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Solar-Powered Reverse Osmosis Brackish Water Treatment for Residential Use in Tripoli: Design, Performance, and Economic feasibility

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Abstract

This study presents the design, performance and economic feasibility of a centralized solar-powered reverse osmosis (RO) desalination system for a residential compound of 10 buildings in Tripoli, Libya. Pretreatment was modeled using Aspen Plus V.12, and the RO unit was simulated with IMSDesign. The FilmTec CPA5-LD-4040 membrane produced permeate meeting WHO and Libyan drinking-water standards (e.g., TDS of 335 mg/L, pH of 7.6). A dosing-sensitivity analysis identified 93 mg/L of 5% $Ca(OH)_2$ solution as the optimal value for post-treatment stabilization. To minimize costs, the system was configured as a battery-free PV-powered design using 4 monocrystalline IBC Solar modules (395 W each, 1.58 kWp total). CO_2-emission sensitivity analysis showed a reduction of 7 kg CO_2/day during fully solar operation. The RO unit's energy demand (7.8 kWh/day) is fully met by the PV array. The Levelized cost of water ranged between 8–21 LYD/m^3 depending on lifetime and assumed discount rate. Compared to bottled water consumption for the 300-resident compound, the system provides substantial annual savings resulting in a payback period of 133 days. Overall, the results confirm the strong technical performance, economic viability, and long-term sustainability of deploying stand-alone PV-driven RO desalination for residential applications in Libya.

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Keywords: Solar Desalination; Reverse Osmosis; Calcium Hydroxide Dosing; Photovoltaic system.

معالجة المياه المالحة بالتناضح العكسي بالطاقة الشمسية للاستخدام السكني في طرابلس: التصميم، الأداء، والجدوى الاقتصادية

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الملخص:

تقدم هذه الدراسة التصميم وتقييم الأداء والجدوى اقتصادية لنظام تحلية مياه يعمل بالطاقة الشمسية باستخدام تقنية التناضح العكسي (RO) لمجمع سكني مكون من 10 مبانٍ في طرابلس، ليبيا. تمت محاكاة المعالجة الأولية باستخدام برنامج Aspen Plus، وتمت محاكاة وحدة التناضح العكسي باستخدام برنامج IMSDesign وتم اختيار غشاء من نوع FilmTec CPA5–LD–4040الذي تمكن من انتاج ماء معالج يتفق مع معايير الصحة العالمية ومعايير مياه الشرب الليبية وتتمثل أهم النتائج المتحصل عليها في تركيز مجموع المواد الصلبة بمقدار لا يتجاوز 335 ملغ/لتر و أس هيدروجيني يساوي 7.6. وحددت التحاليل الحاجة إلى مرحلة معالجة أخيرة وقدرت قيمة الجرعة المثلى بحوالي 93 ملغ/لتر من محلول هيدروكسيد الكالسيوم (بتركيز 5%) للتأكد من مطابقة كل المعايير. لتقليل التكاليف والحفاظ على البيئة، تمت تلبية احتياجات الطاقة لوحدة التناضح العكسي (7.8 كيلو واط

ساعة/اليوم) بالكامل من خلال الطاقة الشمسية، باستخدام 4 ألواح شمسية من نوع (IBC Solar 395). تراوحت التكلفة للمياه (LCOW) بين 8–21 دينار ليبي/م^{3} اعتمادًا على العمر الافتراضي ومعدل الخصم المفترض. أي مقارنة باستهلاك المياه المعبأة لمجمع يضم 300 مقيم، يوفر النظام وفورات سنوية كبيرة مما يؤدي إلى فترة استرداد تبلغ 133 يومًا. بشكل عام، تؤكد هذه النتائج الأداء الفني القوي، والجدوى الاقتصادية، والاستدامة على المدى الطويل لنشر محطات التحلية المعتمدة تماما على الطاقة الشمسية للاستخدامات السكنية في مدينة طرابلس، ليبيا.

