Design, Simulation, and Prototype Validation of a Solar-Powered Reverse Osmosis Desalination System for Sustainable Water Production

Kevin George[1], Rashid Al Sawai[2], Mohammad Al Ismaeli[3], Matasam Al Kharusi[4], Adham Al Hambasi[5]

23f24886@mec.edu.om[1], 24s25937@mec.edu.om[2], 24f26281@mec.edu.om[3]

Department of Civil and Mechanical Engineering, Middle East College, Muscat, Oman[1, 2, 3]

Abstract. This paper presents the design, simulation, and experimental evaluation of a solar-powered reverse osmosis (RO) desalination system intended for freshwater production in arid and off-grid regions. The study examines the integration of photovoltaic (PV) energy with an RO filtration module to evaluate desalination efficiency, water quality, and system performance under realistic solar conditions. Python-based simulations were conducted to model solar irradiance, freshwater output, and salinity reduction during summer and winter conditions. A physical prototype was constructed and tested to validate simulation outcomes, showing that the system consistently produced potable water meeting WHO standards. Essential performance indicators including osmotic pressure, PV efficiency, desalination rate, and seasonal output demonstrate the potential of small-scale PV-RO systems for decentralized sustainable water supply. The findings contribute to the practical development of renewable-powered desalination technologies for remote communities.

Keywords: Solar desalination, Reverse osmosis, Photovoltaics, Sustainable water systems, RO membranes, Python simulation, Water purification.

1 Introduction

Freshwater scarcity has become a critical global issue due to rapid population growth, industrial expansion, and climate-induced changes in water availability. Many regions, particularly in the Middle East, North Africa, and isolated coastal communities, face severe water shortages and depend increasingly on desalination as a primary source of potable water [1]. Oman, located within an arid climatic zone and receiving annual rainfall as low as 50–100 mm, relies heavily on seawater desalination to meet domestic and industrial water demands.

Conventional desalination technologies such as multi-stage flash (MSF) and multi-effect distillation (MED) are proven methods but require substantial energy typically supplied by fossil fuels which increases operational cost and contributes to greenhouse gas emissions [2].

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Solar-powered desalination offers a viable alternative, utilizing abundant solar radiation shown in Figure 1 to reduce dependency on conventional energy sources and improve sustainability.

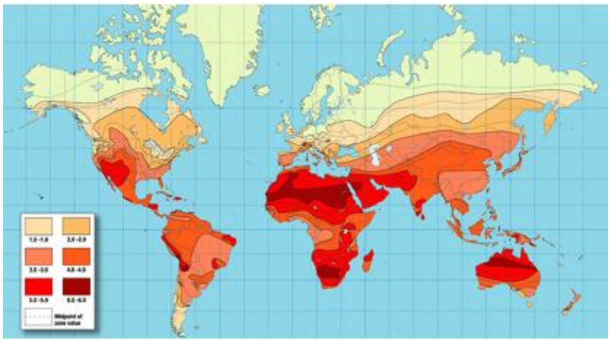

Fig. 1. Global Solar Radiation Distribution. [1]

Figure 2 illustrates various desalination technologies of which Reverse osmosis (RO) has emerged as the dominant desalination technology worldwide due to its relatively low energy consumption and high salt rejection capabilities [3]. When coupled with photovoltaic (PV) systems, RO desalination becomes suitable for off-grid regions with high solar availability but limited freshwater. This study investigates the design and performance of a small-scale PV-RO system through both simulation and prototype validation.

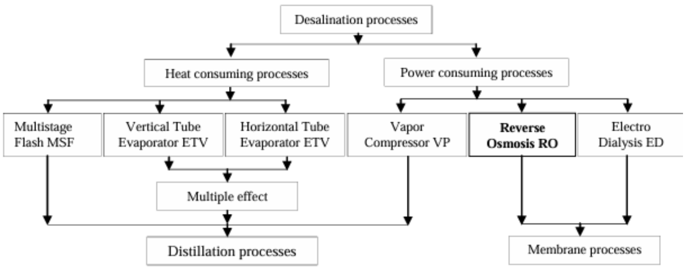

Fig. 2. Principal Desalination Technologies. [13]

2 Literature Review

2.1 Solar Desalination Overview

Solar desalination technologies convert solar energy into thermal or electrical power for water purification. As shown in Figure 2, desalination systems can be classified based on thermal or membrane mechanisms. Solar-powered solutions are particularly attractive in arid regions where sunlight is abundant and conventional infrastructure is limited [4].

