of BWRO desalination plants requires high investments, then proficient and skilled staff are required to protect plants and extend its life. Training of the operations staff and instrumentation maintenance staff in RO desalination technology and plant is essential.

4.3 Approaches to overcome the challenges

1. Developing an efficient implementation plan to achieve the guidelines goals.
2. Groundwater management plan need to be developed to ensure safe and controlled extraction from the groundwater wells. The development in domestic and agricultural

demands took place without planning which led to a significant deterioration in water quality in the groundwater wells in the Jordan Valley.

3. Jericho area has a considerable brackish water resource (16-18 MCM/year, PWA, 2015), and the potential of applying BWRO desalination technology should be assessed in terms of technical, economic and environmental feasibility in these resources.
4. Cooperation on international level should be encouraged and promoted on research, information exchange, and training level in the field of desalination.
5. Standards and guidelines should be adopted for the design and best management practices for BWRO technology.
6. Building public awareness and participation. The enhancement of public awareness and creation of incentives for local ownership and commitment to projects is important. Establishment of awareness and interest, changing the attitudes and conditions, motivating and empowering people is highly recommended.
7. Institutional capacity building and human resources development. It is vital to conclude and implement the institutional reforms of the water sector at national level. Also, to ensure its long term economic and operational sustainability, along with development professional capacity and motivation of human resources. Therefore, a sustainable institutional structure in water desalination sector should be developed. The involvement of the private sector and strengthen its regulatory and institutional capacity should be also enhanced.
8. Monitoring and evaluation should take place to insure the implementation of the strategy approaches.

4.4 Priority research topics

- The strategic application of funding for desalination research can improve the implementation of desalination technologies and reduce the cost of desalination, especially in the field of renewable energy powered RO desalination systems, particularly in remote areas. Responsibility for developing the strategic plan should rest with the Palestinian Water Authority, and Palestinian Energy and Natural Resources Authority, and private sector.

- Researches should focus on developing approaches to lower the cost of BWRO desalination and to help make desalination a competitive option to overcome water challenges in the Jordan Valley. Researches should investigate areas including;

    1. Improving pretreatment methods for membrane desalination and evolving more robust, cost-effective pretreatment processes.
    2. Reducing chemical requirements for pretreatment and post treatment.
    3. Improving existing desalination approaches to reduce energy use.
    4. Recognize the impact of energy pricing on desalination technology over time.
    5. Developing improved energy recovery technologies and techniques for desalination.
    6. Investigate approaches for integrating renewable energy with desalination.

5 Conclusions

- Energy is certainly the most significant item and has a significant effect on UPC for electricity powered BWRO desalination unit, where, energy represents 64% of the total cost in Marj Na'aja unit powered by electricity.
- UPC of Marja Na'aja powered by PV found to be 0.423 $/m^3. Hence, BWRO plants powered by solar PV cells as energy sources can effectively provide fresh water to remote and rural communities, at (reasonably) affordable costs.
- The distribution of cost factors for electrically driven BWRO units is different from solar energy driven units. Energy and labor costs represent the highest two cost components for electrically powered BWRO unit of Marj Na'aja. While, capital and labor costs were representing the highest two components of the solar powered case scenario of Marj Na'aja. Also, the cost distribution for large scale plant is different from the small ones. In the small scale BWRO unit of Al- Zubiedat material and labor costs are accounting for the highest costs components. It can be clearly noticed that for renewable energy coupled RO system, the capital costs are the highest and the energy costs are the lowest.
- The cost of the small scale BWRO desalination units is higher than the larger ones. The estimated UPC found to be between \$0.514-\$6.54 /m^3 for desalination plant with capacity ranges between 10- 200 m^3, while for capacity ranges between 300-5000, the estimated UPC was between \$0.409-\$0.21/m^3.
- Sensitivity analysis results indicate that for high capacity BWRO units, the economy of scale is only a few percent of the UPC. This effect is higher for lower size plants. Moreover, increasing interest rate will increase UPC. While increasing plant availability or feed water temperature will reduce UPC.

