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Engineering Analysis of Innovation and Water Tariff Structure in Solar-Powered Reverse Osmosis (RO) Desalination Plant: Case Study of Muara Angke

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Abstract: Background: Muara Angke experiences chronic clean water and energy shortages, motivating the installation of a solar-powered RO desalination system in 2024. Objective: This study analyzes the economic feasibility of solar-powered RO desalination by estimating clean water production costs based on solar energy economics. Method: A HOMER-based simulation integrates local solar irradiation data, system configuration, desalination load, and techno-economic component parameters. Results: Simulation results show that the photovoltaic system produces 85,848 kWh annually, fully supplying the desalination facility with a 100% renewable energy fraction, ensuring complete independence from fossil-based electricity. The optimized configuration enables continuous operation of the reverse osmosis unit with a capacity of 320 liters per hour, providing a stable clean water supply. Economically, the system has a Net Present Cost (NPC) of IDR 384,050,000, including investment, replacement, and operational costs. The Cost of Energy (CoE) is IDR 575.55 per kWh, resulting in a clean water production cost of IDR 17.27 per liter, significantly lower than diesel-powered desalination systems. Conclusion and Recommendation: The study concludes that solar-powered RO desalination is economically viable and environmentally sustainable, and it is recommended for replication in Indonesia's coastal and remote regions to strengthen water and energy security.

Keywords: Innovation; Water Pricing; Solar-Powered Reverse Osmosis; Desalination System; Muara Angke

INTRODUCTION

Muara Angke, located in the Pluit Village, Penjaringan District, North Jakarta, is an area that frequently experiences difficulties in accessing clean water. This has become a reality faced by the coastal and island communities in the region. Drawing inspiration from previous studies on solar-powered desalination technology in various locations, this initiative aims to implement a desalination system powered by a Solar Power Plant. Situated in a geographically strategic position to harness sunlight, Muara Angke presents a significant potential for maximizing solar energy to convert seawater into potable drinking water. According to the Indonesian Ministry of Health Regulation No. 32 of 2017, the standard for drinking water quality in Indonesia is based on several physical characteristics, including turbidity, color, dissolved solids, temperature, taste, and odor. Therefore, this project not only addresses the urgent need to meet the local community's basic requirement for clean water but also offers a sustainable and environmentally friendly water resource management concept.

To address the issue of clean water availability in Muara Angke, North Jakarta, desalination technology offers a potential solution to convert seawater into drinkable water. According to research conducted by Nugroho (2004), thermal desalination uses heat energy, often waste from power plants, while membrane desalination, such as reverse osmosis, only requires electrical energy to operate pumps (Harris, Politeknik, & Bandung, 2015).

Relevant research on seawater desalination technology has been conducted by Shukla, Shubham Agarwal, and Kuldeep Narwat (2022), who developed a seawater desalination process utilizing solar energy with the reverse osmosis method, capable of filtering large molecules and ions from a solution by applying pressure to the solution when it is on one side of a selective membrane (Shukla, Agarwal, & Narwat, 2022). On the other hand, (Yoshi &

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Widiasa, 2017) examined the reverse osmosis membrane desalination method, which requires pretreatment steps to reduce fouling and scaling (Yoshi & Widiasa, 2017). Advances in reverse osmosis desalination technology, marked by reduced operational costs, improved membrane quality, and better energy efficiency, provide positive prospects for its implementation in Muara Angke.

Research on the use of Solar Power Plant in supporting the desalination process has also been conducted by (Sasongko et al., 2019). The study focused on the use of a Solar Power Plant as a source of electrical energy to operate a reverse osmosis desalination system. The desalination system designed in the study was divided into two types, namely reverse osmosis for seawater and reverse osmosis for tap water, to meet drinking water needs in Sulamu Village, Kupang Regency, East Nusa Tenggara (Isna, 2020). The application of Solar Power Plant in reverse osmosis clean water treatment systems is considered very suitable for application in border and remote areas, and can also be applied in areas affected by drought as a solution for fulfilling water and electricity needs.