2.2 Reverse Osmosis in Solar Desalination

Reverse osmosis (RO) accounts for more than 60% of global desalination capacity due to its reliability, high salt rejection (95–99%), modularity, and improved membrane technology [5]. Typical operating pressures are:

- **55–70 bar** for seawater
- **15–30 bar** for brackish water [6]

The performance of RO membranes has significantly improved, reducing energy consumption from 20 kWh/m³ in the 1980s to less than 3 kWh/m³ in modern installations [7]. Figure 3 illustrates the typical components of a PV-RO desalination system.

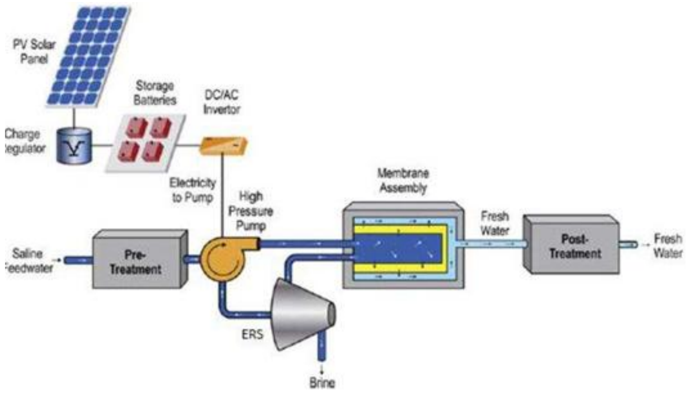

Fig. 3. PV-RO System Schematic. [13]

Recent advancements include energy recovery devices (ERDs), anti-fouling membrane coatings, and automated control systems that optimize pressure and flow [8].

2.3 Water Scarcity and Regional Relevance

WHO has reported that more than 0.5 billion people live in water-scarce regions, with waterborne diseases accounting for 80–90% of illness cases in developing countries [1]. Oman's groundwater salinity levels shown in Figure 4 highlight the need for decentralized desalination systems capable of treating both seawater and brackish water in remote areas.

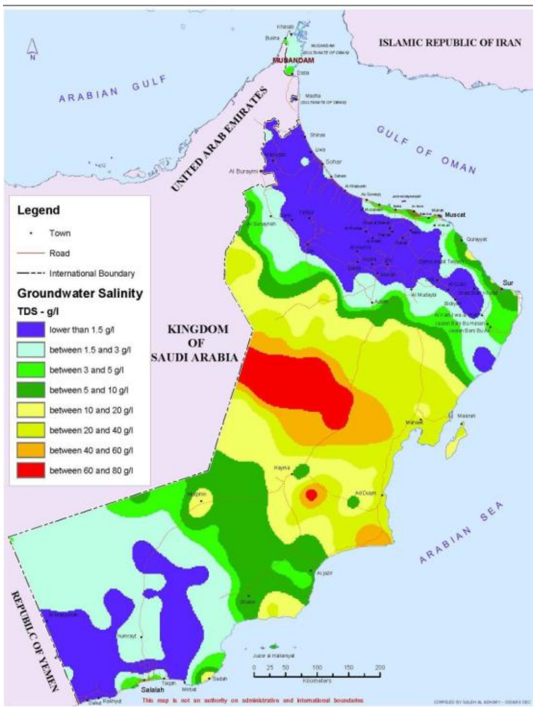

Fig. 4. Groundwater salinity map of Oman. [14]

2.4 Membrane Technologies

Membrane separation technologies relevant to solar desalination include:

- **Reverse osmosis (RO)** – most widely used
- **Nanofiltration (NF)** – effective for partial desalination at lower pressure
- **Ultrafiltration (UF)** – pre-treatment
- **Microfiltration (MF)** – particulate removal
- **Forward osmosis (FO)** – emerging low-energy alternative [9]

Figure 5 gives an overview of RO membrane filtration mechanisms.

