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Analytical Vision for Designing a Wastewater Treatment System Based on Reverse Osmosis and Renewable Energy

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ABSTRACT. *With the world population growth and industrialisation, water and energy challenges are increasing worldwide, including in resource-limited regions. This research presents an analytical vision for an integrated wastewater treatment system using reverse osmosis (RO) and renewable energy. The system vision is designed to be applicable within the climatic conditions of Karak Governorate, Jordan. Computational analysis shows that treating one cubic meter of wastewater requires 5.2 kilowatt-hours, supplied by three solar panels (400-watt) and a specialized low-wind turbine, with an 8-10 kWh battery storage for continuous operation. The energy required to operate this system can be provided by a hybrid of solar and wind energy, which is locally available during the summer, ensuring sustainable, renewable energy. To stabilise production during fluctuations in energy availability, it is recommended to integrate the system with an energy storage unit. This integrated approach supports sustainable water and energy use for agricultural, domestic, and community development projects through wastewater treatment and reuse.*

Keywords: Reverse Osmosis; Off-Grid Desalination; Photovoltaic Water Treatment; Hybrid Solar-Wind; Low-Wind Feasibility; Karak; Jordan; Insustrial Systems Engineering; Sustainable Water-Energy.

1. Introduction. Rapid population growth and industrial development are increasing global demand for water and energy, threatening economic and environmental stability in many countries, particularly developing countries such as the Middle East, Africa, Central Asia, and South America [1-4]. Our dependence on fossil fuels is causing a global environmental crisis and accelerating global climate change, while high industrial consumption increases the scarcity of drinking water and water for agriculture [5-6]. Energy is used to operate agricultural equipment and is vital for the operation of water treatment plants. The treated water is then used for drinking or agriculture [7–9]. Any disturbance in energy supplies can cause the failure of the agricultural system [10].

Addressing the energy-water-food relationship is critical to achieving food security. To achieve the energy-water-food relationship, it is essential to invest in renewable energy and efficient water management [11]. This study explores the vision of using solar and wind energy for wastewater treatment using reverse osmosis (RO) technology by integrating these renewable resources. Sustainable solutions can be developed to improve water security, reduce dependence on fossil fuels, and lower carbon emissions. This vision not only provides a vital source of water for irrigation and industry but also offers sustainable energy and water solutions within industrial systems that reduce pollution and protect ecosystems.

2. Previous studies. A number of studies have shown that the hybrid renewable energy systems and advanced water treatment models are feasible. Chamazkoti et al. [12] studied a flexible hybrid energy model of wastewater treatment plant that integrates power and hydrogen generation, revealing the potential of sustainable energy recovery. Araei and Moghaddam [13] performed a techno-economic analysis of hybrid renewable energy systems for wastewater treatment to highlight the applicability of the hybrid systems in low electricity tariff countries. Erdal et al. [14] designed a stand-alone microgrid for a wastewater treatment plant for the integration of multiple renewable sources to ensure that the microgrid operates reliably with the help of HOMER Pro software.

Manikandan et al. [15] and Ahmad et al. [16] examined the potential of nanotechnology and nanofiltration membranes in drinking water purification and treatment of industrial wastewater. Siddique [17] discussed the issues related to urbanization and sustainable water management, emphasizing the need for water conservation and re-use. Water recovery in industries that require a lot of water, like papermaking was studied by Han et al. [18] who pointed out its environmental and economical advantages. Various studies have been undertaken on renewable energy alternatives. Pandey et al. [19] discussed solar powered waste water treatment technologies including photocatalytic methods and the problem associated with the application. Likewise, Mir and Bicer [20] discussed the combination of electrolysis (ED) with renewable energy, including solar and wind power for fresh water production, focusing on the specific performance of ED to desalinate brackish water.

The following are some of the main themes that can be derived from the studies on water treatment and sustainability:

- Nanotechnology Role: The potential of nanotechnology is enormous, especially nanomaterials and NF membranes, in the field of advanced water purification and wastewater treatment, such as the removal of various pollutants and the recovery of useful substances. Ahmad et al. particularly concentrate on the application of NF in different industries.

