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Renewable energy integration in desalination: A cost analysis of solar and wind-powered seawater RO system

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Abstract

Water scarcity represents one of the most critical environmental and economic challenges worldwide, especially in arid and semi-arid regions lacking access to reliable freshwater sources. In response, seawater desalination has emerged as a strategic solution to ensure a sustainable and secure supply of potable water for various applications. Among desalination technologies, Reverse Osmosis (RO) stands out for its high efficiency and widespread adoption, primarily due to its relatively low specific energy consumption compared to thermal-based methods. However, high operational costs particularly those related to energy consumption remain a barrier, as most conventional desalination plants rely on fossil fuels, contributing significantly to greenhouse gas emissions and environmental degradation. In this context, integrating renewable energy sources, specifically solar photovoltaic (PV) and wind energy, offers a viable pathway to reduce operational expenditures and minimize environmental impact. Several studies have demonstrated that hybrid renewable energy systems can enhance the sustainability and energy autonomy of desalination plants, aligning with Global Sustainable Development Goals (SDGs). This study conducts a techno-economic analysis of a Seawater Reverse Osmosis (SWRO) plant located in Al Wajh, Saudi Arabia. Detailed Capital expenditures (CAPEX) and Operational Expenditures (OPEX) were estimated for both conventional electricity-based operation and for configurations utilizing solar and wind energy in the same location. An energy simulation model was conducted to determine the optimal number of wind turbines required to maximize energy efficiency while minimizing excess power generation. The analysis revealed that the SWRO powered by renewable energy achieved an energy efficiency of 99%, compared to its conventional electricity-powered counterpart, with an energy surplus of no more than 4%. CAPEX and OPEX cost projections were calculated for both scenarios: conventional grid electricity and renewable energy sources. The findings indicated that the unit production cost per cubic meter of the SWRO plant was 0.59–0.76 $/m^3$ in the case of grid electricity, whereas it was 0.74–1.12 $/m^3$ under renewable energy integration. This cost disparity is primarily attributed to the higher CAPEX required for the renewable energy-powered SWRO system, which amounted to 0.28–0.36 $/m^3$, in contrast to a significantly lower CAPEX of only 0.06–0.09 $/m^3$ for the electricity-based SWRO configuration. Moreover, artificial intelligence (AI) was employed to support the results and forecast future water demand based on regional climate conditions and consumption patterns. The study concludes with a set of recommendations aimed at optimizing the integration of renewable energy technologies into desalination systems to enhance long-term economic and environmental sustainability.

Keywords: Artificial intelligence, renewable energy integration, reverse osmosis, seawater desalination, solar energy, sustainable development, techno-economic analysis, water scarcity, wind energy.

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1. Introduction

In recent years, there has been a growing interest in the integration of seawater desalination technologies—specifically reverse osmosis (RO) with renewable energy sources such as solar and wind power to achieve environmental and economic sustainability, especially in water-scarce coastal regions.

Atab et al. [1] conducted an operational and economic assessment of an RO desalination system designed for potable water production and agricultural irrigation. Their findings demonstrated that optimizing system design and incorporating energy recovery devices significantly reduces energy consumption and lowers operational costs.

Similarly, Choi et al. [2] performed an economic evaluation of a hybrid desalination system combining Forward Osmosis (FO) and reverse osmosis. Their analysis highlighted that such hybridization can enhance process efficiency and reduce overall costs in industrial-scale applications.

Caldera et al. [3] provided a global estimation of the Levelized Cost of Water (LCOW) for SWRO desalination powered by solar Photovoltaic (PV) and wind energy. Their study revealed that in regions with abundant renewable resources, the cost competitiveness of renewable-driven desalination rivals that of conventional fossil-fuel-powered plants.

More recently, Salem et al. [4] conducted a techno-economic analysis of a hybrid renewable energy system (solar and wind) powering a small-scale RO desalination plant in Egypt. Their results confirmed that such integration substantially lowers water production costs while improving system reliability.

Furthermore, Reaz [5] evaluated the technical, economic, and environmental aspects of incorporating renewable energy systems into an RO desalination plant in the United Arab Emirates. The study emphasized that utilizing solar and wind energy reduces carbon emissions and enhances the overall sustainability profile of desalination facilities.

Collectively, these studies demonstrate that integrating RO desalination with renewable energy technologies offers a viable and sustainable solution to address water scarcity. However, they emphasize the need to account for site-specific variables such as resource availability, capital investment, and operational costs to optimize system design and efficiency. Nonetheless, critical considerations remain regarding investment feasibility, energy surplus management [6], and the ability to ensure uninterrupted operation across diurnal cycles and varying climatic conditions.

In this study, an analysis will be conducted on a seawater desalination plant located in the city of Al Wajh, in the Tabuk region of northwestern Saudi Arabia, situated along the Red Sea. The area is characterized by a moderately arid desert climate, with temperatures ranging between 23°C and 36°C. The relative humidity is moderately high due to the proximity to the Red Sea. Wind speeds typically range from 12 to 18 km/h, predominantly from the northwest [7].

The CAPEX for the SWRO plant with a capacity of 1,800 m³/day will first be estimated. This includes the cost of pre-treatment systems, the core RO components (such as high-pressure pumps and membrane modules), post-treatment units, electrical infrastructure, control panels, Supervisory Control and Data Acquisition (SCADA), and Programmable Logic Controller (PLC) systems, as well as expenses related to installation, performance testing, and commissioning [8].

The OPEX of the SWRO plant with a capacity of 1,800 m³/day will subsequently be evaluated. Key cost components include energy consumption (primarily electricity), chemical usage, periodic membrane replacement, routine maintenance with associated spare parts, and labor costs for plant personnel and operational staff [8].

The capital and operational costs associated with utilizing solar PV systems and wind turbines to power a SWRO desalination plant with a capacity of 1,800 m³/day will be designed and evaluated. A comprehensive cost analysis of the proposed renewable energy-powered system will be conducted to identify the most efficient and energy-optimized configuration. Subsequently, the total cost of the renewable-powered SWRO system will be compared to that of a conventional grid-powered SWRO system, and the unit cost of water production (per cubic meter) for each scenario will be determined.

2. Cost estimation and analysis of the SW RO plant in Al Wajh - Tabuk (1,800 $m^{3/}$d)

When planning to build a desalination plant using SWRO technology, the financial assessment of the project goes beyond construction costs. It consists of several elements typically categorized into: CAPEX and OPEX:

The CAPEX includes all expenses related to constructing and commissioning the plant. This covers engineering studies and design; major equipment such as membranes, pumps, and control systems; civil and structural works; pre-treatment and post-treatment systems; and installation, testing, and commissioning.

The OPEX are ongoing costs required for the day-to-day operation of the plant, including energy consumption (mainly electricity), chemicals used in water treatment, routine maintenance and membrane replacement, and staff wages and salaries.

2.1. The Capital Expenditures (CAPEX) for the SW RO plant 1,800 m3/d

In estimating capital expenditures, the analysis will be confined to the costs associated with primary process equipment, including membranes, high-pressure pumps, automation and control systems, pre-treatment and post-treatment units, as well as the expenses related to installation, performance testing, and system commissioning.

2.1.1. Pre-Treatment System and Chemicals Estimated Cost

The pre-treatment stage is critical for conditioning the feedwater to prevent membrane fouling, scaling, and biological growth. This stage involves a series of physical and chemical processes designed to reduce turbidity, control pH, and eliminate potential foulants before water enters the RO membranes. Table 1 shows the chemicals commonly used in pre-treatment [9].

Table 1.
Chemicals used in pre-treatment for the SW RO plant.

Chemical	Function
Anti-scalant (e.g., polyacrylates, phosphonates)	Inhibit scale formation from calcium, magnesium, barium, or silica
Acid (e.g., sulfuric acid or hydrochloric acid)	pH adjustment to reduce carbonate scaling
Coagulants (e.g., ferric chloride, aluminum sulfate)	Enhance sedimentation or filtration performance (optional, if turbidity is high).
Sodium metabisulfite (SMBS)	Removes residual chlorine, which can damage membranes

Pre-treatment equipment consists of pumps, filters, and chemical injection systems. Table 2 shows the estimated cost for the pre-treatment system of RO 1800 m^3/d.

Table 2.
Estimated cost for the pre-treatment system for SW RO-1,800 m3/d.