وقد تم عرض هذه الورقة العلمية في جلسات المؤتمر الدولي للطاقة المتجددة والنفط والغاز وتغير المناخ "أيريقو" في الفترة 25–27 ابريل 2026م. طرابلس – ليبيا

الكلمات المفتاحية: تحلية المياه بالطاقة الشمسية؛ التناضح العكسي؛ جرعات هيدروكسيد الكالسيوم؛ نظام الطاقة الشمسية الكهروضوئية.

1- Introduction

Water scarcity is becoming one of the most critical global challenges, as only 2.5% of the Earth's water is freshwater, and less than 1% is accessible for human use [1]. Libya faces an even more severe situation due to extremely low rainfall, over-extraction of fossil groundwater, and the concentration of nearly 75% of the population within less than 1.5% of the country's land area. Groundwater supplies more than 97% of Libya's water demand [2], but its quality often compromises of high salinity, hardness, ammonia, and dissolved minerals, requiring adequate treatment to meet WHO and Libyan drinking-water standards [3]. Desalination technologies vary depending on industry and product specifications. One of the most adopted technologies is reverse osmosis (RO) membranes which depend on selective ion separation through semi-permeable membranes. RO has gained dominance due to its lower energy consumption, high salt-rejection efficiency (>99%), and ease of operation, making it the preferred option in most developed regions. RO technology has revolutionized the desalination industry, now accounting for more than 80% of brackish water (BW) desalination capacity. This widespread adoption is also attributed to its relatively low cost, making it the preferred choice for many industrial and governmental applications [4].

Libya is known for having one of the highest solar irradiance levels in the MENA region, making small-scale photovoltaic (PV)-powered RO units an attractive solution for decentralized water production. Despite this potential, limited research has focused on the techno-economic feasibility of PV-driven RO systems for BW treatment in residential communities within Libya, particularly systems operating without any battery storage. The electricity consumption of a RO plant typically ranges between 4 and 7 kWh/ m^3 of produced water. For instance, the energy required to operate a RO plant serving approximately 48,000 households is equivalent to the electricity consumption of about 10,300 households of similar size [6]. This substantial energy demand often imposes a financial burden on water distribution systems, with electricity accounting for over 11% of the total cost in BW desalination [7].

The main goal of this paper is to design and evaluate a small-scale PV-RO system for treating BW in Tripoli, Libya, a region of annual horizontal radiation above 1972 kWh/m^3, as shown in Fig. 1. The system is designed to fulfil drinking water requirements of a residential compound with 10 buildings, each building with 6 flats. 5 distinct groundwater samples were collected and analysed, and their averaged properties were used to simulate the designed process. The system is configured to operate without batteries and sized to produce 1200 L/day. Hence, the study aims to assess the system’s technical performance and economic feasibility for decentralized residential applications.

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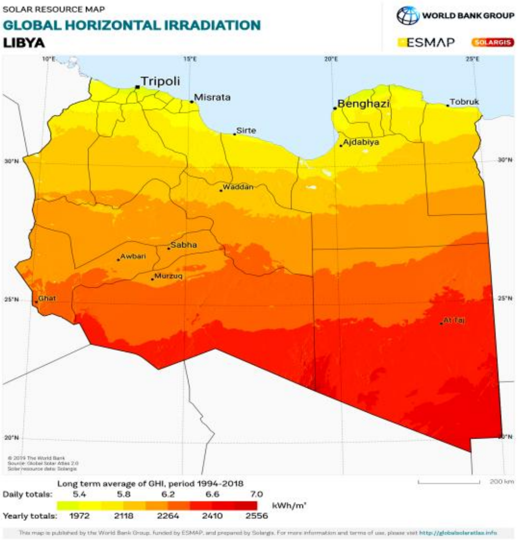

Figure (1): A scan of the global horizontal irradiation in Libya. [8]

2- System Development and Design

The process uses BW as the water source. Fig. 2 shows the process flowsheet. All process development stages and evaluation are explained in this section.

