AMERICAN UNIVERSITY OF BEIRUT

A COMPARATIVE ASSESSMENT OF THE FEASIBILITY OF ADOPTING SMALL-SCALE SOLAR-POWERED BRACKISH DESALINATION UNITS: THE CASE OF BEIRUT CITY

by
HANAN SAMIR HAMDAN

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HANAN SAMIR HAMDAN

Approved by:

Dr. Ibrahim Alameddine, Assistant Professor — Advisor
Department of Civil & Environmental Engineering

Dr. Mahmoud Al-Hindi, Associate Professor — Co-Advisor
Baha and Walid Bassatne Department of Chemical and Petroleum Engineering

Dr. Nesreene Ghaddar, Professor — Member of Committee
Department of Mechanical Engineering

Dr. Hassan Harajli, Lecturer — Member of Committee
Department of Economics

Date of thesis defense: June 21, 2019

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AN ABSTRACT OF THE THESIS OF

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Title: A Comparative Assessment of the Feasibility of Adopting Small-Scale Solar-Powered Brackish Desalination Units: The Case of Beirut City

Population growth, weak water governance, and poor water resources management in Lebanon have all led to the overexploitation of groundwater resources and the intensification of saltwater intrusion. This study assesses the feasibility of implementing brackish water desalination technologies at the building level as a mean to supplement the limited public water supply within the context of Beirut. As such, a comparative assessment was conducted to evaluate the feasibility of adopting Electrodialysis Reversal (EDR) technique instead of the more commonly used Reverse Osmosis (RO) technology. The two technologies were assessed in terms of their economic, environmental, and technical requirements. The outcome revealed that the EDR units were superior to their RO counterparts when the feed water salinity ranged between 2,000 ppm and 5,000 ppm. At these low salinities, EDR had a lower energy consumption and a higher recovery ratio. RO units became more advantageous when salinity levels exceeded the 5,000 ppm threshold.

Furthermore, both desalination technologies were found to be more economical as compared to purchasing water through water tankers. This study also explored the viability of using photovoltaic (PV) units installed on building rooftops to power the energy-intensive desalination systems. The results showed that the costs of producing desalinated water through the use of rooftop PV-powered EDR and RO units ranged between 0.44-0.89 $\$/m^3$ and 0.6-1.37 $\$/m^3$ respectively. Both costs were slightly higher than the cost associated with using power from the electricity grid (0.43-0.85 $\$/m^3$ and 0.58-1.35 $\$/m^3$ for grid powered EDR and RO respectively) when the current subsidized kWh price set by EDL (0.096 $/kWh) was used. When the electricity process was made to reflect the costs related to the use of private diesel-power generators (0.22 $/kWh), linking the desalination units with rooftop PV became economically feasible.

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NOMENCLATURE

A_{Memb}	area of membranes [m^2]
AF	amortization factor [$year^{-1}$]
AP_{PV}	available power of PV [Wp]
A_{PV}	available area of PV [m^2]
APV	annual produced volume [m^3/year]
C_C	cost of carbon [\$/kg of carbon released]
C_{chem}	cost of chemicals [\$/m^3]
C_{ED}	cost of ED without membranes [\$/m^3]
$C_{ED\text{-}GRID}$	cost of water obtained by an ED-GRID plant [\$/m^3]
C_{ElectR}	cost of electrode replacement [\$/m^3]
C_{Energ}	cost of energy [\$/m^3]
C_{INV}	cost of inverter [\$]
C_{Lb}	cost of labor [\$/m^3]
C_{Memb}	cost of membranes [\$]
C_{MembR}	cost of membrane replacement [\$/m^3]
$C_{ED\text{-}PV}$	cost of water obtained by an ED-PV plant [\$/m^3]
C_{Pump}	cost of pump [\$]
C_{PumpR}	cost of pump replacement [\$/m^3]
$C_{RO\text{-}GRID}$	cost of water obtained by the RO-GRID plant [\$/m^3]
$C_{RO\text{-}PV}$	cost of water obtained by the RO-PV plant [\$/m^3]
C_{Sp}	cost of spares [\$/m^3]
C_{Treat}	cost of treating brine [\$/m^3 of treated wastewater]
DC_F	fraction of direct cost [%]
DP	depreciation period [year]
FR	flow rate [m^3/day]
I	average daily global horizontal irradiation [kWh/m^2/day]
IR	interest rate [%]
k	power supplied per unit area of PV [kW_p/m^2]
M_{CO2}	mass of CO_2 released per 1 kWh of electricity [kg/kWh]

P_{Memb}	price of membrane [\$/m^2]
P_{Elect}	price of electrode [\$]
P_E	price of electricity [\$/kWh]
PR_{PV}	performance ratio of PV [%]
P_{PV}	price of PV [\$/kW$_p$]
Q_{Brine}	volume of brine disposed of per volume of produced water [m^3 of brine/m^3 of water]
RF_{Elect}	replacement factor of electrodes [%]
RF_{Memb}	replacement factor of membranes [%]
RFPM	ratio of full plant /membrane [%]
SEC	specific energy consumption per unit of volume produced [kWh/m^3]
TAC_{ED}	total annualized cost of ED [\$/m^3]
TAC_{PV}	total annualized cost of PV [\$/m^3]
TAC_{RO}	total annualized cost of RO [\$/m^3]
TCC_{ED}	total capital cost of ED [\$]
TCC_{PV}	total capital cost of PV [\$]
TCC_{RO}	total capital cost of RO [\$]
TC_{Oper}	total operation cost [\$/m^3]
$TC_{O\&M}$	total operation and maintenance cost (without electricity) [\$/m^3]
TEC	total environmental cost [\$/m^3]
ε_{PV}	efficiency of PV [%]

CHAPTER I

INTRODUCTION

A. Current Issue

Both economic growth and human welfare depend directly on two interlinked resources, namely water, and energy. Water is a valuable resource needed to provide for power generation, crop production, and conventional fuel processing. Likewise, energy is critical for powering the collection, treatment, and distribution of water to consumers (Liu et al. 2015). Population increase, improved living standards, and climate change, have rendered these two vital sources vulnerable and in high demand (Shahzad et al. 2017).

Projections have estimated that water demands double every 20 years, while the increase in global total energy consumption is expected to exceed 44% between 2006 and 2030 (Gonzalez et al. 2017).

Although two-thirds of the Earth's surface is covered by water, only 1% of its volume is suitable for industrial and domestic usage (Abdelkareem et al. 2018). According to the World Health Organization (WHO), 50% of the world's population is projected to suffer from freshwater shortages by 2025 due to global warming and deviations in the climate (Boden and Subban 2018). Severe drought, un-replenished water sources, population growth, over-extraction of underground aquifers, excessive levels of polluted freshwater and seawater intrusion have all contributed to the severity of the situation.

Water desalination is a technologically feasible approach that can expand the available fresh water supply to vulnerable communities. Worldwide, the installed desalination capacity has been consistently growing. It exceeded 85 million cubic meters per day in 2016 (Pinto and Marques 2017). Different desalination technologies have been developed over the years; they can generally be categorized based on the use of phase change thermal processes such as multi-stage flash distillation (MSF), multi-effect distillation (MED), and vapor compression evaporation (VC), or on the use of membrane processes, specifically Reverse Osmosis (RO) and Electrodialysis Reversal (EDR). Concerning the market share of desalination technology, the RO technique was reported to have provided 71% of the world's desalinated water in 2013 (Boden and Subban 2018). While RO has been used to desalinate brackish and seawater, studies have shown that EDR can be a cost-effective technique for desalinating brackish water with low salinity levels (Fernandez-Gonzalez et al. 2015).

One of the main limiting factors hindering the wide adoption of desalination is its high cost. The cost of desalinated water depends on several factors, including the operational and maintenance cost, the capital investment, and the energy cost. The latter has been shown to contribute to about 50% of the total cost of desalination (Al-Karaghouli and Kazmerski 2013, Ghenai et al. 2018). It has been estimated that around 10,000 tons of oil per year are needed to desalinate 1,000 m^3 of water per day (Compain 2012). While brackish water desalination is less energy demanding than seawater desalination, its energy requirements are still higher than other conventional water treatment processes. Energy requirements for water generation range from 0-0.4 kWh/m^3 for local surface water, 0.1-0.9 for local groundwater, 0.3-2.25 for wastewater reuse, 0.3-2.5 for brackish water desalination, 1.6-3.7 for water transportation, and 3.7-4.8 kWh/m^3 for seawater desalination (Boden and Subban 2018). Given that the reliance on non-renewable fossil fuels can be costly and uncertain and is associated with significant adverse environmental concerns, there is a need to shift towards harnessing and using the abundant clean and renewable energy (RE) sources to power the energy-intensive desalination technologies. Although currently, only around 1% of the total global desalination capacity depends on RE as a source of power (Ghaffour et al. 2014), there is potential for increasing its growth in the near future, largely due to developments and progress in the technologies of desalination processes as well as those of RE systems.

B. EDR and RO

Electrodialysis Reversal (EDR) and Reverse Osmosis (RO) are considered as the two most mature membrane desalination technologies. In EDR, cations, and anions in the feed water migrate under the influence of a potential difference towards oppositely charged electrodes, passing through the selectively permeable cation and anion exchange membranes. This results in consecutive compartments of diluate and concentrate solutions (Tsiakis and Papageorgiou 2005). Small and medium-sized EDR desalination plants, with capacities ranging from less than 100 m^3/d up to more than 20,000 m^3/d, have been successfully used to desalinate brackish water with TDS between 1,000 and 5,000 ppm (Strathmann 2004). Of the total global capacity of installed EDR, 31% have been installed in the United States, 23% in the Middle East, and 15% in Europe (Abdelkareem et al. 2018).

Although ED became commercially available more than forty years ago (i.e. ten years before RO) (Eltawil et al. 2009), RO is the most widely used desalination process to generate fresh water from both seawater (33,000 to 45,000 ppm) and brackish water (1,500 to 20,000 ppm) (Al-Karaghouli et al. 2010).

Contrary to EDR, RO relies on high-pressure pumps, that are driven by an alternating current, to force water to move across a semi-permeable membrane, against the osmotic pressure, from the high salinity compartment to the dilute one. This yields the fresh water required and leaves behind the concentrated brine (Wright and Winter 2014).

Seawater RO systems often benefit from the high-pressure rejected brine by recovering part of the energy using turbines in an Energy Recovery Device (ERD), thus diminishing the overall power used in the desalination process (Zarzo and Prats 2018). However, in small-scale brackish water RO units, higher capital investments in an ERD are not compensated for by the power savings (Gude 2012, Wright and Winter 2014).

The EDR and RO technologies differ in many aspects, including the membrane longevity, recovery ratios, vulnerability to feed water changes, the type of essential additives, the amount and quality of rejected brine, as well as energy consumption at different salinities. Table 1 summarizes the main differences between these two technologies. With regards to the use of renewable energy to power desalination units, both technologies have been able to harness solar power. Currently, several PV-RO systems have been installed around the world, mostly with batteries to ensure the continuous functioning of the unit, thus resulting in a high cost of the delivered water. A few PV-EDR projects have also been implemented in various areas, in addition to some pilot plants with capacities less than 100 m^3/day, intended to support the research and development of the technology (Table 2).

Even though many studies have tackled the feasibility of small-scale PV-powered EDR and RO desalination systems, there is a gap in the comparison of the performance of the two units at different salinities and capacities. In addition to that, there is a lack of clear information about the detailed costs associated with desalination for small scale units. In this work, we assess the feasibility of a small-scale EDR unit for brackish water desalination at the building level that is powered by rooftop PV panels. The EDR units are assumed to function as a stopgap when it comes to providing fresh water for water-stressed inhabitants who suffer from the irregular supply of water and electricity through the public networks. To better illustrate this point, this study provides a detailed analysis of the viability of EDR technology for the desalination of brackish groundwater at the building level, taking the city of Beirut as a case study. A comparison between EDR and RO is also performed while considering the environmental impacts, energy consumption, as well as the advantages and disadvantages of each technique. The work also focuses on the viability of using PV units on building rooftops to power the desalination process. Finally, a comparative assessment is conducted between the use of desalination by PV-RO and PV-EDR on the one hand versus adopting other methods for procuring water, such as the purchase of water tankers.

