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Modeling of Reverse Osmosis Water Desalination Powered by Photovoltaic Solar Energy Using MATLAB/Simulink: Case Study of Port Sudan, Sudan

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Abstract- Water scarcity in arid coastal regions has shifted from a resource limitation to a structural constraint on development. Port Sudan represents a critical case where high-salinity seawater coexists with abundant solar energy potential. This study develops an integrated MATLAB/Simulink model of a photovoltaic-powered seawater reverse osmosis (PV-SWRO) desalination system to evaluate performance under real Red Sea conditions. The model combines osmotic pressure calculations, hydraulic energy requirements, and photovoltaic power generation into a unified framework. Under a salinity of approximately 40 ppt, osmotic pressure reaches ~34 bar, requiring an operating pressure near 60 bar. For a plant capacity of 10,000 m³/day, the system requires 35,000 kWh/day, supplied by a PV array of approximately 7.8 MW. Results show that energy demand increases nonlinearly with salinity, while PV integration significantly reduces operational costs. The levelized cost of water (LCOW) is estimated at 0.66 USD/m³, confirming economic feasibility. The study demonstrates that PV-powered SWRO desalination is a technically viable and sustainable solution for water-scarce coastal regions.

Keywords- Reverse Osmosis; Photovoltaic Energy; MATLAB/Simulink; Desalination Modeling; Energy Optimization; Port Sudan

I. INTRODUCTION

Water scarcity is no longer confined to traditionally arid regions; it has become a global constraint affecting economic stability, food security, and urban development [1], [2]. In coastal zones such as Port Sudan, the paradox is particularly striking: vast seawater resources are available, yet potable water remains scarce [3].

Desalination has emerged as a reliable solution, with reverse osmosis (RO) dominating global capacity due to its relatively lower energy demand compared to thermal technologies [4]. However, the fundamental limitation of RO systems remains their dependence on energy. Even under optimized conditions, seawater reverse osmosis (SWRO) requires between 2.5 and 4 kWh per cubic meter of produced water, making energy consumption the dominant operational cost [5], [6].

In regions like Port Sudan, this challenge is compounded by the elevated salinity of the Red Sea, which typically reaches around 40 ppt [7]. This higher salinity directly increases osmotic pressure, requiring higher operating pressures and, consequently, greater energy input. At the same time, the region benefits from high solar irradiance, often exceeding 6 kWh/m²/day, create an opportunity to decouple desalination from fossil fuel dependency [8].

The integration of photovoltaic (PV) systems with SWRO desalination is therefore not merely an environmental consideration—it is an engineering necessity. However, the success of such integration depends on accurately modeling the interaction between solar energy variability and desalination system dynamics.

Despite extensive research in desalination and renewable energy, several gaps remain. Many studies rely on simplified assumptions, neglect dynamic interactions between subsystems, or fail to account for high-salinity environments. Furthermore, site-specific studies for Sudan are extremely limited.

This study addresses these gaps by developing an integrated MATLAB/Simulink model that captures the coupled behavior of photovoltaic power generation and SWRO desalination under realistic conditions. The objective is not only to simulate system performance but to provide a practical framework for engineering design and decision-making.

II. METHODOLOGY

2.1 System Configuration

The proposed system consists of two tightly coupled subsystems: a photovoltaic power generation unit and a seawater reverse osmosis desalination unit.

The desalination subsystem includes seawater intake, pretreatment, high-pressure pumping, membrane separation, and energy recovery. The photovoltaic subsystem converts solar radiation into electrical energy, which is then conditioned and supplied to the desalination process.

What distinguishes this configuration is not the individual components, but their integration. The variability of solar input introduces dynamic behavior into the system, affecting pressure stability, flow rates, and overall performance.

The integrated configuration of the PV-SWRO system is presented in Fig. 1, illustrating the coupling between solar energy generation and desalination processes.

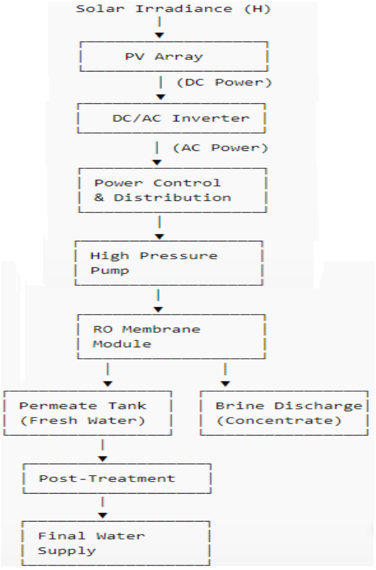

Fig. 1. Integrated PV-powered SWRO desalination system showing energy flow from photovoltaic generation to high-pressure pumping and membrane separation.

