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Design of a Seawater Desalination System Powered by Photovoltaic Cells in Port Sudan, Sudan

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Abstract- Freshwater scarcity in coastal regions such as Port Sudan has become a persistent constraint driven by population growth, climate variability, and infrastructure limitations. While seawater desalination offers a technically viable solution, its implementation is often constrained by high energy requirements and operational costs. This study presents the complete engineering design and techno-economic evaluation of a seawater reverse osmosis (SWRO) desalination system powered by photovoltaic (PV) energy under Red Sea conditions. The system is designed for a production capacity of 10,000 m³/day, incorporating detailed modeling of osmotic pressure, mass balance, hydraulic energy requirements, and photovoltaic power generation. The elevated salinity of the Red Sea (~40 ppt) results in an osmotic pressure of approximately 33.9 bar, requiring an operating pressure near 60 bar. The total energy demand is estimated at 12.78 GWh annually, supplied by a 7.8 MW photovoltaic system based on local solar irradiance data. Economic analysis indicates a capital cost of approximately 22 million USD and a levelized cost of water (LCOW) of 0.66 USD/m³, with a positive net present value over the project lifetime. In addition, the system achieves a significant reduction in carbon emissions compared to conventional fossil-fuel-based desalination. The results confirm that photovoltaic-powered desalination provides a technically feasible and economically sustainable solution for water supply in arid coastal environments.

Keywords- Reverse Osmosis; Photovoltaic Energy; Seawater Desalination; Energy Modeling; Levelized Cost of Water.

I. INTRODUCTION

Water scarcity in coastal regions is increasingly shaped by a combination of environmental and socio-economic pressures [1]. In Port Sudan, the situation is particularly acute due to limited freshwater resources, high evaporation rates, and growing urban demand. Although seawater desalination offers a direct solution, its deployment is often limited by energy availability and cost [2].

Reverse osmosis (RO) has become the dominant desalination technology due to its relatively high efficiency compared to thermal methods [3]. However, its dependence on high-pressure operation makes energy consumption the primary factor governing both operational cost and system feasibility.
In the Red Sea, seawater salinity typically reaches approximately 40 ppt, exceeding the global average of 35 ppt [4]. This increase in salinity significantly raises osmotic pressure, which in turn requires higher operating pressures and increased energy input. As a result, system design must be carefully adapted to local conditions. At the same time, Port Sudan benefits from high solar irradiance, making photovoltaic energy an attractive option for powering desalination systems [5]. The integration of PV systems with SWRO desalination offers a pathway toward reducing both operational costs and environmental impact.
This study aims to develop a complete engineering design framework for a PV-powered SWRO desalination system tailored to Port Sudan. Unlike simplified approaches, the present work combines thermodynamic analysis, hydraulic modeling, energy system design, and economic evaluation within a unified framework.

II. METHODOLOGY

System Configuration

The proposed desalination system consists of an integrated set of components designed to operate under high-salinity conditions.

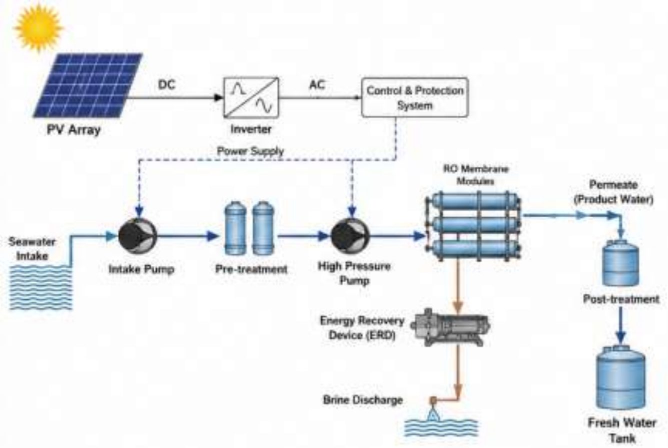

Figure 1. Integrated PV-powered SWRO desalination system showing energy flow and subsystem interaction

The overall configuration of the proposed desalination system is illustrated in Fig. 1, where seawater is processed through multiple stages to produce potable water under controlled operating conditions.

Governing Equations

Osmotic Pressure:

$\pi = iMRT$

For Red Sea conditions:

$\pi \approx 33.9$ bar

Mass Balance:

$$Q_f = \frac{Q_p}{Recovery}$$

$$Q_b = Q_f - Q_p$$

Hydraulic Power:

$$P = \frac{Q \times \Delta P}{\eta}$$

Energy Demand:

$$E = Q \times SEC$$

PV Capacity:

$$P_{PV} = \frac{E}{H \times PR}$$

Simulink Model

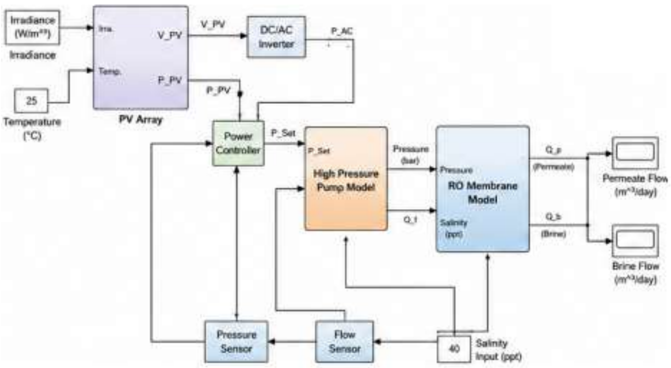

Figure 2 MATLAB/Simulink signal flow representation of the PV-SWRO desalination model

Fig. 2. MATLAB/Simulink model of the PV-powered desalination system showing subsystem interactions and control signals.