Table 1. Comparison Between EDR and RO for Brackish Water Plants Operating Under a Salinity Range Between 2,000 and 5,000 mg/L and With Capacities Between 20 and 1,200 m^3/day.

	RO	EDR
Membrane Lifetime(y)	5 to 7	10+
Membrane Cost	Lower	Higher
Membrane Cleaning	Membrane must be replaced	Manual cleaning
Membrane Fouling	High	Low
Clean-In-Place	Yes	Yes
Membrane Sensitivity to Chlorine	High	Low
Contaminant Removal	Total	Salts only(ions)
Recovery Rate	25 to 60% for a single pass	80 to 95%
	up to 80% for multiple passes	
Pretreatment requirements	High	Low

Mineralization post-treatment	High	Low
Brine Volume Discharged	High	Low
Brine Disposal costs	High	Low
Waste	Highly acidic	Less acidic
Cost as a function of Salinity	More cost-effective above 5,000 ppm	More cost-effective below 5,000 ppm
Adaptation to PV	Lower	Higher
DC/AC Inverter	Required	Not required
Commercial use	High	Low
SEC kWh/m^3	1.5 - 2.5	0.7 - 2.5
Water cost $/$m^3$	0.26 - 1.33	0.6 – 1.05
CO_2 emitted kg/m^3	0.8 - 1.3	0.2 - 2

(Al-Karaghouli and Kazmerski 2013, Alghoul et al. 2016, Bian et al. 2019, Boden and Subban 2018, Fernandez-Gonzalez et al. 2015, Karimi et al. 2015, Ortiz et al. 2007, Sharon and Keddy 2015, Valero et al. 2013, Wright and Winter 2014).

Table 2. Examples of PV-Powered RO and EDR Projects Around the World.

Technology	Location	Capacity	Salinity	SEC	Water Cost	Batteries Used
		(m3/d)	(mg/L)	(kWh/m3)	($/m3)	
PV-ED	Ghazza[a]	10	2,600	2	0.6	
PV-EDR	India[b]	<100	BW		10.4 - 11.7	
PV-ED	Bahrain UNI[c]	0.57	3,300			
PV-EDR	Fukue, Japan[d]	200	700	0.6 - 1		Yes
PV-ED	Alicante,Spain[e]	14.7	4,473	1.33 – 1.47	0.14 - 0.32	No
PV-ED	Canary Islands, Spain[e]	4	2,240 – 3,392	0.618		No
PV-RO	India[b]	50	BW		7.25	
PV-RO	Jordan[f]	13 - 63	BW	6.9 - 10.5		
PV-RO	West bank[a]	10	2,680	2.3	3.17 2.33	Yes No
PV-RO	Aqaba[g]	58	4,000		1.85	
PV-RO	Alamogordo, USA[h]	10			2.41	
PV-RO	Indonesia[d]	12	3,500	8	3.68	Yes
PV-RO	Australia[i]	0.4	5,000	1.86	10-12	No

a: (Ramanujan et al. 2017), b: (Manju and Sagar 2017), c: (AlMadani 2003), d: (Ishimaru,1994) as cited in (Ali et al. 2011), e: (Penate et al.,2013) as cited in (Fernandez-Gonzalez et al. 2015), f: (Abdelkareem et al. 2018), g: (Jouryan et al., 2006) as cited in (Ghermandi and Batayneh 2010), h: (Burrough, 2009) as cited in (Bilton et al. 2011), i: (Al-Karaghouli et al. 2010).

CHAPTER II

METHODOLOGY

A. Area of Study

The study was conducted in the coastal city of Beirut (Figure 1), which constitutes along with its suburbs, the Greater Beirut Area (GBA). Although the GBA occupies only 233 km^2, which represents 2% of Lebanon's total area, around one-third of the country's inhabitants resides in it (Faour and Mhawej 2014). GBA is home to 1.7 million residents, which are predicted to reach 3.5 million by 2035 (dar-al-handasah 2014). Fifteen years of civil war have left a severe impact on GBA, impairing the management of its water sector, and damaging its infrastructure. Post-war, most areas had intermittent and insufficient public water supply to satisfy demands during the winter season while during the dry summer season distribution was often reduced to a few hours every other day (El-Fadel et al. 2003). Thus residents of the GBA supplement their limited public network supply by resorting to water abstraction from personal unlicensed wells, purchasing water through water tankers at a price ranging from 3.5 to 11 $\$/m^3$ (Constantine et al. 2017), and/or depending on bottled water for drinking and cooking (dar-al-handasah 2014). Along the densely populated coastal areas of the GBA, the unregulated installation of private wells without any proper monitoring and mostly without permits that regulate drilling and pumping rates (Fayssal and Slim 2015) have led to the exhaustion of fresh groundwater resources, leading to seawater intrusion into these coastal aquifers. Measured Chloride (Cl-) levels displayed a tenfold increase in Beirut groundwater between 1970 and 1985 (Bou-Zeid and El-Fadel 2002). Salinity data collected in October 2013 from private wells in Beirut showed that TDS levels ranged from below 1,000 ppm to above 20,000 ppm (Alameddine et al. 2018). The study showed that around 40% of the surveyed wells had a salinity in the range of 1,000-5,000 ppm, 27% in the range 5,000-10,000 ppm, 7.5% from 10,000 to 15,000, 3.8% between 15,000 and 20,000 ppm, and 5.6% had a salinity of more than 20,000 ppm. A similar study by Saadeh & Wakim (Saadeh and Wakim 2017) reported that TDS levels have increased between 20% and 5,633% in their sampled wells between 2004 and 2014. In the face of a deteriorated water quality, a growing number of residents has opted for the installation of unlicensed desalination units to treat the high salinity groundwater (Alameddine et al. 2018). Between 1995 and 2009 several brackish water RO desalination units with capacities ranging from 90 to 1,893 m^3/day were installed in Beirut mostly to supply fresh water for industries, municipalities, and tourist facilities (FICHTNER 2011). More recently, residents who could afford the costs of desalination have resorted to using RO units to desalinate their private well water to supplement the insufficient public water supply. The fee that citizens pay for their public water supply has been estimated at around 190 $/year/household (Saidy 2016).

Like the condition of the water network, electricity production and distribution for the GBA post-war has not kept up with demands. Moreover, population growth, heightened by the large influx of Syrian refugees to Lebanon, have put pressure on the electricity supplied by Electricite Du Liban (EDL). As such EDL has not been able to meet the ever-increasing demand and has limited its electricity supply to an average of 15 hours per day. Residents have resorted to the use of private diesel generators to cover the deficit. The penetration of RE to the Lebanese market has been slow. Only 4% of the power produced nationally could be considered as RE, most of which comes from hydropower (Berjawi et al. 2017). With solar insolation between 2 and 8 kWh/m^2/day in

Lebanon, around 300 sunny days yearly, and 8 to 9 hours of sunshine daily (UNDP/CEDRO 2013), PV arrays offer a reasonable substitute for the electricity outages and the reliance on the private generators. In a recent study, Berjawi et al. (Berjawi et al. 2017) generated the Beirut solar map, which accounted for the impediment of the overshadowing by nearby buildings on some rooftops. Their results showed that, depending on the rooftop free-area and the PV panel efficiency, 8 to 34 % of Beirut's power demand could be provided by solar energy. Related to the PV market in Lebanon, between 2011 and 2017, the price of solar PV decreased by 78% from 7,186 $\$/kW_p$ to 1,545 $\$/kW_P$ (UNDP/DREG 2018). The Lebanese Government has committed itself in the 2009 Copenhagen Climate Summit to reach the target of supplying 12% of the total electricity through RE by 2020 (Ayoub et al. 2013). Unfortunately, this target is still far from being met.

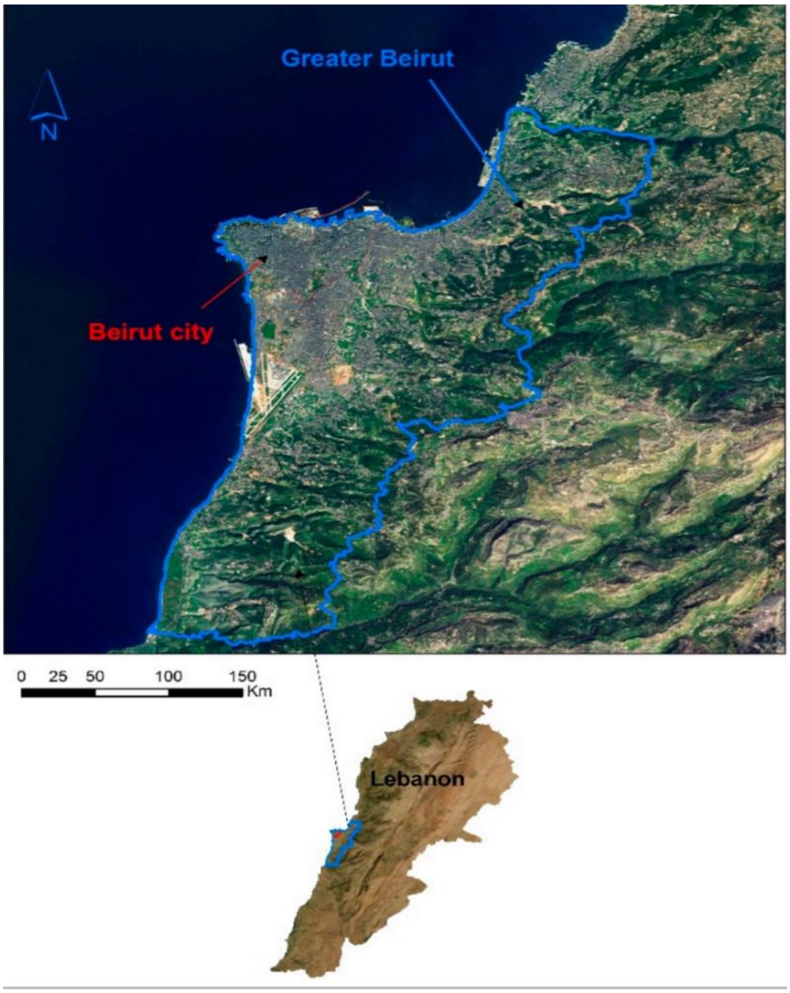


Figure 1. Location of the Greater Beirut Area.

B. Market Survey

A questionnaire (Appendix A) was developed and used to gather information from the main desalination units'suppliers in Lebanon. Informal interviews with the largest four suppliers were also conducted to help fill gaps in the available data relating to private wells in the city and the localized costs associated with installation, operation, and maintenance of the RO systems at the building levels.

The questions focused on the efficiency of the installed RO units, their recovery rates, capacities, lifetime, economic feasibility, as well as the social acceptance and trust in the quality of the finished water. The questionnaire also asked about the applied methods used for brine disposal in Beirut. The assembled quantitative data were used to perform the cost analysis of the RO systems in this assessment using modified equations reported by Fernandez-Gonzales et al. (Fernandez-Gonzalez et al. 2015). Note that since the EDR technique has not yet been used in Lebanon as per the local desalination units'suppliers, relevant information on the technology was only available through data from previous international and regional studies on EDR systems. With regards to the PV potential in Lebanon, an interview was conducted with the National Center for Remote Sensing (NCRS) (Najem 2019) in order to better understand the center's recent assessment of rooftop PV feasibility for Beirut. Finally, a meeting with the project manager and senior energy advisor at CEDRO-UNDP (Harajli 2019) was also held to know more about the latest development of the solar PV market in Lebanon.

C. Cost Analysis

A preliminary cost analysis was conducted to assess the costs ($\$/m^3$) of producing water through EDR and RO using either power from the grid or electricity supplied by roof-installed PV cells.

The cost of producing water by EDR through electricity provided by the grid ($C_{ED\text{-}GRID}$) was calculated employing adapted equations from (Fernandez-Gonzalez et al. 2015). Some economic and technical parameters were obtained from that reference, while other parameters were modified to fit the context of the case study.