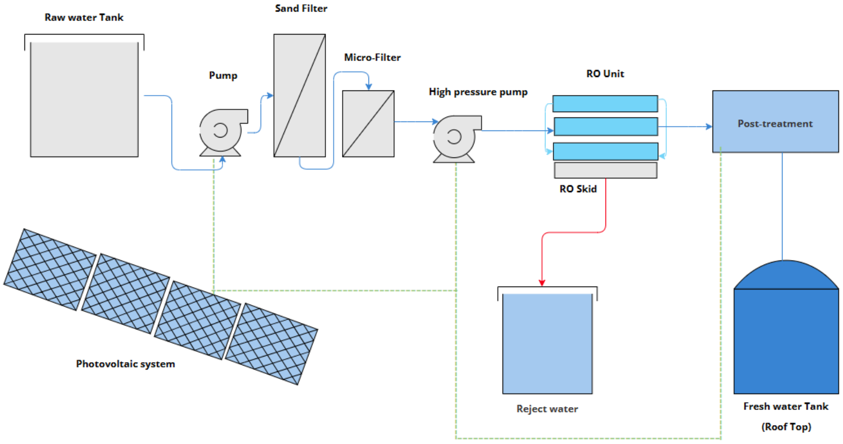

Figure (2): Illustration of the of the solar-powered raw water treatment system. Note: drawn units for demonstration only.

2-1. Water Sampling and Characteristics

Representative BW samples were collected from 5 distinct water wells in Tripoli. Each well is in a different district to represent spatial variation in feedwater quality. Water quality analyses were conducted to characterise the feedwater quality of collected samples, and results of all 5 samples are summarised in Table 1.

The raw BW analysed samples exhibit high salinity and hardness with TDS and E.C. ranges surpassing both WHO and Libyan drinking water standards [9]. Sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) levels in some samples are also above the permissible limits of 200 mg/L, 200 mg/L, and 150 mg/L, respectively. Potassium (K^+) and total suspended solids (TSS) show moderate variation, while pH remains within acceptable bounds. Organic pollution levels suggest negligible biological content. Overall, the collected and mixed samples require further treatment prior to human consumption.

Table (1): raw brackish groundwater quality.

Parameter	Unit	Range
TDS	mg/ L	1141 – 3577
pH	-	7.1 – 7.7
Ca^{2+}	mg/ L	72 – 268
Mg^{2+}	mg/ L	50 – 158
Na^+	mg/ L	180 – 475
TSS	mg/ L	9 – 31
K^+	mg/ L	3.5-30
E.C.	µs/ cm	1681 – 4450
COD	mg/ L	< 0.01
BOD	mg/ L	< 0.06
Ammonia	mg/ L	0.01– 0.11

2-2. Pretreatment Process Simulation

The main purpose of the pretreatment process is to condition the raw feedwater, by removing suspended solids and safeguarding membrane performance i.e., prevent membrane fouling. The process was modelled using Aspen Plus V.12 where all samples were mixed in the raw water tank, then pumped to a sand filter, to remove coarse suspended solids and turbidity, followed by a microfilter to further eliminate any fine particles which provides a protective barrier for the RO membrane. Then, a high-pressure pump is used to deliver the filtered water to about 7.6 bars ensuring stable hydraulic condition for the RO operation. Table 2 summarised input to the RO unit. The volumetric flowrate reflects suitability for small-scale RO systems. In this case, designed to produce 1.2 m^3/day of drinking water, considering daily 6 h operation.

Table (2): Pretreatment resulting water condition.

Property	Unit	Value
H_2O composition	Weight fraction	0.99
Temperature	°C	25
Pressure	Bar	7.6
Mass density	kg/m^3	998.5
Average molecular weight	-	18
Volume flow	m^3/h	0.29
pH	-	6.66
TDS	mg/L	1635

2-3. Reverse Osmosis Unit Design

The RO unit was designed using IMSDesign software, incorporating 1 vessel containing 4 elements of CPA5-LD-4040 low-fouling spiral-wound membrane manufactured by Hydranautics. This membrane features a composite polyamide active layer of 7.43 m^2, with excellent resistance to fouling due to it is Low ΔP design, a long operational lifespan of 3 – 5 years with proper maintenance, and a minimum salt rejection of 99.5%, making it suitable for BW treatment (desalination). A snapshot of the simulated process is shown in Fig. 3. The feed water (Table 2) was supplied at a flow rate of 0.29 m^3/h. Concentrate recirculation (1.50 m^3/h) was employed to stabilize flux and reduce scaling risk. The system achieved a permeate recovery of 70%, producing 0.20 m^3/h of permeate and 0.09 m^3/h of reject.