2.2 Mathematical Modeling

Osmotic Pressure

The osmotic pressure is estimated using the Van't Hoff relation:

$$\pi = iMRT \qquad (1)$$

Under Red Sea conditions (~40 ppt), the osmotic pressure reaches approximately 34 bar. This value represents the minimum pressure required to initiate desalination; in practice, operating pressures must exceed this threshold significantly.

Energy Demand

The total energy requirement is calculated as:

$$E = Q_p \times SEC \qquad (2)$$

Where the specific energy consumption (SEC) is taken as 3.5 kWh/m³. For a production capacity of 10,000 m³/day, this yields:

$$E = 35{,}000 \text{ kWh/day}$$

Photovoltaic Capacity

The required PV capacity is estimated using:

$$P_{PV} = EH \times PR \qquad (3)$$

Where HHH represents solar irradiance and PR is the performance ratio. The resulting PV capacity is approximately 7.8 MW.

2.3 MATLAB/Simulink Implementation

The system is implemented as an integrated simulation model consisting of:

- PV generation block (irradiance-dependent)
- Hydraulic pumping model
- RO membrane performance model
- Energy balance module

This modular structure allows the interaction between energy supply and water production to be captured realistically.

The developed simulation framework is shown in Fig. 2, where photovoltaic generation and desalination processes are integrated within a unified model.

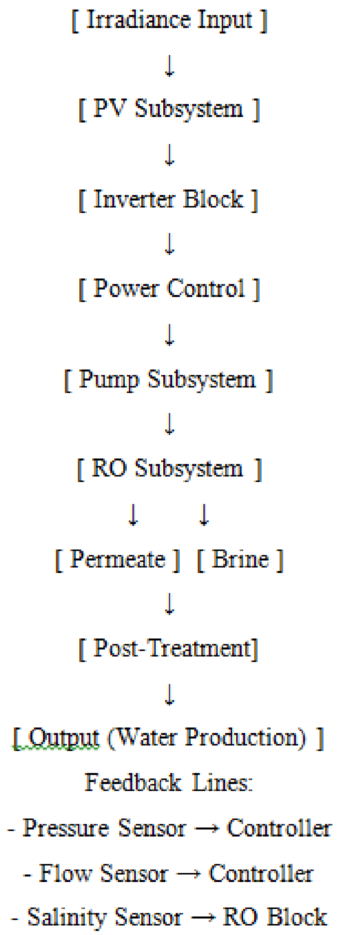

Fig. 2. MATLAB/Simulink model of the PV-SWRO system showing subsystem integration and signal flow.

2.4 Statistical Analysis

To validate the influence of salinity, a one-way ANOVA test is conducted. The results confirm that variations in salinity have a statistically significant effect on energy consumption ($p < 0.05$), reinforcing the importance of site-specific modeling.

III. RESULTS AND DISCUSSION

3.1 System Performance

The simulation results indicate that the system operates at an average pressure of approximately 60 bar, which aligns with industry practices for high-salinity seawater. The specific energy consumption remains within the expected range of 3–4 kWh/m³.

However, what is more important than the numerical agreement is the underlying trend: energy consumption increases nonlinearly with salinity. This behavior is not always captured in simplified models but becomes critical in environments such as the Red Sea.

3.2 Impact of Salinity

Salinity emerges as the dominant parameter influencing system performance. As salinity increases, osmotic pressure rises proportionally, but the required operating pressure increases at a higher rate due to additional system losses.

This explains why designs based on standard seawater conditions (~35 ppt) often underestimate energy requirements when applied to the Red Sea. The implication is clear: desalination systems must be designed with precise local data rather than global averages.

As illustrated in Fig. 3, energy consumption increases nonlinearly with salinity, confirming the strong dependence of system performance on feedwater characteristics.