1. Capital Cost

a. EDR

The total annualized capital cost TAC_{ED} ($/m^3) was obtained by multiplying the total capital cost TCC_{ED} ($) by the amortization factor AF (year^{-1}) and dividing it by the annual produced water volume APV (m^3/year) as shown in equation (1):

$$TAC_{ED} = TCC_{ED} \times \frac{AF}{APV} \quad (1)$$

$$AF = \frac{IR}{1-(1+\mathrm{IR})^{-\mathrm{DP}}} \quad (2)$$

where IR is the interest rate set at 10% by the Beirut Reference Rate (BRR, 2019) and DP is the depreciation period.

TCC_{ED} was calculated by using the fraction of direct cost (DC_F) along with the cost of the membranes C_{Memb} ($) and the cost of EDR, C_{ED}, ($) as shown in equation (3):

$$TCC_{ED} = (DC_F + 1) \times (C_{Memb} + C_{ED}) \quad (3)$$

C_{Memb} was found by multiplying the area of the membranes A_{Memb} (m^2) by the price per unit area of the membrane P_{Memb} ($/m^2) (Equation 4):

$$C_{Memb} = A_{Memb} \times P_{Memb} \quad (4)$$

As for $C_{ED,}$ it was found by multiplying C_{Memb} by the ratio of full plant to membrane (RFPM) parameter (Equation 5) :

$$C_{ED} = RFPM \times C_{Memb} \quad (5)$$

Based on the cost data provided by Fernandez-Gonzales et al. (Fernandez-Gonzalez et al. 2015) for a 48 m^3/day brackish water unit with an effective membrane area of 60 m^2, costs were calculated for scaled-down units with capacities ranging from 10 to 30 m^3/day. This was achieved by recalculating the needed membrane areas based on the relations proposed by Strathmann (Strathmann 2010), where membrane area was found to be proportional to the output flow (A α Q) as well as to the difference between the feed (C^f) and diluate water (C^d) concentrations (A α (C^f - C^d).

Assuming all other factors constant, membrane areas are expected to scale down with flow perfectly. As such, when the flow rate decreases from 48 to 10 m^3/day, the membrane area is expected to decrease from 60 m^2 to 12 m^2. Similarly, flows of 20 and 30 m^3/day capacities are expected to require 24 and 36 m^2 of membranes, respectively. For a given flow, the initial salinity plays a significant role in determining the required membrane area, with larger areas associated with higher initial salinities.

Accordingly, for a feed salinity of 2,000 ppm and a flow of 10 m^3/day 12 m^2 of membrane are needed. The membrane area increases to 20 m^2 at 3,000 ppm and to 36 m^2 at 5,000 ppm assuming the same flow of 10 m^3/day. At a flow rate of 20 m^3/day the membrane areas required are estimated to be 24 m^2 at 2,000 ppm, 40 m^2 at 3,000 ppm and 72 m^2 at 5,000 ppm. Likewise, for a 30 m^3/day capacity, the required membrane areas of 36, 60, and 108 m^2 for initial salinities of 2,000 ppm, 3,000 ppm, and 5,000 ppm respectively.

b. RO

The total annualized capital cost for RO (TAC_{RO}) was calculated using a similar equation to that of EDR (Equation 6):

$$TAC_{RO} = TCC_{RO} \times \frac{AF}{APV} \quad (6)$$

Note that the total capital cost (TCC_{RO}) at different salinities and capacities were obtained directly from interviewed local RO suppliers.

2. Operational Cost

a. EDR

The total operational cost (TC_{Oper} \$/m^3) for the EDR was calculated by summing the total operational and maintenance cost $TC_{O\&M}$ (\$/m^3) with the cost of energy C_{Energ} (\$/m^3) :

$$TC_{Oper} = TC_{O\&M} + C_{Energ} \quad (7)$$

$TC_{O\&M}$ includes the cost of membrane replacement, C_{MembR} (\$/m^3), the cost of electrode replacement, C_{ElectR} (\$/m^3), cost of chemicals, C_{Chem} (\$/m^3), cost of spares, C_{Sp} (\$/m^3), and the cost of labor, C_{Lb} (\$/m^3) as shown in equation 8:

$$TC_{O\&M} = C_{MembR} + C_{ElectR} + C_{Chem} + C_{Sp} + C_{Lb} \quad (8)$$

C_{MembR} was found by multiplying the membrane replacement factor (RF_{Memb}) by C_{Memb} and by AF, then dividing by APV:

$$C_{MembR} = RF_{Memb} \times C_{Memb} \times \frac{AF}{APV} \qquad (9)$$

C_{ElectR} was found by multiplying the electrode replacement factor (RF_{Elect}) by the price of the electrodes P_{Elect} (\$) and by AF then dividing by APV:

$$C_{ElectR} = RF_{Elect} \times P_{Elect} \times \frac{AF}{APV} \quad (10)$$

C_{Energ} was found by multiplying the price of energy P_E (\$/kWh) by the specific energy consumption per unit volume of water produced, SEC (kWh/m^3) :

$$C_{Energ} = P_E \times SEC \qquad (11)$$

The varied range of SEC values encountered in different studies of EDR systems (Al-Karaghouli and Kazmerski 2013, Ali et al. 2011, Boden and Subban 2018, Fernandez-Gonzalez et al. 2015, Ghaffour et al. 2013, Gonzalez et al. 2017, Karimi et al. 2015, Ortiz et al. 2007, Ramanujan et al. 2017, Schäfer et al. 2014, Sharon and

Keddy 2015, Valero and Arbós 2010, Wright and Winter 2014) necessitated working within an envelope and as such the minimum, average and maximum values of SEC at each salinity were used.

Finally, the cost of water produced ($/m^3) using the grid as a source of power for the EDR system was found by adding the total annualized capital cost and the total cost of operation:

$$C_{ED-GRID} = TAC_{ED} + TC_{Oper} \quad (12)$$

b. RO

Equation (7) was also used to calculate the operational cost of RO. But for RO, $TC_{O\&M}$ was modified to include the cost of pump replacement C_{PumpR} ($/m^3) instead of electrodes, since in RO units high-pressure pumps are used and there are no electrodes.

$$TC_{O\&M} = C_{MembR} + C_{PumpR} + C_{Chem} + C_{Sp} + C_{Lb} \quad (13)$$

$$C_{PumpR} = RF_{Pump} \times P_{Pump} \times \frac{AF}{ATV} \quad (14)$$

where RF_{Pump} is the replacement factor of the pumps, and P_{Pump} is the price of the pumps ($).

The cost of energy was calculated using equation 15:

$$C_{Energ} = P_E \times SEC \quad (15)$$

For RO, the SEC values reported in the literature were more consistent as compared to the EDR (Al-Karaghouli and Kazmerski 2013, Bilton et al. 2011, Boden and Subban 2018, Fornarelli et al. 2018, Ghaffour et al. 2013, Goosen et al. 2014, Karimi et al. 2015, Mezher et al. 2011, Shahzad et al. 2017, Sharon and Keddy 2015, Wright and Winter 2014).

Based on these studies, the SEC for small-scale RO and EDR units (<100 m^3/day) were found not to differ significantly with increasing flow rates.

Finally, the cost of water produced ($\$/m^3$) using the grid as a source of power for the RO systems was found by adding the total annualized capital cost and the total cost of operation:

$$C_{RO-GRID} = TAC_{RO} + TC_{Oper} \quad (17)$$

3. PV-Powered Desalination Units

a. EDR

If PV modules were to be used to power the EDR system, the cost of water produced, $C_{ED\text{-}PV}$ ($\$/m^3$) was calculated as follows :

$$C_{ED-PV} = TAC_{ED} + TAC_{PV} + TC_{O\&M} \quad (18)$$

where TAC_{PV} is the total annualized cost of PV ($\$/m^3$ of produced water), calculated using the following equation:

$$TAC_{PV} = TCC_{PV} \times \frac{AF}{APV} \quad (19)$$

where TCC_{PV} is the total capital cost of PV ($), including all electronic components needed, which was computed using Equation 20:

$$TCC_{PV} = k \times A_{PV} \times P_{PV} \quad (20)$$

where P_{PV} is the price of PV ($\$/kW_P$), A_{PV} is the area of PV used (m^2), and k is the power per unit area of the PV module kW_P/m^2.

$$A_{PV} = SEC \times \frac{FR}{PR_{PV} \times I \times \varepsilon_{PV}} \quad (21)$$

Equation 21 was modified from the equations used by (Bian et al. 2019) and (Berjawi et al. 2017), where I is the average daily global horizontal irradiation ($kWh/m^2/day$), FR is the flow rate (m^3/day), PR_{PV} is the performance ratio of the PV panels, and ε_{PV} is their efficiency. Based on Najem (Najem 2019), the average daily global horizontal irradiation (*I*) in Beirut is 2.05 kWh/m^2 including overshadowing at the buildings'rooftops as compared to a climatic zoning value of 4.855 kWh/m^2. Since the PV panels were assumed to be mounted at an angle of 25 degrees, the average daily global tilted irradiation was used for calculation purposes rather than the average daily global horizontal irradiation, which was considered as 5.74 kWh/m^2/day based on the Global Solar Atlas (WorldBankGroup 2016). Using the same correction factor, this value was adjusted and found to be 2.5 kWh/m^2/day. The latter value was used in all subsequent calculations.

b. RO

Since RO units necessitate the use of alternating current (AC) power for the high-pressure pumps, a direct current/alternating current (DC/AC) inverter will be needed. The inverter's cost C_{INV} ($) was assumed to be 1% of the TCC_{PV}, based on data provided by an interviewed engineer who works with CEDRO.

As such, the equation used to calculate the total annualized cost of PV was modified, as shown in equation 22:

$$TAC_{PV} = (TCC_{PV} + C_{INV}) \times \frac{AF}{APV} \quad (22)$$

Thus the total cost of water produced by RO-PV was calculated based on equation 23:

$$C_{RO-PV} = TAC_{RO} + TAC_{PV} + TC_{O\&M} \quad (23)$$

Currently, the one kW$_p$ solar PV has a cost of 1,100 $ in the local market, and each 1 m^2 of PV panels can supply 0.11 kW$_p$ (Harajli 2019).

4. Environmental Cost

Besides being energy-intensive, grid-powered desalination plants have an adverse impact on the environment, namely through the release of greenhouse gases and the discharge of the generated brine. Currently, 76 million tons of CO_2 are emitted each year by desalination systems worldwide. By 2040, it is expected to reach 218 million tons (Shahzad et al. 2017). Moreover, the rejected concentrate from these plants, which includes high salinity brine that comprises several potentially harmful chemicals, is considered an environmental threat whether it is disposed of in the sewer network, surface water, evaporation ponds or in the sea (Miller et al. 2015, Morillo et al. 2014). The total environmental cost TEC ($/m^3) for grid-tied desalination units, was calculated using equation 24:

$$TEC = (Q_{Brine} \times C_{Treat}) + (M_{CO2} \times SEC \times C_C) \quad (24)$$

Where M_{CO2} (kg/kWh) is the mass of CO_2 released to the atmosphere per 1 kWh of electricity produced. In Lebanon, this value was assumed to be 0.65 kg of CO_2/kWh of generated power by EDL (UNDP/CEDRO 2013, UNDP/DREG 2018). The cost of carbon C_C was assumed to be 0.02 $/kg of carbon released (WorldBank 2018), although, in Lebanon, this carbon tax has never been applied.

With regards to the cost of brine disposal, we assumed that the brine generated at the building level in Beirut would be discharged directly into the sewage network, increasing the corresponding treatment cost. A treatment cost (C_{Treat}) was supposed to be 0.8 $ per m^3 of treated wastewater (ESCWA 2003). Assuming that the recovery ratio, which is defined as the volume flow rate of product to that of input feed water, is 95% for the EDR units (Nayar et al. 2017, Ramanujan et al. 2017) and 60% for a single pass RO unit (based on local market), the ratio of brine generated to generated finished water, Q_{Brine} (m^3 of brine/m^3 of produced water) was found to be 0.053 for the EDR system, and 0.66 for the RO system in Beirut.