Subcomponent	Description	Estimated Cost (USD)
Feedwater Pumps	Raw water intake and pressurization – 2pcs	20,000 – 30,000
Multimedia Filters	Sand or anthracite filtration for suspended solids removal	100,000 – 80,000
Cartridge Filters	Fine filtration (1–5 µm) to protect RO membranes	15,000 – 20,000
Chemical Dosing Systems	Skid-mounted units with dosing pumps	30,000 – 40,000
Chemical Storage Tanks	Tanks with bunds for safe chemical containment	25,000 – 30,000
Total Estimated Cost		170,000 – 220,000

2.1.2. Reverse Osmosis Core System Estimated Cost

The core RO system includes high-pressure pumps, membrane pressure vessels, RO membranes, instrumentation, and a Clean-In-Place (CIP) unit for membrane maintenance. The configuration includes a two-stage design with a recovery rate of 40%. Table 3 shows the estimated cost of the RO plant.

Table 3.
The estimated cost for the SW RO core system 1,800 m3/d.

Subcomponent	Description	Estimated Cost (USD)
RO Membranes	8-inch spiral wound membranes, 144 units	220,000 – 250,000
Pressure Vessels	Fiberglass housings – 24 units	80,000 – 100,000
High-Pressure Pump	Duplex steel construction	50,000 – 60,000
Instrumentation	Pressure gauges, flow meters, and conductivity meters	30,000 – 50,000
CIP System	Tank, pump, heater, and controls for chemical cleaning	40,000 – 50,000
Total Estimated Cost		420,000 – 510,000

2.1.3. Post-Treatment and Water Stabilization Estimated Cost

The permeate water produced by RO is typically low in mineral content and may be slightly acidic. Post-treatment is necessary to stabilize pH, add essential minerals, and disinfect the water prior to distribution. Chemicals Used in Post-Treatment: Calcium carbonate or calcite is added to add hardness and alkalinity and prevent pipe corrosion. Sodium hydroxide (caustic soda) is added to adjust the pH value. Chlorine gas or sodium hypochlorite is added for disinfection against microbial contamination. Table 4 shows the Post-treatment and Stabilization Estimated [10].

Table 4.
Post-treatment and stabilization estimated for the SW RO system: 1,800 m^3/d.

Subcomponent	Description	Estimated Cost (USD)
Remineralization Unit	Chemical dosing pumps with tanks	10,000 – 20,000
Disinfection System	Chlorination or UV system	20,000 – 30,000
Product Water Storage	Clean water tanks before distribution	35,000 – 40,000
Total Estimated Cost		65,000 – 80,000

2.1.4. Electrical Equipment and Control System Estimated Cost

This section includes electrical infrastructure, automation systems, and backup systems for safe and reliable operation. A fully integrated SCADA system provides remote monitoring and control of all plant processes Table 5 [11].

Table 5.
Electrical Power Supply and Control System Estimated for the RO System.

Subcomponent	Description	Estimated Cost (USD)
Main Electrical Panels	MCCs and switchgear for equipment control	40,000 – 50,000
SCADA & PLC System	Programmable logic controllers with HMI	50,000 – 60,000
Cabling & Power Transformers	Site-wide electrical distribution	20,000 – 25,000
Backup Power/UPS	Uninterruptible power for control systems	10,000 – 20,000
Total Estimated Cost		120,000 – 155,000

2.1.5. Installation, Testing, and Commissioning Estimated Cost

Installation and commissioning ensure that all systems are mechanically and electrically integrated, tested, and prepared for full-scale operation. This phase also includes staff training and performance verification Table 6.

Table 6.
Installation, Testing, and Commissioning Estimated Cost for RO 1,800 m^3/d.

Subcomponent	Description	Estimated Cost (USD)
Mechanical Installation	Equipment assembly and piping	10,000 – 15,000
Electrical Installation	Power wiring and automation integration	10,000 – 15,000
Start-up and Commissioning	Functional and performance testing	10,000 – 15,000
Training	Operator and maintenance staff instruction	10,000 – 15,000
Total Estimated Cost		40,000 – 60,000

The summary of total estimated capital expenditure (CAPEX) for the Al Wajh SW RO 1,800 m3/d powered by electricity is shown in Table 7.

Table 7.
Total CAPEX estimated for RO 1,800 m^3/d powered by electrical energy.

Major Cost Category	Estimated Range ($)
Pre-Treatment System & Chemicals	170,000 – 220,000
RO Core System	420,000 – 510,000
Post-Treatment & Stabilization	65,000 – 80,000
Electrical & Automation	120,000 – 155,000
Installation & Commissioning	40,000 – 60,000
Total Estimated CAPEX	815,000 – 1,025,000 $

The SWRO desalination plant with a capacity of 1,800 m^3/d has a total capital investment that typically ranges from USD 815,000 to USD 1,025,000, with an average estimated cost of approximately USD 920,000. This estimate excludes expenditures related to land acquisition, civil infrastructure development, engineering and design consultancy services, as well as governmental permitting and licensing requirements.

2.2. The Operating Expenditures (OPEX) for SW RO Al Wajh plant 1,800 m3/d

Seawater reverse osmosis (SWRO) is one of the most widely used and efficient technologies for desalinating brackish water. Although highly effective, the operation of such a plant incurs ongoing operational expenditures (OPEX), which are distributed across several key categories. When estimating operating costs, the focus is on the recurring expenses necessary for the continuous operation of the desalination facility. These include energy consumption (primarily electricity), chemical materials used in water treatment processes, routine maintenance activities, membrane replacement, and staff wages and salaries. For a plant with a daily production capacity of 1,800 cubic meters, here is the detailed breakdown of operational cost components:

2.2.1. Electrical Energy Consumption for Operation SW RO 1,800 m³/d:

Electricity is the largest cost component in the operation of reverse osmosis desalination plants, accounting for 30% to 50% of the total operating expenses. It is primarily used to operate high-pressure pumps that force feedwater through semi-permeable membranes, in addition to powering pre-treatment systems and auxiliary equipment.

The main energy consumers in RO plants are high-pressure pumps, pre-treatment pumps, control and instrumentation systems, and auxiliary equipment, including lighting, heating, ventilation, and air conditioning (HVAC) systems, chemical dosing pumps, and CIP systems. The high-pressure pumps are the most energy-intensive component for generating pressures between 50 and 60 bar for brackish water; the energy consumption depends on feedwater salinity, system design, and pump efficiency.

The electrical load for the SWRO plant of Al Wajh is calculated by adding the loads of all the equipment in the system, Table 8.

Table 8.
List of electrical equipment with its loads for SWRO Plant 18.000 m^3/d.

Equipment Description	Quantity (duty)	Power load (kW)	Total (kW)
High-pressure Pump – FEDCO – MSS 9016	1	100	100 kW
Filter Feed Pumps – GRUNDFOS – CRN64-1	1	11	11 kW
Backwash Pumps – GRUNDFOS – NK100-200	1	15	15 kW
Permeate Transfer Pump	2	20	20 kW
Product Water Pump	2	20	20 kW
Air Blower – MAPRO - CL42/21 D	1	13	13 kW
Dosing pumps, lighting / AC, etc.	1	10	10 kW
Total Load for all Equipment			189 kW

The total load for all equipment is 189 kW, and the total power required is 125% of the load.
189 x 1.25 = 236 Kw. The total power for one day is 236 x 24 = 5,664 kWh for the SWRO system.
The power required to produce 1 m^3 is: 5,664 / 1,800 = 3.15 kWh/m^3
The price of a kilowatt-hour in Saudi Arabia is assumed to be USD 0.06-0.08. The total daily consumption is:
Total Daily consumption Cost = Daily power consumption x Price of kilowatt-hour (1)
Total Minimum Daily Power Cost = 5,664 (kWh/day) * 0.06 = USD 340
Total Maximum Daily Power Cost = 5,664 (kWh/day) * 0.08 = USD 453
Minimum Power Cost for 1 m^3 = 340 / 1,800 = USD 0.19
Maximum Power Cost for 1 m^3 = 453 / 1,800 = USD 0.25

2.2.2. Chemical Consumption for operation BW RO 1,800 m3/d

Chemical dosing is essential for effective pre-treatment and stable operation of RO systems. Chemicals help prevent membrane scaling, biofouling, and pH fluctuations that can compromise system performance. The type and dosage of chemicals depend on feedwater composition and treatment objectives. Table 9 shows the estimated cost of chemical consumption.

Table 9.
Chemical Consumption Estimated Cost for SWRO Plant 18.000 m^3/d.