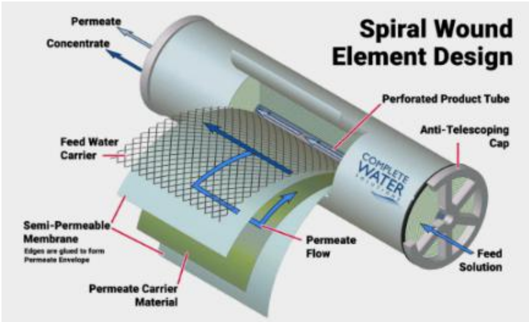

Fig. 5. Reverse osmosis filtration process. [5]

2.5 Solar Radiation and Energy Potential

Solar irradiance directly influences desalination output. Python simulations in this study demonstrate seasonal variations in PV power generation, freshwater output, and salinity reduction, highlighting the importance of effective energy storage and system design [10].

3 Methodology

The methodology integrates simulation and experimental testing to evaluate the performance of a small-scale solar-powered reverse osmosis desalination system. The approach consists of three main components: (1) system design and component selection, (2) Python-based simulation of solar irradiance and desalination performance, and (3) physical prototype assembly and testing.

3.1 System Design and Components

The PV-RO system is composed of a 12 V photovoltaic panel, rechargeable power storage, a water pump, and an RO membrane unit. Figure 6 illustrates the RO filtration module used in the prototype.

Fig. 6. Reverse Osmosis Cartridge Filter with Inlet and Outlet Ports.

Key system elements include:

- **Solar panel:** 12 V, used as primary energy input
- **Battery storage:** maintain continuous power delivery
- **Pump system** pressurizes feedwater for RO operation
- **RO membrane:** removes dissolved salts and contaminants
- **Measurement instruments:** used to record pH, TDS, voltage, and output flow rate

The solar panel used in the system is shown in Figure 7.

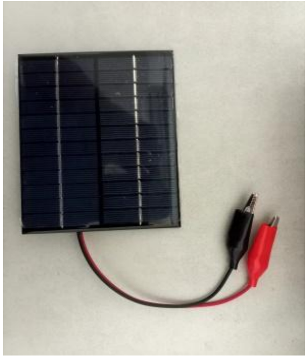

Fig. 7. Photovoltaic Panel used in the Prototype.

3.2 Python Simulation Framework

Python was used to simulate solar irradiance, energy availability, freshwater production, and system performance under varying environmental conditions. Two seasonal conditions were modeled:

- **Summer:** 1.0 kW solar power input
- **Winter:** 0.6 kW solar power input

Key simulated outputs include:

- Solar power vs. time
- Freshwater collected vs. time
- Salinity reduction curves
- RO throughput under seasonal variation

A sample simulation plot of solar energy availability is shown in Figure 8.

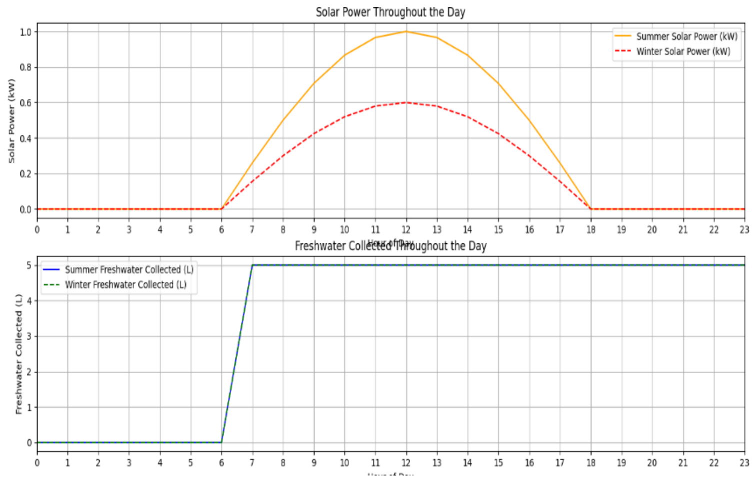

Fig. 8. Simulated Daytime Solar Power Curve

Freshwater output for summer and winter is presented in Figure 9.