- Sustainable Urban Water Management: Siddique [17] highlights the threats and challenges of urbanisation to water resources and calls for adopting integrated, sustainable water management practices.
- Water Reclamation in Industry: Han et al. [18] highlighted the importance of water reclamation in water-intensive industries such as paper manufacturing.
- Solar-Powered Treatment: Pandey et al. [19] and Mir and Bicer [20] discussed the renewable energy for the case of solar energy and water treatment technology. Pandey et al. discuss a few of the solar-powered methods including photocatalysis and desalination. Mir and Bicer focused on the hybrid solar wind electrodialysis method. Both refer to the environmental benefits and to economic considerations of these approaches, such as storage of energy for night-time use. Mir and Bicer point out the effectiveness of electrodialysis in brackish water desalination.

3. Design Methodology. The proposed system consists of a comprehensive treatment system using RO technology and optimized hybrid renewable energy system. The treatment process starts with multi stage pre-filtration with gravel, sand and activated carbon to protect the RO membranes and then pressurisation occurs where a high pressure pump (0.5 HP) is employed at 15-20 bar pressure. The core RO unit consists of spiral-wound, 50 GPD capacity polyamide membranes and Post-Treatment involves pH stabilisation for agricultural reuse.

The hybrid energy system combines three Jinko Solar 400-W Tiger Neo panels for a total of 1.245 kW, a specially designed low-wind vertical-axis wind turbine with a 8-10 kWh $LiFePO_4$ battery bank. The control strategy is a hierarchical, in which solar energy is the main energy source (85%), and wind the secondary one (15%), with the smart hybrid controller acting as a dynamic decision-making tool that continuously optimizes energy distribution and use in real-time, based on the level of energy available and the level of load demand.

3.1 System Design and Key Components. The system is designed based on the key findings of the previous research, which combine a number of treatment methods to form an overall and energy-saving wastewater treatment process. The system includes the following main components:

- Preliminary Filtration: Wastewater is subjected to a primary filtration process that requires no outside energy. This is done by passing the sewage through sand and gravel layers, and solid waste traps to eliminate suspended and insoluble material. RO Purification: The pre-treated water is pressurized by a high-pressure pump and forced through semi-permeable RO membranes to remove dissolved salts, bacteria, and other contaminants.
- Permeate Collection and Post-Treatment: The purified water (permeate) is collected and undergoes post-treatment such as pH stabilisation to make it suitable for agricultural reuse.
- Renewable Energy Integration: To power the high-pressure pump and control systems, the system incorporates renewable energy sources such as solar panels and wind energy.

- Hybrid Energy Storage System: Batteries are included to store excess energy. The batteries are supported by charge regulators to maintain system efficiency and allow operation during periods of low energy availability.

3.2 Implementation Steps. The methodology is structured in the following steps:

Site Assessment and Resource Availability:

- Identify the wastewater source and analyse its composition.
- Assess environmental factors such as sunlight availability, wind patterns, and water demand.

System Configuration and Design:

- Construct the primary filtration unit using gravel, sand, and solid waste traps.
- Design and install the high-pressure pump and RO membrane modules.
- Set up the post-treatment system for water stabilisation.

Renewable Energy Setup and Integration:

- Install solar panels or wind turbines based on location-specific energy potential.
- Integrate energy storage components (batteries and charge controllers) to ensure continuous operation.
- Implement energy management strategies for hybrid operation and optimising power distribution between solar and wind sources.

Testing and Optimisation:

- Conduct initial tests to evaluate treatment efficiency and energy consumption.
- Optimise membrane performance, pump efficiency, and energy utilisation to enhance the system performance.
- Make necessary adjustments to improve water recovery rates and minimize energy losses.

Deployment and Scalability:

- Develop small portable water treatment units suitable for remote and off-grid locations.
- Explore scaling options for larger industrial or municipal applications.
- Implement monitoring and automation systems to enhance long-term reliability and efficiency.

4. Expected Outcomes and Sustainability

The integrated system is designed to achieve:

- Efficient Water Recycling: High-purity water output with minimal environmental impact.
- Energy Self-Sufficiency: Continuous operation using renewable energy sources.
- Scalability and Portability: A modular design that can be expanded or transported based on demand.
- Cost-Effectiveness: Reduction in dependence on fossil fuels and operational costs.

