Harnessing Solar Energy for Sustainable Desalination: A Small-Scale Reverse Osmosis Approach

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Abstract

This paper presents the design, implementation, and testing of a small-scale, solar-powered reverse osmosis (RO) system aimed at addressing water purification needs in off-grid and remote locations. The system utilized a 36V solar panel, SS-MPPT-15L charge controller, and a 12V lead-acid battery to power a reverse osmosis membrane. Although initial tests were conducted using municipal tap pressure, the configuration effectively demonstrated membrane performance, achieving a permeate flow rate of 146.43 ml/min and a brine flow rate of 32.14 ml/min, corresponding to a recovery rate of approximately 82.00%. Total Dissolved Solids (TDS) measurements confirmed a salt rejection efficiency of 96.09%, reducing feed water TDS from 128 ppm to 5 ppm. Solar output measurements showed peak voltage of 36.9V and current of 8.3A, supporting a theoretical maximum output of 306W. A cost analysis estimated the system cost at $317.5, resulting in a projected clean water cost of approximately $0.0055 per liter over a three-year period. These results indicate the potential for reliable, low-cost water purification using renewable energy. Future improvements include the integration of a high-pressure DC pump, automated monitoring, and extended durability testing.

Introduction

Access to clean drinking water remains a global challenge, particularly in off-grid and underserved regions. Desalination using reverse osmosis (RO) offers an effective method for water purification, but it typically requires significant energy input and infrastructure. Solar energy, as a renewable and decentralized resource, presents a promising solution to these challenges. This project aimed to design and test a compact, solar-powered RO system that could provide clean water independently of the electrical grid.

The system was designed to be modular, cost-effective, and simple to assemble using commercially available components. Initial testing was performed under municipal pressure to validate the membrane's performance while solar output and battery behavior were evaluated under natural sunlight. The goals of this research were to assess the technical feasibility, energy efficiency, and economic viability of such a system for practical deployment.

This paper is structured as follows: the background section reviews relevant solar and desalination technologies, the experimental section outlines the setup and data collection methods, and the conclusion discusses key findings and proposes directions for future work.

Background

The goal of this project is to develop a small-scale solar-powered reverse osmosis desalination system that can operate efficiently in remote and resource-limited areas. The proposed system will hopefully allow renewable energy to minimize environmental impact and provide a sustainable source of potable water.

Solar Energy

Solar energy is one of the most abundant and sustainable sources of renewable energy available today. The Sun provides an estimated 173,000 terawatts of solar energy to Earth at any given moment, which is more than 10,000 times the world's total energy consumption [1]. Harnessing solar energy efficiently can significantly reduce dependence on fossil fuels, mitigate greenhouse gas emissions, and provide clean energy solutions to remote and underserved areas.

There are two primary technologies used to harness solar energy: photovoltaic (PV) systems and solar thermal systems.

Photovoltaic (PV) Systems: PV systems convert sunlight directly into electricity through the photovoltaic effect. When sunlight strikes semiconductor materials such as silicon, it excites electrons, generating an electric current. PV technology has evolved significantly, with improvements in efficiency, cost reduction, and the development of different types of solar panels, including monocrystalline, polycrystalline, and thin-film solar cells [2].

Solar Thermal Systems: Unlike PV systems, solar thermal technologies use sunlight to heat a working fluid, which is then used for heating applications or to drive turbines for electricity generation. Concentrated Solar Power (CSP) systems are a prominent example, utilizing mirrors or lenses to focus sunlight onto a small area to generate high temperatures [3].

Solar energy offers several key benefits that make it an attractive alternative to traditional energy sources:

- **Renewable and Sustainable:** Solar energy is inexhaustible, making it a sustainable option for long-term energy needs.
- **Environmentally Friendly:** Solar power systems produce no greenhouse gas emissions during operation, contributing to reduced carbon footprints.
- **Energy Independence:** Utilizing solar energy reduces dependence on imported fossil fuels and enhances energy security.
- **Scalability:** Solar power systems can be deployed in small-scale residential installations or large-scale solar farms to meet various energy demands.

Moreover, recent advancements in solar technology have focused on improving efficiency, reducing costs, and integrating solar energy into smart grids. Innovations include the development of perovskite solar cells, which offer high efficiency and lower production costs compared to traditional silicon-based panels [4]. Additionally, bifacial solar panels that capture sunlight from both sides have gained popularity for their enhanced energy yield.