Indonesia, located along the equator, has great potential for solar energy utilization. This energy can be converted into electricity through photovoltaic (PV) technology. This technology uses semiconductor materials, commonly silicon, which are modified with additional elements to create solar cells. When sunlight hits these cells, the electrons in the silicon are released and move, generating an electric current and producing electricity. The output from photovoltaic cells depends on sunlight intensity; with lower intensity, the power generated is smaller, while higher intensity allows for greater power generation. With an average daily insolation rate between 4.5 KWh/m^2 per day to 4.8 KWh/m^2 per day, the potential for solar energy development in Indonesia is highly significant (Yuliananda, Sarya, & Hastijanti, 2015).

LITERATURE REVIEW

Life Cycle Cost (LCC) Theory

Life Cycle Cost (LCC) theory evaluates infrastructure based on total lifetime costs, including capital, operation, maintenance, and replacement expenses. It emphasizes long-term cost efficiency over initial investment, particularly in renewable systems with high upfront but low operating costs (Aghaei et al., 2020; Rahimi et al., 2021).

Energy–Water Nexus Theory

Energy–Water Nexus theory explains the interdependence between energy supply and water production systems. In desalination, stable and renewable energy inputs reduce operational volatility, enhance affordability, and strengthen long-term sustainability of water infrastructure in resource-constrained regions (Shukla et al., 2022; Rahimi et al., 2021).

METHOD

This study employs a simulation-based research method to evaluate the technical and economic performance of a solar-powered desalination system using HOMER (Hybrid Optimization of Multiple Energy Resources) software. The simulation approach is used to model the integration between the Solar Power Plant (PV system) and the Reverse Osmosis (RO) desalination unit, enabling the assessment of system feasibility under real operational conditions.

Data Collection

The first stage of the research involves collecting the necessary technical and economic data. The collected data include site location data, electrical load requirements of the desalination system, and technical specifications of the Solar Power Plant components. Location data are required to determine the solar irradiation potential, which directly affects the energy production of the photovoltaic system. Component data include both technical parameters and economic parameters, such as system capacity, procurement cost, replacement cost, and operation and maintenance (O&M) cost.

Desalination System Operational Parameters

The Reverse Osmosis desalination system used in this study operates with a nominal production capacity of 320 liters per hour. The system is assumed to operate 24 hours per day, supported by the solar power system and energy storage configuration in the HOMER simulation. Thus, the daily operational time of the RO unit is:

Operating Time = 24 hours/day

This operational duration results in a theoretical daily water production capacity of:

$Q_d = 320 \times 24 = 7{,}680$ liters/day

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and a monthly production capacity of approximately:

Q_m = 7,680 × 30 = 230,400 liters/month

The technical specifications of the desalination system used in the simulation are summarized as follows:

Table 1. Parameter

Parameter	Value
RO production capacity	320 L/hour
Operating time	24 hours/day
Feed water salinity	~30,000–35,000 ppm
Pump pressure	55–60 bar
Recovery rate	35–45%
System efficiency	85–90%

These parameters represent typical operating conditions for small-scale seawater reverse osmosis (SWRO) desalination systems.

System Simulation Using HOMER Software

After the required data are collected, a system schematic model is developed within the HOMER software environment. The model consists of the main system components, including:

- Photovoltaic (PV) modules with a total installed capacity of 7.7 kWp
- Power conditioning units
- Energy storage system (if required)
- Electrical load from the RO desalination unit

All technical and economic parameters are then entered into the HOMER simulation interface. The software performs optimization and simulation processes to determine the optimal configuration and evaluate system performance based on energy production, system reliability, and economic feasibility.

Economic Evaluation and Net Present Cost (NPC)

To assess the economic feasibility of the system, the simulation uses Net Present Cost (NPC) as the primary economic indicator. NPC represents the total life-cycle cost of the system, calculated by discounting all capital, replacement, operation, and maintenance costs over the project lifetime.