5. Quantitative and Mathematical Analysis. The total energy demand of 5.2 kWh/m^3 is derived from established values for small-scale RO systems. This covers high-pressure pump operation (3.5 kWh), pre-treatment (0.3 kWh), control systems (0.1 kWh), and ancillary loads (1.0 kWh).

5.1 Water Flow Rate and Treatment Capacity. The flow rate of wastewater processed per unit time was determined using Equation (1):

$$F = A \times v, \tag{1}$$

Where F is the flow rate (m^3/s), A is the cross-sectional area (m^2), and v is the velocity (m/s).

Designing the filtration unit is based on the expected wastewater inflow. The efficiency of filtration can be analysed by measuring turbidity reduction before and after filtration.

5.2 Comparison: Thermal Vaporisation vs Reverse Osmosis Energy Requirement. For comparison purposes, the energy requirements are calculated for thermal vaporisation to demonstrate the significant efficiency advantage of RO technology using Equation (2):

$$Q = MC(T_V - T_0) + ML_V, \tag{2}$$

where Q is the total energy required for heating and vaporisation (J), M is the mass of water to be vaporised (kg), C is the specific heat capacity of water (4184 J/kg$^{\circ}$.C), T_v is the vaporisation temperature ($^{\circ}$C), T_0 is the room temperature ($^{\circ}$C), and L_v is the latent heat of vaporisation of water (2.26×10^6 J/kg at 100°C).

This determines the heating power needed from the renewable energy system. Based on Equation (2), the thermal energy required to convert one cubic meter of water into steam is 2.5738×10^9 J.

The electrical energy ($E_{\text{electrical}}$) required is calculated using Equation (3) to be 2.7052 ×10^9 J (751.44 kWh), considering a thermal efficiency η_{th} = 0.95.

$$E_{electrical} = \frac{Q}{\eta_{th}}, \tag{3}$$

5.3 Renewable Energy Generation and Storage Requirements. The system can be powered by solar panels and/or wind turbines.

5.3.1 Solar Energy Calculation. The energy generated by solar panels is given by Equation (4):

$$E_s = P_s A v d_s \eta_s, \tag{4}$$

E_s is the energy generated per day (J), P_s is the solar panel rating (W), Avd_s is the average daily sunlight hours (h), and η_s is the system efficiency (including inverter and losses).

Based on the result from Equation (3), the amount of energy the solar system needs to generate is given by Equation (5):

$$\text{Required solar power} = \frac{E_{electrical}}{Avd_s}, \quad (5)$$

For comparison, if this system used thermal vaporisation (requiring 751.44 kWh), it would need approximately 313 solar panels, demonstrating why RO technology was selected for this application.

Using Karak average solar irradiance of 5.8 kWh/m^2/day [21] and following established methodology, the calculation for three 400 W panels with 6 peak sun hours and system efficiency of 75% yields approximately 5.4 kWh of daily generation. The calculation of solar energy generation follows established methodology using solar irradiance data, as presented in the relevant research [22].

Based on the total daily energy requirement of 5.2 kWh, the solar energy contribution is sized. Average peak sun hours in Karak (6 h) and a system efficiency (75%), and the energy generated per 400 W panel are used to calculate E_s per panel = 0.4 kW × 6 h × 0.75 = 1.8 kWh/panel/day.

The number of panels required to meet the full load is: Number of Panels = 5.2 kWh / 1.8 kWh/panel ≈ 2.88 rounded to 3 panels.

5.3.2 Wind Energy Calculation. The power generated (P_w) by a wind turbine is given in Equation (6):

$$P_w = \frac{1}{2}\rho S_a (v_w)^3 C_p, \quad (6)$$

Where ρ is the air density, S_a the swept area of the turbine blades, v_w the wind speed, and C_p the power coefficient.

Based on Equation (6), where $\rho = 1.225\ kg/m^3, v_w = 2.5$ m/s, and $P_C = 0.4$, the diameter of the turbine blade is 1.5 m. The wind-speed value used here is selected based on prior investigations to ensure accurate system performance under local conditions [22].

