Design and Optimization of Eco-Friendly Solar-Powered Desalination Systems for Clean Water Access

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ABSTRACT:

This research aims to optimize solar-powered desalination systems for cleaner water access in water-scarce areas. This study focuses on enhancing the performance and efficiency of solar desalination by incorporating sustainable design principles and innovative technologies. The major driving forces affecting system performance (in terms of maximizing freshwater output, material selection, thermal efficiency and feed water system optimization) were extensively explored. A structural analysis of components is performed ensuring the best material is chosen and that it is stress resistant. Thermal modeling and performance analysis are performed to see the potential of improving the efficiency of the solar panel, which calculates a thermal efficiency of 14.69% with 834.62 watts of water output. It is calculated that the power usage for the desalination system is 18 amps over a 3-day period, and the frame displacement of the system, as well as the frame factor of safety, are determined as to be 0.708 mm and 6.014, respectively. It also shows that the purified water met three safety benchmarks; it had a pH of 6.8, proving that is safe to drink. Solar-powered desalination plants offer a sustainable alternative for access to clean water, particularly in areas with limited freshwater supplies.

Keywords: Solar desalination, optimization, clean water access, thermal efficiency, solar energy, system design, water purification, Bahrain, sustainability.

I. Introduction

The global challenge of water scarcity is becoming increasingly critical, especially in regions where access to fresh water is limited or non-existent. As populations continue to increase and natural water resources diminish, there is an urgent need to develop innovative methods for water production. A notable solution with significant potential is solar-powered desalination systems, which represent a sustainable and effective option compared to other available alternatives [1]. Solar-powered desalination devices create clean water without relying on external energy or hazardous chemicals. This subsequently facilitates the application of solar energy for desalination, offering a sustainable alternative to address water scarcity, particularly in off-grid or remote areas where conventional water treatment facilities are not feasible [2]. This project aims to develop a green energy solution to address the clean water demands of poor populations. This system, therefore, can be autonomous providing the ability to independently generate water by including solar panels, a battery storage system, an inverter, and water filtration components. It is designed to use low energy and extract as much water efficiently as possible. A significant aspect of this project involves enhancing thermal efficiency, water purification capabilities, and structural integrity of the system [3]. Solar desalination systems, despite their potential, face several challenges. One of the main problems is the vast surface area needed to capture sufficient solar energy, particularly in lower sunlight regions. The desalination process is also slow, and it can be difficult to supply enough water to a large number of people in a short time. Moreover, although solar desalination has the potential to remove salts and some minerals, heavy metals or chemical contaminants cannot be excluded from the water supply, which needs more technical developments. Solar-driven desalination has the ability to address the worldwide water scarcity problem in a sustainable and cost-effective manner [4]. This area of investigation aligns with the growing need for sustainable and low-maintenance water treatment solutions, including the combination of solar energy with desalination methods. The predominant desalination techniques, namely reverse osmosis (RO) and multi-effect distillation (MED), can be energized through solar power. The focus of this research is on improving solar-powered desalination systems, particularly highlighting the reverse osmosis approach, which is extensively used in industrial desalination due to its effectiveness in processing seawater. Developing a compact, portable, low-cost solar desalination unit would provide access to clean drinking water while enhancing environmental sustainability by reducing reliance on fossil fuels [5]. This study is important as it presents a viable solution to a critical global concern—water scarcity—through an approach that is both economically and environmentally sustainable. Enhancing the efficiency of solar-powered water desalination systems can provide fresh water to local communities while reducing the environmental impact associated with traditional water purification methods. This project illustrates how solar desalination can effectively and on a large scale address water scarcity in impacted areas, contributing to the overarching objective of alleviating global water shortages [6]. The need for sufficient usable water is crucial, especially given the increasing worldwide demand, resulting in a situation in which almost a billion individuals need clean water to drink and 2.4 billion individuals are at danger of waterborne diseases [7]. Desalination has been found as an acceptable answer to these problems, offering a potentially dependable and renewable source of clean water. Reverse osmosis, developed in 1959, has proven to be one of the most effective technologies for large-scale desalination. Additionally, solar desalination utilizes solar energy to power reverse osmosis systems, which can significantly reduce the carbon footprint associated with conventional desalination methods that typically require considerable energy and rely on fossil fuels. As the demand for clean water grows worldwide, solar-powered desalination systems offer a sustainable approach to transform saline water into potable water, particularly in arid regions with limited freshwater access [8]. The utilization of sunlight for distillation represents a renewable and cost-effective alternative compared to traditional desalination plants. Advancements in technology have led to improved efficiency of solar desalination systems, especially in areas where conventional extraction methods are constrained, and energy development has advanced. The goal of this research is to create an affordable and scalable solar-powered desalination process to provide clean drinking water for communities in water-scarce regions [9]. This project aims to enhance the operation of solar desalination systems by optimizing thermal efficiency, reducing land use and costs, while ensuring quick and reliable performance under challenging conditions. The findings of this research have the potential to significantly improve access to clean water and contribute to global initiatives aimed at alleviating water scarcity. Solar-powered desalination systems are sustainable alternatives that can ensure long-term water security while minimizing harm to the environmental ecosystem.