III. RESULTS

Mass Balance Results

- Feed flow rate: 22,222 m³/day
- Brine flow rate: 12,222 m³/day

Energy Requirements

- Daily energy: 35,000 kWh
- Annual energy: 12.78 GWh

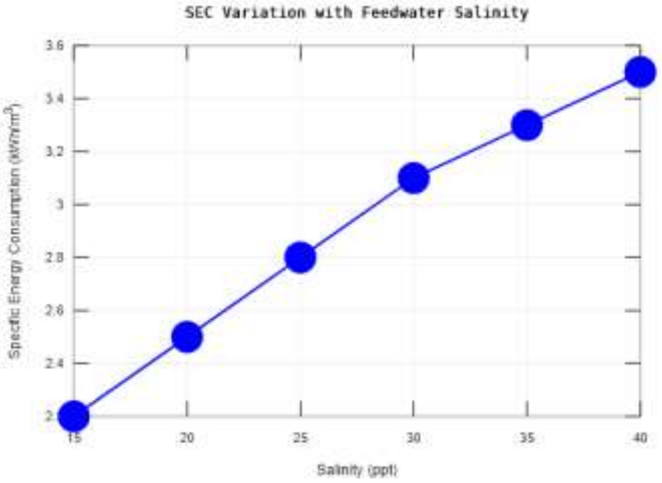

Figure 3. Variation of specific energy consumption with feedwater salinity.

Fig. 3 demonstrates the increasing energy demand with salinity, confirming the need for high-pressure operation under Red Sea conditions.

PV System Design

- PV capacity: 7.8 MW
- Number of panels: 14,141
- Land area: 5.9 hectares

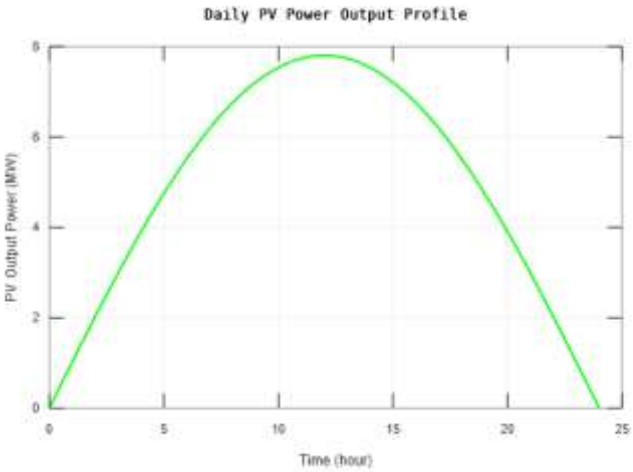

Fig. 4. Daily photovoltaic power output profile under Port Sudan conditions.

Economic Analysis

- CAPEX: 22 million USD
- OPEX: 0.88 million USD/year
- LCOW: 0.66 USD/m³
- NPV: +8.4 million USD

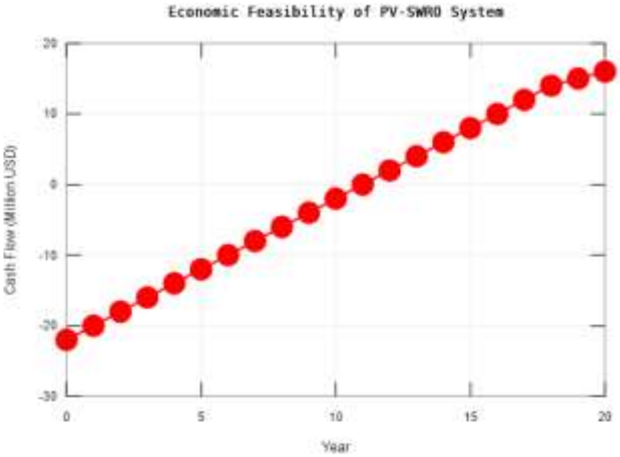

Figure 5 Economic feasibility analysis of the PV-SWRO desalination system

Fig. 5. Economic performance of the desalination system showing cumulative cash flow and project feasibility.

IV. DISCUSSION

The results highlight the critical influence of salinity on system design. Under Red Sea conditions, the increase in osmotic pressure leads to higher energy demand compared to standard seawater assumptions. This reinforces the importance of site-specific design.

The integration of photovoltaic energy significantly improves system sustainability by reducing dependence on fossil fuels. Although solar energy introduces variability, its high availability in Port Sudan compensates for intermittency when properly designed.

From an economic perspective, the obtained LCOW is competitive with global benchmarks, confirming the feasibility of the proposed system.

V. CONCLUSION

This study presents a complete engineering design of a PV-powered SWRO desalination system tailored to Port Sudan.

Key conclusions:

- High salinity requires ≈60 bar operating pressure
- Energy demand ≈ 3.5 kWh/m³
- PV capacity ≈ 7.8 MW
- LCOW ≈ 0.66 USD/m³
- Positive economic feasibility

The integration of renewable energy with desalination represents a sustainable solution for water scarcity in coastal regions.

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