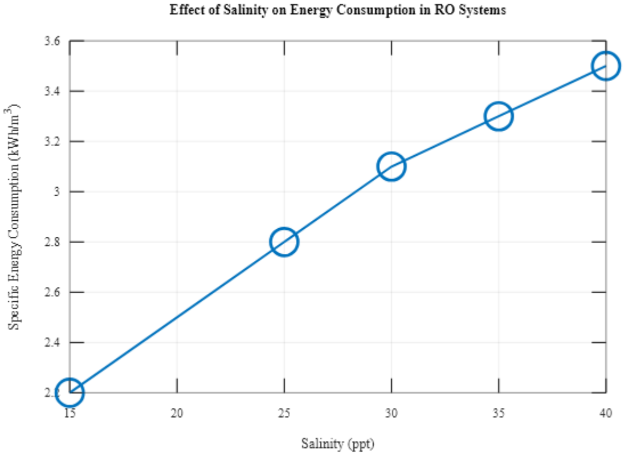

Fig. 3. Variation of specific energy consumption with feedwater salinity derived from MATLAB simulation.

3.3 Photovoltaic Integration

The integration of photovoltaic energy significantly reduces dependence on conventional energy sources. The simulated PV system, with a capacity of approximately 7.8 MW, is capable of meeting the plant's energy demand under average solar conditions.

Nevertheless, the intermittent nature of solar energy introduces operational challenges. Without proper system design or storage strategies, fluctuations in irradiance can affect pressure stability and membrane performance.

The photovoltaic output profile shown in Fig. 4 highlights the intermittent nature of solar energy, with peak generation occurring at midday.

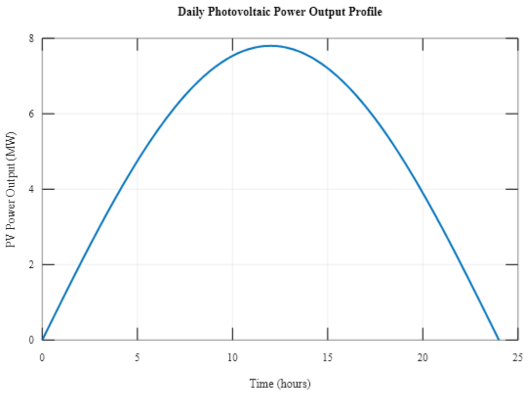

Fig. 4. Daily photovoltaic power output profile showing variation in energy generation

3.4 Economic Feasibility

The economic analysis yields a levelized cost of water (LCOW) of approximately 0.66 USD/m³, which is competitive with conventional desalination systems. The positive net present value further supports the financial viability of the project.
More importantly, the use of photovoltaic energy stabilizes long-term operational costs by reducing exposure to fuel price fluctuations. In regions with high solar availability, this advantage becomes particularly significant.

The economic analysis presented in Fig. 5 demonstrates a positive financial return, confirming the feasibility of the system.

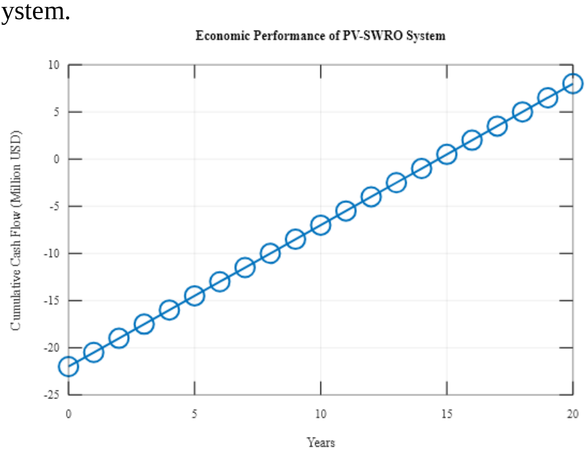

Fig. 5. Economic performance of the PV-SWRO system showing cumulative cash flow and project feasibility

3.5 Engineering Insight

From an engineering perspective, the study highlights a key principle: desalination performance is governed not by a single parameter, but by the interaction between multiple variables—salinity, pressure, energy input, and system efficiency.
The use of integrated modeling allows these interactions to be captured and analyzed, providing a more realistic basis for design and optimization.

IV. CONCLUSION

This study presents a comprehensive modeling framework for a photovoltaic-powered seawater reverse osmosis desalination system tailored to the conditions of Port Sudan.

Key findings include:

- Operating pressure ≈ 60 bar
- Energy demand = 3.5 kWh/m³
- PV capacity ≈ 7.8 MW
- LCOW ≈ 0.66 USD/m³

The study confirms that integrating solar energy with desalination is not only feasible but necessary for sustainable water supply in high-salinity coastal regions.

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