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# Bidding optimization for a reverse osmosis desalination plant with renewable energy in a day ahead market setting

Ebaa Al Nainoon[1,a*] and Ali Al Awami[2,b]

[1]Electrical Engineering Department, KFUPM, Dhahran, Saudi Arabia

[2]K.A.CARE Energy Research & Innovation Center, Dhahran, Saudi Arabia

[a]g202202180@stu.kfupm.sa, [b]aliawami@kfupm.edu.sa

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**Abstract.** This study explores the relationship between power system electrical generation with PV and grid-connected reverse osmosis (RO) water desalination plants in an electricity market setting. It aims to optimize bidding strategies for renewable energy companies in this market, maximizing profits by optimizing coordination and utilizing the flexibility of RO desalination facilities. The research aims to improve economic efficiency, revenue production, and promote renewable energy resource exploitation through better coordination and integration of water desalination processes.

## Introduction

Water scarcity presents a global challenge, necessitating the development of sustainable water production solutions. Grid-connected RO desalination, powered by renewable energy sources like PV, offers a promising approach. This research aims to investigate the interdependent relationship between a power system with PV generation and grid-connected reverse osmosis (RO) water desalination plants in an electricity market setting. It will examine how to best bid for a renewable energy generation company and reverse osmosis (RO) desalination plant in a future market setting with an objective to maximize profits by optimizing the coordination of PV as well as leveraging the inherent flexibility of RO plants within the bidding strategy.

Hence, this research aims to present an optimization case study with an objective to improve economic efficiency in the electrical market, maximize revenue production, and promote the exploitation of renewable energy resources through better coordination and enhanced integration of water desalination processes within an electricity market.

## Literature Review

Water scarcity is a major worldwide crisis as per the United Nations as reported in [1] that around 2 billion individuals which comprise 26% of the global population didn't have access to clean, readily available drinking water on-site. Even basic access to drinking water was unavailable to 771 million people. Eight in ten were from rural areas. The majority of them were in least developed nations. In order to ensure that everyone has access to safely managed drinking water by 2030, current rates of progress must be quadrupled. Pollution and climate change are the main reasons why freshwater resources are insufficient. This imposes the development of efficient and sustainable water production technologies. Among these technologies Reverse Osmosis (RO) desalination has become a well-known technology solution to address the growing need for freshwater in coastal and dry locations. In order to guarantee economical and ecologically sustainable water production, it is crucial to investigate the operational elements of RO desalination plants and their integration into the energy market as the demand for freshwater rises [2,3].

This literature review explores RO desalination plant operational features, energy consumption, cost structures, and flexibility, and their integration into renewable energy generation companies' bidding strategies, aiming to understand system operation and market dynamics. [3]. The primary sources of cost in any of these processes that produce water are energy, operating and maintenance expenses, and capital investments. This is the case in many countries around the world where water production process consume hefty amounts of electricity [4,5]. Thermal and membrane water desalination facilities are the main types of water desalination facilities. Thermal WDP uses steam to produce saline water, which is then condensed to create freshwater. Some steam is fed into steam turbines to generate energy, enabling simultaneous generation of electricity and desalinated water. The energy for heating steam can be produced off-grid using renewable resources or fossil fuels. [6].