II. METHODOLOGY AND ANALYSIS

II.1 Selection Matrix for Material

The matrix values show that AISI 1020 gets the lowest rating, owing to its lower ultimate tensile and yield strength. In contrast, AISI 1040 achieved the best possible rating and meets the specified requirements due to its superior properties within the matrix. As a result, the chassis will be made of AISI 1040.

material	The criteria							
	Material property				Cost	Ability to be Machined	Ability to be welded	Total points
	Young modulus	Ultimate tensile strength	Yield strength	Density				
AISI 1018	5	2	3	3	4	5	5	27
AISI 1020	5	2	2	3	4	4	5	25
AISI 1040	5	5	4	5	5	5	5	34
AISI 4130	5	4	5	4	2	5	5	30

Figure1. Selection Matrix for Material

II.2 Selection Matrix for solar panel

Monocrystalline solar panels have been selected for this project due to several factors. They are the greatest effective type of solar energy system, with effectiveness ratings varying between 15% and 24%, allowing for greater electricity generation. Additionally, their compact design makes them space-efficient. Furthermore, they typically surpass the lifespan indicated by the warranty. The selected solar panel for this project, the SUNEX 100-36M features a 0.67 m² area of surface, 23% STC efficiency, an average electricity consumption of 100 W, an electrical output of 5.56 A, and measurements of 1030 mm x 670 mm x 35 mm.

	MONOCRYSTALLINE	POLYCRYSTALLINE
Efficiency	Higher efficiency 15-24%	Lower efficiency 12-15%
Temperature coefficient	Lower temperature coefficient, More effective during temperature changes	Higher temperature coefficient, less effective during temperature changes
Lifespan	25+ years	25+ years
Cost	Higher cost because of production	Lower cost
Space	Maximizes electricity production with less amount of panels	Lower electricity production with same amount of panels
Waste	More production waste	Less waste

Figure2. Selection Matrix for solar panel

II.3 Solar Panel Efficiency Calculations

Table 1. Given specifications by the manufacturer of the Solar Panel

Manufacturer's efficiency in Standard Test Conditions (STC)	23%
Manufacturer's Power (Pmax)	100W
Manufacturer's maximum current	5.56A
Manufacturer's standard voltage	18V
Area	0.67m²

Note: Typically, STC is defined as:

- Irradiance: 1000 W/m²
- Panel temperature: 25°C
- Air mass: 1.5 (which reflects the amount of atmosphere the sunlight passes through)

$$\text{Efficiency (\%)} = \frac{\text{Initial Power}}{\text{Area x Irradiance}} \text{ x } 100$$

$$= \frac{100}{0.67 \text{ x } 1000} \text{ x } 100$$

$= 14.93\%$

$$\text{Real Power Output} = \text{Power} \times \frac{\text{Real Efficiency}}{\text{Manufacturer's Efficiency}}$$

$$= 100\text{W} \times \frac{14.93\%}{23\%}$$

$$= 65\text{W}$$

Actual current (I) produced = $\frac{Real\ Power\ Output}{Voltage}$

$$= \frac{65}{18}$$

$$= 3.61\text{A}$$

Thus, the actual current produced is approximately 3.61A under ideal conditions with 1000W/m² irradiance.