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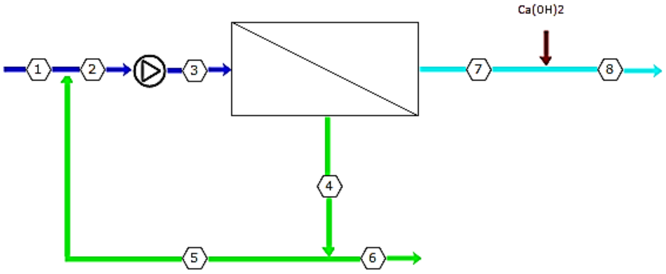

Figure (3): Illustration of the simulated single-pass RO membrane via IMSDesign, with recirculation and Ca $(OH)_2$ dosing.

Permeate quality analysis (Table 3) reveal significant reductions in ionic concentrations.

Table (3): Permeate quality.

Parameter	Unit	Range
Flow	m^3/h	0.2
Pressure	bar	2.5
TDS	mg/ L	133
pH	-	5.95
E.C.	µs/ cm	185
LSI	-	-4.21
CCPP	mg/L	-198.98

2-4. Post-treatment and Stabilisation

Results in Table 3 indicate the necessity of a post-treatment process to adjust the pH, reintroduce minerals, and assess scaling and corrosive potential of the post-treated water using the Langelier Saturation Index (LSI) and calcium carbonate precipitation potential (CCPP).

Permeate water quality was adjusted via dosing calcium hydroxide ($Ca(OH)_2$) 5% solution, which is a common chemical used in the industry, with a dosing rate of about 93 mg/L and a total consumption of 0.4 kg/h. This treatment elevated the quality of water and confirmed absence of any scaling risk. Results are shown in Table 4.

Table (4): Post-treatment permeate quality

Parameter	Unit	Range
Flow	m^3/h	0.2
Pressure	bar	2.5
TDS	mg/ L	335
pH	-	7.58
E.C.	µs/ cm	445
LSI	-	0.00
CCPP	mg/L	1.02

Overall, the RO unit effectively transformed raw brackish groundwater into low salinity permeate, suitable for further conditioning and drinking (potable) use. Moreover, sensitivity analyses were conducted to further investigate the effect of dosing and feed pressure on the membrane performance and permeate water quality. Fig. 4 illustrates the effect of $Ca(OH)_2$ dose concentration on important metrics such as pH, TDS, and LSI of treated water. The used dose of 92.7 mg/L of 5% $Ca(OH)_2$ represents the optimum condition.

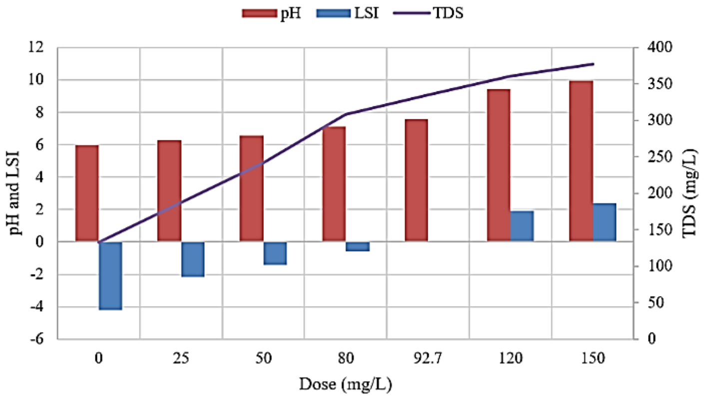

Figure (4): Effect of $Ca(OH)_2$ dosing concentration on TDS, LSI and pH of the permeate water.

To maintain permeate quality within acceptable ranges and attain the 2.5 bar limit, required to supply water to the roof top of a typical 2 story building, the effect of varying the feed pressure was analysed as shown in

http://www.doi.org/10.62341/istj-vol38-2- irego99

Fig. 5. In which lower feed pressure reduces permeate recovery and increases reject flow, while TDS shows a non-linear trend, indicating improved water quality at lower pressures but reduced overall efficiency. The optimum selected, condition is the 70% recovery as it corresponds to a low reject flow, i.e., the brine solution which requires adequate disposal.