Reverse Osmosis (RO) water desalination uses a semi-permeable membrane filter to filter out salt, resulting in concentrated water on the membrane's high-pressure side. Electricity powers the pump, which produces the pressure needed to push water through the membrane. The desalination pressure ranges from 17 to 27 bars for brackish water and 55 to 82 bars for seawater. [7,8] Renewable energy sources like solar thermal, photovoltaic, wind, and geothermal technologies can be used as energy suppliers in water desalination plants, especially in remote areas with acute water shortages where public electricity grid connections are not practical or cost-effective. Ghaithan et.al [3] offered a multi-objective model for a grid-connected photovoltaic-wind system that would supply energy to a Saudi Arabian RO desalination plant. The model aims to reduce life cycle costs and greenhouse gas emissions by considering economic and non-economic factors. It selects three Pareto-optimal solutions and provides management insights from economic and environmental perspectives. Additionally, in their study referenced as [9] The authors introduced the two-stage pricing (TSP) method for Northeast China's electric power auxiliary service market. This involves a freshwater supply and demand balance model, upper-level optimization, and low-level wind power pricing to maximize profits and enhance energy flexibility. In addition, Authors form Malaysia in [10] designed a mini-grid hybrid power system for rural communities and emergency relief situations. This system relies solely on solar power as its primary source and incorporates renewable energy applications to minimize greenhouse gas emissions. In a pool-based energy market, retailers of electricity face several uncertainties, including those related to market pricing and demand [11]. The integration of hybrid energy sources with energy storage devices in micro-grid operations is complicated by the intermittent nature of renewable energy sources. This challenge leads retailers to face difficulties in maintaining a real-time supply-demand balance, as highlighted by Chakraborty and colleagues [12]. The authors reviewed optimization approaches aimed at achieving accurate load forecasting and maximizing profits for retailers and energy users, with the goal of reducing electricity bills. In addition, in [13] Parvania and Oikonomou disscused using desalination plants to help meet electricity demand. It discusses the challenges of desalination plants' high electricity consumption and proposes a model to optimize their participation in electricity markets. Operators of water distribution systems would be able to offer the flexibility of desalination plants in energy markets thanks to the approach. This would help to offset the costs of desalination and make it more sustainable. The model also considers the hydraulic constraints of the water distribution system and the availability of freshwater resources. Elsir and colleagues [13] Also discuss coordinating the water desalination and demand response facilities' day-ahead operation scheduling in smart grids. It talks on the necessity of water desalination and the difficulties in incorporating renewable energy sources. The authors propose a market-clearing mechanism that maximizes the performance of renewable-rich power systems and grid-connected reverse osmosis water desalination plants (RO-WDPs). The study uses a mixed-integer linear programming problem to develop a market clearing method that integrates electric demands into demand response programs, improving system efficiency without compromising water supply-demand balance.

This literature review highlights the growing need for sustainable water production and the potential of integrating grid-connected RO desalination with renewable energy like PV. It goes over the energy dependence of RO plants, integration challenges in micro-grids, and existing optimization approaches for cost reduction and profit maximization. This knowledge lays the foundation for developing an effective bidding strategy that leverages the flexibility of RO desalination within an electricity market, ultimately maximizing profits for renewable energy companies while promoting sustainable water production.

## Methodology and Problem Formulation

This study aims to develop the optimal bidding strategy for renewable energy companies with RO desalination plants. It focuses on how these businesses can optimize their bidding techniques to maximize profits in the electricity market and utilize the flexibility of desalination facilities. The study examines a generation company entering the power market with renewable resources and desalination facilities in a future market setting. Our example will represent the future electricity market pool of Bahrain.

This section discusses the mathematical equations for optimizing bidding in an electricity market, focusing on cost-effective and sustainable desalination operations. The formulation uses renewable energy resources and RO flexibility, and employs the General Algebraic Modeling System (GAMS) to optimize the bidding strategy, considering energy consumption, cost structures, and market dynamics.

*Profit Cost function.* The problem formulation involves creating a profit cost function that considers variable operation and maintenance costs to accurately reflect the desalination plant's operation viability. This function captures the interplay between energy prices, renewable energy generation, and electricity market dynamics, allowing for optimized bidding strategies. The goal is to maintain water sales revenue while minimizing variable costs to enhance the desalination plant's profitability.

$$Profit = RT - CT \quad (1)$$

Where RT in Equation. 1 is the total revenue and CT is the total cost. calculated as:

$$R_T = \sum_{t=t_o}^{t_f} (R_{Electricity}(t) + R_{Water}(t)) \quad (2) \qquad C_T = \sum_{t=t_o}^{t_f} (C_{Electricity}(t) + C_{Water}(t)) \quad (3)$$

Where $R_{Electricity}(t) = E_{Surplus}(t) \times \pi_E(t)$ and $R_{Water}(t) = V_{demand}(t) \times \pi_W(t)$

And $C_{Electricity}(t) = E_{deficit}(t) \times \pi_E(t)$ and $C_{Water}(t) = V_{RO}(t) \times MC$

$\pi_E(t)$ represents the Price of electricity for hour t and $\pi_W(t)$ represents the price of water, while MC represents the variable Maintenance Cost per $m^3$ of Water Produced.

The energy requirement will be represented by the energy balance equation:

$$E_{RO}(t) = E_{PV}(t) + E_{deficit}(t) - E_{Surplus}(t) \quad (4)$$

These equations will be further elaborated in the relevant following subsections.