Table 3. Summary of the Parameters Used to Perform the Calculations of Desalination Costs in the Study Area.

	UNIT	BWRO	BWEDR
DP	(year)	20[b]	20[a]
RF_{Memb}	(%)	40[c]	15[a]
RF_{Pump}	(%)	20[c]	
C_{chem}	$(\$/m^3)$	0.11[b]	0.0008[a]
C_{Sp} (at 2,000, 3,000, 5,000, 10,000 ppm)	$(\$/m^3)$	0.05[b]	0.25[a]
C_{Sp} (at 25,000 ppm)	$(\$/m^3)$	0.08[b]	
C_{Lb}	$(\$/m^3)$	0.137[b]	0.02[a]
P_{Memb}	$(\$/m^2)$		160[d]
C_{Memb} (at 2,000, 3,000, 5,000, 10,000 ppm)	($)	500[b]	
C_{Memb} (at 25,000 ppm)	($)	600[b]	
RFPM	(%)		71[a]
RF_{Elect}	(%)		100[a]
DC_F	(%)		10[a]
P_{Elect}	($)		100[e]
PR_{PV}	(%)	75[f]	75[f]
ε_{PV}	(%)	18[g]	18[g]
k	(kW_p/m^2)	0.11[h]	0.11[h]
IR	(%)	10	10
P_E (by EDL)	($/kWh)	0.096[i]	0.096[i]
P_E (Private Generators)	($/kWh)	0.22[b]	0.22[b]

a (Fernandez-Gonzalez et al. 2015), b (local market), c (Bilton et al. 2011), d (Bian et al. 2019), e (Nayar et al. 2017), f (Berjawi et al. 2017), g (Abdelkareem et al. 2018), h (UNDP/CEDRO 2013), i (Bouri and El Assad 2016, El-Fadel et al. 2010).

D. Scenario Analysis

Three main scenarios were developed to assess the feasibility of small-scale brackish desalination in Beirut. The first looked at installing the desalination units in small buildings with 50 inhabitants, the second looked at installing the units in a medium-sized building with 100 inhabitants, and lastly the third assessed installation in a large building with 150 inhabitants. The size of the building affects the amount of PV energy that can be produced on the roof as well as the daily water requirements. The required water consumption rate was assumed to be 200 L/person/day (El-Fadel et al. 2010).

On the other hand, two values for the grid-provided electricity price were used in the calculation. The first accounted for the current EDL tariff of 0.096 $/kWh (Bouri and El Assad 2016, El-Fadel et al. 2010), while the second represented the price of electricity delivered by private diesel generators (0.22 $/kWh). With regards to the use of PV, the desalination units were assumed to be directly connected to the rooftop PV, without any storage batteries and thus would only operate when solar power is available. Any excess desalinated water was assumed to get stored in water tanks to be consumed on cloudy days. In order to ensure stable operation, the units were assumed to be linked to the electricity grid so as to guarantee continuous electricity supply in case PV power was not adequate.

Based on the assessment of (Berjawi et al. 2017), a minimum of 30% of the rooftop area of a typical building in Beirut can be considered available to install PV modules. The PV panels are recommended to be fixed at an angle of 25 degrees facing South and flush-mounted. So the maximum free area to be occupied by the panels can be determined by dividing the available rooftop area by cos (25).

Given that the required energy for both EDR and RO desalination systems depends on the feed water salinity, different feed salinities were considered with a required product water salinity of 500 ppm. The 500 ppm TDS level represents the potable water standard for salinity as set by the World Health Organization (WHO) which was updated in 2011 to a value of 600 ppm (Pinto and Marques 2017). Table 4 summarizes the scenarios considered in the analysis.

Table 4. Scenarios Considered for Assessing the Economic Feasibility of Small-Scale Desalination Units in the Study Area.

Building	UNIT	Small	Medium	Large
Inhabitants		50	100	150
Water Demand	m^3/day	10	20	30
Rooftop Area	m^2	100	300	600
EDR & RO Salinities	ppm	2,000 3,000 5,000	2,000 3,000 5,000	2,000 3,000 5,000
RO only Salinities	ppm	10,000 25,000	10,000 25,000	10,000 25,000

CHAPTER III

RESULTS

A. Survey Results

Since the early 1990s, RO systems in Beirut have been installed at the building level to treat brackish groundwater with salinities ranging from 1,200 ppm up to 25,000 ppm. The capacities of these units have ranged between 10 and 100 m^3/day. The associated capital cost for these units has been reported to vary between 10,000 $ and 100,000 $. Given the relatively high capital and operational costs associated with RO, adoption of the technology has largely been restricted to high-end buildings, especially those newly constructed in upmarket areas of the city. With regards to their operational reliability, the suppliers stated that frequent electricity shortages, the act of mixing the brackish feedwater with chlorinated public water, as well as poor post-sales maintenance were the main reasons negatively affecting the performance of these units. The poor performance manifested itself with a shortened serviceable life, a low recovery rate (< 60%), and a weak social confidence in the quality of the produced water as a suitable drinking water source. On the environmental end, the interviewed suppliers showed little knowledge and concern with the negative environmental impacts of RO. Most indicated that the generated brine was mainly disposed of either in the sewage system or reinjected into the aquifer itself. The latter practice can further aggravate the salinity levels of the aquifer. We think that this low environmental awareness is largely due to the lack of any environmental regulations for the desalination industry in Lebanon. In many countries, desalination units must comply with the National Pollutant Discharge Elimination System (NPDES) and/or with the

International Environmental Agency’s (IEA) regulations and undergo continuous monitoring (Sadhwani Alonso and Melián-Martel 2018). Finally, with regards to the membrane requirements, the suppliers explained that a single-membrane RO unit was able to supply around 7 m^3/day of desalinated water. Therefore, a building with a 10 m^3/d demand would require two membranes, a 20 m^3/d building requires three membranes, and finally, a 30 m^3/d building needs five membranes.

B. Energy Consumption at Different Salinities

Figure 2 shows the SEC at different salinities for small-scale EDR units, with capacities less than 100 m^3/day. The graph was based on data provided from several previous studies (Al-Karaghouli and Kazmerski 2013, Ali et al. 2011, Boden and Subban 2018, Fernandez-Gonzalez et al. 2015, Ghaffour et al. 2013, Gonzalez et al. 2017, Karimi et al. 2015, Ortiz et al. 2007, Ramanujan et al. 2017, Schäfer et al. 2014, Sharon and Keddy 2015, Valero and Arbós 2010, Wright and Winter 2014). As can be seen, the minimum SEC range tended to increase linearly with increased salinity, while for the upper bound of the SEC, the increase appears to be exponential particularly beyond the 4,000 ppm salinity. With regards to RO, the information received from the local suppliers was found to be neither specific nor reliable, therefore data from published papers were used instead to provide more consistent values as shown in Figure 3 (Al-Karaghouli and Kazmerski 2013, Bilton et al. 2011, Boden and Subban 2018, Fornarelli et al. 2018, Ghaffour et al. 2013, Goosen et al. 2014, Karimi et al. 2015, Mezher et al. 2011, Shahzad et al. 2017, Sharon and Keddy 2015, Wright and Winter 2014).

As can be seen from Figure 3, the increase in energy consumption was more or less linear relative to the increase in salinity. The SEC on average increased by 1 kWh/m^3 for every 10,000 units increase in salinity. Ultimately, the SEC reached 5 kWh/m^3 when seawater (35,000 ppm) was desalinated.

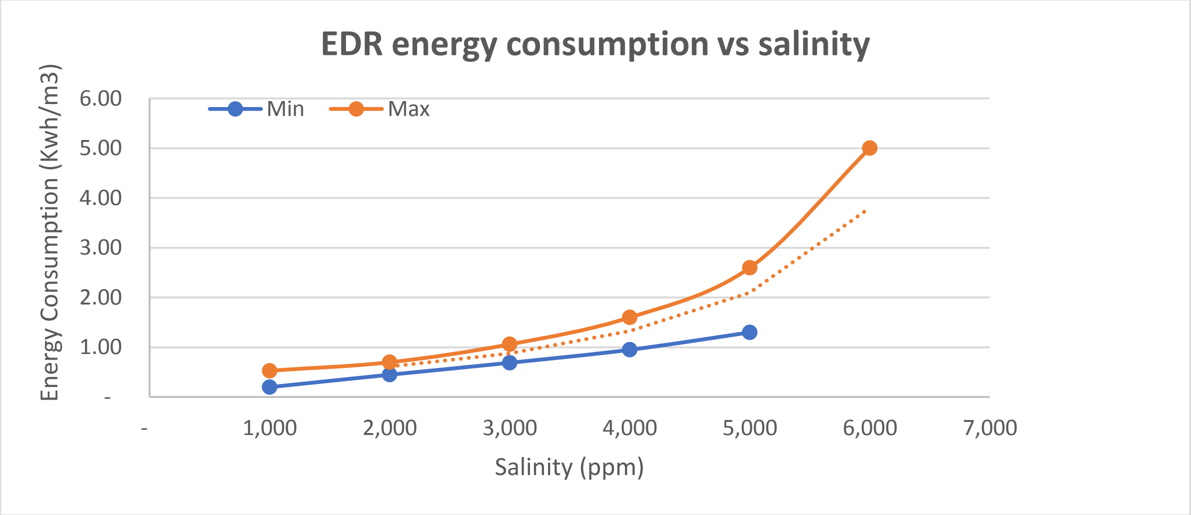


Figure 2. Energy Consumption of EDR at Different Salinities for Small-Scale Units (<100 m^3/d).

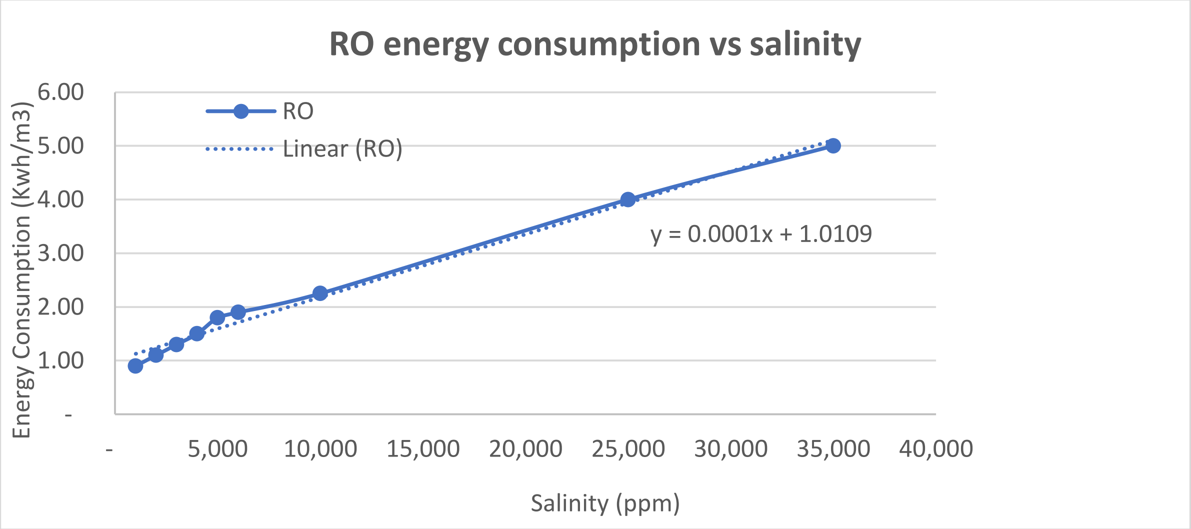


Figure 3. Energy Consumption of RO at Different Salinities for Small-Scale Units (<100 m3/d).

C. Cost Analysis

1. Grid-powered EDR

The calculated direct cost of water desalinated by grid-powered EDR ($C_{ED\text{-}Grid}$) ranged from 0.43 \$/m^3 at 2,000 ppm, assuming the lowest SEC, up to 0.85 \$/m^3 at 5,000 ppm using the maximum SEC. In both cases, the current subsidized electricity tariff was assumed to be 0.096 \$/kWh. When a higher more realistic electricity price was used (0.22 \$/kWh), the cost range increased to 0.49 \$/m^3 for a 2,000 ppm feed and reached 1.17 \$/m^3 of produced water when the feed water had a salinity of 5,000 ppm. Note that since the EDR equations were linear with regards to capacity, the economies of scale were not accounted for. Therefore, the same water cost was obtained for the three considered capacities, namely 10, 20, and 30 m^3/day.