Chemical	Function	Estimated Cost (USD/m³
Anti-scalant	Prevent scaling caused by calcium carbonate, sulphate salts, etc.	0.01 – 0.02
Acids (e.g., H_2SO_4 or HCl)	Adjust feedwater pH to reduce scaling potential.	0.005 – 0.01
Oxidizing agents (e.g., chlorine)	Disinfect feedwater and inhibit microbial growth	0.003 – 0.005
De-chlorination agents (e.g., sodium metabisulfite	Protect RO membranes from oxidative damage	0.001 – 0.003
Cleaning chemicals (CIP solutions)	Used periodically to remove fouling from membranes	0.005 – 0.01
Total Estimated Cost for 1 m3		0.024 – 0.048

From Table 9, the estimated cost for chemicals is USD 0.024 - 0.048 for 1 m^3

2.2.3. Membrane Replacement for Operation SWRO 1,800 m3/d

RO membranes are the core separation units in the desalination process and are subject to gradual degradation due to scaling, fouling, and chemical exposure. Membranes typically require replacement every 3 to 5 years, and their cost is amortized over their useful life. From Table 3, the estimated cost for all membranes is USD 250,000.

$$\text{The daily cost of replacement membranes} = \frac{\text{Total price of membranes}}{\text{Total Production x Life (year)}} \quad (2)$$

$$The\ maximun\ daily\ cost\ of\ replacement\ membranes\ =\ \frac{250{,}000}{365\ x\ 3} = 228\ USD\ /day$$

$$The\ maximum\ cost\ for\ 1\ m3 =\ \frac{228}{1{,}800} = 0.12\ USD$$

$$The\ mimimum\ daily\ cost\ of\ replacement\ membranes\ =\ \frac{250{,}000}{365\ x\ 5} = 137\ USD\ /day$$

$$The\ minimum\ cost\ for\ 1\ m3 =\ \frac{171137}{1{,}800} = 0.076\ USD$$

2.2.4. Maintenance Cost for SWRO 1,800 m3/d

Maintenance is a critical pillar of operational reliability and asset longevity in RO desalination facilities. It encompasses a wide range of activities designed to keep equipment running safely, efficiently, and within design specifications. A well-executed maintenance strategy minimizes unplanned downtime, optimizes energy usage, and extends the service life of membranes and mechanical components.

Preventive Maintenance (CP) consists of scheduled activities aimed at reducing the risk of failure and ensuring steady performance. Corrective Maintenance (CM) involves unplanned repairs due to unexpected failures or degradation. While harder to predict, budgeting for CM is essential. As well, the membranes in brackish water RO systems typically require 2 to 4 CIP procedures per year, depending on feedwater quality and fouling potential. On the other hand, maintaining a stock of critical spares ensures quick restoration in case of failure and avoids costly downtimes. Table 10 shows the estimated cost of maintenance.

Table 10.
Maintenance Estimated Cost for SWRO Plant 1,800 m^3/d per year.

Maintenance Component	**Cost Estimate (USD/year)**
Preventive Maintenance	5,000 – 10,000
Corrective Repairs	5,000 – 10,000
CIP Chemicals	5,000 – 10,000
Spare Parts & Consumables	5,000 – 10,000
Total Maintenance Cost	20,000 – 40,000

$$The\ maximum\ cost\ for\ 1\ m3 =\ \frac{20{,}000}{1{,}800\ x\ 365} = 0.03\ USD$$

$$The\ maximum\ cost\ for\ 1\ m3 =\ \frac{40{,}000}{1{,}800\ x\ 365} = 0.04\ USD$$

2.2.5. Manpower Wages Costs for Operating SWRO Plant 1,800 m³/day

Manpower wages and maintenance activities are critical components for ensuring the safe, efficient, and uninterrupted operation of reverse osmosis (RO) desalination facilities. Although these factors typically account for approximately 30–40% of the total operational expenditure (OPEX), their role in minimizing system downtime, optimizing operational performance, and extending the service life of equipment is indispensable.

The staffing structure of the reverse osmosis (RO) desalination plant comprises the following key personnel Table 11.

Table 11.
Manpower Estimated Cost for SWRO Plant 1,800 m^3/d per month.

Position	**Duties**	**Cost Estimate (USD/month)**
Plant Manager	Responsible for overall plant oversight, including operational management, regulatory compliance, and budget administration	3,000 - 5,000
Engineers Operators	Tasked with monitoring and adjusting system parameters, managing control systems, and diagnosing operational issues to ensure optimal performance.	5,000 - 7,000
Laboratory Technicians	Perform routine water quality analyses for both feedwater and permeate, ensuring compliance with quality standards.	3,000 - 4,000
Support Staff	Provide essential services such as logistics coordination, facility sanitation, and enforcement of health and safety protocols.	1,000 - 3,000
Total Estimated Cost		**12,000 – 19,000**

$$The\ minimum\ cost\ for\ 1\ m3 =\ \frac{12{,}000}{1{,}800\ x\ 30} = 0.22\ USD$$

$$The\ maximum\ cost\ for\ 1\ m3 = \frac{19{,}000}{1{,}800\ x\ 30} = 0.35\ USD$$

2.2.5.1. The Annual Manpower Wages for SWRO Plant Will be 144,000 to 228,000 USD/year

The total operating costs for one year are the sum of the costs from Table 8 to Table 11. These costs are shown in Table 12.

Table 12.
Total Operation Estimated Cost for SWRO 1,800 m^3/d per year.

Description	OPEX Cost Estimate per year ($/year)	Cost Estimate ($/ m3)
Electrical Energy	124,100 – 165,400	0.188 – 0.251
Chemical Consumption	15,800 – 31,100	0.024 – 0.048
Membrane Replacement	50,000 – 84,000	0.076 – 0.128
Maintenance and Spare Parts	20,000 – 40,000	0.030 – 0.060
Manpower Rages	144,000 – 228,000	0.219 – 0.347
Total RO Operation Cost powered by Electricity	353,900 – 548,500	0.537 – 0.834
Total RO Operation Cost without Electrical Power	229,800 – 383,100	0.350 – 0.583

2.6. The Cost of Electrical Power Consumption Is 30 - 35% of the Total Operation Cost.

All the above costs do not include the land value, civil infrastructure works, licensing, environmental compliance fees, and contingency.

2.6.1. Design of Solar System and Wind Turbine System

It was determined that the energy consumption for operating a seawater desalination plant with a capacity of 1800 cubic meters per day amounts to 5664 kilowatt-hours per day. It is assumed that 50% of the energy demand will be supplied by a photovoltaic solar energy system, and the remaining 50% will be provided by a wind energy system. Thus, the daily energy requirement from the solar photovoltaic system equals the daily energy requirement from the wind turbine system:

5,664 / 2 = 2,832 kW/day (Power required from both the solar system and the wind turbines).

2.6.2. Solar Photovoltaic System Calculation

The study area is located in the Al-Wajh region of the Kingdom of Saudi Arabia. According to data from the Global Solar Atlas (Figure 1), the Global Horizontal Irradiance (GHI) in the Al-Wajh area is 6.4 kWh/m². As of 2023, the Huasun Himalaya G12-132 HJT panel is recognized as the most powerful solar panel currently available, offering a maximum output of 750.54 watts and a conversion efficiency of 24.16% [12].

To calculate the number of solar panels needed, we use the following data:

- GHI = 6.4 kWh/m²/day
- Solar panel capacity = 0.75 kW (750 watts)
- Daily energy demand = 2832 kWh/day

To calculate the daily energy output of one panel:

Panel output per day = Panel capacity × GHI × System efficiency (3)

Assuming a typical system efficiency of 0.8 (or 80%) to account for losses (inverter, shading, temperature, etc.):

Panel output per day = 0.75 × 6.4 × 0.8 = 3.84 kWh/day

To calculate the number of panels required:

Number of PV panels = Daily energy requirement / Panel daily output (4)