Another promising area of research is the integration of artificial intelligence (AI) in solar energy management systems to optimize energy production and consumption. AI algorithms can analyze weather patterns, predict energy demand, and adjust solar panel orientations to maximize efficiency.

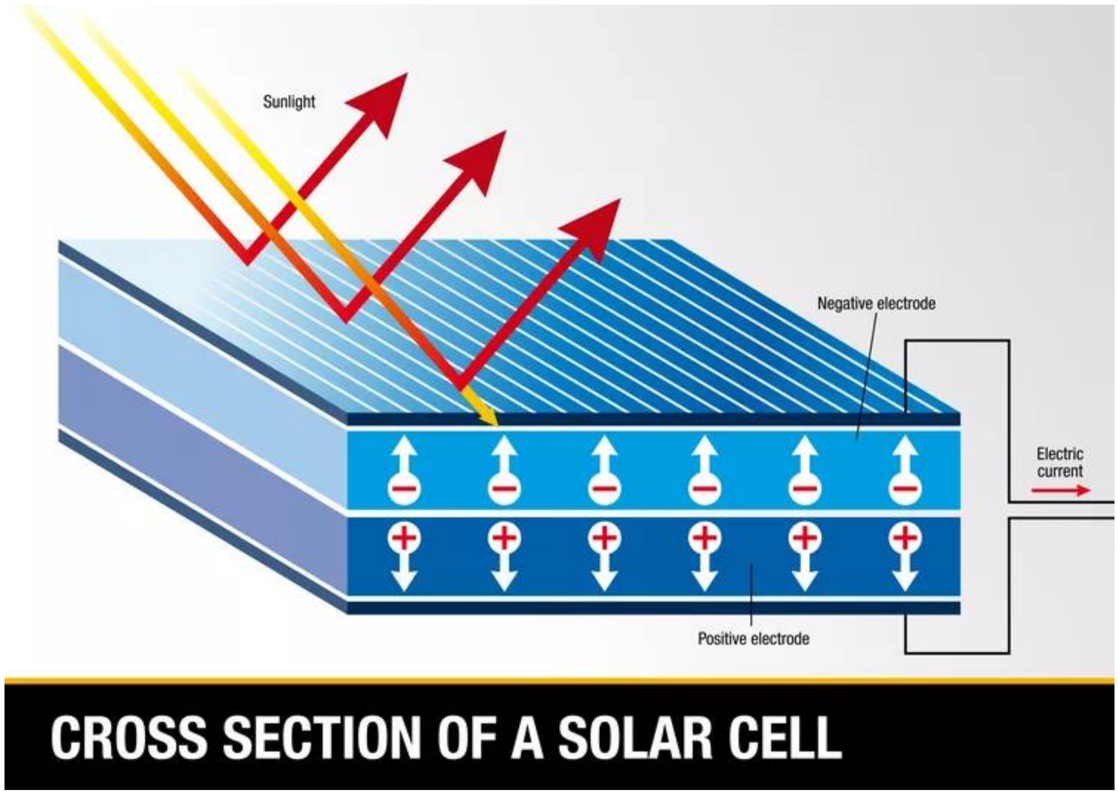

Figure 1: Image demonstration of how a solar cell produces electric current [5]

Energy Storage Challenges

Effective energy storage is vital for off-grid solar systems. Lead-acid batteries, despite being heavier and less energy-dense compared to lithium-ion alternatives, are widely used due to their affordability and robustness. The charge-discharge efficiency of lead-acid batteries is approximately 80–90%, and their lifecycle ranges from 500 to 1,000 cycles depending on depth of discharge and maintenance practices [8].

Charging protocols also significantly impacts the system's overall efficiency. Overcharging or deep discharging can drastically shorten battery lifespan, necessitating intelligent charge controllers that manage float, bulk, and absorption charging stages.

Desalination Technologies

Existing research on solar-powered desalination technologies highlights various approaches to achieving efficient water purification. Reverse osmosis, which utilizes semi-permeable membranes to separate dissolved salts and impurities from water, is one of the most effective methods for desalination. Studies have shown that integrating photovoltaic panels with RO systems can significantly reduce operational costs and reliance on non-renewable energy sources.