When the indirect environmental costs were quantified and included in the calculations, the range of the costs increased to 0.48-0.93 \$/m^3, when the electricity tariff was 0.096 \$/kWh (Figure 4), and to 0.54-1.25 \$/m^3, when the electricity tariff was assumed to be 0.22 \$/kWh (Figure 5).

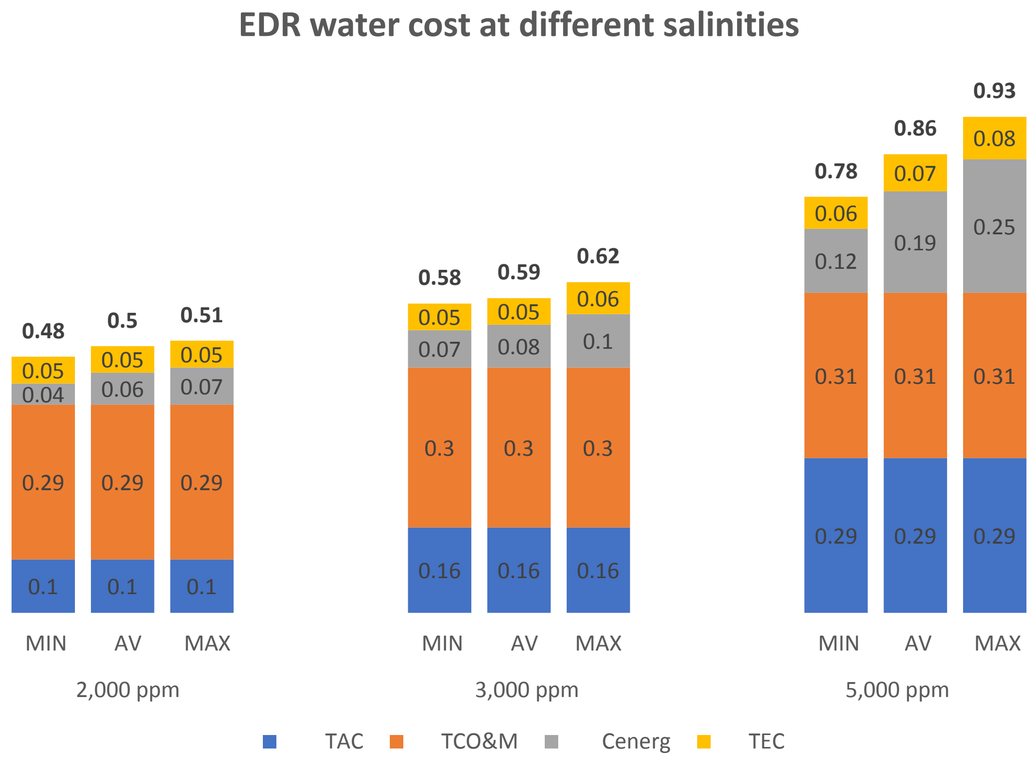


Figure 4. Cost of Desalinated Water ($/m^3) by Grid Powered EDR at Different Salinities Assuming an Electricity Price of 0.096 $/kWh. MIN, AV, and MAX represent the minimum, the average, and the maximum specific energy. TAC stands for the total annualized cost, $TC_{O\&M}$ the total operation and maintenance cost, C_{Energ} is the cost of energy, and TEC is the total environmental cost.

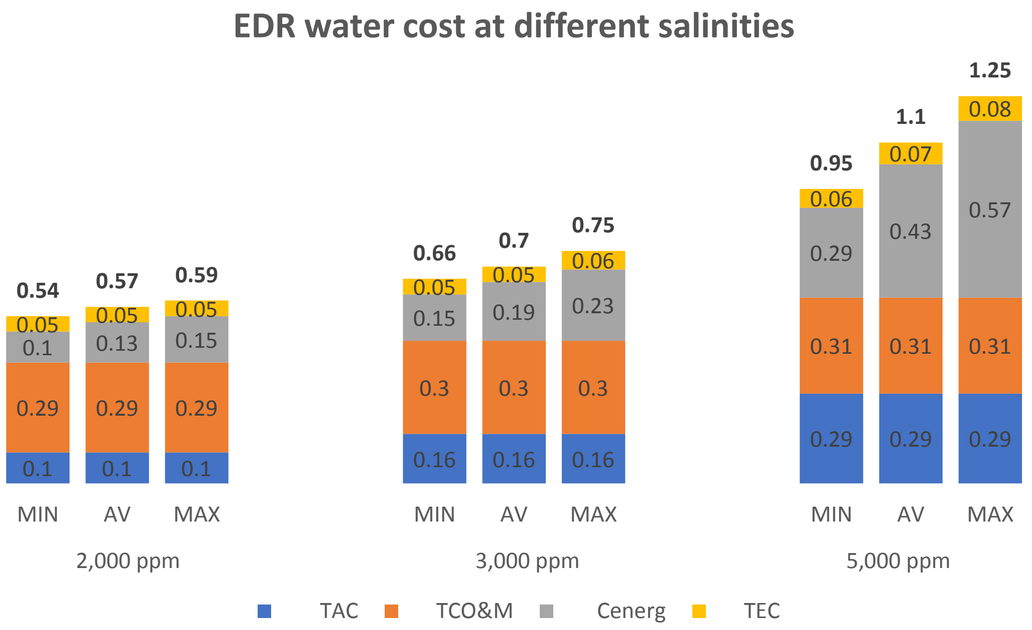


Figure 5. Cost of Desalinated Water ($/m^3) by Grid Powered EDR at Different Salinities Assuming an Electricity Price of 0.22 $/kWh. MIN, AV, and MAX represent the minimum, the average, and the maximum specific energy. TAC stands for the total annualized cost, TC$_{O\&M}$ the total operation and maintenance cost, C$_{Energ}$ is the cost of energy, and TEC is the total environmental cost.

2. Grid-Powered RO

At the lower electricity bound of 0.096 $/kWh, the RO cost per m^3 ranged from 0.58 $/m^3 for an inflow salinity of 2,000 ppm and a capacity of 30 m^3/day up to 1.35 $/m^3 for a salinity of 25,000 ppm and with a capacity of 10 m^3/day. At the higher electricity cost of 0.22 $/kWh, the range increased to 0.71-1.85 $/m^3. Note that although the same linear equations as those for the EDR were used to calculate the cost of produced water by RO units, the TCC values for the latter were obtained from local suppliers, and they accounted for the economies of scale.

Upon including the environmental costs, the costs rose significantly to reach 1.12-1.92 $/m^3 (Figure 6), and 1.25-2.42 $/m^3 (Figure 7) for 0.096 $/ kWh and 0.22 $/ kWh respectively taking into account capacities between 10 and 30 m^3/day.

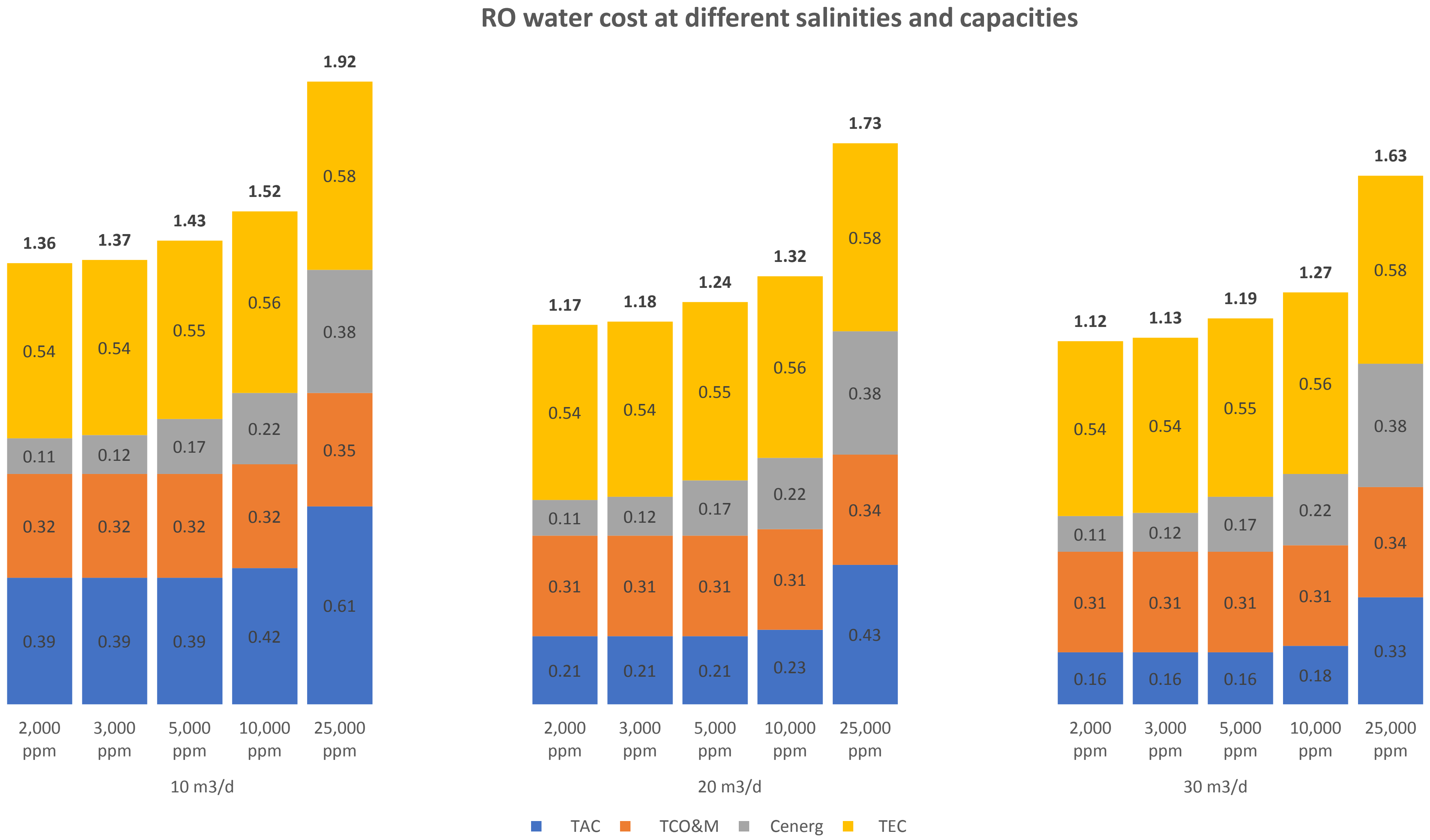


Figure 6. Cost of Grid Powered RO Desalinated Water (\$/m^3) at Different Salinities and Capacities Assuming an Electricity Price of 0.096 \$/kWh. TAC stands for the total annualized cost, TC$_{O\&M}$ the total operation and maintenance cost, C$_{Energ}$ is the cost of energy, and TEC is the total environmental cost.