Then: Number of PV panels = 2,832 / 3.84 ≈ 738 panels

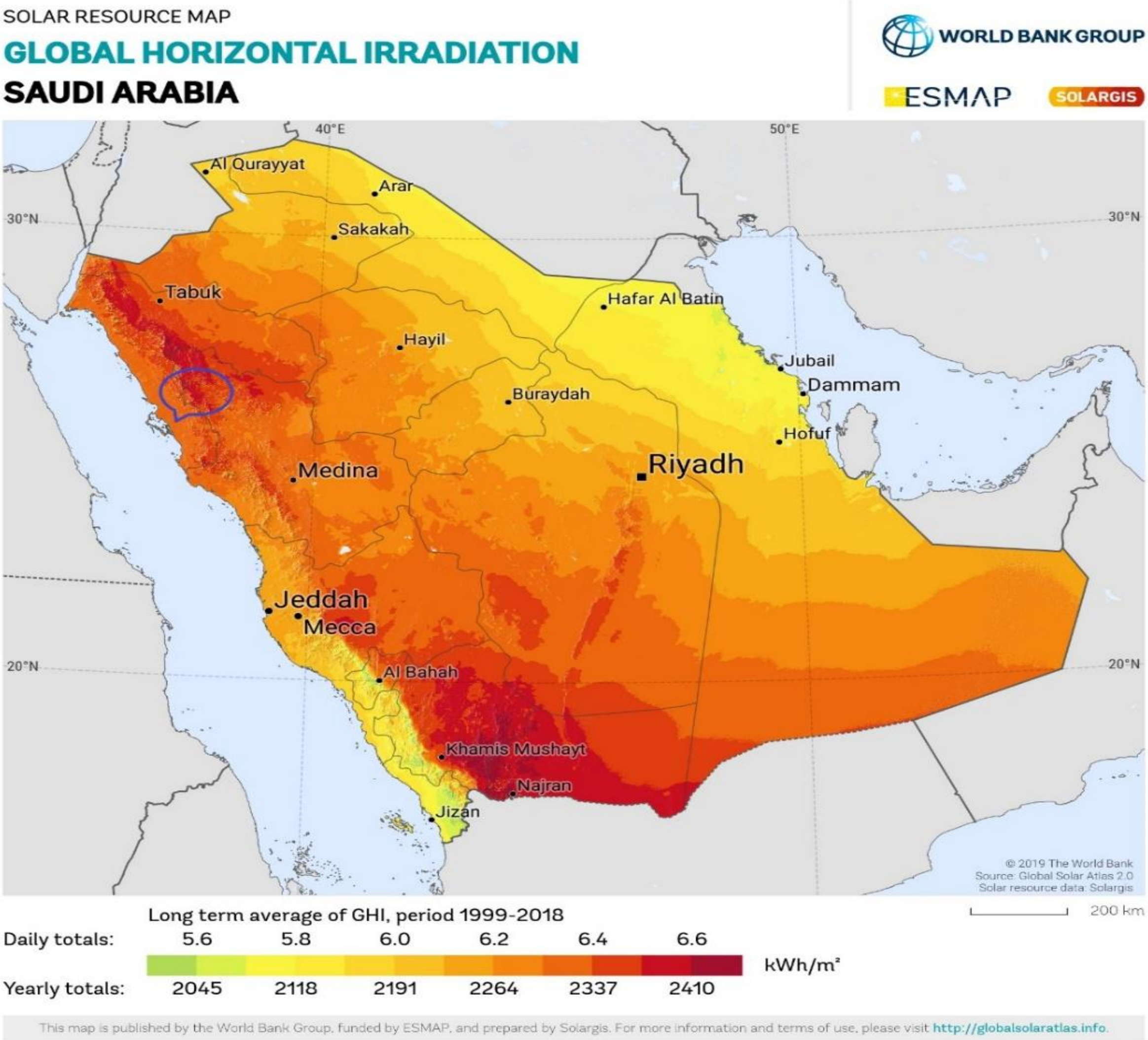

Figure 1.
Global Solar Atlas for Saudi Arabia – Al Wajh area- GHI: 6.4 [12].

2.6.3. Wind Turbine System Calculation

The wind speed of the Wind Turbine (WT) profile for the year 2024 at Weather Atlas [7] indicates that the wind speed in the Al Wajh region ranges between 12.8 and 17.3 kilometers per hour (Figure 2). However, the minimum speed occurs in November, measuring 12.8 kilometers per hour, which equals 3.6 m/s. The wind speed for November will be selected as the design basis for the worst-case scenario.

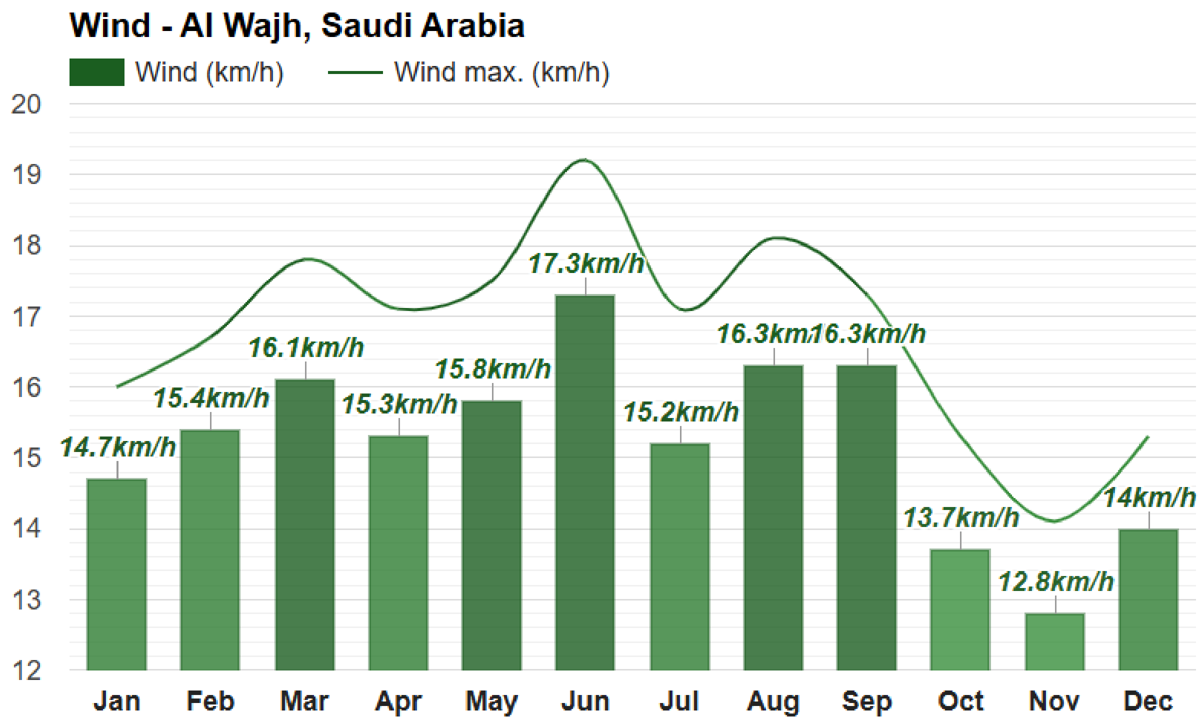

Figure 2.
Wind speed in Al Wajh - Saudi Arabia in the year 2024 [7].

Wind turbines are to be selected from Suzlon, a distinguished manufacturer within the Indian renewable energy sector, renowned for its specialization in wind power technologies. The company engineers a range of turbine systems with variable rated capacities, optimized to meet techno-economic operational criteria. For the purposes of this assessment, the Suzlon S64-1000W wind turbine model has been selected, characterized by a hub height of 65 meters, a rotor diameter of 64 meters, and a tri-blade configuration. According to the turbine's performance curve (refer to Figure 3), and under the assumption of an average wind velocity of 3.6 m/s recorded in November 2024, the corresponding power output is projected to reach approximately 60 kilowatts.

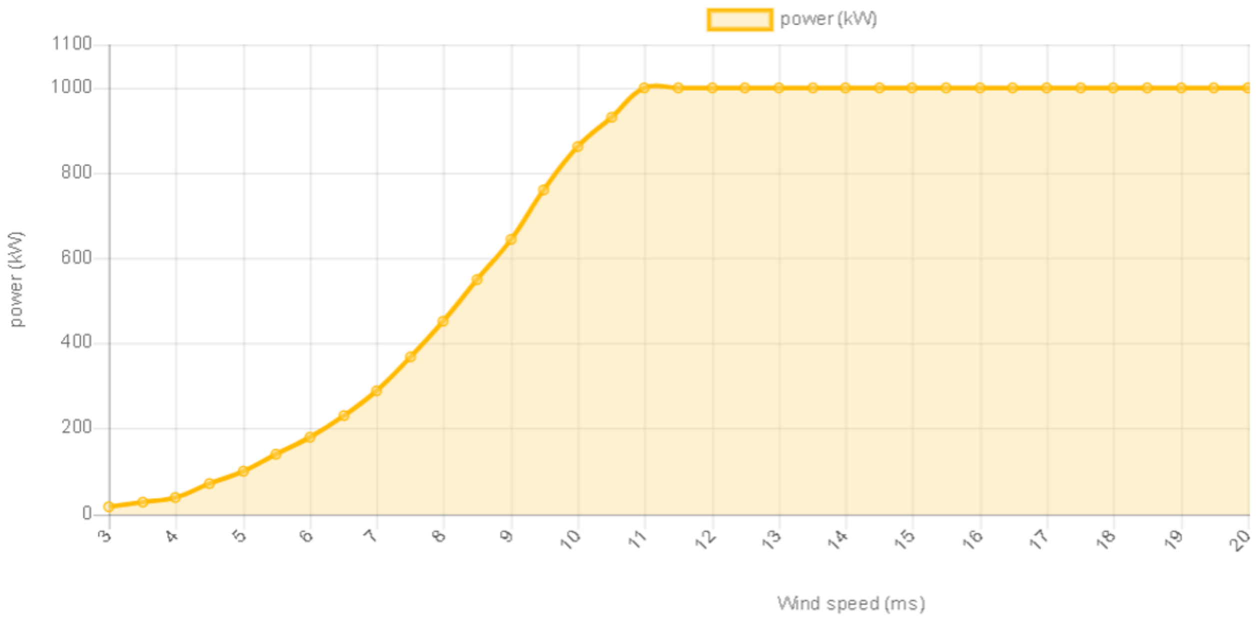

Figure 3.
The power curve according to the wind speed for the WT Sulzon S64-1000W.