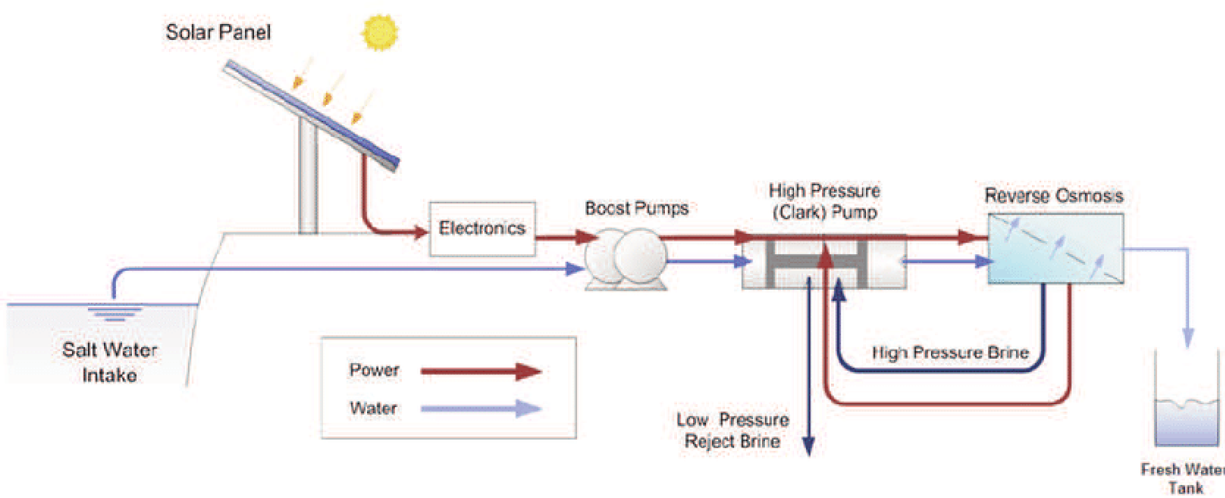

Figure 2: Schematic diagram of a solar-powered reverse osmosis desalination system [6]

Several studies have investigated the performance of solar-powered RO systems in different environmental conditions. A study by Ghaffour et al. examined the energy efficiency of solar-driven desalination plants and identified key factors affecting performance, such as solar radiation intensity, water salinity levels, and membrane properties [7].

The energy consumption of reverse osmosis desalination is governed by the following equation:

$$SEC = \frac{W_{\text{Total}}}{Qp} \tag{1}$$

where $\boldsymbol{W}_{\mathbf{Total}}$ is the total power required, $\boldsymbol{Qp}$ is the volumetric flow rate, and SEC is the specific energy consumption of the system.

To better understand the benefits of solar-powered RO systems, a comparison with other desalination technologies is provided in the following table:

Table 1: A comparison of desalination technologies

Parameter	Solar-Powered RO	Conventional RO	Thermal Distillation
Energy Source	Solar PV	Fossil Fuel	Fossil Fuel
Energy Efficiency	High	Moderate	Low
Capital Cost	Moderate	High	Very High

Reverse osmosis operates by applying pressure greater than the osmotic pressure of saline water to force water molecules through a semi-permeable membrane while rejecting salts and impurities. The *osmotic pressure (π)* can be estimated by the van 't Hoff equation:

$$\boldsymbol{\pi = iMRT} \tag{2}$$

where i is the ionization constant, M is molarity, R is the gas constant, and T is the absolute temperature.

Electrodialysis and thermal processes like MSF and MED require either significant electrical input or thermal energy, making them less suited for small, solar-powered setups [9].

Limitations of Reverse Osmosis

While RO is highly effective, it has inherent limitations, including membrane fouling, scaling, and high operational pressures. Typical RO membranes for brackish water require input pressures of 50–80 psi, with salt rejection rates of 90–99% [10]. Membrane maintenance, periodic replacement, and pretreatment of feed water are necessary to sustain long-term efficiency.

Membrane fouling results from biological growth, particulate accumulation, or scaling by dissolved minerals like calcium carbonate. This can be mitigated by installing pre-filters and conducting periodic backwashing or chemical cleaning.

Innovations and Future Directions

Recent advances focus on developing fouling-resistant membranes, hybrid systems combining RO with renewable energy, and decentralized desalination units for disaster response and rural applications. The integration of solar energy with small-scale RO presents an exciting opportunity to create sustainable, affordable, and accessible clean water solutions.