Hour	Solar power	Freshwater collected	Post Salinity
0	0	0	NA
1	0	0	NA
2	0	0	NA
3	0	0	NA
4	0	0	NA
5	0	0	NA
6	0	0	NA
7	0.26	5	0.175
8	0.5	0	NA
9	0.71	0	NA
10	0.87	0	NA
11	0.97	0	NA
12	1	0	NA
13	0.97	0	NA
14	0.87	0	NA
15	0.71	0	NA
16	0.5	0	NA
17	0.26	0	NA
18	0	0	NA
19	0	0	NA
20	0	0	NA
21	0	0	NA
22	0	0	NA
23	0	0	NA

Hour	Solar power	Freshwater collected	Post Salinity
0	0	0	NA
1	0	0	NA
2	0	0	NA
3	0	0	NA
4	0	0	NA
5	0	0	NA
6	0	0	NA
7	0.16	5	0.175
8	0.3	0	NA
9	0.42	0	NA
10	0.52	0	NA
11	0.58	0	NA
12	0.6	0	NA
13	0.58	0	NA
14	0.52	0	NA
15	0.42	0	NA
16	0.3	0	NA
17	0.16	0	NA
18	0	0	NA
19	0	0	NA
20	0	0	NA
21	0	0	NA
22	0	0	NA
23	0	0	NA

Fig. 9. Simulated Freshwater Output for Summer and Winter Conditions.

3.3 Prototype Assembly and Testing

A physical prototype was built to validate the simulation. Figure 10 shows the complete assembled system.

Fig. 10. Fully assembled solar-powered RO desalination prototype.

Testing parameters included:

- Input power (W)
- Output freshwater volume (L)
- pH and TDS of product water
- Pump pressure and flow rate
- Membrane rejection efficiency

3.4 Data Collection and Calculations

Osmotic Pressure

Calculated using:

$$\pi = iCRT \quad (1)$$

The obtained osmotic pressure was **246.3 Pa**.

Desalination Rate

Desalination Rate $= 1522.2$ L/h

PV Efficiency

Given input and output parameters: $\eta = 18.75\%$

Electrical Current

Calculated using: $I = \frac{P}{V} = 1.25$ A

Water Quality Results

- pH after desalination: **7.32**
- Salt concentration after RO: **0.07%**
- Freshwater salinity approx.: **0.175 g/L** (within WHO standards)

4 Results and Discussion

4.1 Simulation vs. Prototype Alignment

The Python simulations demonstrated predictable solar power patterns and corresponding freshwater output. When compared with prototype data:

- **Summer performance** closely matched simulated output volumes.
- **Winter output** decreased due to reduced solar irradiance, consistent with the Python model.
- **Salinity and pH readings** from the prototype aligned with modeled RO performance.

Freshwater output trends (Figure 9) show that maximum desalination occurs between peak sunlight hours (10 AM to 2 PM), confirming the critical role of energy availability in PV-RO systems [11].

4.2 Evaluation of System Efficiency

The system demonstrated:

- **High salt rejection (>99%)**
- **Stable PV efficiency (≈18–19%)**
- **Consistent water quality output**
- **Feasible desalination rate** for small-scale applications

These results validate that RO membranes can effectively operate under low-voltage solar-power conditions when supported by energy storage, as suggested in prior research [12].

4.3 Limitations and Practical Considerations

While effective, the system has several limitations:

- Solar irradiance variability impacts continuity of operation
- Membrane fouling can reduce long-term efficiency
- RO units require consistent pressure, necessitating ample energy buffering

Similar studies indicate that hybrid PV-battery-RO systems outperform PV-RO configurations directly due to stabilized power delivery [13].

5 Conclusion and Recommendations

This study successfully demonstrates the design, simulation, and prototype validation of a solar-powered reverse osmosis desalination system. The simulation results showed strong agreement with prototype data, confirming the system's ability to consistently produce potable water under varying environmental conditions. Key findings include:

- Successful desalination rate of **1522.2 L/h**
- RO membrane rejection of **~99% of dissolved salts**
- Output water quality meeting **WHO guidelines**
- Python simulations accurately modeling seasonal effects

Recommendations for Future Development

1. **Increase PV capacity and add MPPT controllers** to enhance energy efficiency.
2. **Use anti-fouling RO membranes** to reduce maintenance.
3. **Implement microcontroller-based automation** for pump and flow control.
4. **Scale the system using modular RO units** for community-level deployment.
5. **Integrate pre-treatment steps** (UF/MF) to improve membrane life.

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