- Sensitivity analysis also has shown that, higher feed will increase the power consumption and UPC. The salinity variations also have an effect on the recovery ratio, desalinated water quality, feed water flow, brine flow, and brine salinity.
- The main considerations that improve planning, implementation, operation, and economic evaluation of BWRO desalination project found to be: feed water source, quality and plant location, costs and benefits of BWRO desalination, The linkage between energy consumption and desalination cost, economy of scale, public acceptance, and development of skills and local capacity.

6 Recommendations

- Focused research on optimizing the PV cells to use the solar energy should be a significant boost to the BWRO powered by those cells.
- The suggested key considerations should be translated into action plans.
- Awareness campaigns targeting the localized desalination plants owners and stalk holders are essential.
- The option of combining power plant for energy generation to a large-scale desalination plants should be investigated**.**

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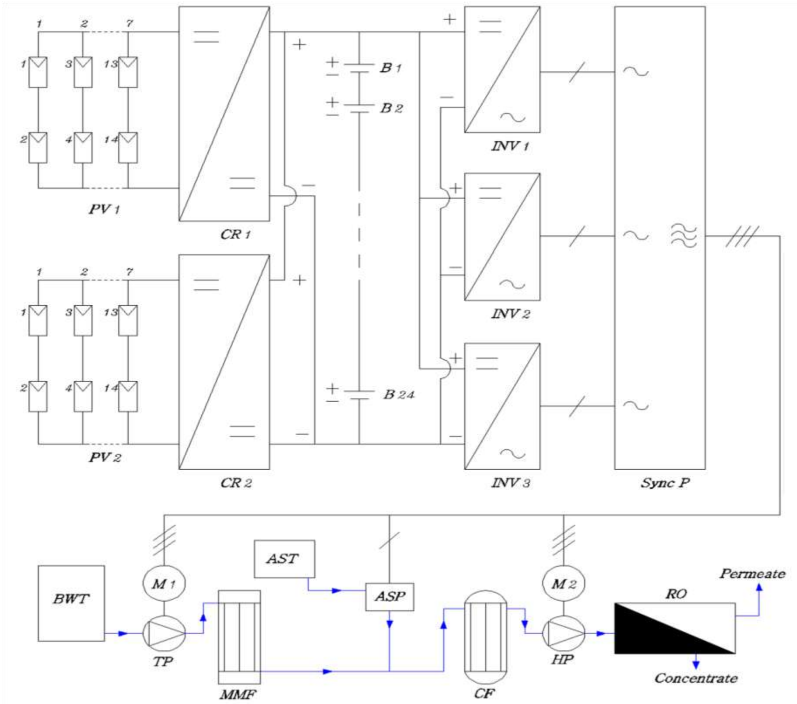
Appendices

Appendix 1-A: Photos of Maarj Na’aja BWRO unit

Figure 17: Photos of BWRO desalination unit in Maraj Na’aja

Appendix 1-B: Photos of Al- Zubiedat BWRO unit



PV1, PV2: Photovoltaic arrays.	M2-HP: RO-HP motor pump.
CR1, CR2: Battery charge regulators.	AST: Anti scaling tank.
B1-B24: Storage battery cells.	ASP: Anti scaling pump.
NV1, NV2, NV3: DC/AC Inverters.	BWT: Brackish water storage tank.
Sync p: Synchronizing control panel.	MMF: Multimedia filter.
M1-TP: Transfer motor pump.	CF: Cartridge filter
	RO: RO Vessels containing the membranes

Figure 18: The schematic diagram of Al -Zubiedat BWRO desalination unit (Yousef, 2013)

Figure 19: Photo of the PV arrays in Al- Zubiedat BWRO dealinatio unit, (Yousef, 2013)