The daily energy generated by one turbine = Power (kW) x 24 (hour) = 60 x 24 = 1440 kW/day
The daily energy requirement from the WT system is estimated at 2,832 kWh/d.
The number of WT required = Power required / Power energy generated in 1 turbine (5)
The number of WT required = 2,832 / 1440 = 1.9 Turbine (between 1 and 2)

This number of WT represents the maximum required to supply half of the energy demand for operating a reverse osmosis desalination plant with a capacity of 1,800 m3/d in the Al-Wajh region of the Kingdom of Saudi Arabia.

2.4. CAPEX and OPEX of Solar System and Wind Turbine System

Based on the above, the results of this first case can be summarized in Table 13, which presents the CAPEX estimated cost for solar system equipment, excluding the land value, permits, and legal fees.

Table 13.
CAPEX Estimated Cost of Solar System 2,832 kW/day.

System Equipment	**Total Cost ($)**
Huasun G12 Panel – 750W (738 pcs)	110,700 – 147,600
Inverters (Converts DC to AC, capacity 600-700 kW)	60,000 – 80,000
Mounting system (Fixes panels at an optimal angle to the sun)	20,000 – 30,000
Cables & protection devices…etc. (Electrical safety and secure connections)	10,000 – 15,000
Installation labour (varies)	15,000 – 20,000
Monitoring & control system	4,300 – 7,400
Site preparation and infrastructure	30,000 – 50,000
Engineering and design	10,000 – 15,000
CAPEX Estimated Cost ($)	250,000 – 365,000

Table 14 presents the CAPEX estimated cost for wind turbine system equipment, excluding the land value, permits, and legal fees.

Table 14.
CAPEX Estimated Cost of one Wind Turbine 1 MW.

System Equipment	**Total Cost ($)**
Turbine Purchase (blades, nacelle, tower) Sulzon S64-1MW	1,200,000 – 1,400,000
Site preparation and infrastructure	60,000 – 80,000
Shipping and logistics	10,000 – 20,000
Installation and commissioning	40,000 – 60,000
Engineering and design	10,000 – 20,000
CAPEX Estimated Cost ($)	1,320,000 – 1,580,000

Table 15 shows the detailed estimate of the annual operating expenses for a 2,832 kW solar power plant:

Table 15.
Estimated Annual Operating Costs for Solar System.

System Requirements	**Estimated Cost per year ($)**
Routine maintenance and panel cleaning	10,000 – 16,000
Monitoring and control (SCADA)	2,000 – 4,000
Spare parts (e.g., transformers)	10,000 – 12,000
Technician or management company wages	12,000 – 16,000
Administrative and other expenses	4,000 – 6,000
OPEX Estimated Cost ($)	38,000 – 54,000

$$The\ minimum\ OPEX\ cost\ for\ 1\ m3 = \frac{38{,}000}{1{,}800\ x\ 365} = 0.057\ US$$

$$The\ maximum\ OPEX\ cost\ for\ 1\ m3 = \frac{54{,}000}{1{,}800\ x\ 365} = 0.082\ USD$$

Table 16 shows the annual operating cost estimate for a 1 MW wind turbine:

Table 16.
Estimated Annual Operating Costs for one Wind Turbine 1MW.

System Requirements	**Estimated Cost per year ($)**
Preventive and routine maintenance	15,000 – 20,000
Spare parts, oil, and lubrication	5,000 – 10,000
Remote monitoring (SCADA)	3,000 – 5,000
Technician or management company wages	15,000 – 20,000
Other expenses	2,000 – 5,000
OPEX Estimated Cost ($)	40,000 – 60,000

$$The\ minimum\ OPEX\ cost\ for\ 1\ m3\ for\ one\ WT = \frac{40{,}000}{1{,}800\ x\ 365} = 0.060\ USD$$

$$The\ maximum\ OPEX\ cost\ for\ 1\ m3\ for\ 1\ WT = \frac{60{,}000}{1{,}800\ x\ 365} = 0.091\ USD$$

2.4.1. Cost Analysis of SW RO plant 1,800 $m^{3/}d$ powered by Wind and Solar Systems

Subsequent to the estimation of both CAPEX and OPEX, a comprehensive cost assessment is performed by annualizing the total lifecycle costs, predicated on a projected operational lifespan of 20 years.

Annualized CAPEX = Total CAPEX / Project Lifetime (6)

Annualized CAPEX = CAPEX (RO system + Solar system + Wind turbine) / 20 year

- CAPEX RO (SW 1,800 m3/d) = 815,000 – 1,250,000 $
- CAPEX PV (738 PV PANEL) = 250,000 – 365,000 $
- CAPEX WT (1 Wind turbine 1MW) = 1,320,000 – 1,580,000 $, for 2 Wind turbine = 2,640,000 – 3,160,000 $

Then, the minimum Annualized CAPEX for RO powered by electrical energy = 815,000 / 20 = 40,750$

The maximum Annualized CAPEX for RO powered by electrical energy = 1,250,000 / 20 = 62,500 $

Then, the minimum Annualized CAPEX for RO powered by renewable energy = (815,000 + 250,000 + 2,640,000) / 20 = 185,250$

The maximum Annualized CAPEX for RO powered by renewable energy = (1,250,000 + 365,000 + 3,160,000) / 20 = 238,750 $

CAPEX cost per cubic meter of water = Annualized CAPEX / RO Capacity per year (7)

$$The\ minimum\ Total\ CAPEX\ \ Water\ \ cost\ for\ 1\ m3\ in\ RO\ powered\ by\ electrcial\ energy = \frac{40{,}750}{1{,}800\ x\ 365} = 0.062\ USD$$

$$The\ maximum\ Total\ CAPEX\ \ Water\ \ cost\ for\ 1\ m3\ powered\ by\ electrcial\ energy\ = \frac{62{,}500}{1{,}800\ x\ 365} = 0.095\ USD$$

$$The\ minimum\ Total\ CAPEX\ \ Water\ \ cost\ for\ 1\ m3powered\ by\ renewable\ energy\ = \frac{185{,}250}{1{,}800\ x\ 365} = 0.281\ USD$$

$$The\ maximum\ Total\ CAPEX\ \ Water\ \ cost\ for\ 1\ m3\ powered\ by\ renewable\ energy\ = \frac{238{,}750}{1{,}800\ x\ 365} = 0.363\ USD$$

On the other hand, the annual operating expenses will be calculated based on the combined operating costs of the reverse osmosis plant, the solar power system, and the wind turbine system, as shown in Table 17.

Table 17.
Estimated Annual Operating Costs for RO, PV, and WT.

System	**Estimated Cost per year ($)**	**Cost of 1 m^3 of water ($)**
SW RO (plant 1,800 m3/d) without Electrical Power	229,800 – 383,100	0.350 – 0.583
PV system (738 PV panels)	38,000 – 54,000	0.058 – 0.082
Wind Turbine (2 nos., 1 MW)	80,000 – 120,000	0.121 – 0.182
OPEX Estimated Cost ($)	347,800 – 437,220	0.529 – 0.665

After obtaining the annual capital and operational expenditures, the total costs are calculated for two scenarios: the first scenario involves a reverse osmosis (RO) desalination plant powered by conventional electricity, and the second consists of an RO plant powered by renewable energy sources (solar and wind Table 18 presents the total cost for the RO desalination plant utilizing conventional electrical power.

Table 18.
CAPEX / OPEX of SWRO Powered by Electrical.

Description	**Estimated Cost per year ($)**	**Cost of 1 m^3 of water ($)**
Annualized CAPEX (SWRO)	40,750 – 62,500	0.062 – 0.095
Annualized OPEX (SWRO Plant Powered by Electricity)	347,800 – 437,220	0.529 – 0.665
TOTAL	388,550 – 499,720	0.591 – 0.760

When evaluating the costs of the RO plant integrated with renewable energy sources, it is essential to conduct a comprehensive data analysis to determine the optimal number of wind turbines that yields maximum desalination output. Based on the dataset and calculations presented in the Excel sheet Table 19, it has been deduced that the optimal number of 1 MW wind turbines ranges between one and two. Accordingly, the assessment will be carried out for both scenarios: utilizing a single turbine and then utilizing two turbines. A comparative analysis will be conducted in terms of the specific water production cost (USD/m³), system efficiency, generated energy, and surplus energy under both configurations.

Table 19.
Excel sheet database of calculation of SWRO plant 1,800 m^3/d.