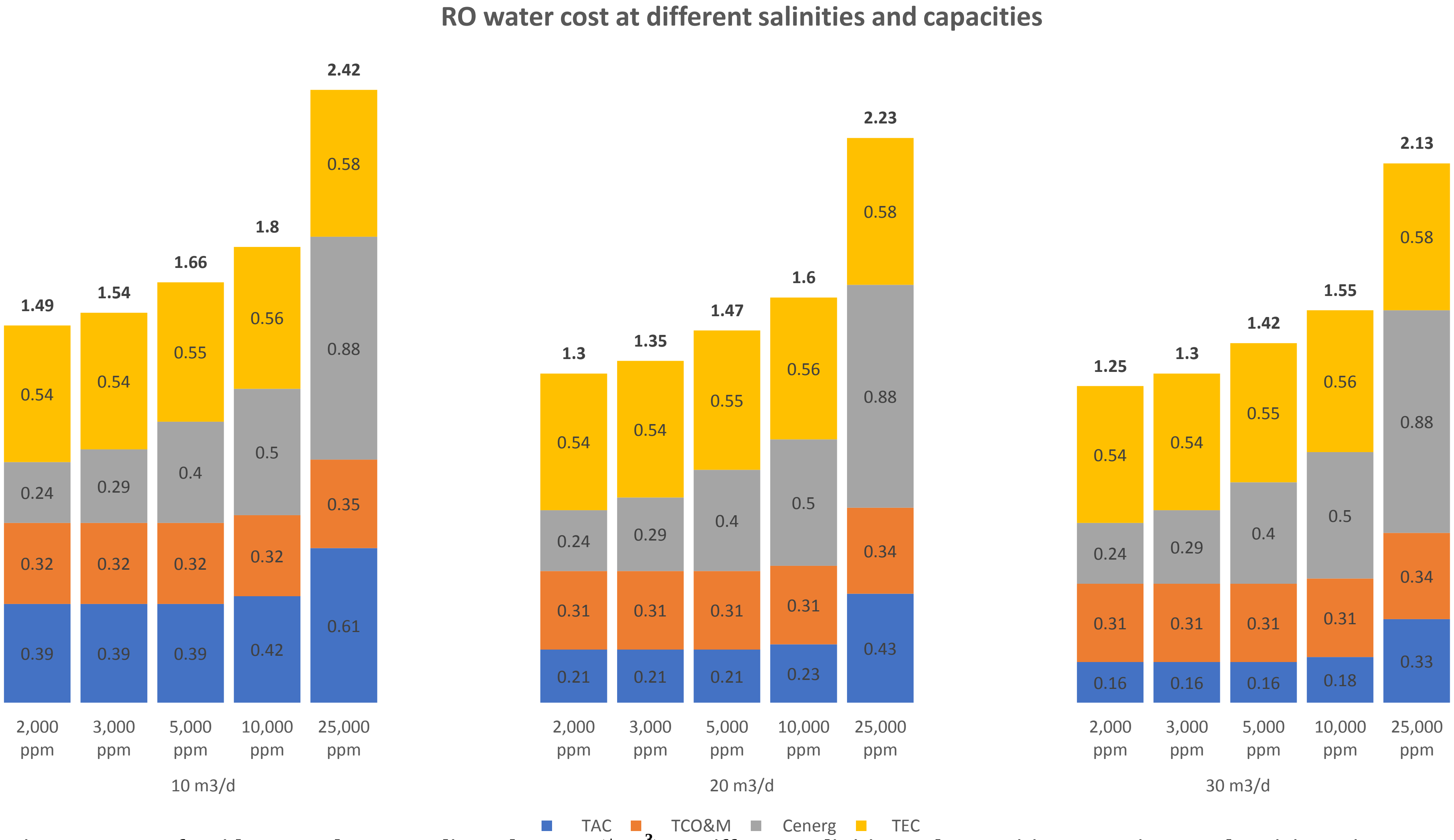


Figure 7. Cost of Grid Powered RO Desalinated Water (\$/m^3) at Different Salinities and Capacities Assuming an Electricity Price of 0.22 \$/kWh. TAC stands for the total annualized cost, TC$_{O\&M}$ the total operation and maintenance cost, C$_{Energ}$ is the cost of energy, and TEC is the total environmental cost.

3. ED-PV

When using rooftop PV panels to power the EDR units, the water cost for a small building ranged from a minimum of 0.44 \$/m^3 at a salinity of 2,000 ppm up to a maximum of 0.87 \$/m^3 at a 5,000 ppm TDS when the cost of energy was based on a value of 0.096 \$/kWh. The maximum reached 1.06 \$/m^3 when the cost of energy was 0.22 \$/kWh. When the environmental costs were included, the ranges increased to 0.48-0.93 \$/m^3 and 0.48-1.12 \$/m^3 for the two aforementioned electricity tariffs. For a medium-sized building, the water cost was found to be similar to that for a small building at the lower energy cost (0.096 \$/kWh). At the higher energy cost, the range was between 0.44 and 0.99 \$/m^3. As for the large building, the ranges were 0.44-0.89 \$/m^3 and 0.44-0.94 \$/m^3 at electricity costs of 0.096 \$/kWh and 0.22 \$/kWh respectively. These increased to 0.48-0.93 \$/m^3 and to 0.48-0.98 \$/m^3 when the environmental costs were considered.

When using the maximum value of SEC needed by EDR units and assuming the high electricity cost, the water costs increased to reach a range of 0.511-1.122 \$/m^3 including the environmental costs (Figure 8).

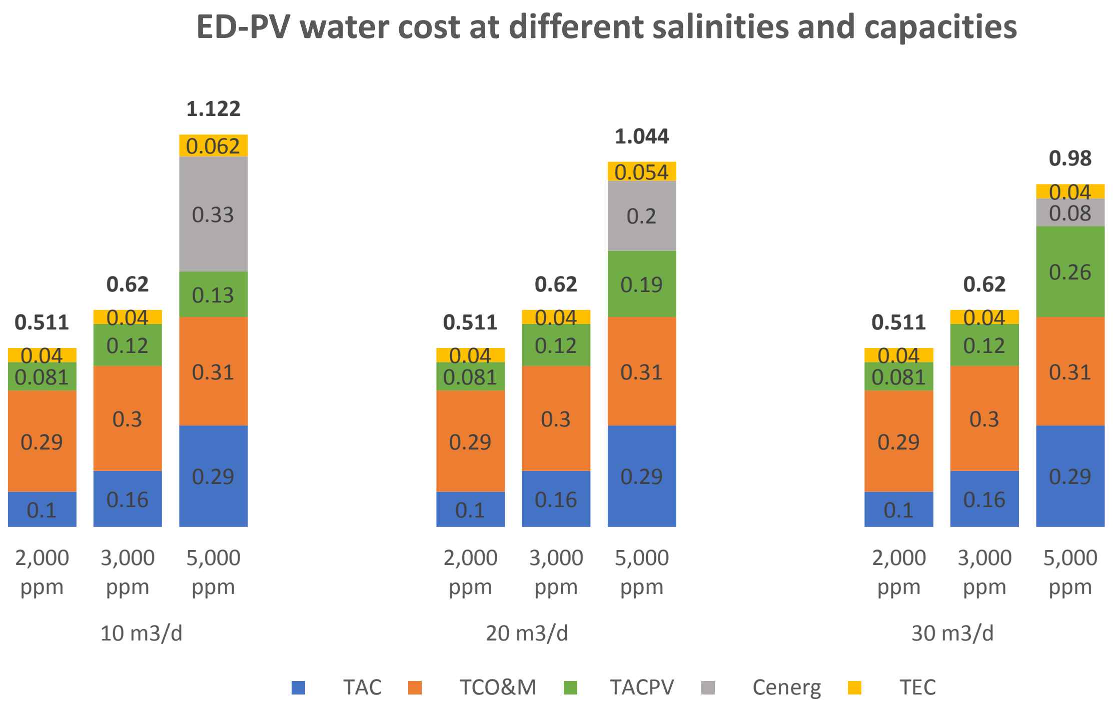


Figure 8. Cost of PV-Powered EDR (\$/m^3) at Different Salinities and Capacities. The energy cost C_{Energ} represents the system's electricity cost when the price of grid-power was assumed to be 0.22 \$/kWh and when the power supplied by PV was not sufficient (the SEC value used in this graph was the maximum). TAC_{PV} represents the total annualized cost of PV, $TC_{O\&M}$ the total operation and maintenance cost, C_{Energ} represents the cost of energy, and TEC the total environmental cost.

4. RO-PV

At an electricity cost of 0.096 \$/kWh, the water cost generated by PV-powered RO ranged from 0.84 to 1.37 \$/m^3 for a small building, 0.65 to 1.19 \$/m^3 for a medium-sized building, and 0.60 to 1.1\$/m^3 for a large building. With the inclusion of environmental costs, these ranges increased to 1.37-1.94 \$/m^3, 1.18-1.76 \$/m^3 and 1.13-1.67 \$/m^3 respectively (Figure 9).

When the energy cost was assumed to be the more realistic value of 0.22 \$/kWh, the costs of desalinated water increased to reach 0.84 to 1.72 \$/m^3 for a small building, 0.65 to 1.48 \$/m^3 for a medium-sized building and 0.6 to 1.32 \$/m^3 for a large building. Upon accounting for the environmental costs, these ranges increased further to reach 1.37-2.29 \$/m^3, 1.18-2.05 \$/m^3, and 1.13-1.89 \$/m^3 respectively (Figure 10).

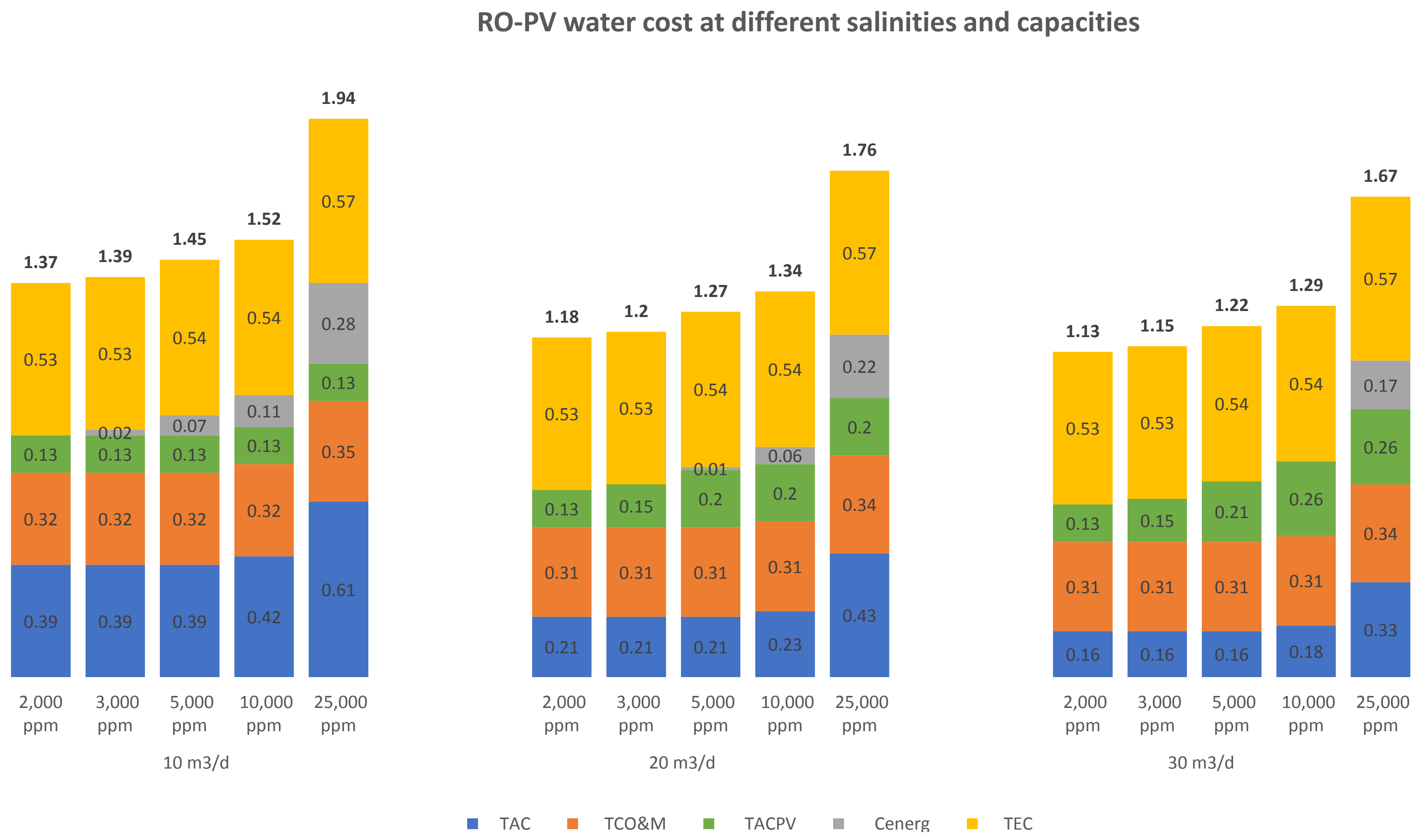


Figure 9. Cost of desalinated water ($\$/m^3$) by PV-powered RO at different salinities and capacities.TAC stands for total annualized cost, $TC_{O\&M}$ for total operation and maintenance cost, TAC_{PV} represents the total annualized cost of PV, C_{Energ} is the cost of electricity when its price was 0.096 $/kWh and when the power supplied by PV was not sufficient, and TEC is the total environmental cost.