In this study, the following economic assumptions are applied:

Table 2. Economic Parameter

Economic Parameter	Value
Project lifetime	25 years
Discount rate	8%
Inflation rate	3%
PV lifetime	25 years

The Net Present Cost is calculated using the standard economic formula:

$$NPC = (C_{annual})/CRF_{(i,n)}$$

where:

C_{annual} =total annualized cost
CRF =capital recovery factor
i =discount rate
n = project lifetime

Sensitivity Analysis

To evaluate the robustness of the system design, a sensitivity analysis is conducted within the HOMER simulation environment. This analysis examines the influence of key parameter variations on system performance and economic feasibility. The sensitivity variables considered in this study include:

- Variation in PV module cost
- Solar irradiation fluctuations
- PV panel degradation over time
- Changes in operation and maintenance (O&M) costs

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The sensitivity analysis enables the identification of critical parameters that significantly influence the Net Present Cost (NPC) and the cost of water production. This step is essential to ensure that the proposed solar-powered desalination system remains economically viable under different future scenarios.

Research Process

Overall, this research consists of three main stages: case study, simulation analysis, and scientific reporting.

1. Case Study
   A comprehensive literature review is conducted using books, scientific journals, and previous studies related to solar-powered desalination systems. This stage aims to identify research gaps and define the focus of the study.
2. Simulation and Performance Analysis
   The collected data are processed using HOMER simulation software to analyze the performance, energy balance, and economic feasibility of the Solar Power Plant in supporting the desalination system.
3. Research Reporting
   The final stage involves compiling the research findings into a scientific manuscript that presents the methodology, simulation results, analysis, and conclusions in accordance with academic research standards.

RESULT

In 2024, a water desalination facility project was inaugurated in RT 006 and RT 007 RW 022 in Pluit Village, Penjaringan District, North Jakarta, specifically in the Muara Angke area. This project is part of a Community Service initiative run by the Defense University of Indonesia (Universitas Pertahanan RI). The facility adopts Reverse Osmosis (RO) Membrane technology for water filtration, with a production capacity of 320 liters per hour. To support sustainable and environmentally friendly operations, the system is powered by solar panels, demonstrating Universitas Pertahanan RI's commitment to providing efficient and eco-friendly technological solutions for the residents. The use of solar energy as a resource for this desalination system requires the collection of specific data, such as the electricity consumption per liter of water produced, which is essential for the management team to set the price per liter of clean water (Rahimi et al., 2021). In order to effectively operate and maintain this desalination system, an economic analysis is necessary, focusing on determining the cost for consumers using the desalinated water, which includes long-term operational and maintenance costs.

Location Of The Solar Power Plant

The Solar Power Plant for the water desalination facility is located at coordinates 06° 07' 07.87" S 106° 46'47.39" E. The location of the Solar Power Plant can be seen in Figure 3.1.

Figure 1. Location of the Solar Power Plant Electrical Load
Source : Data processed by the researcher(s), 2025

The power requirements for the desalination system using reverse osmosis technology have been calculated based on the energy consumption of each component within the system. This information is then used to

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determine the total electricity consumption of the desalination system with a production capacity of 320 liters per hour. These components, including various types of pumps, have a total maximum power of 9.8 kilowatts. The details of electricity consumption from each component are presented in the table below:

Table 3. Reverse Osmosis Desalination System Components

No	Machine Unit	Quantity	Power (Watt)	Ampere
1	Muara Suction Pump	1	1300	5.8
2	Pre-Treatment FRP Pump	1	550	3.8
3	Feeder Pump	2	1500	8.2
4	RO Booster	2	4400	20
5	Clean Water Distribution Pump	2	750	4.2
6	Reject Water Distribution/60&	1	750	4.2
7	Backup Distribution Pump/60&	1	550	3.8
Total		8	9800	50

Source : Data processed by the researcher(s), 2025

Solar Power Plant Components

Sistem The Solar Power Plant is a sustainable technology that harnesses solar energy to generate electricity. This process is made possible by solar panels composed of photovoltaic cells, which are thin layers of pure silicon or other semiconductor materials. These cells work by absorbing photons from sunlight, which causes electron excitation to a higher energy level, creating free electrons that generate direct current (DC) electricity. Three critical components define the core operation of Solar Power Plant: solar modules, controllers, and storage batteries (Aghaei et al., 2020).

