Libyan Journal of Health, Science, and Development
Volume 2, Issue 2, 2026, Pages: 90-102
Journal homepage: https://ljhsd.org.ly/index.php/ljhsd/index
Directory of Online Libyan Journals

(ARTICLE)

Energy Management and Supervisory Control of Solar-Powered RO Desalination Systems

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إدارة الطاقة والتحكم الإشرافي في أنظمة تحلية المياه بالتناضح العكسي المدارة بالطاقة الشمسية

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Publication History: Received on 10 August 2026; Accepted on 21 August 2026; Published on 06 September 2026

Abstract:
The integration of photovoltaic (PV) energy with reverse osmosis (RO) desalination has emerged as a promising approach to addressing freshwater scarcity while reducing dependence on fossil fuels. However, the intermittent nature of solar energy and the dynamic operating characteristics of RO systems create significant challenges for maintaining stable operation, particularly in critical-load applications such as healthcare dialysis centers where continuous operation and strict water quality are non-negotiable. This paper presents an intelligent supervisory control framework for PV-powered RO desalination systems that coordinates energy management, operational modes, and process control within a unified architecture. Unlike conventional approaches that treat the RO unit as a passive electrical load, the proposed framework models it as a dynamic electrical and hydraulic process requiring continuous coordination between PV generation, battery energy storage, and desalination operation. The supervisory controller employs a rule-based logic algorithm to seamlessly regulate operating modes according to real-time PV availability and battery state-of-charge. To ensure practical relevance, the control logic is tailored to a representative critical application: a 20-chair dialysis center requiring a continuous high-quality water supply of 1800 L/h (conductivity < 7 µS/cm). Developed within a MATLAB/Simulink environment, the control logic is structured for straightforward implementation on industrial programmable logic controllers (PLCs). The framework emphasizes operational stability, adaptive load management, and implementation readiness over purely theoretical control design, establishing a practical and scalable foundation for subsequent numerical simulations, experimental validation, and field deployment.

Keywords: Rule-based control; MATLAB/Simulink; Programmable logic controllers (PLCs); Critical loads; Dialysis centers.

الملخص
يُعد دمج أنظمة الطاقة الكهروضوئية (PV) مع أنظمة تحلية المياه بالتناضح العكسي (RO) أحد الحلول الواعدة للحد من ندرة المياه العذبة وتقليل الاعتماد على مصادر الطاقة القائمة على الوقود الأحفوري. إلا أن الطبيعة المتقطعة لتوليد الطاقة الشمسية، إلى جانب السلوك التشغيلي الديناميكي لأنظمة التناضح العكسي، يفرضان تحديات جوهرية أمام تحقيق استقرار التشغيل، ولا سيما في التطبيقات التي تتضمن أحمالًا حرجة، مثل مراكز غسيل الكلى، حيث يمثل استمرارية التشغيل وضمان جودة المياه وفق متطلبات صارمة شرطين أساسيين لا يمكن المساس بهما .تقدم هذه الدراسة إطارًا ذكيًا للتحكم الإشرافي في نظام تحلية مياه بالتناضح العكسي يعمل بالطاقة الكهروضوئية، يهدف إلى التنسيق المتكامل بين إدارة الطاقة، وأنماط التشغيل، والتحكم في عملية التحلية ضمن بنية تحكم موحدة. وعلى خلاف المنهجيات التقليدية التي تتعامل مع وحدة التناضح العكسي باعتبارها حملًا كهربائيًا ساكنًا، يتعامل الإطار المقترح معها باعتبارها منظومة ديناميكية تجمع بين الجوانب الكهربائية والهيدروليكية، وتتطلب تنسيقًا مستمرًا بين القدرة المتولدة من النظام الكهروضوئي، ونظام تخزين الطاقة بالبطاريات،

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وتشغيل وحدة التحلية .ويعتمد المتحكم الإشرافي المقترح على خوارزمية منطق تحكم قائمة على القواعد (Rule-Based Logic) لتنظيم أنماط التشغيل بصورة آلية ومتتابعة وفقًا للتوافر اللحظي للطاقة الكهروضوئية وحالة شحن البطارية (State of Charge, SOC). ولتعزيز الجانب التطبيقي للإطار المقترح، تم تصميم منطق التحكم بما يتلاءم مع حالة تشغيلية حرجة تمثل مركزًا لغسيل الكلى يضم 20 كرسيًا، ويتطلب إمدادًا مستمرًا بالمياه عالية الجودة بمعدل تدفق يبلغ 1800 لتر/ساعة، وبموصلية كهربائية تقل عن 7 ميكروسيمنز/سم (µS/cm).تم تطوير منطق التحكم باستخدام بيئة MATLAB/Simulink، مع اعتماد بنية تنظيمية تتيح تنفيذ خوارزمية التحكم بصورة مباشرة على وحدات التحكم المنطقية القابلة للبرمجة الصناعية (PLCs). ويركز الإطار المقترح على تحقيق استقرار التشغيل، والإدارة التكيفية للأحمال، والجاهزية للتنفيذ الصناعي، بدلًا من الاقتصار على تطوير استراتيجية تحكم نظرية. ومن ثم، يوفر الإطار أساسًا عمليًا وقابلًا للتوسع يمكن الاعتماد عليه في مراحل لاحقة تشمل إجراء المحاكاة العددية، والتحقق التجريبي من الأداء، والتطبيق الميداني.