Experimental

This project aims to design and construct a small-scale solar-powered reverse osmosis desalination system. The goal is to evaluate the feasibility of using solar energy to power a reverse osmosis unit for clean water production in remote or off-grid locations.

Overview of System Components

A 36V, 100W solar panel mounted on the college building provides the energy input for the system. The panel connects to an SS-MPPT-15L charge controller, which optimizes energy capture by adjusting for real-time voltage and current fluctuations. The MPPT controller also safely regulates the charging of a 12V lead-acid battery, ensuring protection against overcharging and deep discharge.

The decision to use a 36V panel rather than a 12V panel was based on maximizing power conversion efficiency in varying light conditions, especially during partially cloudy days. MPPT controllers perform best with a higher voltage differential between the panel and the battery.

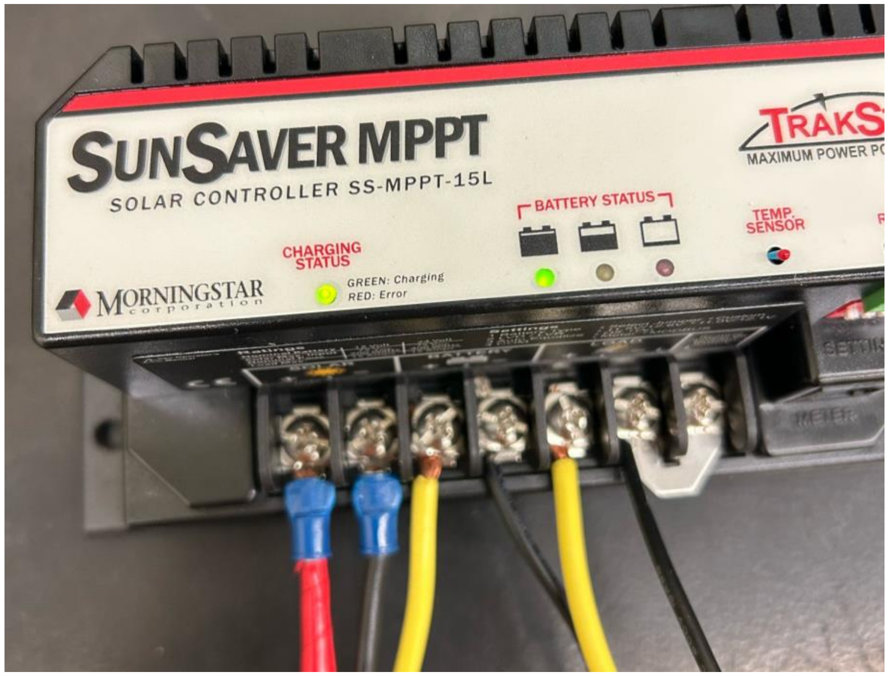

Figure 3: Charge controller displaying positive charging and battery status

Battery Storage

A 12V, 18Ah sealed lead-acid battery stores the energy harvested during peak sunlight hours. This stored energy powers the pumping subsystem even during cloudy periods or evening operation. The battery was chosen for its low cost, accessibility, and tolerance for intermittent charging typical of solar-powered systems.

Pump and Flow Control

Initial trials with a low-pressure pump proved inadequate for pushing water through the RO membrane. The system was temporarily adapted to use municipal tap pressure (~40 psi) to verify RO functionality. Future iterations would include a 12V DC diaphragm pump capable of delivering 60–80 psi, which is ideal for the 75 GPD RO membrane.

RO Membrane Integration

The heart of the filtration unit is an iSpring Greatwell 75 GPD reverse osmosis membrane housed in a standard pressure vessel. The membrane is fed by pressurized water from the pump (or temporarily from a sink faucet) and separates clean permeate from high-TDS brine water. The housing is fitted with 1/4" tubing connectors and flow restrictors to ensure appropriate backpressure and optimal rejection rates.