The solar photovoltaic (PV) array used in the Solar Power Plant for the desalination facility consists of 14 panels, each with a rated capacity of 550 Wp, resulting in a total installed capacity of 7.7 kWp. In the system modelling process using HOMER simulation software, the PV module input parameters were configured to represent the actual site conditions, with the installed system capacity set at 7.7 kWp as the primary generation source for the desalination unit.

The initial procurement cost of the PV module system is Rp 23,800,000, with an estimated operational lifespan of 25 years, which aligns with the typical service life of photovoltaic modules under standard operating conditions. The replacement cost is assumed to remain equal to the initial procurement cost, amounting to Rp 23,800,000, reflecting the projected cost required for full module replacement at the end of the system life cycle.

The operation and maintenance (O&M) cost of the PV system is estimated at 10% of the initial procurement cost per year, which includes periodic inspection, cleaning of the panel surface, electrical component checks, and minor system servicing. The annual O&M cost is therefore calculated as follows:

O&M Cost = 10% × 23,800,000
= 0.10 × 23,800,000
= 2,380,000 Rupiah per year

Complementing the PV components, the system also includes a hybrid inverter, an intelligent device that combines the functions of a standard inverter with a charge controller, utilizing technologies like Maximum Power Point Tracking (MPPT) for improved efficiency (Joisher et al., 2020). The specific parameters of the hybrid inverter used in the Homer simulation include an MPPT capacity of 10 kW. The initial investment for the MPPT is 24,000,000 Rupiah, with an estimated lifespan of 15 years and a replacement cost identical to the initial cost. The operational and maintenance costs for the MPPT system are also estimated at 10% of the initial cost, totaling 2,400,000 Rupiah per year.

Batteries, as another key component of the Solar Power Plant , serve to store electricity and provide it as needed. The battery parameters in the Homer simulation show a capacity of 3.2 kWh, with an initial procurement cost of 90,000,000 Rupiah, an identical replacement cost, and annual operational and maintenance costs of 9,000,000 Rupiah.

The economic feasibility and performance efficiency of these Solar Power Plant components are critical to their application in the desalination system. Their combined operation not only reflects an integrated approach to sustainable energy production but also represents the potential for scalable renewable energy solutions. The table below presents the parameters of the PV module, Hybrid Inverter, and batteries used in the simulation, showing specific operational and financial implications.

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Table 4. Solar Power Plant Simulation Parameters

Parameter	Value
PV Capacity	7.7 kWp
PV Procurement Cost	Rp 28,300,000
PV Replacement Cost	Rp 28,300,000
PV Operational and Maintenance Cost	Rp 2,830,000/year
PV Lifetime	25 years
Hybrid Inverter Capacity	10 kW
Hybrid Inverter Procurement Cost	Rp 24,000,000
Hybrid Inverter Replacement Cost	Rp 24,000,000
Hybrid Inverter Operational and Maintenance Cost	Rp 2,400,000/year
Hybrid Inverter Lifetime	15 years
Battery Capacity	3.2 kWh
Battery Procurement Cost	Rp 90,000,000
Battery Replacement Cost	Rp 90,000,000
Battery Operational and Maintenance Cost	Rp 9,000,000/year
Battery Lifetime	15 years

Source : Data processed by the researcher(s), 2025

Solar Power Plant Simulation Schematic

The HOMER simulation diagram for the Solar Power Plant at the desalination facility illustrates the system configuration, which includes the main components: PV, batteries, inverter, and the electrical load representing the desalination equipment. Each of these components plays a vital role in running and optimizing the desalination process through clean and renewable energy (Rezk et al., 2020). The schematic diagram, shown in Figure 3.2, provides a visual representation of the energy flow and relationships between each component within the system, facilitating understanding of the interaction and management of energy resources in supporting the desalination system's operation.