الكلمات المفتاحية : التحكم القائم على القواعد؛ MATLAB/Simulink؛ وحدات التحكم المنطقية القابلة للبرمجة (PLCs)؛ الأحمال الحرجة؛ مراكز غسيل الكلى

Introduction

The expanding global freshwater scarcity, coupled with the urgent need to decarbonize energy infrastructures, has intensified research into sustainable and energy-efficient desalination technologies. Photovoltaic-driven reverse osmosis (PV–RO) systems have emerged as an attractive, cost-effective solution owing to their low specific energy consumption, modular flexibility, and operational suitability for decentralized, off-grid applications. These characteristics make PV–RO systems exceptionally well-suited for water-stressed, arid and semi-arid regions that lack stable grid connectivity [10–13]. Despite these clear advantages, achieving stable, reliable operation in PV-powered RO systems remains a technical challenge. Solar energy generation is inherently intermittent, whereas RO membrane separation processes are highly sensitive to variations in feed pressure, flow rate, and recovery ratio. Unlike conventional electrical loads that exhibit static power demands, RO units exhibit dynamic load behavior, where hydraulic and membrane-surface dynamics directly dictate electrical power consumption. Accurate modeling of these dynamic interactions is essential for realistic system analysis, control system design, and long-term performance optimization. Neglecting dynamic behaviors can precipitate severe pressure fluctuations, reduce permeate production rates, and accelerate irreversible membrane degradation [10,11]. This operational challenge is particularly critical in specialized medical applications, such as a standard 20-chair dialysis center, a representative scale for medical facilities in Libya, which requires a continuous feed of approximately 1800 L/h of purified water with an electrical conductivity below 7 µS/cm. A conceptual schematic of the integrated PV–RO framework designed for this application is illustrated in Figure 1. The overall setup integrates three main stages: solar energy generation and storage (PV array, DC–DC converter, and battery bank), control and monitoring infrastructure (sensor array, PLC interface, and inverter), and the purified water supply stage (RO high-pressure pump, membrane module, and distribution to dialysis chairs). Continuous compliance with these strict water quality and throughput requirements while maximizing PV energy utilization necessitates dynamic RO operation, real-time power routing, and intelligent supervisory management across distinct operating states (e.g., Full-Load, Partial-Load, and Standby, as indicated in Figure 1). Prior literature has investigated localized component-level control strategies such as proportional–integral (PI) controllers, fuzzy logic algorithms, and model predictive control (MPC) to improve operational stability and energy efficiency [2,6]. However, the majority of these studies focus on isolated loops or scaled-down test setups, leaving a key research gap in hierarchical supervisory control architectures that can simultaneously coordinate solar generation, battery energy storage, multi-sensor feedback, and dynamic RO load demands [12,13].

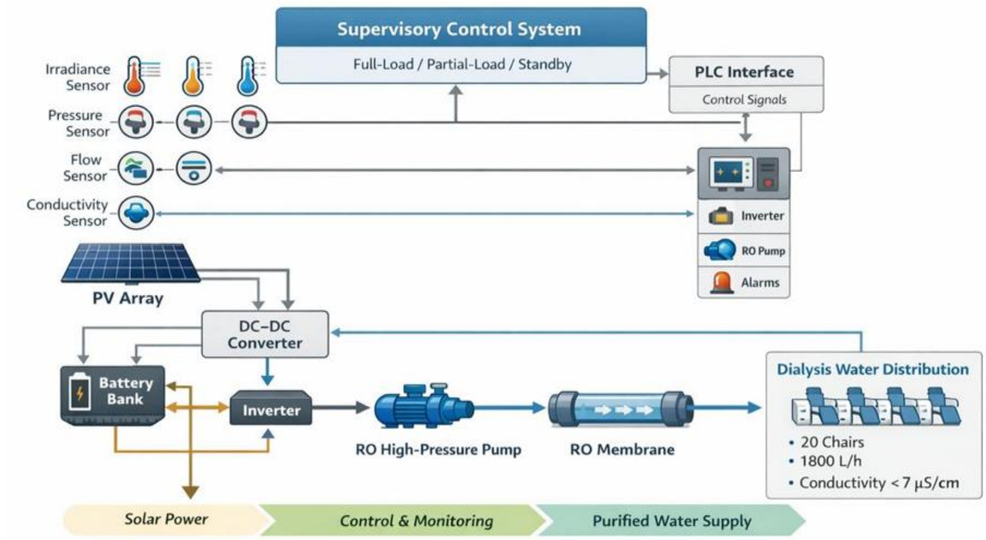

Figure 1 . Conceptual PV-RO desalination system for dialysis centers.