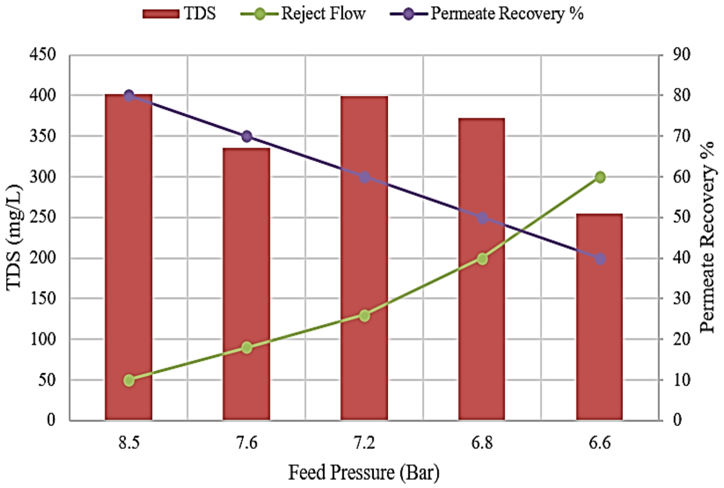

Figure (5): Effect of feed pressure on permeate recovery, reject flow, and TDS in a BWRO system.

3 - Energy Requirements and PV System Sizing

The solar-powered BWRO system was sized to supply drinking water based on the calculated pumping requirements, as conservative figures, the pre-treatment pump demands 0.1 kW while the RO high-pressure pump requires 0.9 kW, resulting in a total instantaneous power consumption of approximately 1 kW for the desalination unit. For the residential complex comprising 10 buildings, each containing 6 apartments, a centralized solar-powered RO system was considered to supply potable water to all buildings. Each building is equipped with a storage tank, placed on the roof top, that distributes the treated permeate to each apartment. Table 5 summarised the results from simulations. The 30% safety margin in daily required demand account for any system inefficiencies, inverter losses, cloudy weather, etc…

http://www.doi.org/10.62341/istj-vol38-2- irego99

Table (5): PV array sizing and specifications for the BWRO designed system.

Parameter	Unit	Value
Daily permeate production	L/ day	1200
Daily energy demand	kWh/ day	6
Daily operating hours	h/ day	6
Required daily PV energy (30% safety margin)	kWh/ day	7.8
Average peak sun hours (Tripoli)	h/ day	5
Required PV size	kWp	1.56
Selected PV module rating	Wp	395
Optimal tilt angle	Degree	30
Number of PV modules required	-	4
Maximum power voltage	V	31.3
Maximum power current	A	12.6
Open circuit voltage	V	37.2
Short circuit current	A	13.4
Maximum system voltage	V (DC)	1000
Total installed PV power	kWp	1.58
VFD (inverter-based)	kW	1.5
Inverter voltage	V	200-240

The specification of the PV module IBC SOLAR 395 W module (GS10-HC series) is selected due to its efficiency, widespread availability in the Libyan market. The efficiency is 20.2% and dimensions of 1722x1134x30 mm. The modules are IEC 61215/61730 certified, which is adequate to power the small RO unit during daytime operation. As the system is designed to operate without batteries, the use of a dedicated solar pump drive variable frequency drive (VFD) is essential. This allows direct coupling of the PV array to the pump, ensuring reliable performance during daylight hours. The selected VFD, ABB Solar Pump Drive, rated at 1.5 kW [10] was selected to operate the high-pressure pump and regulate motor speed to match the RO system's flow and pressure requirements. The ABB drive is a well-established product in the Libyan market [11], offering robust performance, integrated motor protection, and compatibility with solar direct-drive applications.

4- Preliminary Environmental Impact Assessment

Emissions were calculated using the Libyan grid emission factor, accounting for roughly an average of 0.857 $kgCO_2/kWh$ [12]. In a grid only scenario, the system would produce around 7 kg of CO_2 a day (2,442 kg/ year). A European car emits about 104 g CO_2 per km [13], running this system on grid electricity for one year is equivalent to driving a typical car from Tripoli to Tokyo and back. Alternatively, fully relying on the solar PV modules eliminates such emissions.