*RO Water Desalination Energy Consumption and Cost structure.* Reverse osmosis (RO) is a process that removes impurities from water by pressurizing it through a semipermeable membrane, leaving only pure water. The energy input for RO water production is influenced by the pressure needed to overcome osmotic pressure. This text presents a straightforward mathematical generalization of energy use, cost structures, and the adaptability of RO.

In terms of Energy Consumption RO systems require energy to operate the high-pressure pumps that push water through the membrane. The energy consumption of an RO system depends on various factors such as feed water quality, system design, and recovery rate [7]. RO systems consume significant energy, especially in large-scale applications. Advancements in technology have led to more energy-efficient membranes. The cost structure of an RO system includes capital and operating expenses, including equipment, energy, membrane replacement, sanitization, and monitoring. The complexity and capacity of the system influence these costs. Capital costs are disregarded for bidding purposes. A simplified equation for RO water production accounting for operating costs and energy consumption with temperature can be obtained using the following formulation.

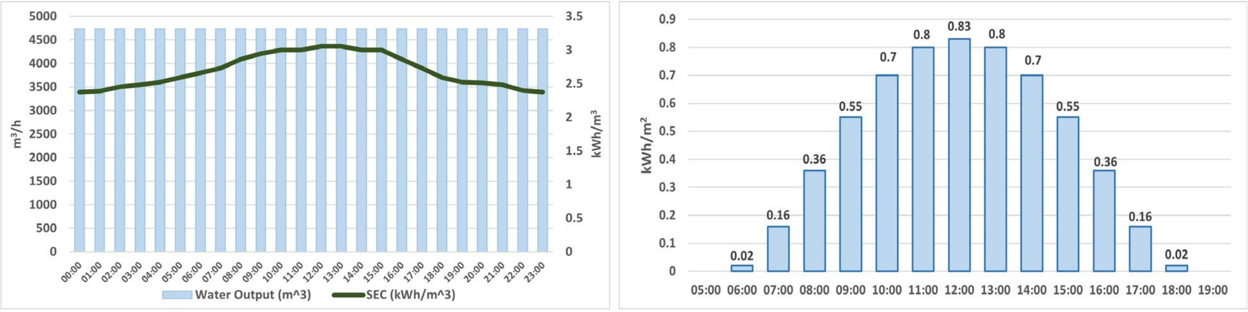
*Operational Cost = Energy Cost + Maintenance Cost*

The energy cost component is reliant on the RO system's energy consumption, which is impacted by the surrounding ambient temperature. Higher or lower temperatures may increase energy requirements due to reduced water flux and increased osmotic pressure whenever you deviate from the optimal operating temperatures [14,15,16].

The connection between the production of water in RO and energy input is referred to as specific energy consumption (SEC). Which measures the energy needed to use the RO process to generate a specific volume of purified water. Usually, it is given as (kWh/m3) or kWh/gal. [7].

$$E_{RO}(t) = SEC(t) \times V_{RO}(t) \quad (5) \qquad C_{Water}(t) = V_{RO}(t) \times MC \quad (6)$$

The calculation of energy requirement as depicted in Equation. 5 will involve multiplying the SEC (kWh/m$^3$) by the volume of water produced in m$^3$ to obtain the total energy input needed at a certain hour to produce the desired water output, which is part of the energy balance in Equation 4. In addition, the costs of replacing membranes, cleaning, sanitizing, and other regular maintenance tasks are included in the maintenance cost component. An estimate of the maintenance cost (MC) for a certain RO system can be made using industry standards or historical data. It can be stated as a price per generated unit of filtered water (cost/m$^3$) for example as in Equation. 6 Above. As such, Total cost of RO Water Production was summarized in Equation. 3.



(a) (b)

*Figure 1. (a) Relationship between SEC and output of a SWRO plant (b) Average energy output for solar PV system in Bahrain [19].*

We mentioned that SEC can be affected by ambient temperature, therefore for a summer day in GCC greater SEC would be required for hotter times of day to produce the same water output. this shall be taken into account while scaling SEC input parameters. For this proposal, since it is in a future market setting we will scale data for a current IPWP in Bahrain. This IPWP has a generation capacity of 50 MIGD for Sea Water RO (SWRO) which is equal to 227,304.5 m$^3$/day and is expected to keep an almost constant water production in its two production blocks throughout the day with an average of 9,471.02 m$^3$/hr [17] total and 4,735.51 per block. Therefor the expected water output for 1 block vs. SEC should look like the graph in Fig. (1a) for 24 hours if we take into consideration the effect of ambient temperature on SEC and an average SEC of 2.374 kWh/m$^3$ for seawater [7].