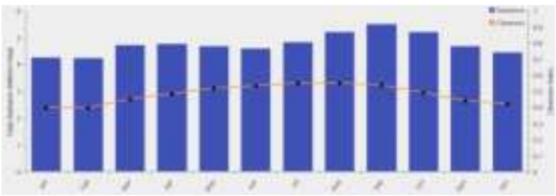

Figure 4.2 Solar Power Plant Simulation Schematic with HOMER Simulation and Calculation
Source : Data processed by the researcher(s), 2025

Simulation and Calculation

Solar energy is an exceptional natural resource, where heat energy from the sun is converted through various mediums into different forms of energy, which can be utilized for various purposes. In RT 006 and RT 007 RW 022, Pluit Village, Penjaringan District, North Jakarta, located in the Muara Angke area, an assessment of solar energy potential was conducted as a preliminary step in simulating the construction of a Solar Power Plant (Rezk et al., 2020). The data used in this analysis were obtained from NASA Surface Meteorology and Solar Energy datasets, which provide detailed information on solar energy potential. To give a clearer picture of this potential, a graph illustrating the solar energy potential in the Muara Angke area over one year is visually presented in Figure 3.3

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Figure 4.3 Solar Energy Potential in Muara Angke
Source : Data processed by the researcher(s), 2025

Table 5. Solar Power Plant Simulation Results in HOMER

Parameter	Value
PV Energy Production/year (kWh/year)	85,848 kWh/year
Renewable Fraction (%)	100%
Net Present Cost (NPC)	Rp 384.050.000.
Cost of Energy (CoE)	Rp 575,55/kWh

Source : Data processed by the researcher(s), 2025

Based on the simulation, it was revealed that over one year, the Solar Power Plant successfully produced 85,848 kWh of energy. This is a positive result, especially considering that the system exclusively relies on a sustainable energy source, with a 100% commitment to renewable energy.
The total Net Present Cost (NPC), which includes all construction or initial investment costs and system operation costs, amounted to Rp 384,050,000. The NPC calculation is based on the equation:
NPC = CC + RC + O&M cost + FC – S
CC (Capital Cost) = component budget
RC (Replacement Cost) = component replacement budget
O&M cost = operational and maintenance budget
FC (Fuel Cost) = fuel budget
S (Salvage) = remaining component costs
Further analysis determined that the Cost of Energy (CoE), the cost to produce each kWh of energy, was valued at Rp
575.55 based on the calculation:

$$CoE = \frac{Tac}{Etotal\ served} \quad (1)$$

Where:
T_{ac} (Total Annualized Cost) = total annual cost of power generation
Etotal served = total annual load energy (kWh)
Based on this CoE value, we can estimate the monthly raw water production cost of the desalination system by applying the equation:
CoE × Monthly Electricity Consumption (2)

With a daily electricity consumption of 235.2 kWh and a monthly consumption of 7,056 kWh, the monthly cost is approximately Rp 4,061,080. To determine the cost per liter, we can use the equation:

$$\frac{\text{Monthly Cost}}{\text{Monthly Raw Water Volume}}$$

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By dividing the monthly operational cost of Rp 4,061,080 by the total raw water production of 235,200 liters, the cost of producing desalinated water is calculated at Rp 17.27 per liter. This figure provides a clear and quantifiable measure of the system's economic performance. More importantly, it demonstrates that the integration of solar energy with desalination technology can achieve cost efficiency while maintaining environmental sustainability. The analysis highlights how renewable energy not only supports continuous raw water production but also ensures predictable and relatively low operational costs, emphasizing the economic relevance of green technology in natural resource management.