Note that conventional turbines require minimum 3 – 4 m/s cut-in speeds, making specialized low-wind turbines essential for this application, because standard wind turbines cannot operate efficiently under low-speed air conditions and the low-speed air technology context provides guidance for such designs [23].

For the low-wind conditions in Karak (e.g., v_w = 2.5 m/s), a small turbine with a 1.5 m diameter (S_a = 1.77 m^2), ρ = 1.225 kg/m^3, and C_p = 0.25, the average power output is: P_w=0.5×1.225×1.77×(2.5)^3×0.25≈8.5 W. Daily Energy = 8.5 W × 24 h = 0.204 kWh.

6. Hybrid System. The hybrid system relies on primary water filtration through an energy-free system to remove solid impurities from the water, followed by pressure-based filtration through membranes. This stage requires the presence of pressure pumps that require an electrical system.

Figure 1 shows the components of the system and the sequence of operations from the entry of wastewater to the arrival of clean water. This is a solar-wind driven water purification system. It is especially useful in remote areas where there is no access to the main electricity grid. It consists of the solar panels, which are connected to a small wind turbine that in turn supplies electricity to a charge controller. This is a controller which regulates the power from both sources and stores it in a lithium battery pack (approx. 8-10 kWh). Then, this stored energy is converted to the proper type by an inverter to drive the system.

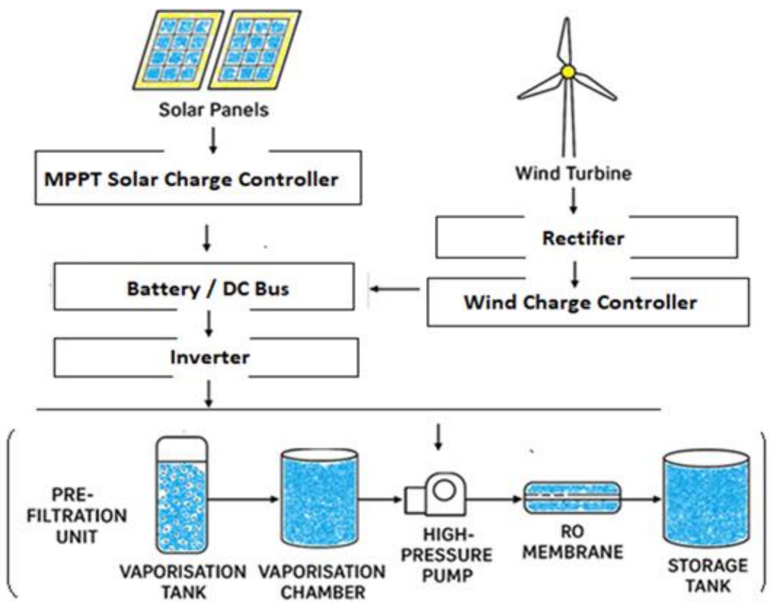

FIGURE. 1. System components and process sequence

The main component powered by this energy is a high-pressure pump, which is needed to push the water through the RO membrane. The water passes through a few filters before it reaches the membrane, to remove dirt, chlorine and larger particles to protect the membrane and enhance performance. After pressurization, the water passes through the RO membrane. The RO membrane filters out the dissolved salts, heavy metals, bacteria and other contaminants.

At the end of the process, clean water (called permeate) is collected in a storage tank for use. The leftover water (called brine) that contains the removed salts and contaminants is either disposed of or reused, depending on the situation. Overall, the system is simple, efficient, and works completely on renewable energy, making it a great choice for clean water in off-grid or rural locations. Table 1 shows the main components and approximate physical layout for a compact, modular unit.