Appendix 2-A: DEEP input data and assumptions

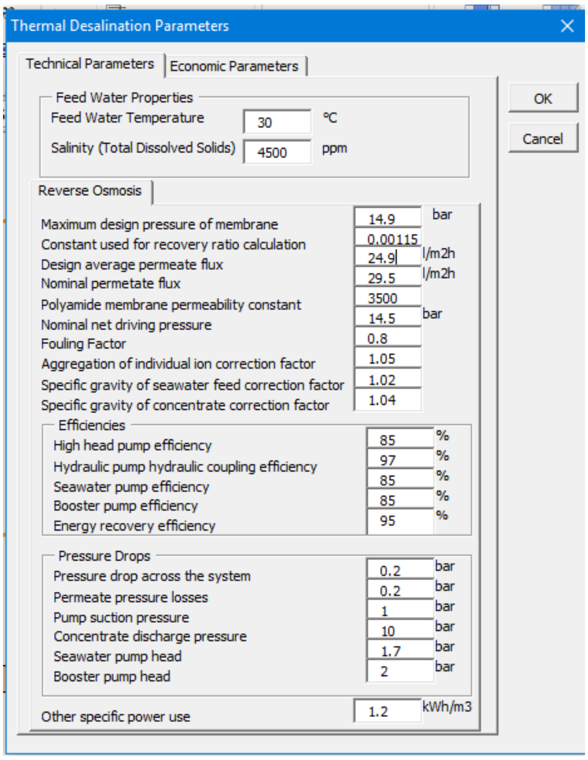


Figure 20: Main Input parameter required by DEEP software

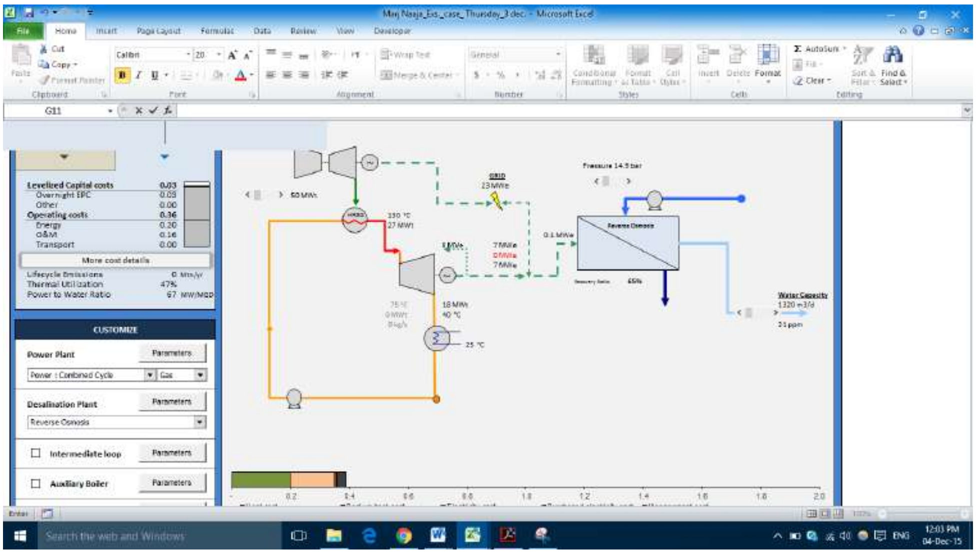


Figure 21: Results and schematic diagram page in DEEP software

Appendix 2-B: The design and cost calculation of the solar PV system

Table 19: Sizing the solar PV system component

Equation		Value	
Sizing of the PV-generator	Photovoltaic power = P_{pv} =$(E_l \times S_f)/(\eta_r \times \eta_v \times PSH)$	373.78	kW h
Number of modules	$N_{pv}=P_{pv}/P_{mpp}$	2020	Modules
Sizing of the battery block	The ampere hour capacity= C_{Ah}= $(1.5 \times E_L)/(V_B \times DOD \times \eta_B \times \eta_v)$	77647.10	Ah
	watt hour capacity= C_{Wh}= $C_{Ah} \times V_B$	3727059	kW h
	Number of battery needed	1695	

Where,

	Assumed value[3]	
Average daily consumption (EL) [4]	1584	kW h
Module power (P_{mpp})	185	Wh
The peak sun hours(PSH)	5.4	hrs
Efficiency of inverter (η_r)	0.95	
Efficiency of battery charge controller (η_v)	0.95	
Safety factor for losses (S_f)	1.15	
The voltage of battery block (V_B)	48	v
The efficiency of battery block (η_B)	0.85	
The permissible depth of discharge rate of a cell (DOD)	0.75	