The economic performance of the solar-powered Reverse Osmosis (RO) desalination system was evaluated by calculating the unit cost of water production, which links the total operational expenditure with the actual production capacity of the system. The installed RO unit in Muara Angke has a nominal production capacity of 320 litres per hour (L/h). If the system operates continuously, the theoretical monthly production capacity can be expressed as:

$$Q_t = C \times H_d \times D_m$$

where:
(Q_t) = theoretical monthly production (litres)
(C) = system production capacity (litres/hour)
(H_d) = operating hours per day (hours/day)
(D_m) = number of operating days per month (days)

Substituting the operational parameters:
Qt =320x24x30
Qt = 230,400 litres/month

In practice, desalination systems rarely operate at full theoretical capacity due to maintenance cycles, membrane flushing, pressure stabilization, and minor system downtime. Therefore, the effective production volume is influenced by a capacity factor (CF) that reflects the actual operational efficiency of the system.

$$Q_a = Q_t \times CF$$

where:
(Qa) = actual production volume (litres)
(CF) = capacity factor (system operational efficiency)

Field observations at the Muara Angke facility indicate that the system operates with a capacity factor of approximately 1.02 within the observed production cycle, resulting in an effective monthly production volume of approximately 235,200 litres. This value is consistent with the operational range considering variations in flow rate and system pressure during peak solar irradiation periods.

The unit production cost of desalinated water (UC) is calculated using the following economic function:

$$UC = \frac{OC}{Q_a}$$

where:
(UC) = unit cost of water production (Rp/litre)
(OC) = total monthly operational cost (Rp)
(Qa) = actual water production (litres)

Based on financial records of the desalination plant, the total monthly operational cost—including routine maintenance, membrane depreciation allocation, pump operation, and supporting system expenses—amounts to Rp 4,061,080 per month. Substituting these values into the equation yields:

$$UC = \frac{4,061,080}{235,200}$$

$$UC = 17.27 \text{ Rp/litre}$$

Thus, the cost of producing desalinated water is calculated at approximately Rp 17.27 per litre. This value demonstrates that the solar-powered RO desalination system achieves a relatively low operational cost due to the use of renewable energy as the primary power source, which significantly reduces energy expenditures compared with conventional desalination systems that rely on fossil-fuel-based electricity.

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From an engineering economics perspective, the integration of solar photovoltaic energy with RO desalination technology not only ensures continuous raw water production but also stabilizes operational costs by minimizing energy price volatility. Sensitivity considerations further indicate that fluctuations in maintenance costs or minor reductions in system efficiency would only moderately affect the unit water cost due to the dominant contribution of renewable energy to the system's energy supply. Consequently, the Muara Angke desalination system demonstrates that renewable-energy-based desalination can provide an economically viable and environmentally sustainable solution for freshwater supply in coastal urban settlements.

DISCUSSIONS

The finding that desalinated water in Muara Angke can be produced at a cost of Rp 17.27 per liter serves as a critical benchmark for evaluating the feasibility of solar-powered reverse osmosis (RO) systems. Beyond numerical efficiency, this result reflects the broader potential of renewable-based desalination to address water scarcity challenges in coastal areas. In regions such as Muara Angke, where access to clean water remains limited, achieving a stable and affordable production cost illustrates how renewable energy can bridge technological innovation and community needs. This aligns with previous studies indicating that renewable-powered desalination enhances both affordability and sustainability in water-stressed regions (Rahimi et al., 2021).

From an energy perspective, the system's cost efficiency is strongly linked to the integration of photovoltaic (PV) technology with the RO process. The solar power plant produces approximately 85,848 kWh annually, enabling a 100% renewable energy fraction for the desalination facility. This configuration eliminates dependence on fossil fuels, significantly reducing greenhouse gas emissions and shielding operational costs from fuel price volatility. Research has consistently shown that fluctuating fossil fuel prices undermine the long-term viability of conventional desalination systems, particularly in developing countries (Shukla et al., 2022). In contrast, solar-powered systems provide stable energy inputs, allowing water production costs to remain consistent over time and improving long-term water supply planning.