TABLE 1. Integrated System Design & Dimensions

Component	Description	Approximate Size (L×W×H)
Pre-filtration Unit	Gravel sand layers in vertical tank	0.5 m × 0.5 m × 1.2 m
Vaporisation Tank	Insulated stainless-steel tank	1.0 m × 1.0 m × 1.2 m
Condensation Chamber	Air-cooled or water-cooled coils	1.2 m × 0.8 m × 1.2 m
Solar Panels (3 units)	Mounted at 30–35° angle, facing south	1.6 m × 1 m each
Wind Turbine (optional)	Vertical or horizontal axis (1–2 m dia.)	1.5 m pole height + blades
Battery Bank	Li-ion or gel battery bank (8-10 kWh)	0.6 m × 0.4 m × 0.4 m
Control Unit		0.4 m × 0.4 m × 0.2 m
Piping and Plumbing	PVC or steel connections	As needed

The above system can be implemented and improved by designing a system carrier vehicle to contribute to the sustainability of water supply in remote areas and under changing environmental conditions generated from renewable energy and stored in the battery. For 24-hour autonomy, the battery capacity is calculated as:

Battery (kWh) = Daily Energy (kWh) / (DoD × $\eta_{inverter}$). Using DoD = 0.8 and $\eta_{inverter}$=0.9: Battery = 5.2 kWh / (0.8 × 0.9) = 5.2 / 0.72 ≈ 7.22 kWh. Therefore, an 8-10 kWh battery bank is recommended.

Tables 2 and 3 show simulation values for the system quantum calculations in terms of energy and resources.

TABLE 2. Estimated Energy Requirements and Renewable Energy Supply for Treating 1 m^3 of Wastewater (Karak, Summer Conditions)

System Component	Function	Energy Required (kWh/day)	Notes
Pre-filtration Unit	Sediment and impurity removal.	0.3	Low-pressure pump or gravity-based system.
High-Pressure Pump	Drives water through membrane (~15 bar).	3.5	Major load: ~3.5 kWh needed for 1 m^3.
Control & Monitoring System	Sensors, flow control, and data logging.	0.2	PLC, flowmeters, TDS sensor, etc.
Water Recovery Heater	Heats reject water to reuse part of it.	1.2	Optional; improves efficiency in closed-loop setup.
Total Energy Required (Daily)		5.2	

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Figure 2 shows the amount of energy required to treat one cubic meter of water per day, and gives a breakdown of the energy used at each stage.

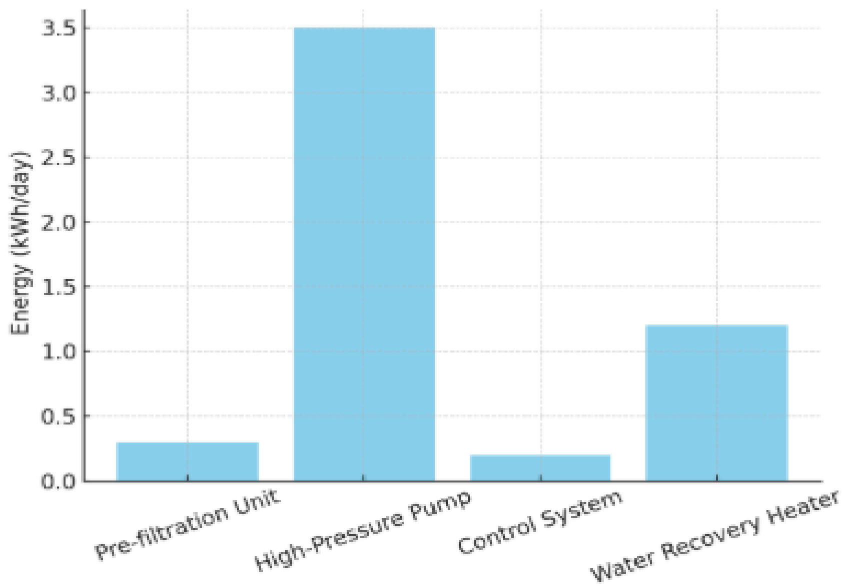

FIGURE. 2. Daily energy requirement for 1 m^3 wastewater treatment

TABLE 3. Available Renewable Energy (Based on Local Conditions in Karak)

Source	Details	Estimated Output (kWh/day)
Solar Energy	3 × 400W panels × 6 hours sun × 75% efficiency.	5.4
Wind Energy	1 × small turbine (1.5 m diameter) at avg. 2.5 m/s, 24h/day.	0.2
Total Supply		5.6