Table 2. Given coefficients by the manufacturer of the Solar Panel

Co_1: Coefficient of dust = 0.9
Co_2: Coefficient of inhomogeneity panels = 0.9
Co_3: Coefficient of panels connecting cables = (
Co_4: Coefficient of energy transfer losses from t
system to consumption = 0.92
Co_5: Coefficient of inverter efficiency = 0.96
Co_6: Coefficient of aging=0.90

Temperature Drop (December) = temperature coefficient x (25- Panel Temperature) × Efficiency

= 0.0035 x (25-48) × 0.2325

= -1.87%

Therefore, Temperature Drop Calculation is -1.87%

Total coefficient is the total without units coefficients of loss caused by local environment and operational circumstances, such as particles, heterogeneity in sheets, wires, transmission loss, converter efficiency, and age.

Total coefficient = Co1 × Co2 × Co3 × Co4 × Co5 × Co6

= 0.9×0.98×0.98×0.92×0.96×0.9

= 0.687

The Real Efficiency = (Efficiency - Temperature Drop) × Total Coefficient

= (23.25-1.87) × 0.687

= 14.69%

Total Energy = (Average irradiance in December) × (Area of panel)

= 4240×0.67

= 2840.8 W

Produced Energy = Total Energy × Real Efficiency

= 2840.8 × 14.69%

= 417.31 W

Total Produced Energy = 417.31 W * 2

= 834.62 W

II.4 Power Usage Calculation Solar

Because individuals consume 2 liters of water per day, a reverse osmosis water purifier with a 2-liter water filtration capacity uses 0.06 kW of energy. The drinking water filter requires 33.3 liters of fresh water to utilize 1 kW of energy.

For water pump usage per 1 liters, we assume Current per pump is 0.24 Amps

Voltage: 24 volts

Power consumption per pump = current x Voltage

= 0.24 x 24

= 5.76 W

Total current from two pumps running at 10 liters = 0.24 Amperes * 10 liters * 2 pumps = 4.8 Amperes each day.

Adding 25% for extra components = 4.8 * 1.25

= 6 A

If you are accounting for 2 days without sun = 6*3

= 18 A

Since the batteries were 12V 150Ah, just 50% may be depleted (75Ah useable).

Number of batteries needed= 18 / 75A

= 0.24

Batteries so one battery will be enough

To charge batteries within 8 hours of sunlight from 50% to 100% (150A)

Charging Batteries Within 8 Hours = 150A / (10.22 Ah from the solar panels x 8 Hours of sunlight)

= 1.834 Solar Panels (2 Panels)
The solar cells will generate 81.76 A per day ((5.11Ah*2) x 8), resulting in a daily excess of 57 A (the parts only consume 18Amperes). As a result, just two solar panels are necessary, since it generates 57Amperes excess everyday, and since it is unusual in Bahrain to experience periods without sunlight then the batteries are always powered
Therefore, for the days lacking sunlight (or solar cells repair), the batteries remain charged more than 50%.

II.5 Selection Matrix for Inverters

Microinverters were selected due to their efficiency and compact size, which makes them suitable for small-scale applications such as our streetlight. They also offer the potential for future expansion if additional power becomes necessary. Furthermore, monitoring power usage from the system is straightforward. Currently, the project's components have a daily consumption of only 18A, which supports the decision to use a microinverter.

Solar Inverter	Advantages	Disadvantages
String	• Cheap • Standard and Commonly Used	• Production decreases if panel is damaged or if there is shade on panel • Not able to monitor each panel's output • Increasing power may be more difficult
Power Optimizer	• More efficient than string inverters alone • Less expensive than microinverters • Can monitor panel's output	• High initial cost • Required string inverter to work
Microinverter	• Easily expandable if more power is required in the future • Improved safety features • Easily track solar panel's output • Longer lifespan • Good for small projects • Efficient	• High initial cost • If it were to fail, there will be no power provided to the lights

Figure3. Selection Matrix for solar panel

II.6 Selection Matrix for Battery

The selection of solar gel batteries was influenced by their characteristics. Their stability allows for easy installation in multiple orientations. These batteries are classified as deep-cycle batteries, which contain thicker lead plates designed to generate energy more steadily and at a slower rate. This feature makes deep-cycle batteries particularly suitable for solar panel systems. Additionally, our decision to use 12V 150Ah Solar Gel Batteries was based on our power calculations.