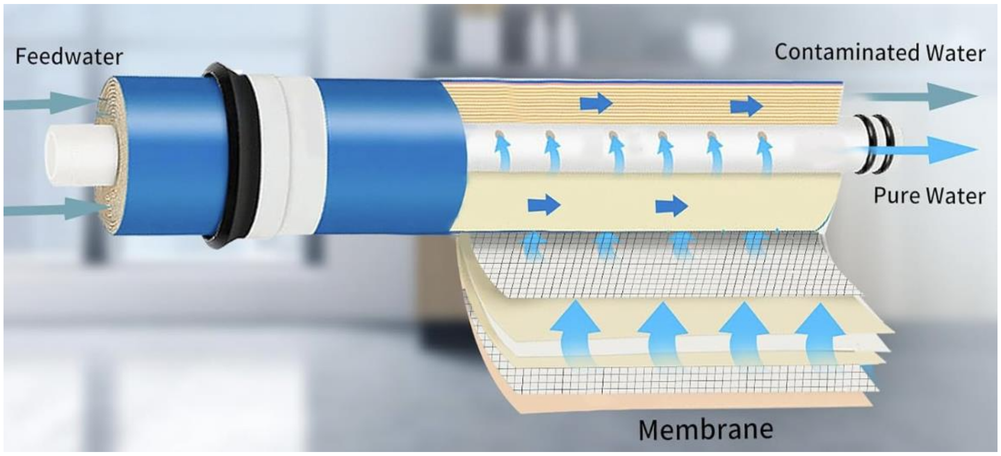

Figure 4: Illustration of iSpring Greatwell 75 GPD, piece that goes inside the membrane housing

Tubing, Valves, and Fittings

Standard 1/4" polyethylene tubing was used to connect the system components. Inline valves allow for controlled flushing and brine discharge, while barbed and quick-connect fittings simplify disassembly and maintenance. Flow restrictors were inserted at the brine outlet to maintain membrane pressure.

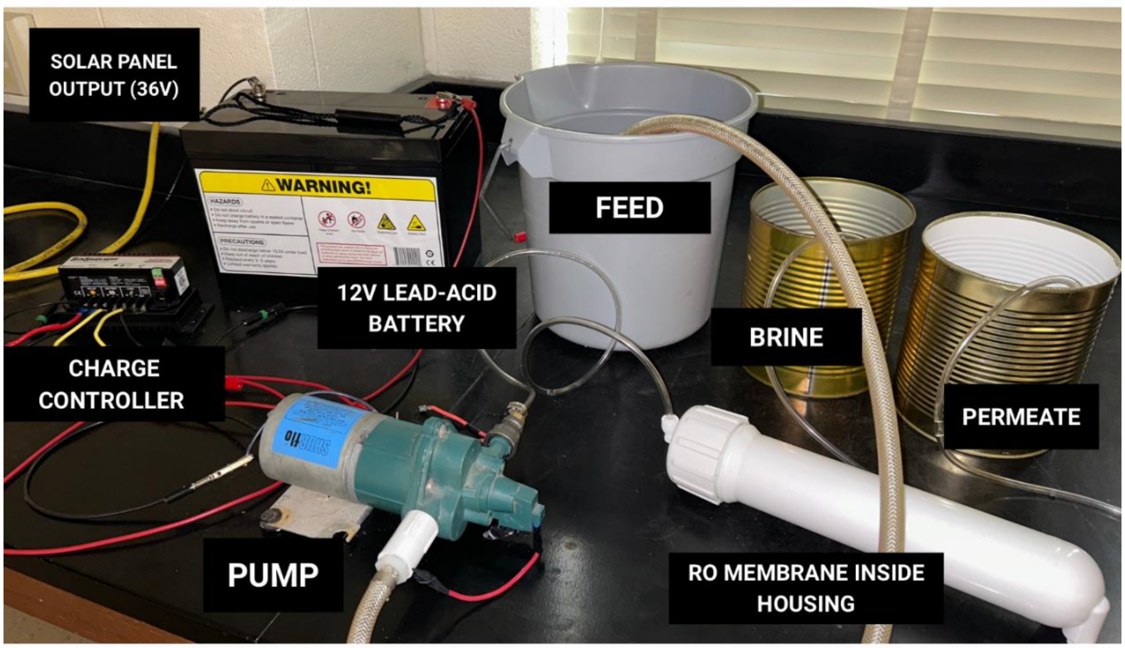

Figure 5: Fully Assembled System

Safety and Modularity

The system was arranged to allow relatively easy access to individual components for testing and minor adjustments. While not mounted on a fully portable platform, the layout was kept adaptable to accommodate future modifications. A fuse was included in the battery line with the charge controller to provide basic electrical protection.