[3] Adapted from Mahmoud and Ibrik , 2006
[4] Average daily consumption (EL)= 1.2 kWh*1320 m^3/d

Table 20: Installation cost of the PV system

Component, material or work	Quantity	Unit price ($)[5]	Life time (years)	Total price ($)[6]
PV module (185 W)	373776WP	1/Wp	20	560,664
Batteries (2V/1100 Ah)	1695	350	10	118,650,0
Charge Controller (2.5 kW)	2	1500	20	4500
Inverter (3.6 kW)	3	2100	20	9450
Installation Material	---	---	20	9000
Installation (electrical , mechanical and civil) Cost	---	---	---	8000
Total cost ($)				177,811,4

[5] Adapted from Yousef, 2013
[6] The units life time vary between 5-20 years, however, the calculated total price based on the life time of the whole BWRO plants which is 30 years

Appendix 2-C: Capital cost calculation of Al- Zubeidat unit

Table 21: Capital costs of Al-Zubeidat BWRO desalination unit

Component	Quantity	Unit price ($)	Life time(year)	Total price ($)[7]
PV module (185 W)	5180 WP	1/Wp	20	7770
Batteries (2V/875 Ah)	24	437.5	10	31500
Charge Controller (2.5 kW)	2	1500	20	4500
Inverter (3.6 kW)	3	2100	20	9450
Installation Material	---	---	20	1500
Installation (electrical & mechanical) Cost	---	---	---	2000
Transfer pump	1	2400	30	3600
High pressure pump	1	3500	30	5250
Anti-scaling pump	1	1000	20	1500
Multimedia filter	2	1100	5	13200
Cartridge filter	2	600	5	13200
RO membrane vessel	3	3500	5	13200
Piping, valves, gages	1	3900	20	5850
Electric control panel	1	1200	20	1800
Instrument control panel	1	2000	20	3000
Cleaning system	1	1500	20	2250
Steel structure (epoxy coated)	1	1400	20	2100
Total capital cost of the system ($)				121670

[7] The units life time vary between 5-20 years, however, the calculated total price based on the life time of the whole BWRO plants which is 30 years

APPENDIX 3-A: progress report Work

PROJECT PERIOD: 20 months **START DATE:** June 2014

PROJECT TITLE: Techno-economic analysis of using RO systems for water desalination in Jordan valley

PROJECT NO: Project Number: 013-CoE-031 **END DATE:** January 2016

Task	progress	Jun. – Dec. 2014	Jan-Oct. 2015	Dec.2015- Jan. 2016
literature review	Completed			
Data collection	Completed			
Field visits	Completed			
Data Processing, analysis and	Completed			
Outcomes and conclusion	Completed			
Writing Final report	Completed			
Defense session	Completed			

Interim Budget Report (in US$)

Middle East Desalination Center
Interim Budget Report (in US$)

Principle Investigator: Wala' Alsheikh Abdallah

Project No: 013-CoE-03

Project Title: Techno-economic analysis of using RO systems for water desalination in Jordan valley

Report Period From: To: Report No:2

TRAVEL (attach detail of travel cost/accommodation/meals/incidental expenses)

MEDRC Budget	Total Expenditure to			Previous Periods		Reporting Period		Organizations Visited/ Purpose	Name/Organization
	Total	Breakdown In-Kind	Breakdown MEDRC	Total	From 1 sep 2012 - 1 april 2013	Total	From 1 April 2013-until now		
Field visits	250								
PWA	100								
Jericho Municipality	200								
Ministry of Agriculture	50								
	600								SUB-TOTAL 600

MEDRC Budget	Total Expenditure to			Previous Periods			Reporting Period			Details
	Total	Breakdown In-Kind	Breakdown MEDRC	Total	Breakdown In-Kind	Breakdown MEDRC	Total	Breakdown In-Kind	Breakdown MEDRC	
Printing report	350									
Equipment and software	600									
Tuition fees	3000									
										SUB-TOTAL 3950 $

										GRAND-TOTAL 4500 $

FOR COMPLETION BY CONTRACTOR

Attested & Certified as correctly extracted from accounting books and records

Principal Investigator (name & signature): Wala' Al sheikh Abdallah wala'

Financial Officer (name & signature)