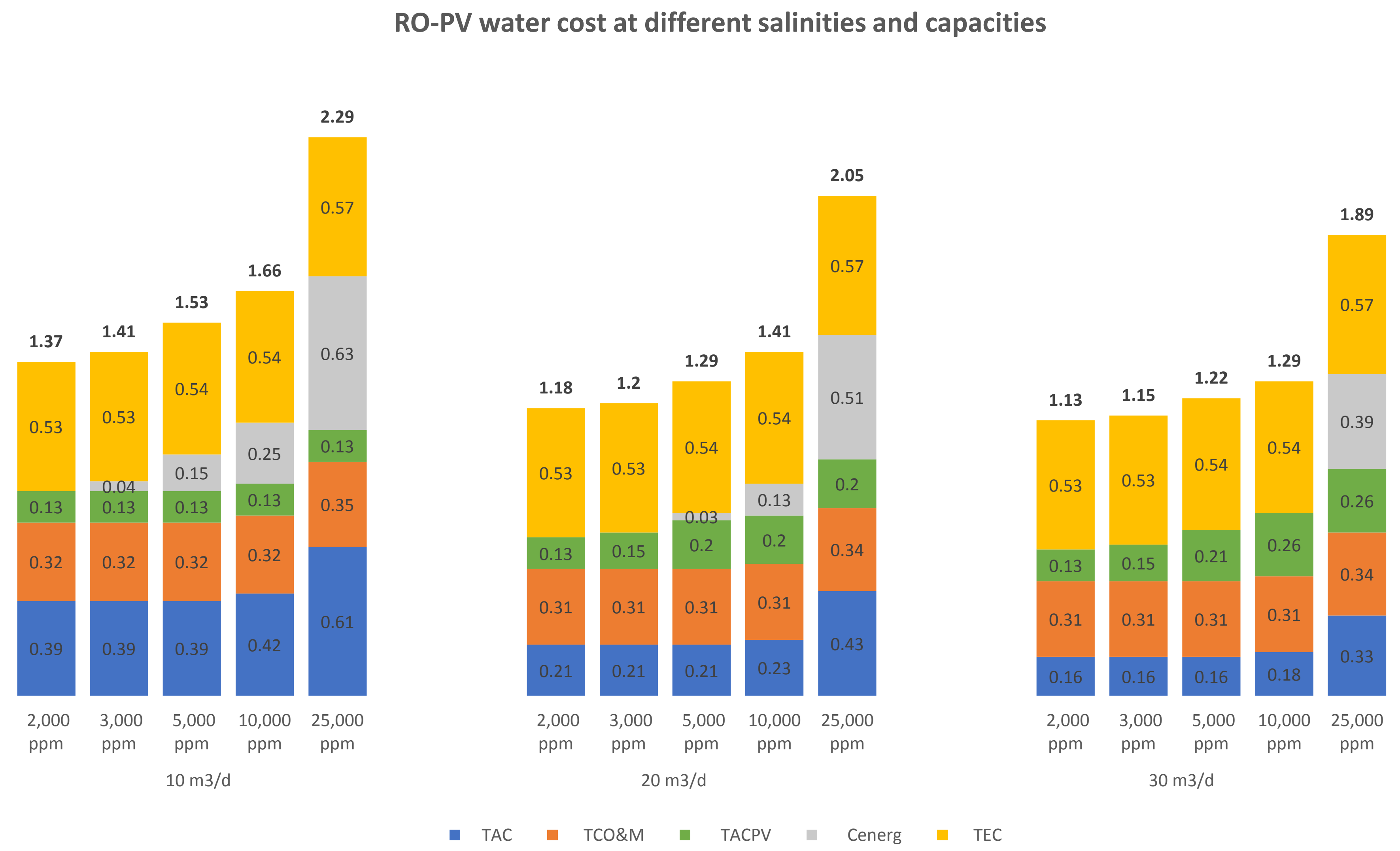


Figure 10. Cost of Desalinated Water (\$/m^3) by PV-Powered RO at Different Salinities and Capacities. TAC stands for total annualized cost, TC$_{O\&M}$ for total operation and maintenance cost, TAC$_{PV}$ represents the total annualized cost of PV, C$_{Energ}$ is the cost of electricity when its price was 0.22 \$/kWh and when the power supplied by PV was not sufficient, and TEC is the total environmental cost.

CHAPTER IV

DISCUSSION

The direct costs calculated for the desalination of the brackish water by small-scale grid-powered EDR and RO units were comparable to those reported in previously published papers, as shown in Table 5. Note that in all reviewed papers, the environmental costs associated with desalinating BW was emphasized but not quantified. Only (Saidy 2016) reported that the total desalinated water cost, including the environmental cost, ranged between 1.06 and 2.67 $\$/m^3$ for small-scale BWRO units at the building level.

In our analysis we found that for a unit with a 10 m^3/d capacity, the costs of water produced by EDR were significantly lower in terms of direct cost as compared to water produced by a similar capacity RO units, irrespective of the salinity assessed, namely at 2,000 ppm, 3,000 ppm, and 5,000 ppm. Upon including the environmental costs, the difference between the two technologies widened further, even when the maximum values of specific energy consumption (SEC) for EDR were assumed. At the higher capacities of 20 and 30 m^3/d, water costs produced by EDR were still lower at the 2,000 and 3,000 ppm salinities as compared to the RO units; yet at a salinity of 5,000 ppm, RO became more feasible as compared to EDR. Note that for the RO systems operating at 20 and 30 m^3/d capacities, their water costs benefited from the economy of scale while the EDR units did not. Costs reported in the literature had also shown that EDR is more advantageous than RO when it came to desalinating BW up to a salinity of 5,000 ppm (Al-Karaghouli et al. 2010, Fernandez-Gonzalez et al. 2015, Manju and Sagar 2017, Strathmann 2010).

Table 5. Cost of Water Produced by ED-GRID and RO-GRID ($/m^3).

ED-GRID	RO-GRID	References
0.6 - 1.05	0.26 -1.33	(Al-Karaghouli and Kazmerski 2012)
1.05	0.56 -12.98	(Fernandez-Gonzalez et al. 2015)
1.5	1.9	(Abraham and Luthra 2011)
-	0.7 -1.72	(Shahzad et al. 2017)
	0.693-1.186	(Sarai Atab et al. 2016)
	0.8 -2.13	(Saidy 2016)
0.43-0.85	0.58 -0.88	This work (P_E 0.096 $/kWh, TDS 2,000-5,000 ppm, TEC not included)
0.49-1.17	0.71 -1.11	This work (P_E 0.22 $/kWh, TDS 2,000-5,000 ppm, TEC not included)

Since desalination is an energy-intensive process, the energy cost has a substantial impact on the final cost of the desalinated water. The energy consumption and cost are affected by both the feed water salinity as well as the set electricity tariffs. Energy costs were found to account for up to 50% for the generated water for an EDR system when the feed water salinity is 5,000 ppm, the SEC was set to its maximum and the electricity price used was 0.22 $/kWh. The same percentage of the total cost was obtained for the RO units desalinating water with a salinity of 25,000 ppm and assuming the same electricity price. With the current electricity shortage in Lebanon, introducing solar energy through rooftop PV panels to power desalination units is a reasonable approach towards decreasing the reliance on the intermittent EDL power supply or the expensive power provided by private generators.

The results show that at the current subsidized electricity tariffs set by EDL, the use of rooftop PV systems, which have the advantage of not incurring the high land cost associated with PV farms, were not economically feasible for both EDR and RO units. The results show that the costs of water produced by ED-PV and by RO-PV were both higher than ED-grid and RO-grid respectively when the price of electricity was set at 0.096 $/kWh. However, ED-PV and RO-PV water costs became much more advantageous as compared to grid-powered units when the electricity price was assumed to be 0.22 \$/kWh. With the expected increase in electricity tariffs in Lebanon as part of the governmental reform plan, the price of power is anticipated to reach 0.14 \$/kWh soon and to be tied to global oil prices (Azhari 2019). In 2009, the average electricity generation cost by EDL stood at 0.171 \$/kWh, 62% of which was due to the cost of fuel (Bouri and El Assad 2016). In 2014, the cost of electricity generation by EDL reached 0.227 \$/kWh due to the high price of crude oil (more than 100 \$/barrel) at that time (BlomInvestBank 2015). The subsidies paid by the government are non-sustainable in the long run and are the largest source of budget deficit at the national level. As such, the assumption of 0.22 \$/kWh electricity tariff in the near future is reasonable. Note that the electricity prices in many European countries range between 0.12 and 0.36 \$/kWh (EuropeanCommission 2019).

With regards to the ability of PV to power the desalination units, we found that at the low feed water salinities of 2,000 and 3,000 ppm the power supplied by PV was sufficient to power the desalination units at the three considered capacities of 10, 20 and 30 m^3/d (Figure 8). However when the salinity reached 5,000 ppm and when the SEC was set at its maximum, we found that the PV panels were only able to supply 43% of the electricity needed by the EDR system for small-sized buildings. For medium-sized buildings, the percentage of power that can be supplied by PV increased to 64%. The percentage increased further for large buildings and reached 86%. The increase is due to the availability of more roof area for the installation of PV panels.

When comparing the direct costs of PV-powered ED and RO units, our results showed that at the scale of small buildings (capacity = 10 m^3/d), the ED-PV costs ranged between 0.44 and 0.87 \$/m^3. These costs are lower as compared to a similar RO-

PV unit, whose costs range between 0.84 and 0.9 $/m^3 for salinities between 2,000 and 5,000 ppm. With increasing capacities, the economies of scale favored RO-PV units over ED-PV units only at the higher salinity of 5,000 ppm. When compared to the costs reported in the literature, we found that our estimated costs were generally lower. Yet some studies reported similar or even lower costs of water produced by PV-powered BW desalination units, as shown in Table 6. The wide range reported for PV-powered desalinated water could be due to the high variability in the PV capital costs as well as the effect of local constraints such as irradiations and temperature on the performance ratio of PV.

Moreover, the inclusion of the value of land required to install a PV array and the cost of batteries needed for storage are major elements that may explain the differences in the prices of PV-powered desalination units. In this work, the cost of land was not considered since the PV modules were assumed to be installed on the building rooftops. Also, the fact that no batteries were used for storage led to lowering the direct cost of the water produced. The excess water produced on sunny days was assumed to be stored in water tanks to be used on cloudy days, thus selecting water storage instead of energy storage can increase the economic feasibility of the system at the cost of lower reliability. Note that the summer months that are endowed with the highest solar irradiation also coincide with the period of highest water demand. This ensures that enough power is produced by the installed PV for the continuous functioning of the desalination units throughout the year. In this study, only 30% of the building’s rooftop area was assumed to be available for PV installation. In numerous buildings, the available roof area can be higher and therefore more power can potentially be supplied by the PV arrays.

Table 6. Cost of Water Produced by ED-PV and RO-PV ($/m^3).

ED-PV	RO-PV	References
2	2.62	(Abraham and Luthra 2011)
6.34-11.93	4.84-6.78	(Al-Karaghouli and Kazmerski 2013)
10.4-11.7	6.5-9.1	(Abdelkareem et al. 2018)
	5.2	(Pinto and Marques 2017)
	3.17 with batteries	(Ramanujan et al. 2017)
	2.33 no batteries	(Ramanujan et al. 2017)
	7 to 9	(Goosen et al. 2014)
4.81-6.11	5.85-7.9	(Xevgenos et al. 2014)
	0.7-1.72	(Shahzad et al. 2017)
0.19-0.43		(Ortiz et al. 2008)
10.4-11.7	7.25	(Manju and Sagar 2017)
0.34-0.94		(Fernandez-Gonzalez et al. 2015)
0.47-0.89	0.6-0.91	This work (P_E 0.096$/kWh, TDS 2,000-5,000 ppm, TEC not included).
0.47-1.06	0.84-0.99	This work (P_E 0.22 $/kWh, TDS 2,000-5,000 ppm, TEC not included).