With further development, the system could support future expansion, such as automated data logging, pressure monitoring, or upgrades to lithium-ion batteries for greater energy efficiency.

Set Up Configuration

The RO membrane housing was connected directly to a municipal sink faucet using 1/4" polyethylene tubing and standard RO connectors. This configuration allowed water to flow through the membrane using household water pressure (approximately 45 psi), bypassing the need for a high-pressure DC pump during initial testing. The permeate and brine outputs were directed into separate graduated containers to facilitate flow rate measurement.

To evaluate the solar energy system independently, the 36V panel was connected through the SS-MPPT-15L controller to a 12V lead-acid battery. A multimeter was used to log input voltage and current from the panel at multiple times throughout the day. The battery voltage was also recorded to monitor charging behavior.

Flow Rate Measurement

Flow rates for permeate and brine were measured using a stopwatch and different sizes graduated cylinder. Volume collected over 7-minute intervals was converted to milliliters per minute (ml/min). Multiple trials were conducted, and average values were used in performance calculations.

TDS Monitoring

A handheld digital TDS meter was used to measure total dissolved solids (ppm) in the feed water (municipal tap), permeate, and brine. Readings were taken immediately after sample collection to prevent contamination or evaporation effects.

Solar Output Logging

Solar panel output was recorded three times during daylight hours (morning, noon, afternoon) on a clear day. Measurements included panel voltage, panel current, and battery voltage. This data provided insight into the system's ability to sustain load under natural sunlight.

Observations:

- The RO membrane produced a consistent permeate flow rate of ~146 ml/min and a brine flow of ~32 ml/min, resulting in a high recovery rate.
- TDS readings indicated a significant drop from 128 ppm (feed) to ~5 ppm (permeate), showing effective salt rejection.
- Solar output reached up to 36.9V with peak currents above 8A, and battery charging was successful under midday conditions.

This experimental configuration, while simplified, allowed for critical validation of system performance metrics and demonstrated the feasibility of solar-powered RO desalination in a controlled setting.

Table 2: Total Dissolved Solids and Flow Measurements (Weekly Average)

Sample Type	TDS (ppm)	Flow Rate (ml/min)	Daily Volume (L)
Feed	128	178.57	64.28
Permeate	5	146.43	52.70
Brine	353	32.14	11.57

System Performance Summary

The experimental trials provided strong initial evidence that the small-scale solar-powered RO system can produce clean water efficiently under basic pressure conditions. When powered by municipal tap pressure, the system generated an average permeate flow of 146.43 ml/min and brine flow of 32.14 ml/min. This results in a recovery rate of approximately 82%, which is significantly above the typical 40–60% found in many standard small-scale RO systems.

$$\boldsymbol{Recovery\ Ratio}(\%) = \left(\frac{\boldsymbol{Permeate\ Flow\ Rate}}{\boldsymbol{Feed\ Flow\ Rate}}\right) \times \mathbf{100} \tag{3}$$

Substituting values:

$$\boldsymbol{Recovery\ Ratio}(\%) = \left(\frac{\mathbf{146.43}}{\mathbf{178.57}}\right) \times \mathbf{100} = \mathbf{82.00}\%$$

Salt rejection performance was also favorable. The feed water had a TDS concentration of approximately 128 ppm, while the permeate dropped to 5 ppm, achieving a calculated salt rejection of 96%:

$$\boldsymbol{Salt\ Rejection}(\%) = \left(\frac{\boldsymbol{TDS_{feed}} - \boldsymbol{TDS_{permeate}}}{\boldsymbol{TDS_{feed}}}\right) \times \mathbf{100} \tag{4}$$

Substituting values:

$$\boldsymbol{Salt\ Rejection}(\%) = \left(\frac{\mathbf{128 - 5}}{\mathbf{128}}\right) \times \mathbf{100} = \mathbf{96.09}\%$$

This level of rejection is within expectations for RO membranes operating under moderate pressure and supports the conclusion that the iSpring Greatwell 75 GPD membrane performs well even when driven by faucet pressure.