Battery	Lead-Acid Battery	Lithium-Ion Battery	Sodium Nickel Chloride	Solar Gel
Advantages	- Lowest cost - Easily recycled - Regular Maintenance	- Long lifespan - High DoD and density - Compatible size - Free Maintenance - Lightweight - No gas emissions - Self-discharge	- Fully recyclable - Safe - NO overheat - Broad operation temperature	- Little to no maintenance - Low chance of leaks and other issues because the liquid will be replaced with gel. - Flexible to install - Resistant to heavy vibrations and other impacts
Disadvantages	- Short lifespan - low depth of discharge (DoD) - Takes space - Emit hydrogen gas - Leak	- High cost - Overheat	- High Cost - Short lifespan	- Requires to be monitored when charging, leaving it can cause voids with electrolyte - Withstands certain temperatures

Figure4. Selection Matrix for battery

III. MODELLING DETAILS

The FE simulation was performed on a Solar-Powered Desalination System to analyze structural behavior under applied loads. Table 2 outlines the design parameters, including the load details used for static simulation. Standard gravity (9.81 m/s²) and applied normal forces (830 N on one face and 150 N distributed over three faces) were considered, as shown in the input data. The fixture setup involved fixed geometry on four faces, with reaction forces calculated as 0.0001 N, 1,456.79 N, and 0.00003 N in the X, Y, and Z directions, resulting in a magnitude of 1,456.79 N. A curvature-based mesher with high-quality settings was used for discretization, generating 127,958 nodes and 66,211 elements. The finite element analysis included creating the CAD model, assigning material properties, applying loading conditions, generating a fine mesh, and performing static structural analysis to evaluate system performance under realistic conditions.

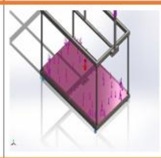
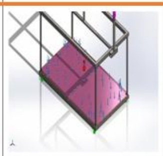
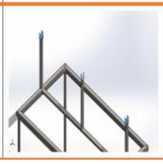
Load name	Load Image	Load Details
Gravity-1		Reference: Face< 1 > Values: 0 0 -9.81 Units: m/s^2
Force-2		Entities: 1 face(s) Type: Apply normal force Value: 830 N
Force-3		Entities: 3 face(s) Type: Apply normal force Value: 150 N

Table 2 Design parameters

IV. RESULTS AND DISCUSSION

IV.1 Finite Element Analysis Results of the frame:

Eco-friendly solar-powered desalination systems harness solar energy for clean water production. This study addresses the optimization of structures under specific conditions. The system's reliability is assessed with a stress distribution frame, yielding a displacement of 0.708 mm and a safety factor of 6.014. Stress measures reveal minimum stress at 8.485e+03 N/m^2 and maximum stress at 2.993e+07 N/m^2, indicating durability.

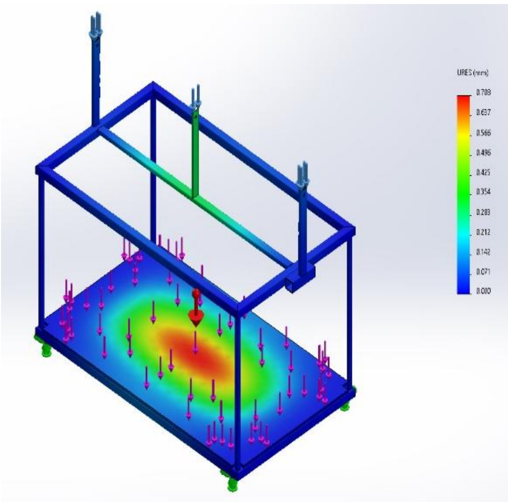


Figure5. Von Mises Stress results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	8.485e+03N/m^2 Node: 49379	2.993e+07N/m^2 Node: 80135
Displacement1	URES: Resultant Displacement	0.000mm Node: 9219	0.708mm Node: 11231
Strain	ESTRN: Equivalent Strain	6.133e-08 Element: 51486	8.470e-05 Element: 39702
Factor of Safety	Automatic	6.014 Node: 80135	21,214.881 Node: 49379