In addition, the Maintenance cost has been approximated by averaging the cost of replacement of different kinds of membranes as stated in [18] which came to about 0.1638 \$/m$^3$ and it was rounded to 0.2 \$/m$^3$ to account for other maintenance or operational aspects.

PV Generation and Cost structure. The variable cost of PV power production requires precise data collection and analysis, tailored to the specific PV system. The capacity, efficiency, sun irradiation, and ambient temperature of a photovoltaic system are some of the elements that affect its energy generation rate. A generic formula will be examined, considering operational expenses and energy generation, for simplicity. Since the company already owns the PV panels Energy costs for PV will be very minimal and Maintenance costs (MC) are relatively very small and thus can be ignored. For this problem we will use the simulated data for the solar system which is already deployed in Bahrain as seen in [19] to more realistically tailor the optimization problem for an IPWP in Bahrain.

The Energy output of the PV will be calculated for this proposal using the previously stated PV system data in [19] which has the energy output in Fig. 3 per m$^2$. In order to calculate the Relevant Energy production for the IPWP we are studying, we will assume that PV panels are installed on 60% of the total land area of the power plant, where the total area for the IPWP in the proposal is approximately 32,400 m$^2$ according to coordinates. Therefore, we'll assume the total area of PV installation is around 19,440 m$^2$ and we'll assume a higher efficiency of PV panels (10%) since it is a future application. As observed in Figure. (1a) we can achieve higher energy output with higher ambient temperatures, since higher temperature is usually correspondent with higher solar irradiance. which is where the PV characteristics can nicely align with optimal generation for an RO facility in the summer during higher SEC hours.

## Problem Definition

The above equations have been used to formulate the profit maximization objective function with constraints and relevant variables. Thus, the problem formulation will be as follows:

Maximize Equation. (1) $Profit = RT - CT$

subject to:

$$\begin{aligned}
&Eqution. (4)\ and\ Eqution. (5)\\
&E_{deficit}(t).E_{surplus}(t) \leq 0\\
&V_{demand}(t) = Hourly\ Demand\ Target\\
&V_{RO}(t) \leq Production\ Block\ Maximum\\
&V_{tank}(t) \leq Tank\ Storage\ Capacity\\
&V_{RO}(t).V_{tank}(t) \geq 0\\
&V_{tank}(t) = V_{tank}(t-1) + V_{RO}(t) - V_{demand}(t)
\end{aligned}$$

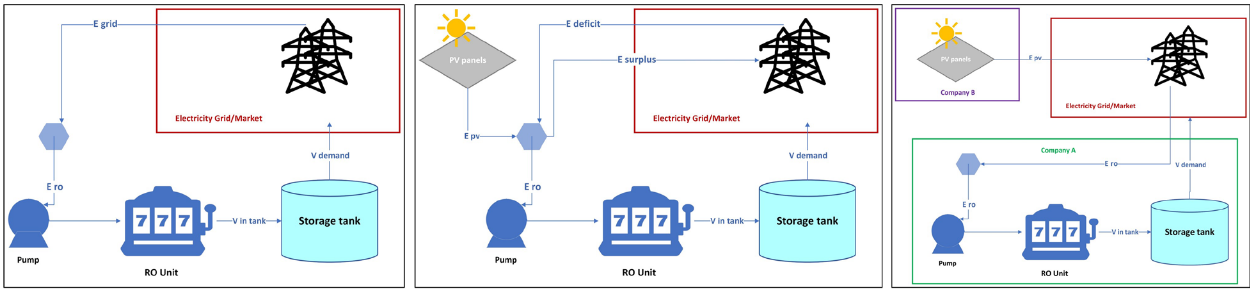
where t ranges between $t_o = 1$ and $t_f = 24$ for a 24 hour time period.

Since Bahrain doesn't currently have a market setting and hourly pricing, we will use Day ahead hourly market prices available in [20] and scale it with the same pattern to match the regional prices in GCC. As for the water price, a constant value of \$2.012/m$^3$ will be considered.