SW RO Plant - AL WAJH- 40,000 TDS	Date- 2024	Temperature	Wind Speed km/h	Wind Speed m/s	Product Water Capacity- M3/day	working hours per day	total power KW/d	KWh per M3 Required	Total Power with loss- KWh/day	Power by PV KWhr/day	Power by WT KWhr/day	Solar Panel Capacity Type (750W)	Work hours per day for PV	The seasonal average peak sun-hours (PSH)	No. of PV Panels	Output power kWhr/day	Wind Turbine Capacity	WT Power Output KW/hr	WT Work hours per day	Number of Turbine Suggested	Power output from WT- KWh/Day	POWER OUTPUT FROM PV+WT - KWhr/d	Power Efficiency %	Productivity m3/d
1,800 m3/d - RR:40	Jan	20	14.7	4.1	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	5	6.40	738	2,767.5	1MW - Sulzon S64	68	24	2	3,264	6,032	106%	1,800
1,800 m3/d - RR:40	Feb	22	15.4	4.3	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	6	6.40	738	3,321.0	1MW - Sulzon S65	72	24	2	3,456	6,777	120%	1,800
1,800 m3/d - RR:40	Mar	24	16.1	4.5	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S66	75	24	1	1,800	5,675	100%	1,800
1,800 m3/d - RR:40	Apr	26	15.3	4.3	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S67	72	24	1	1,728	5,603	99%	1,780
1,800 m3/d - RR:40	May	29	15.8	4.4	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S68	73	24	1	1,752	5,627	99%	1,788
1,800 m3/d - RR:40	Jun	31	17.3	4.8	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S69	80	24	1	1,920	5,795	102%	1,800
1,800 m3/d - RR:40	Jul	32	15.2	4.2	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S70	70	24	1	1,680	5,555	98%	1,765

1,800 m3/d - RR:40	Aug	33	16.3	4.5	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S71	75	24	1	1,800	5,675	100%	1,800
1,800 m3/d - RR:40	Sep	30	16.3	4.5	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S72	75	24	1	1,800	5,675	100%	1,800
1,800 m3/d - RR:40	Oct	28	13.7	3.8	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	7	6.40	738	3,874.5	1MW - Sulzon S73	63	24	1	1,512	5,387	95%	1,712
1,800 m3/d - RR:40	Nov	26	12.8	3.6	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	6	6.40	738	3,321.0	1MW - Sulzon S74	60	24	2	2,880	6,201	109%	1,800
1,800 m3/d - RR:40	Dec	22	14	3.9	1800	24	236.00	3.15	5,664	2,832	2,832	0.75	6	6.40	738	3,321.0	1MW - Sulzon S75	65	24	2	3,120	6,441	114%	1,800
																				AVERAGE POWER EFFICIANCY			**104%**	
																				TOTAL SWRO DAILY PRODUCT (m3/d)				**1,787**

When only a single turbine is utilized, the capital and operational expenditures of the renewable energy-integrated desalination plant, as presented in Table 20, resulted in total annual costs ranging from (USD 387,050 – 616,850). The specific water production cost was estimated to lie between (USD 0.59 – 0.94) per cubic meter.

Table 20.
CAPEX / OPEX of SWRO Powered by PV / 1WT.

Description	Estimated Cost per year ($)	Cost of 1 m^3 of water ($)
Annualized CAPEX (SWRO)	40,750 – 62,500	0.062 – 0.095
Annualized CAPEX (PV)	12,500 – 18,250	0.019 – 0.028
Annualized CAPEX **(1WT)**	66,000 – 79,000	0.100 – 0.120
Annualized OPEX (SW RO Plant Powered by PV / WT)	267,800 – 457,100	0.407 – 0.695
TOTAL	**387,050 – 616,850**	**0.589 – 0.938**

Figure 4 shows the daily water production in the scenario where only a single wind turbine is operational. It also depicts the combined power output generated from both the wind turbine and the solar photovoltaic (PV) system. Notable fluctuations in production are observed, particularly during January, February, November, and December 2024. In this case, it is necessary to develop a solution to address the decline in productivity during these four months.

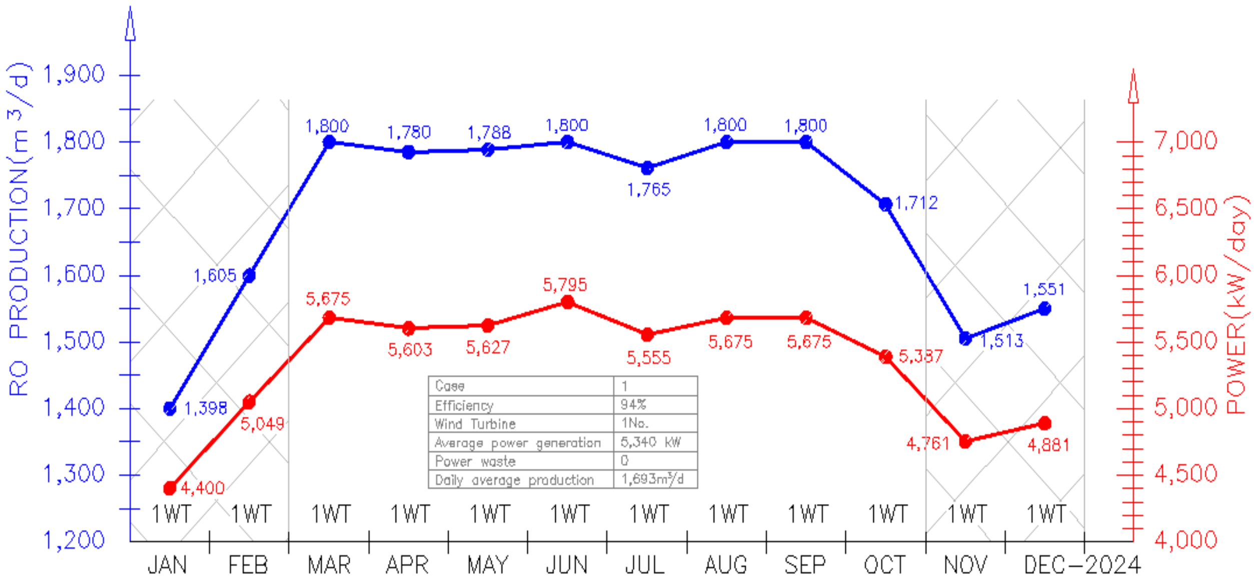

Figure 4.
Case (1) RO Production diagram, and Power diagram in 2024 with 1 WT.

Table 21 presents the capital and operational costs of the desalination plant integrated with renewable energy, specifically incorporating two wind turbines, each with a capacity of 1 MW, are analyzed. The total annual costs ranged from USD 513,050 to USD 775,850, while the unit cost of desalinated water was estimated to be USD 0.78 to USD 1.18 per cubic meter.

Table 21.
CAPEX / OPEX of SWRO Powered by PV / 2WT.

Description	Estimated Cost per year ($)	Cost of 1 m^3 of water ($)
Annualized CAPEX (SWRO)	40,750 – 62,500	0.062 – 0.095
Annualized CAPEX (PV)	12,500 – 18,250	0.019 – 0.028
Annualized CAPEX **(2WT)**	132,000 – 158,000	0.200 – 0.240
Annualized OPEX (SW RO Plant Powered by PV / WT)	327,800 – 537,100	0.498 – 0.817
TOTAL	**513,050 – 775,850**	**0.78 – 1.18**

Figure 5 shows the operational scenario involving two wind turbines in conjunction with a solar photovoltaic (PV) system. The curves present both the water production curve and the corresponding energy generation curve under this configuration. In this case, a significant amount of energy is generated, while the water production remains consistently at its maximum design capacity of 1,800 m^3/d. In this scenario, the surplus energy could be exported to an external entity, such as by connecting to the electrical grid, to utilize the energy surplus.