Table3. FE analysis results

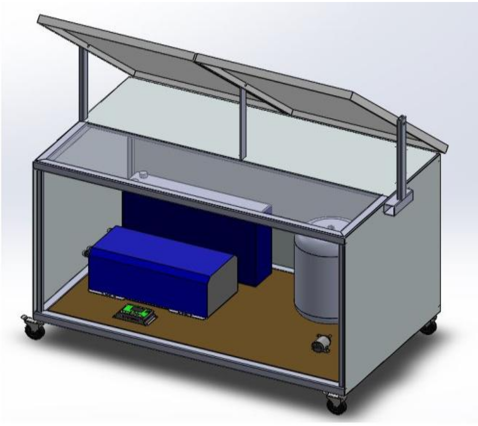


Figure6. Final Assembly

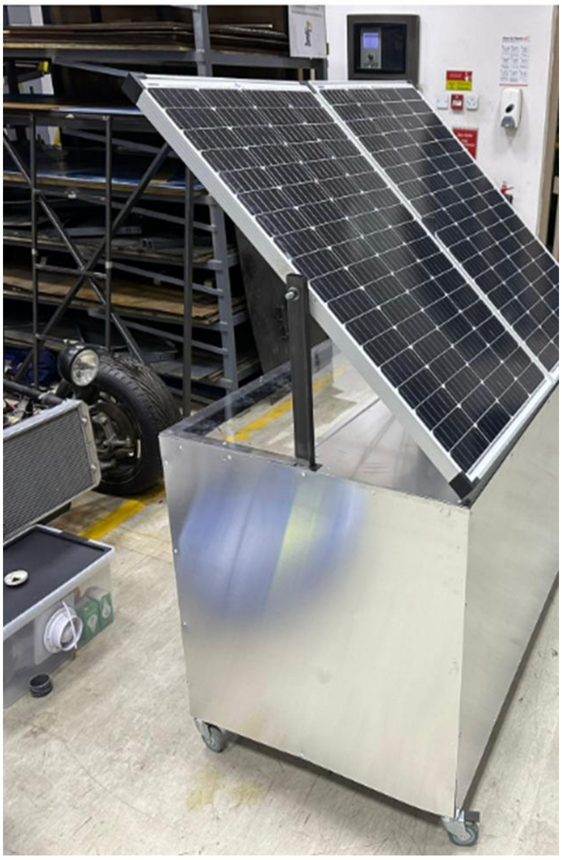


Figure7. Real prototype

To maintain the quality of desalinated water, it is essential to conduct regular tests of seawater both prior to and following process. The pH of desalinated water ought to be between 6.5 and 8.5 to guarantee that it is acceptable to consume and does not constitute an environmental problem. Supervisors can ensure that the generated water meets the necessary requirements for usage by humans and sustainability by performing regular pH measurements on the seawater prior to and after reverse osmosis. The pH of water from desalination should typically range from 6.5 and 8.5 to guarantee that it is acceptable to consume and does not constitute an environmental problem. Supervisors can ensure that the generated water meets the necessary requirements for consumption by individuals and sustainability by performing regular pH testing on the seawater prior to and after the process of reverse osmosis.

Test	Symbol	Pretreatment results	Post treatment results
Acidity	pH	6.4	6.8
Carbonate hardness	KH	0	0
Nitrite	NO2	5	0
Nitrate	NO3	25	10
Chlorine	Cl2	0	0.8
Results shows that the water is safe for human consumption with a pH level of 6.8			

CONCLUSION:

In summary, this project has the potential to mitigate water scarcity on a global scale. It provides a movable source of clean water capable of meeting the needs of at least seven adult individuals for a duration of three to six months without the need for maintenance, relying solely on renewable energy. In the context of Bahrain, the initiative is particularly advantageous for military operations, where access to clean water in remote locations is essential. It could also be integrated into military vessels. Both private and government entities might consider incorporating this system into coastal projects to ensure that workers in isolated areas have access to potable water. Thermal efficiency calculations for the solar panel indicate an efficiency rating of 14.69%, with a projected output of 834.62 watts over an 8-hour period, accounting for the month with the least solar exposure, December. The power consumption of the system is estimated at 18 amps over a span of three days. The frame's displacement is measured at 0.708 mm, with a safety factor calculated at 6.014. The minimum tolerance is identified as 8.485e+03 N/m^2, while the maximum stress recorded is 2.993e+07 N/m^2. The results of the purity tests reveal that the water passes safety guidelines for use by humans, with a pH value of 6.8. In addition to the research findings, various enhancements could be made to the powered by sunlight desalination device. Installing an additional water storage tank could enable the generation and storage of up to 36 liters of clean water. Installing a larger water pump may increase the flow rate, improving efficiency. An exterior power switch could facilitate easy operation and enhance safety by enabling emergency shutdowns. Employing lighter materials like aluminum or carbon fiber for the frame could reduce weight, improving transport and installation ease while ensuring structural integrity. These enhancements could boost the system's effectiveness as a long-term solution for water scarcity in affected regions.

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