The calculated Net Present Cost (NPC) of Rp 384,050,000 further illustrates the importance of appropriate capital investment strategies in renewable-based infrastructure. Although the initial investment for PV modules, inverters, and battery storage is relatively high, these components offer long operational lifespans. Solar panels, for instance, typically operate efficiently for up to 25 years, enabling costs to be distributed across decades of water production. This capital-intensive yet low-operational-cost structure reflects global trends in renewable energy adoption, where high upfront costs are offset by minimal recurring expenses (Aghaei et al., 2020). In the context of Muara Angke, where communities often face irregular access to electricity and clean water, this model provides economic predictability that is essential for sustainable water pricing.

Affordability for local residents represents another critical dimension of the system's economic feasibility. While Rp 17.27 per liter is relatively low compared to diesel-powered desalination alternatives, the price must still be evaluated against the socio-economic conditions of Muara Angke. Many households in the area belong to lower-income groups, making affordability a key determinant of project success. Studies on rural and coastal desalination projects emphasize the need to balance cost recovery with social equity (Yoshi & Widiasa, 2017). In this context, subsidy mechanisms or cross-subsidization schemes may be required to ensure equitable access to clean water, particularly for vulnerable populations. Involving local stakeholders in tariff-setting processes can further enhance transparency and community trust in renewable-based water systems.

Technological reliability plays a decisive role in sustaining cost efficiency over time. The HOMER simulation confirms the robustness of the system design, demonstrating that the selected PV capacity, inverter efficiency, and battery storage configuration collectively support continuous RO operation. Previous research highlights that the use of high-quality RO membranes and effective pretreatment systems can significantly reduce fouling and scaling, thereby lowering maintenance costs and extending system lifespan (Rezk et al., 2020). In Muara Angke, where seawater quality varies due to tidal changes and coastal pollution, these technological considerations are particularly important to prevent performance degradation and unexpected operational disruptions.

Beyond its local benefits, the Muara Angke project holds broader strategic implications for Indonesia's water and energy sectors. As an equatorial country, Indonesia receives average daily solar irradiation between 4.5 and 4.8 kWh/m², placing it among the world's most favorable regions for solar energy utilization (Shepovalova et al., 2023). Harnessing this abundant resource for desalination can reduce reliance on centralized water infrastructure, especially in archipelagic and remote regions. Replicating the Muara Angke model across other coastal communities could facilitate the development of decentralized, community-based water systems aligned with national energy transition and climate resilience objectives.

The integration of solar power and desalination also aligns closely with global sustainability agendas, particularly the United Nations Sustainable Development Goals (SDGs). This project directly contributes to SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy), while indirectly supporting SDG 13 (Climate Action). By demonstrating that renewable energy can sustain desalination economically, the Muara

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Angke initiative provides a practical example for other developing countries facing similar water scarcity challenges. As noted by Harris et al. (2015), aligning technological innovation with renewable resources strengthens resilience to environmental and socio-economic vulnerabilities.

Scalability represents another important lesson derived from the Muara Angke case. Modular system design allows solar-powered RO units to be adapted to varying local water demands. Smaller, modular systems reduce the risks associated with overinvestment and underutilization, while also simplifying maintenance and component replacement. This flexibility is particularly valuable in island and rural contexts where technical expertise and logistical support may be limited (Joisher et al., 2020). Modular designs therefore enhance both the technical and economic sustainability of decentralized desalination systems.

Despite its advantages, maintaining cost efficiency throughout the system's lifecycle remains a challenge. Battery storage constitutes one of the most expensive components and typically has a shorter lifespan of 10–15 years. Anticipating replacement costs is essential to avoid sudden financial burdens that could disrupt water supply operations. Advances in battery technologies, including lithium-ion and flow batteries, are expected to reduce costs and improve durability in the future, further enhancing system sustainability. Additionally, capacity-building initiatives that train local operators in system maintenance are critical to preventing technical failures and ensuring long-term reliability (Aghaei et al., 2020).

Finally, the Muara Angke project demonstrates the broader socio-political value of renewable-powered desalination. Reliable access to clean water enhances community resilience, reduces dependence on external water suppliers, and strengthens local self-sufficiency. In disaster-prone coastal regions, decentralized and self-sustaining water systems can serve as vital lifelines when conventional infrastructure is disrupted. This dimension underscores how investments in renewable energy and water infrastructure contribute not only to environmental sustainability but also to human security and social stability (Rahimi et al., 2021).