*Table 1. Optimization Problem Input Parameters*

| *t* | EPV | $/MWh | $/m³ | *t* | EPV | $/MWh | $/m³ | *t* | EPV | $/MWh | $/m³ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 39.698 | 2.012 | 9 | 8.9813 | 75.267 | 2.012 | 17 | 8.9813 | 87.658 | 2.012 |
| 2 | 0 | 48.52 | 2.012 | 10 | 13.721 | 78.533 | 2.012 | 18 | 3.9917 | 105.22 | 2.012 |
| 3 | 0 | 47.522 | 2.012 | 11 | 17.464 | 78.753 | 2.012 | 19 | 0.499 | 111.18 | 2.012 |
| 4 | 0 | 39.698 | 2.012 | 12 | 19.958 | 80.718 | 2.012 | 20 | 0 | 101.36 | 2.012 |
| 5 | 0 | 42.268 | 2.012 | 13 | 20.707 | 78.042 | 2.012 | 21 | 0 | 92.534 | 2.012 |
| 6 | 0 | 54.16 | 2.012 | 14 | 19.958 | 82.669 | 2.012 | 22 | 0 | 84.075 | 2.012 |
| 7 | 0.499 | 67.571 | 2.012 | 15 | 17.464 | 83.19 | 2.012 | 23 | 0 | 76.469 | 2.012 |
| 8 | 3.9917 | 75.819 | 2.012 | 16 | 13.721 | 85.64 | 2.012 | 24 | 0 | 73.77 | 2.012 |

Table. 1 Displays the expected output of the PV panels EPV values and market day ahead prices of power and water for the time frame of 24 hours. 4 scenarios of power/water exchange dynamics have been considered as follows.



(a) (b) (c) (d)

*Figure 2. Modeling Scenarios*

Scenario A in Fig 2a. represents the basic, classical Energy in - Water out RO system where no optimization can be done, and you have to operate the system in the same way to produce the same output regardless of energy prices or system conditions (no storage tank). On the other hand, Scenario B is an upgrade to the basic system in which a water storage tank is added to the system allowing some degree of flexibility in production.

Thirdly, Scenario C considers the full PV-RO system in which there is one main company that owns both RO facilities and PV facilities. The optimization problem will revolve around how the energy cost efficiency with the addition of PV and flexibility of RO can be maximized.

For the last case, Case D, the PV and RO facilities are owned by two separate companies that bid separately into the electricity market.

Each of the above cases will be examined in terms of profit and cost vs. revenue to observe the optimization process for each configuration.

## Results and Discussion

The Four above Scenarios were simulated using GAMS software to obtain the profit maximization results while considering a 24-hour time period.

*Table 2. Scenario Comparison of Cases A and B*

| Variable | Total Cost | Total Revenue | Total Profit |
|---|---|---|---|
| Scenario A | $28,994.91 | $144,864.00 | $115,869.09 |
| Scenario B | $27,446.62 | $144,864.00 | $117,417.38 |

As can be seen from the table when the storage was added in scenario B the flexibility of the RO allowed for reduced water production during higher price periods while still maintaining the supply demand. This is done by increasing the water production during the periods of time where the electricity is cheaper and then utilizing the water storage to maintain demand during the pricey hours to buy less electricity. Hence, the cost reduced for scenario B allowing for increased profits for the same revenue and demand.

This process can be observed in Table. 3 with details about charging, discharging, electricity price and SEC for the 24 h period.

*Table 3. Variation of storage tank with respect to time*

| t | $/MWh | SEC | in tank | out tank | Tank (t) |
|---|---|---|---|---|---|
| 1 | 39.69756 | 0.002374 | 4735.51 | 3000 | 1735.51 |
| 2 | 48.52008 | 0.002388 | 4735.51 | 3000 | 3471.02 |
| 3 | 47.52216 | 0.002456 | 4735.51 | 3000 | 5206.53 |
| 4 | 39.69756 | 0.002483 | 4735.51 | 3000 | 6942.04 |
| 5 | 42.26796 | 0.002524 | 4735.51 | 3000 | 8677.55 |
| 6 | 54.15984 | 0.002592 | 3322.45 | 3000 | 9000 |
| 7 | 67.57128 | 0.002661 | 3000 | 3000 | 9000 |
| 8 | 75.81924 | 0.002729 | 3000 | 3000 | 9000 |
| 9 | 75.26736 | 0.002865 | 3000 | 3000 | 9000 |
| 10 | 78.53328 | 0.002947 | 3000 | 3000 | 9000 |
| 11 | 78.75252 | 0.003002 | 3000 | 3000 | 9000 |
| 12 | 80.71812 | 0.003002 | 1264.49 | 3000 | 7264.49 |
| 13 | 78.04188 | 0.003056 | 4735.51 | 3000 | 9000 |
| 14 | 82.6686 | 0.003056 | 1264.49 | 3000 | 7264.49 |
| 15 | 83.19024 | 0.003002 | 4735.51 | 3000 | 9000 |
| 16 | 85.63968 | 0.003002 | 0 | 3000 | 6000 |
| 17 | 87.6582 | 0.002865 | 4735.51 | 3000 | 7735.51 |
| 18 | 105.2201 | 0.002729 | 0 | 3000 | 4735.51 |
| 19 | 111.1774 | 0.002592 | 0 | 3000 | 1735.51 |
| 20 | 101.3645 | 0.002524 | 1264.49 | 3000 | 0 |
| 21 | 92.5344 | 0.00251 | 3000 | 3000 | 0 |
| 22 | 84.07476 | 0.002483 | 3000 | 3000 | 0 |
| 23 | 76.4694 | 0.002401 | 3000 | 3000 | 0 |
| 24 | 73.77048 | 0.002374 | 3000 | 3000 | 0 |