Upon including the environmental costs in the cost calculations of PV-powered desalination units, the results showed that the EDR (0.48-0.93 $/m^3 at 0.096 $/kWh electricity price) was more cost-effective as compared to RO (1.13-1.94 $/m^3 at 0.096 $/kWh electricity price) systems. Up to a salinity of 5,000 ppm, the carbon cost was nearly similar for the two desalination technologies. The biggest difference was in the volume and ultimately, the cost associated with brine disposal, which was much higher for RO as compared to EDR. The high recovery rate of EDR units at these low salinities resulted in a smaller volume of brine to be disposed of and eventually a lower cost of disposal. Above and beyond, EDR's higher efficiency also leads to lower groundwater pumping rates as compared to RO, and as such, its adoption will decrease the pressure on the groundwater resources.

Currently, the environmental costs associated with desalination are not accounted for in Lebanon, and as such, the choice of the desalination technology is often not optimal. As seen from our results, the EDR, with its high recovery ratio, appears to be the most suitable option to adopt at the building level when the salinity is less than 5,000 ppm. Whereas RO, with its lower recovery ratio, should only be used where the salinities increase beyond 5,000 ppm. When compared to buying water from water tankers whose costs range between 3.5 and 11 $\$/m^3$ (Constantine et al. 2017), both EDR and RO units were found to be more cost-effective and as such the market penetration of desalination is expected to continue to increase in the Lebanese market in the face of chronic water shortages.

With proper maintenance and monitoring along with the addition of UV units as post-treatment option for the desalinated water, the generated desalinated water could be used for potable as well as domestic uses. Thus the adoption of desalination may decrease a household’s water expenditures even more.

Although EDR and RO desalination units powered by rooftop PV were found to be capable of offering a short-term solution to provide freshwater for the citizens of Beirut, long-term centralized plans must be taken by the government to limit the growth of desalination in Beirut. These steps include water conservation, reuse, restructuring the water tariff, recycling, and rainwater harvesting. Above all that, social awareness about the importance of water preservation and usage must be enhanced.

CHAPTER V

CONCLUSION

This paper assessed the feasibility and affordability of grid-powered and PV-powered EDR and RO systems as a short-term stopgap measure that aims to resolve chronic water shortages and increased groundwater salinity in the city of Beirut. Our results showed that PV-powered small-scale desalination units were more economically viable as compared to grid-powered units when the electricity tariffs reflected non-subsidized electricity prices. Our results also showed that up to a salinity of 5,000 ppm, the ED-PV units outperformed their RO-PV counterparts with regards to cost and environmental impacts. Beyond that salinity, the EDR's energy consumption increased significantly, and RO was found to be a more feasible option. A comparison between the costs associated with ED-PV and RO-PV versus the costs associated with the purchase of water tanks from unknown and untrusted sources revealed that desalination was much more economically feasible. As such, it is expected that the market penetration of these small-scale desalination units will continue to increase in the near future in Beirut. With the current lack of a regulating framework that governs their operations and licensing, their continued growth will be a double-edged source. On one hand, they are effective short-term solutions that can provide safe water to the city, allowing it to compensate for its current chronic shortages. Yet on the long run, the current status will result in the depletion of the groundwater resources of the city by those who can afford the technology. Ultimately, the increased penetration of small-scale desalination units is another modern example of the tragedy of the commons.

APPENDICES

APPENDIX A

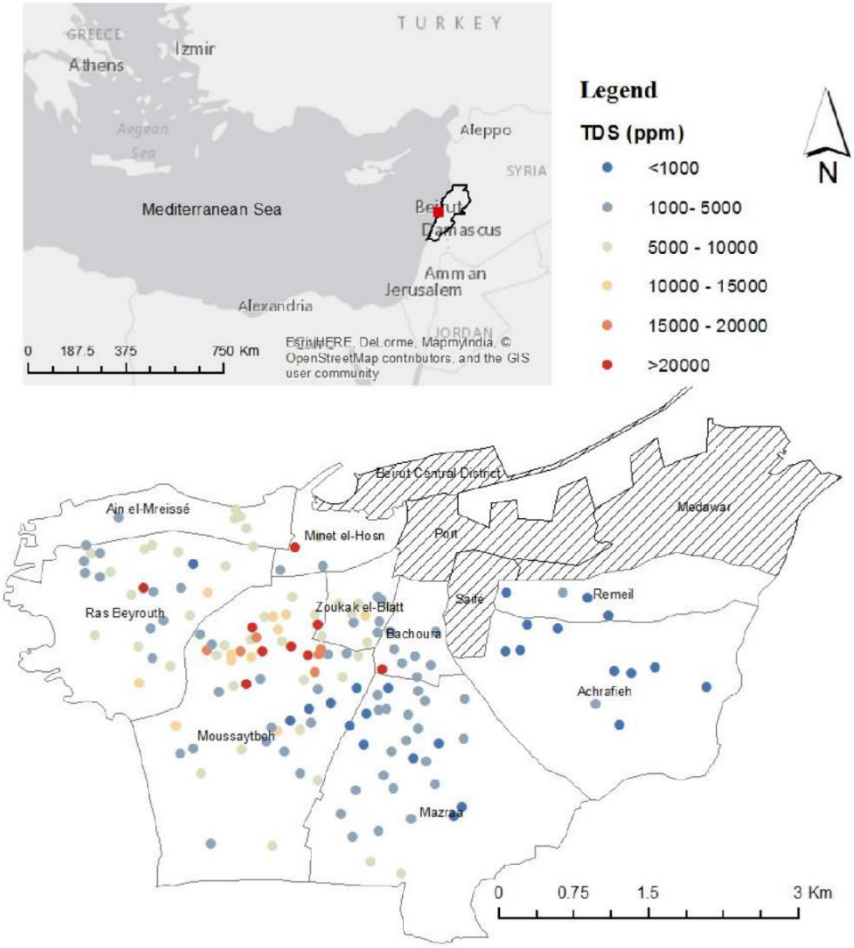
QUESTIONNAIRE

1. Since when has Reverse Osmosis (RO) desalination been applied at the building level in Lebanon?
2. Around how many buildings in Beirut have installed RO units through your company?
3. What is the range of encountered salinity in the underground feed water in the wells in Beirut?
4. Is the treated water considered potable, or is it limited to domestic use? What is the TDS (Total Dissolved Solids) of the produced water?
5. What is the maximum TDS level that can be treated by RO to reach the required product water?
6. What are the capacities (m^3/day) of the units you are installing at the building level?
7. Are water meters being set along with the installations of the RO systems?
8. How is the Brine produced being disposed of?
9. Do frequent electricity outages cause any damage to the RO unit?
10. Should the RO unit work uninterruptedly?
11. What is the % recovery rate of the installed RO systems?
12. What is the expected electricity consumption of the RO unit at the building level?
13. What is the life span of the equipment?
14. What is the lifetime of the membrane and its average cost?
15. What is the range of capital cost of the installed RO unit in a building in Beirut?
16. What is the range of operation and maintenance costs? (membrane replacements, chemicals for pre and post-treatment, pumps, spares, labor)
17. Form your experience in the field, do you sense a social awareness, acceptance, and trust in the effectiveness of the installed desalination systems and resulting water produced?

18. What is the presumed environmental impact of the RO desalination?
19. Do you have any experience with the Electrodialysis Reversal (EDR) technique for brackish water desalination? If yes, the previous set of questions would be applicable related to this alternative desalination method.

APPENDIX B

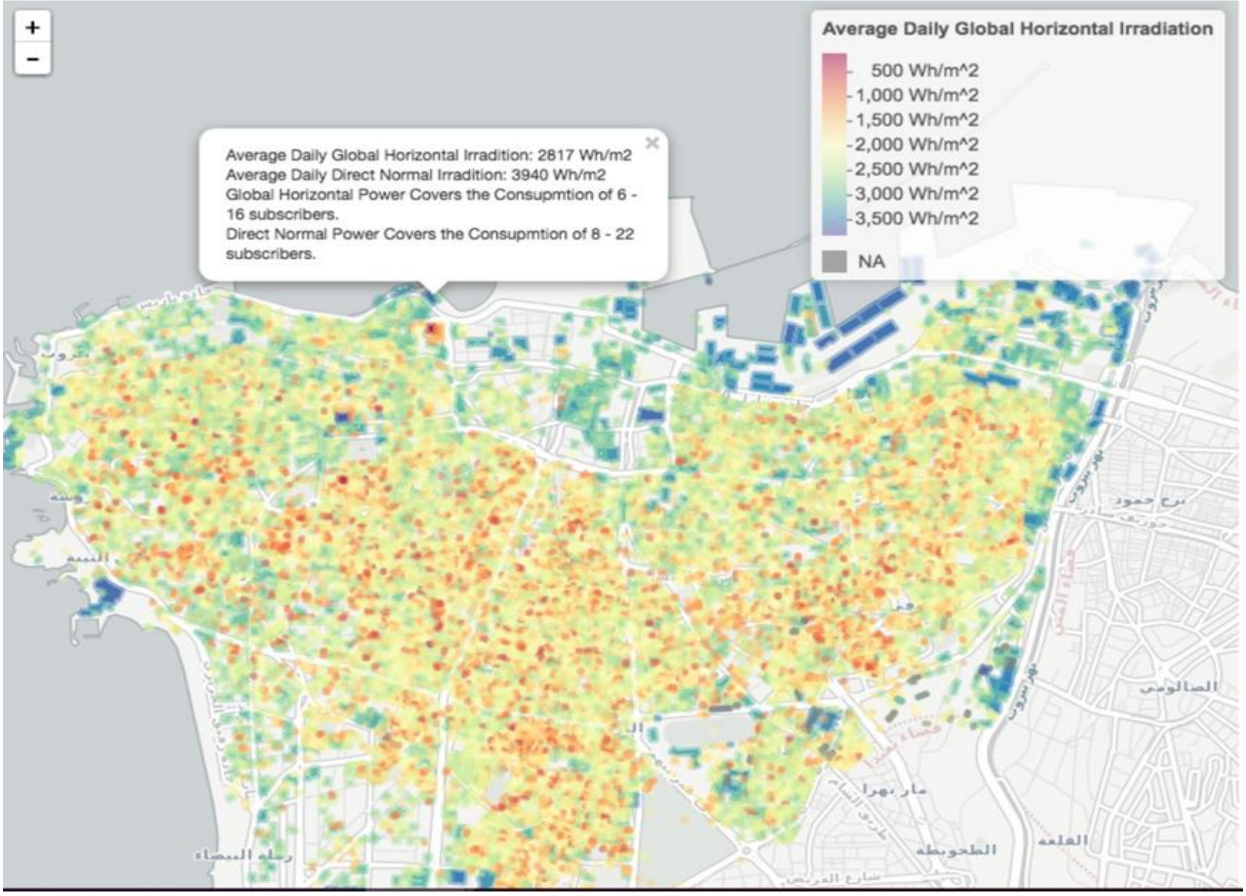
GROUNDWATER SAMPLING IN BEIRUT



Groundwater sampling in Beirut, Total Dissolved Solids (TDS) were measured in October 2013 (Alameddine et al. 2018).

APPENDIX C

BEIRUT SOLAR MAP



Average Daily Global Horizontal Irradition: 2817 Wh/m2
Average Daily Direct Normal Irradition: 3940 Wh/m2
Global Horizontal Power Covers the Consupmtion of 6 - 16 subscribers.
Direct Normal Power Covers the Consupmtion of 8 - 22 subscribers.

Average daily global horizontal irradiation in Beirut, Beirut Solar Map (Berjawi et al. 2017).

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