To further characterize system performance, the concentration factor (CF) was calculated as the ratio of brine TDS to feed TDS:

$$\boldsymbol{Concentration\ Factor} = \left(\frac{\boldsymbol{TDS_{brine}}}{\boldsymbol{TDS_{feed}}}\right) \tag{5}$$

Assuming a brine TDS of 353 ppm, the CF is:

$$\textbf{\textit{Concentration Factor}} = \left(\frac{\mathbf{353}}{\mathbf{128}}\right) = \mathbf{2.7578}$$

This concentration factor suggests effective rejection of dissolved solids, with the brine stream being three times more concentrated than the feed, indicating efficient membrane separation. This supports the conclusion that the iSpring Greatwell 75 GPD membrane performs well even when driven by faucet pressure.

Energy Performance

Solar panel performance was monitored throughout a couple full days of sunlight. The highest recorded voltage was 36.9V, with peak currents approaching 8.3A. This indicates a peak power output of roughly 306W, demonstrating the panel’s ability to charge the 12V battery through the SS-MPPT-15L controller under ideal conditions.

Table 3: One Day Example of Solar Panel Output

Time of Day	Panel Voltage (V)	Panel Current (A)	Power Output (W)
9:00 AM	34.2	5.6	191.5
12:00 PM	36.9	8.3	306.3
3:00 PM	35.1	6.9	242.2

Battery voltage steadily rose during daylight hours, reaching full charge (~13.8V), and was capable of powering small DC loads such as a 12V fan and lighting system. These results validate the solar subsystem's potential to drive a higher-pressure pump in future testing.

Cost Efficiency

Based on estimated component prices, the complete system costs approximately $317.50. Over a projected three-year lifespan and daily clean water output of ~52.7 liters, the cost per liter is roughly:

Table 4: Estimated Unit Price by Components

Component	Estimated Cost (USD)
Solar Panel (100-150W)	$100
MPPT Charge Controller	$40
12V Lead-Acid Battery	$55
RO Membrane (75 GDP)	$27.50
Membrane Housing +Tubing	$25
Pump (12V Diaphragm)	$60
Accessories	$10
Total Estimated Cost	$317.50

$$\frac{\mathbf{317.5}\ \boldsymbol{USD}\ (\boldsymbol{Average\ Unit\ Price})}{(\mathbf{52.7}\frac{\boldsymbol{L}}{\boldsymbol{day}})(\mathbf{365}\frac{\boldsymbol{days}}{\boldsymbol{year}})(\mathbf{3}\ \boldsymbol{years})} = \mathbf{0.0055}\frac{\boldsymbol{USD}}{\boldsymbol{L}} \tag{6}$$

This cost per liter is significantly lower than bottled water or most commercial filtration alternatives, supporting the system's long-term affordability.

Limitations and Considerations

The current results are limited to performance under municipal pressure rather than pump-driven flow. Consequently, while membrane behavior and solar efficiency were validated, full off-grid integration remains to be tested with the intended 60–80 psi pump. Additionally, prolonged testing is necessary to assess membrane fouling rates, system durability, and battery cycling behavior under real-world solar variability.

Despite these limitations, the system has demonstrated that small-scale solar-powered desalination is both technically feasible and economically attractive. Future testing will complete the loop by validating sustained performance under fully off-grid conditions.

Conclusions

This project successfully demonstrated the feasibility of a small-scale solar-powered reverse osmosis (RO) system for water purification. The system achieved high recovery and salt rejection rates while relying solely on solar energy and modest municipal water pressure. Key findings included a recovery rate of approximately 82%, salt rejection of 96%, and a cost-per-liter of clean water as low as $0.0055 over three years. These results confirm that such systems could serve as low-cost, sustainable solutions in remote or underserved communities.

The integration of a 36V solar panel with an MPPT charge controller and a 12V lead-acid battery provided stable energy storage and delivery. Although the final configuration did not include a high-pressure DC pump, testing under municipal pressure enabled validation of the RO membrane's performance and provided a benchmark for future comparisons. Observed solar performance suggested that the energy output would be sufficient to support higher-pressure operations once the appropriate pump is installed.

Future work will focus on fully transitioning the system to off-grid conditions by integrating a pump capable of sustaining 60–80 psi, the optimal range for most small-scale RO membranes. Additional enhancements include installing inline pressure gauges and digital TDS sensors for real-time monitoring, as well as incorporating data logging with a microcontroller. Long-term testing under varied weather and usage conditions will also be important for evaluating membrane fouling, battery cycling durability, and system resilience.

Ultimately, the success of this project highlights the potential for renewable energy to power effective water treatment technologies. With further refinement and field validation, this system could be deployed in real-world applications where access to electricity and clean water is limited.

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