In the (out tank) column of Table. 3 we see that the number is constant which is the water demand that should be supplied at all times, and you can notice the relationship between state of storage and electricity price. Moreover, tank capacity can also play a role in the optimization process. Therefore, Scenario B has been simulated considering 3 different water tank capacities.

*Table 4. Scenario B: Capacity Comparison*

| Capcity | 9000 $m^3$ | 18000 $m^3$ | 36000 $m^3$ |
|---|---|---|---|
| Total Cost | $27,446.62 | $26,978.74 | $26,950.05 |
| Total Revenue | $144,864.00 | $144,864.00 | $144,864.00 |
| Total Profit | $117,417.38 | $117,885.26 | $117,913.95 |

As observed from Table 4 increasing the capacity can increase the profits due to the added flexibility, however at some point increasing the capacity beyond a certain volume will be unprofitable. Increasing the capacity from 18000 $m^3$ to 36000 $m^3$ will only increase the profits by $ 28.69 per day, this small increase in profit will likely only be worth it if the cost of upgrading the tank can be justified.

Meanwhile, for scenarios C and D, it can be noticed that there is an extra source of revenue. Therefor in Table. 5 for C not only did the cost reduce significantly due to utilizing energy from PV, but the revenues have also increased as the company can sell excess PV energy to the grid.

*Table 5. Scenario Comparison of Cases C and D*

| Variable | Total Cost (W) | Total Revenue | PV Revenue | RO Revenue | Total Profit | RO Profit |
|---|---|---|---|---|---|---|
| Case C | $21,469.325 | $150,007.47 | $5,143.47 | $144,864 | $128,538.144 | $123,394.675 |
| Case D | $27,446.623 | $155,984.77 | $11,120.767 | $144,864 | $128,538.14 | $117,417.38 |

Moreover, for scenario D this will be different, as PV is no longer part of the same company and is selling energy separately to the grid, the interesting thing is, that both scenarios C and D have reached the same optimal profit value for the total system. However, the profits here are divided between 2 companies, the revenues from selling PV power have increased because the output of the PV is sold entirely to the grid. But, for the RO company the costs saw an increase, as there is no longer a free energy source to use, and more must be bought from the grid. This is probably due to the balance of Energy bought and sold, as the same amount of energy is still being exchanged however it is in different directions (for different beneficiaries). Assuming, Company B were to sell Electricity to Company A directly under a predetermined contract, profits might improve because both parties would be able to take advantage of the flexibility of these resources accessible for their best interests.

## Conclusion

The study examined the connection between power system electrical generation, PV, and grid-connected reverse osmosis (RO) water desalination plants in an electricity market setting, aiming to maximize profits by optimizing RO facility coordination and flexibility. The study examined four scenarios: basic RO system, RO with water storage tank, combined PV-RO system, and Seperate PV-RO system with energy optimization. It found that incorporating a water storage tank and using PV energy during daylight hours can reduce costs, increase revenues and profits. Moreover, while bidding the PV separately can result in the same combined profits it would mean compromising on some profits for the RO owner compared to the combined system. Additionally, the simulation considered different water tank capacities where the results indicated that increasing the capacity can enhance profits and earnings only up to a certain point, beyond which incremental benefits become negligible.

The study highlights the economic benefits of integrating RO desalination plants into renewable energy generation companies' bidding strategies. It emphasizes the cost reduction and revenue maximization benefits of water storage and PV energy utilization, while balancing profits and costs in a day ahead electricity Market setting.

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