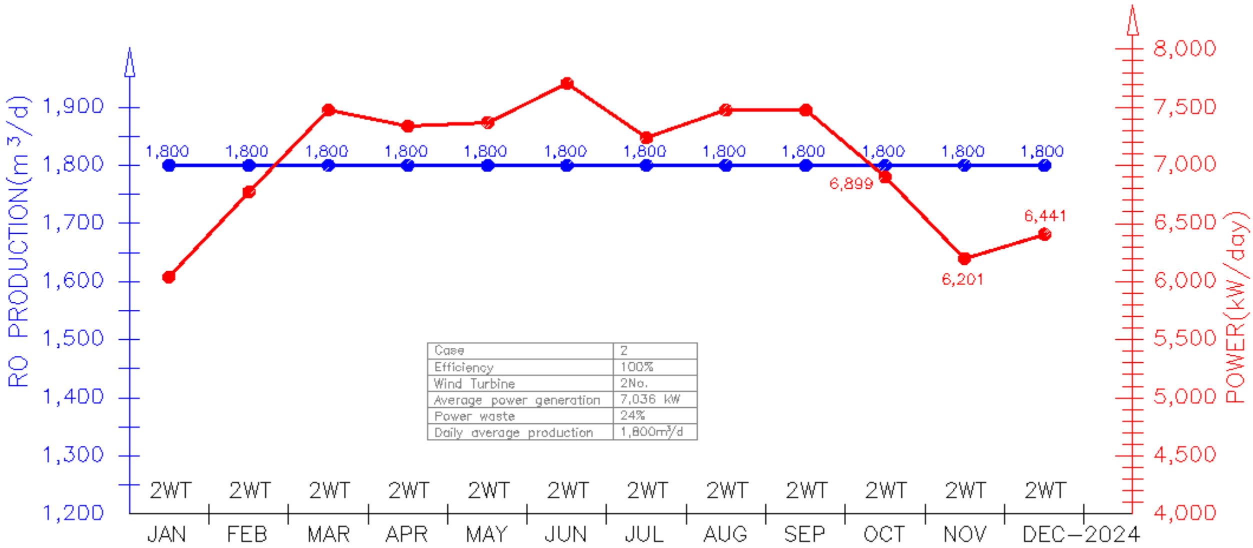

Figure 5.
Case (2) RO Production diagram, and Power diagram in 2024 with 2 WT.

The capital and operational costs were compared for three scenarios: (1) a seawater desalination plant producing 1,800 m^3/d powered by electricity; (2) the same plant powered by solar energy combined with two turbines; and (3) the plant powered by solar energy with a single turbine. Table 22 presents a comparative analysis of the total costs, productivity, efficiency, energy generated by each system individually, and finally, the energy surplus associated with each case.

Table 22.
Comparison between the Cost of SWRO Powered by PV / WT.

Description	Estimated CAPEX / OPEX per year	Cost of 1 m^3 of water ($)	SWRO Production m^3/d	Efficiency (%)	Average Power Generation (kW)	Energy Surplus (%)
SWRO Powered by **Electricity**	388,550 – 499,720	0.59 – 0.76	1,800	100%	5,664	0%
SWRO Powered by **PV / 2WT**	513,050 – 775,850	0.78 – 1.18	1,800	99%	7,036	24%
SWRO Powered by **PV / 1WT**	387,050 – 616,850	0.59 – 0.94	1,693	94%	5,340	0%

From the database provided in the Excel sheet (Table 19), it can be observed that the lowest wind speed and ambient temperature occurred during January, February, November, and December 2024. During these months, wind speeds ranged from (3.6 - 4.3 m/s), while temperatures varied between (20°C - 26°C). A recalculation was performed based on the assumption that two turbines would be operated during these four months, while only one turbine would be in operation for the remainder of the year. This operational strategy is reflected in Table 23.

Table 23.
Cost of SWRO Powered by PV / (1 WT + 1 WT for only 5 months per year).

Description	Estimated CAPEX / OPEX per year	Cost of 1 m^3 of water ($)	SWRO Production m^3/d	Efficiency (%)	Average Power Generation (kW)	Energy Surplus (%)
SWRO Powered by PV / (1 WT + 1 WT for only 4 months per year)	486,400 – 735,850	0.74 – 1.12	1,787	99%	5,870	4%

Table 23, The latest scenario, involving the partial operation of multiple turbines during a decrease in wind speed and temperature, resulted in a slight reduction in operational costs. Consequently, the production cost ranged between (0.74–1.12 $/$m^3$) while the desalination plant produced 1,787 m^3/d, achieving an efficiency of 99%. Additionally, the amount of surplus energy decreased to 4%. This outcome represents the best performance attained in this search for a seawater desalination plant producing 1,800 m^3/d, operating on renewable energy sources.

Figure 6 shows the third operational scenario, in which two wind turbines are operated exclusively during the four months when energy generation is insufficient under the single-turbine configuration. This scenario demonstrates stable water production with a relatively moderate reduction in total energy generation. It is considered the most optimal configuration identified in this study.

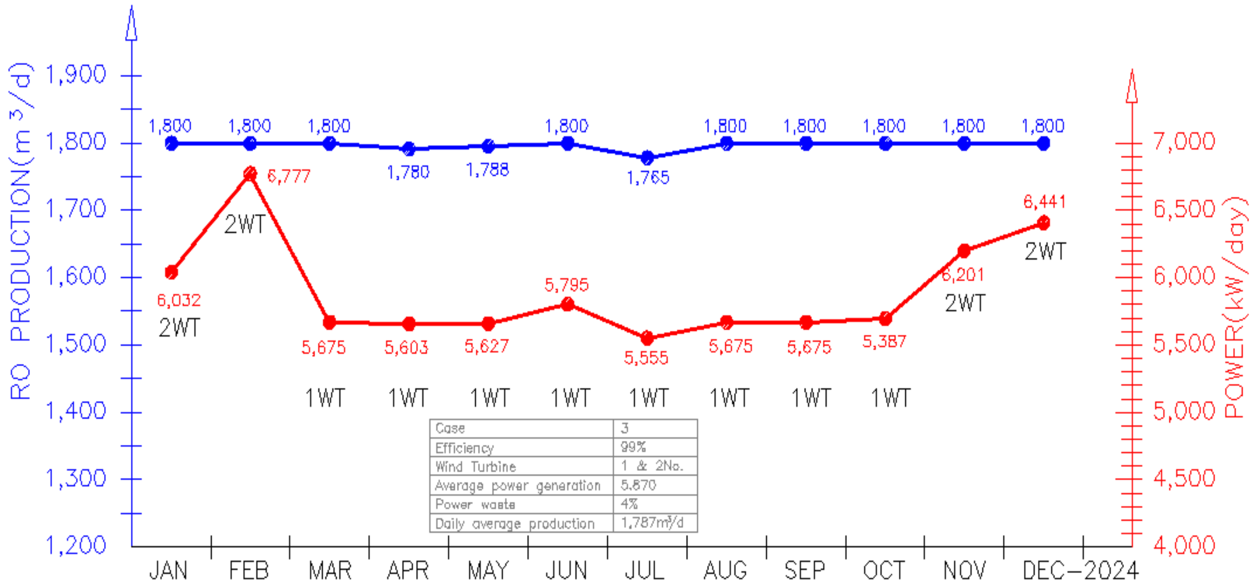

Figure 6.
Case (3) RO Production diagram, and Power diagram in 2024 with 1WT and 2 WT.

2.5. The Utilization of Artificial Intelligence (AI) to Determine the Optimal Number of Turbines Required for Achieving Maximum Production Efficiency and to Forecast Future Demand Under Varying Meteorological Conditions in Al Wajh Region:

ChatGPT was given the full input data, and the answer was as follows:
Seawater Reverse Osmosis Desalination Plant Data – Al Wajh, Saudi Arabia:

- *Daily Water Production Target: 1800 cubic meters (m³) per day*.
- *Daily Energy Demand: 5664 kWh.*
- *Wind Turbine Capacity: 1 MW (1000 kW) each*.
- *Number of Wind Turbines: 2*.
- *Solar PV Array: 738 panels × 750 W = 553.5 kW peak capacity*.
- *Estimated Effective Solar Irradiance Hours: 6 to 9 hours, varying by month*.

2.5.1. Methodology

- *Calculate wind energy generation based on average monthly wind speeds*.
- *Estimate solar photovoltaic (PV) energy production according to effective sun hours*.
- *Decide the operation of one or two wind turbines to meet the plant's daily energy requirement of 5664 kWh.*
- *Compute daily water output proportional to available energy (assuming a linear relation with energy demand).*
- *Assess the surplus (unused) energy percentage after meeting the desalination plant load.*

ChatGPT gave the results shown in Tables 24 and 25*:*

Table 24.
ChatGPT result.

Month 2024	Wind Speed (m/s)	Wind Energy (1 Turbine) (kWh)	Wind Energy (2 Turbines) (kWh)	Peak Sun Hours per day	Solar Energy (kWh)	Turbine Operation	Total Energy 1 or 2 Turbines + Solar) (kWh)	Water Production (m³)	Production Efficiency (%)	Surplus Energy Turbines (%)
1	4.1	3300	6600	5	2768	**2**	9921	1800	100	65
2	4.3	3900	7800	6	3321	1	7221	1800	100	28
3	4.5	4500	9000	7	3875	1	8651	1800	100	47
4	4.3	3900	7800	7	3875	1	8051	1800	100	37
5	4.4	4200	8400	7	3875	1	8351	1800	100	42
6	4.8	5400	10800	7	3875	1	10381	1800	100	63
7	4.2	3600	7200	7	3875	1	8581	1800	100	31
8	4.5	4500	9000	7	3875	1	9481	1800	100	47
9	4.5	4500	9000	7	3875	1	8651	1800	100	47
10	3.8	2400	4800	7	3875	**2**	8951	1598	88.8	53
11	3.6	1800	3600	6	3321	**2**	6921	1200	66.7	22
12	3.9	2700	5400	6	3321	**2**	8721	1512	84	53

Table 25.
ChatGPT result.