5- Levelized Cost of Water (LCOW) Analysis

LCOW is a widely used economic indicator that expresses the average unit cost of producing 1 m^3 of water over the entire operational lifetime of a desalination system. Unlike simple payback calculations, LCOW incorporates both the CAPEX and the OPEX, distributed across the total volume of water produced during the system's lifetime. This approach provides a fair and standardized basis for comparing different desalination technologies and energy supply options. The PV modules and solar pump drive were priced based on the official 2025 pricelist of INSIAB Libya solar company, which provides reliable market values for photovoltaic system in the Libyan context. The CAPEX includes costs of installation, distribution piping, and BOS components represent, pretreatment units, mounting system, etc. The OPEX were estimated based on components requiring periodic maintenance or replacement: membranes every 3-4 years, microfilters every 6 months, chemical cleaning twice a year, and annual calculations for chemical dosing and labour based on system output. Since this design is still at its feasibility stage, a 40% additional margin was added to the obtained costs. Over a 20-year operational lifetime, the LCOW is given by:

$$LCOW = \frac{Total\ lifetime\ cost}{(Total\ lifetime\ water\ production)} \tag{1}$$

Equation (1) is used when 0% discount rate is assumed.

To assess the system economics, ± 10 years of operation have been assumed with various discount rates. Results shown in Fig. 6, indicate that the maximum LCOW would result from the shortest life span and highest discount rate, which is around 21 LYD/m^3.

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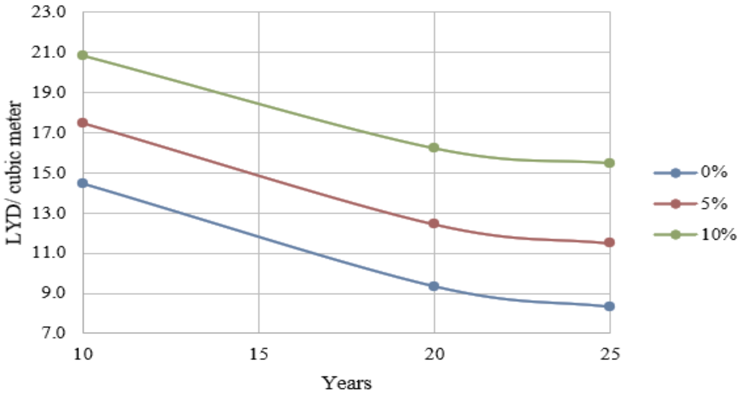

Figure (6): LCOW under various lifetimes and discount rates ranging from 0% to 10% for the developed solar powered BWRO system.

A simple payback period calculation, and taking the recent cheapest price for bottled water in the Libyan market which 2 LYD/ 7 L. Then, the payback period is given by:

$$Payback\ period\ (years) = \frac{CAPEX}{Annual\ net\ revenue} \tag{2}$$

The annual net revenues = 123, 237 LYD. Hence, the payback period = 0.362 years i.e., 133 days. Which exceptional considering the system offer a sustainable drinking water production relying only on solar energy.

6- Conclusion

This study presents a conceptual design of a small-scale PV-powered RO desalination system for residential use in Libya. The IMSDesign results confirmed that the CPA5-LD-4040 membrane is the most suitable option for the target 1.2 m^3/day capacity, providing high recovery and excellent permeate quality at relatively low operating pressure and cost. Dosing sensitivity demonstrated that a 5% $Ca(OH)_2$ solution at about 93 mg/L achieves optimal stabilisation of pH and LSI. CO_2-emission analysis showed a dramatic reduction as a battery-free PV system is integrated. The LCOW ranged between 8–21 LYD/m^3, while the system outperformed bottled-water costs for the 300-resident compound. Overall, the project achieved an outstanding payback period of 133 days, confirming the strong technical, environmental, and economic feasibility of the proposed PV-RO system.

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passenger-cars/?filter=average-co2-emissions-per-km-from-new-passenger-cars&sort=ASC&syear=2023&mo=164558