The performance of the proposed hybrid system was evaluated based on two main tables. Table 2 outlines the total daily energy required to treat one cubic meter of wastewater, which includes energy for pre-filtration, RO pumping, system control, and partial thermal recovery of rejected water. The total demand is estimated at approximately 5.2 kWh per day. Table 3 shows the estimated renewable generation of the energy system for summer average conditions in Karak, Jordan. Three 400W solar panels with 6 hours of daylight generate approximately 5.4kWh. Also, the contribution of a small wind turbine in operation 24×7 with an average wind speed of 2.5 m/s is approximately 0.2 kWh/day. An 8-10kWh micro grid is recommended to maintain stable operation during the periods of low sun or wind. The setup is a practical and energy-balanced solution for water treatment in remote regions, particularly in the summer climate of the region.

The analysis shows that in order to reach a community level implementation (10 m^3/day), this system would need about 28 solar panels, several wind turbines, and 80 kWh of battery storage, which would allow for further scaling up while keeping the system operational.

7. Economic Analysis. The total cost of the components in Jordanian market prices 2024 is about $12,350, which is made up of solar panels ($2,650), wind turbine ($1,200), batteries ($4,000), RO system ($3,000), and balance of system components ($1,500). Over 10 years, the levelized cost of water is $4.06/$m^3$, which falls to $2.03/$m^3$ when funded with 50% subsidies, making water from the tankers competitive in remote areas of Jordan.

8. Discussion and Conclusion. The energy analysis shows the clear advantage of RO technol ogy which requires only 5.2 kWh/m^3 compared to 751.44 kWh/m^3 for thermal vaporisation, m aking RO the only feasible option for off-grid renewable energy systems.

The proposed system demonstrates technical feasibility for decentralized wastewater treatment, yet the minimal wind contribution (4%) warrants consideration of its economic justification. The strategic value lies in risk mitigation during extended cloudy periods. The economic analysis shows that while the levelized cost of water of $2.1-4.1/$m^3$ exceeds conventional treatment costs. This represents a sustainable solution for off-grid areas. The limitations of the present study are the dependence of the design upon accurate solar/wind data, moreover, this study assumes consistent inflow of wastewater to the unit which would require an equalised flow rate to operate in real-life applications.

This study presents a design for a wastewater RO treatment facility which use hybrid power supply systems. The study introduces the combination of solar and wind energy into one (hybrid) power supply for the treatment of sewage using renewable resources. The system design utilises three major activities of the treatment process: prefiltration, pressurisation, and membrane filtration. The basis of the activities are supported by a quantitative analysis of available local solar and wind resources, volume of wastewater to be treated, and quality of water required after treatment. The quantitative data from the present study is used in a practical case study of the climatological conditions of the Karak Governorate, Jordan, and the results show that on average 5.2 kWh is required to treat one m^3 of wastewater. The output from combined solar and wind energy sources is sufficient to provide the necessary amount of energy to power the RO facility; therefore, the RO facility is self-sustaining at all times based on typical conditions. In addition, it is recommended to include battery protection for the generated power to provide short-term backup power for the RO facility during periods when solar or wind production is less than average. The proposed system is scalable and easily portable. These advantages makes it applicable to a variety of uses in rural communities and emergencies. This design provides a vision for energy and water solutions, and a vision for further applied research in this important field.

Nomenclature

A = cross-sectional area
Avd_s = average daily sunlight hours
C = specific heat capacity
C_p = power coefficient (wind turbine efficiency)
DoD = Depth of Discharge (battery)
$E_{electrical}$ = electrical energy
E_s = solar energy generated per day
F = flow rate
L_v = latent heat of vaporisation
M = mass of water
P_s = solar panel rating
P_w = power generated
Q = total energy required
S_a = swept area of turbine blades
T_0 = room temperature
T_v = vaporisation temperature
v = velocity
v_w = wind speed
$\eta_{inverter}$ = inverter efficiency
η_{th} = thermal efficiency
η_s = solar panel system efficiency
ρ = air density

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Declarations. The authors declare that they have no competing interests.

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