Parameter	Average Value
Wind Speed (m/s)	4.24
Wind Energy per Turbine (kWh) per day	3925
Wind Energy (2 Turbines) (kWh) per day	7850
Solar Energy (kWh) per day	3644
Total Energy (1 Turbine + Solar) (kWh) per day	8012
Total Energy (2 Turbines + Solar) (kWh) per day	11937
Average Daily Water Production (m³)	**1725**
Average Production Efficiency (%)	**95%**
Average Surplus Energy (2 Turbines for 4 months + 1 Turbines for 8 months) (%)	44%

2.5.2. Interpretation

- *The average wind speed of 4.21 m/s provides moderate wind energy input for the turbines.*
- *Combined wind and solar energy with a single turbine generally exceeds the desalination plant's 5664 kWh daily requirement, yielding an average surplus of 44%.*
- *During months with lower wind speeds, operation of both turbines is necessary, resulting in average energy surpluses exceeding 100%.*
- *The average water production efficiency reaches approximately 95%, indicating that the system consistently meets near-full production targets throughout the year.*
- *Lower water output during winter months necessitates increased turbine operation to maintain capacity.*

The demand forecast for this project based on weather conditions and wind speed in the Al Wajh region of Saudi Arabia for the next twenty years**:**

Forecasting the energy demand for the seawater reverse osmosis (SWRO) desalination plant in Al Wajh, Saudi Arabia, over the next 20 years involves considering both the projected climate conditions and the anticipated growth in water demand.

2.5.3. Climate Trends and Wind Speed Projections

Al Wajh has experienced a warming trend of approximately 0.06°C per decade from 1978 to 2009, which is consistent with broader regional climate patterns in Saudi Arabia. This warming is expected to continue, potentially leading to increased temperatures and altered wind patterns. While specific long-term wind speed projections for Al Wajh are limited, studies indicate that the north-western region of Saudi Arabia, which includes Al Wajh, has acceptable wind energy resources for the long term, suggesting that wind speeds may remain favorable for wind energy generation.

2.5.4. Projected Water Demand Growth

The demand for desalinated water in Al Wajh is expected to increase due to population growth, urban development, and industrial expansion. While specific growth rates for Al Wajh are not readily available, similar regions in Saudi Arabia have experienced significant increases in water demand. For instance, national oil consumption in Saudi Arabia is increasing by 7% annually, and domestic water demands are expected to double in the coming decade.

2.5.5. Renewable Energy Generation Outlook

The renewable energy potential in Al Wajh, particularly from wind and solar sources, is promising. The average wind speed in Al Wajh is around 15.9 km/h, with the windiest month being June at 17.3 km/h. Additionally, the region receives substantial solar radiation, with average daily global horizontal irradiance (GHI) values ranging from 15.2 to 29.8 MJ/m² throughout the year. These conditions are conducive to the generation of renewable energy, which can support the desalination plant's operations.

2.5.6. Demand Forecast and Energy Supply Strategy

Given the expected increase in water demand and the potential for stable renewable energy generation, it is advisable to plan for a gradual expansion of the desalination plant's capacity over the next 20 years. This expansion should align with the projected growth in water demand and the capacity of renewable energy sources to meet the plant's energy requirements. Regular assessments of climate conditions, renewable energy potential, and water demand trends will be essential to ensure the sustainability and efficiency of the desalination operations.

In summary, while specific long-term projections for wind speeds in Al Wajh are not available, the region's renewable energy potential appears favorable. Coupled with the anticipated growth in water demand, strategic planning for the expansion of desalination capacity, supported by renewable energy sources, will be crucial to meet future needs. Here ends the ChatGPT report.

Table 26 shows a comparison between the results of ChatGPT and the results obtained in the research. The energy surplus in the research was calculated to be 4%, whereas it reached 44% when calculated using ChatGPT. This discrepancy arises from the calculation methodology. In the research, the estimation was based on the power curve provided by the turbine manufacturer. In contrast, ChatGPT relied solely on the fundamental wind power equation, which is a purely theoretical approximation. If ChatGPT were provided with the actual power curve of the selected turbine, the calculations would have been significantly more accurate.

Table 26.
Comparison between the results of ChatGPT and the results obtained in the research.

Description	Research	ChatGPT
Number of months in which only one turbine is operated	8	8
Number of months in which two turbines are operated	4	4
Months in which 2 turbines are operated	Nov, Dec, Jan, and Feb	Oct, Nov, Dec, and Jan
Average Daily Water Production (m^3)	1,787 m^3/day	1,725 m^3/day
Average Production Efficiency (%)	99%	95.8%
Average Surplus Energy (2 Turbines for 4 months + 1 Turbines for 8 months) (%)	4%	44%

3. Results

The study revealed that seawater desalination plants consume significant amounts of electrical energy, reaching 3.15 kWh/m^3, making energy costs one of the critical factors for the sustainable and economical operation of the plant.

The capital cost CAPEX of a SWRO desalination plant with a capacity of 1,800 m3/d in the Al-Wajh region of Saudi Arabia was estimated to be approximately USD 920,000. Operational costs OPEX were also calculated, with the average operational cost found to be 0.46 $/m3, the electricity expenses accounting for 33% of the total operational cost.

A reverse osmosis plant powered by solar and wind energy was designed specifically for the Al-Wajh region. It was found that, in order to produce 1,800 m^3/day, the plant would require a solar array consisting of 738 solar panels rated at 750 watts each, in addition to one to two wind turbines, each with a capacity of 1 MW.

CAPEX and OPEX costs for the renewable-energy-powered plant were assessed under three scenarios: using one wind turbine, using two wind turbines, and using one turbine fully, and operating the second one partially.

The third scenario was identified as the most optimal, achieving a high productivity rate of 99%, with an average water production cost of 0.93 $/m3. Although this is higher than the cost per cubic meter for a conventionally powered RO system 0.67 $ /m^3, the reason is due to the high capital costs of renewable energy equipment.

Although the initial investment cost of a renewable energy system is higher than that of a conventional system, the reduced operation and maintenance costs make renewable energy economically viable over time. Additionally, it contributes to lowering the cost of water production per cubic meter in the long term.

The feasibility of replacing grid electricity with renewable energy sources was analyzed. Results showed that relying on solar and wind energy can effectively meet the plant's energy demands.

Artificial Intelligence tools (such as ChatGPT) were employed to estimate the optimal number of wind turbines required for maximum efficiency. The AI-generated results were found to closely approximate the actual research findings, with minor discrepancies.

These differences are attributed to the AI model's reliance on general theoretical equations, while the research was based on real-world data derived from the technical specifications of commercially available turbines, providing higher accuracy and practical applicability.

The study demonstrated that systems powered by renewable energy offer stable water production, energy savings, and notable reductions in production costs compared to conventional systems. Furthermore, renewable systems offer better scalability for future expansion.

4. Recommendations

The study strongly recommends a gradual transition from conventional electricity to renewable energy sources in desalination plant operations, especially in coastal regions with abundant solar irradiance and wind resources.

To ensure greater stability in power supply, the integration of solar and wind systems into a hybrid configuration is recommended, enabling one source to compensate for reduced output from the other during different times of the day or seasons.

The provision of financial and regulatory incentives is essential to encourage investment in renewable-powered desalination projects. This could include tax exemptions, technical support, and funding schemes for emerging initiatives.

The study recommends establishing mechanisms for periodic monitoring and performance evaluation of renewable-powered desalination plants to ensure sustainable production and continuous improvement in efficiency and water quality.

It is advisable to utilize AI tools during the preliminary stages of feasibility assessment and resource estimation. However, AI-generated data should be validated against real-world manufacturer data to ensure design accuracy and implementation precision.

Abbreviations:

CAPEX	Capital Expenditures
CIP	Clean-In-Place
CM	Corrective Maintenance
CP	Preventive Maintenance
FO	Forward Osmosis
GHI	Global Horizontal Irradiance
HVAC	Ventilation and Air Conditioning
LCOW	Levelized Cost of Water
OPEX	Operational Expenditures
PV	Photovoltaic
PLC	Programmer Logic Controller
RO	Reverse Osmosis
SCADA	Supervisory Control and Data Acquisition
SDGs	Global Sustainable Development
SWRO	Seawater
USD	United States Dollar
WT	Wind Turbine

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