In conclusion, the economic analysis of the Muara Angke desalination project confirms that solar-powered RO technology is both cost-efficient and socially impactful. The production cost of Rp 17.27 per liter demonstrates the feasibility of renewable-based desalination, while the broader discussion highlights its relevance for sustainable development, community resilience, and national energy transition strategies. Replicating this model across Indonesia and other water-scarce regions can play a pivotal role in addressing global clean water challenges through integrated renewable energy solutions.

From a theoretical perspective, the cost efficiency observed in the Muara Angke desalination system can be interpreted through the lens of Life Cycle Cost (LCC) theory. LCC emphasizes evaluating infrastructure projects based on total costs incurred over their entire lifespan rather than focusing solely on initial capital expenditure. The relatively low cost of water production at Rp 17.27 per liter reflects how high upfront investments in renewable energy infrastructure are offset by low long-term operating costs. This confirms that solar-powered desalination aligns well with LCC principles, particularly in contexts where long-term service reliability and cost stability are prioritized over short-term financial considerations (Rahimi et al., 2021).

The strong linkage between energy stability and water affordability in this project can also be explained using Energy–Water Nexus theory. This framework highlights the interdependence between energy systems and water production processes (Kalogirou et al., 2021). In Muara Angke, the achievement of a 100% renewable energy fraction illustrates how decarbonized energy inputs directly enhance water system resilience and affordability. By decoupling desalination from fossil fuel dependency, the project reduces exposure to energy price volatility, thereby stabilizing water costs (Li et al., 2020). This finding reinforces the argument that integrated energy–water planning is essential for sustainable resource management in coastal and resource-constrained regions (Shukla et al., 2022).

From a socio-economic standpoint, the affordability dimension of the desalinated water price can be interpreted through Social Equity and Public Goods theory (Gaithan et al., 2022). Clean water is widely recognized as a basic public good, and its pricing must reflect both economic viability and social inclusiveness. The Muara Angke case demonstrates that renewable-powered desalination can lower production costs to levels that make social pricing mechanisms feasible(Zhao et al., 2023). This supports the argument that green infrastructure investments can reduce the trade-off between financial sustainability and equitable access, particularly when combined with targeted subsidies or community-based governance models (Yoshi & Widiasa, 2017).

The scalability and modularity of the system align closely with Adaptive Systems and Resilience theory. This theoretical approach emphasizes flexibility, redundancy, and adaptability in infrastructure design to cope with uncertainty and environmental variability. The modular solar-powered RO configuration allows capacity adjustments in response to changing water demand and population dynamics, enhancing system resilience. In coastal environments like Muara Angke, where seawater quality and demand fluctuate, such adaptability reduces the risk of system failure and long-term inefficiency, reinforcing the value of decentralized renewable infrastructure (Yoshi & Widiasa, 2017).

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CONCLUSION

Based on the analysis of the solar-powered desalination system implemented in Muara Angke, this study demonstrates that the integration of photovoltaic energy with Reverse Osmosis (RO) desalination technology can provide a technically feasible and economically viable solution for freshwater production in coastal areas. The simulation results using HOMER software indicate that the system configuration achieves a Net Present Cost (NPC) of Rp 384,050,000 and a Cost of Energy (CoE) of Rp 575.55 per kWh, indicating that the use of solar energy significantly reduces long-term operational energy costs compared with conventional electricity-based desalination systems.

The analysis further shows that the application of renewable energy in desalination systems can support stable water production while maintaining relatively predictable operational costs. The findings also confirm that small-scale solar-powered desalination systems can be considered a potential alternative for improving freshwater supply in coastal communities that experience limited access to conventional water infrastructure. Therefore, the Muara Angke case study provides empirical evidence that the integration of solar photovoltaic technology with desalination systems can contribute to sustainable water resource management when supported by appropriate technical design and economic planning.

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