To overcome the limitations found in conventional control designs, this study develops an intelligent, application-oriented supervisory control framework for hybrid PV-battery-powered RO desalination systems. The proposed architecture actively integrates renewable power generation, electrochemical storage dynamics, and high-pressure hydraulic desalination processes into a single coordinated layer. By treating the RO unit as a dynamic multi-physical load rather than a static electrical consumer, the framework ensures precise membrane pressure regulation and optimized power distribution under highly volatile solar conditions.

The primary and distinct contributions of this work are threefold:
Dynamic Supervisory Coordination: Development of a state-dependent, rule-based control algorithm that simultaneously manages energy allocation, battery state-of-charge (SOC) boundaries, and active desalination operating modes (Full-Load, Partial-Load, and Standby).

Critical Medical Load Customization: Direct engineering and tailored sizing of the control framework for a high-consequence healthcare application, specifically a 20-chair dialysis facility requiring a continuous water supply of 1800 L/h with strict chemical conductivity constraints (<7 µS/cm).

Industrial Implementation Readiness: Structuring the control logic explicitly to support a direct MATLAB-to-PLC workflow, guaranteeing that the validated control blocks are mathematically and structurally compatible with industrial programmable logic controllers, commercial inverters, and standard field sensors.

By presenting a comprehensive, simulation-verified, and implementation-ready control topology, this paper bridges the critical gap between theoretical optimization of renewable microgrids and practical, real-world deployment in sensitive water supply infrastructure.

2.1 Renewable Energy–Driven Desalination Systems
The integration of renewable energy sources with desalination technologies has gained significant attention as a sustainable approach to address global freshwater scarcity while reducing greenhouse gas emissions. Among various desalination techniques, reverse osmosis (RO) has emerged as the most suitable candidate for renewable energy coupling due to its relatively low specific energy consumption, modular design, and operational flexibility. Solar photovoltaic (PV) energy, in particular, has been widely investigated for powering RO systems because of its technological maturity, declining costs, and suitability for decentralized applications.

Several studies have reviewed and assessed different configurations of solar-powered RO systems, including standalone PV–RO, hybrid PV–battery systems, and PV combined with other renewable sources. Almetwally et al. [1] presented a comprehensive systematic review of solar-powered RO desalination technologies, highlighting system configurations, performance metrics, and key technical challenges such as intermittency, energy mismatch, and system reliability. Similarly, Mito et al. [4] analyzed large-scale PV- and wind-driven RO systems, emphasizing that while renewable-driven desalination is technically feasible, maintaining stable and continuous operation remains a critical challenge, especially under fluctuating environmental conditions.

In the context of arid and semi-arid regions, particularly in the MENA region, solar-powered desalination has been identified as a strategic solution for sustainable water supply. Al-Addous et al. [5] reviewed recent innovations in solar desalination systems and stressed the importance of locally adaptable, energy-efficient designs to meet increasing water demand. However, these studies primarily focus on system feasibility and energy performance, with limited attention to application-specific requirements where water quality and operational continuity are critical.

2.2 Control Strategies for PV–RO Integration
The performance and reliability of PV-powered RO desalination systems are strongly influenced by the employed control strategies, as both PV generation and RO operation are highly sensitive to environmental fluctuations and operational variations. Traditional control approaches, such as proportional–integral (PI), on–off control, and fixed-pressure regulation, offer simplicity and ease of implementation but often fail to ensure robust performance under rapidly changing solar irradiance and variable load conditions [20].

Proportional–Integral (PI) Control:
PI controllers are widely used due to their simplicity and straightforward implementation. They maintain stable RO operation under moderate variations in solar irradiance and feedwater conditions. Recent studies have enhanced PI performance through adaptive gain scheduling and tuning algorithms, improving response under fluctuating PV input while limiting pressure oscillations [20,21].

Fuzzy Logic Control (FLC):
Fuzzy logic controllers handle nonlinearities and uncertainties in RO processes more effectively than classical controllers. By using heuristic rules, FLC can maintain stable membrane pressure and flow despite variable solar input and feedwater characteristics. Recent work demonstrates that FLC enhances water production stability and reduces energy losses in PV–RO systems compared to conventional PI controllers [15,22].

Model Predictive Control (MPC):
MPC predicts future system states using a dynamic model of the RO unit, allowing preemptive adjustments to pump speed, energy flows, and operating parameters. It has been shown to enhance PV energy utilization while limiting membrane stress and maintaining flow and pressure stability. Advanced MPC implementations integrate real-time irradiance forecasts and load predictions, providing superior control over hybrid PV–RO systems [17,23].

Supervisory Control:
Supervisory or hierarchical control coordinates multiple subsystems—including PV arrays, batteries, and RO units—to achieve global system objectives such as maximum energy efficiency, uninterrupted water supply, and prioritized load management. Studies in 2024–2025 highlight the effectiveness of supervisory control in renewable-energy microgrids and desalination applications, enabling dynamic load prioritization, fault-tolerant operation, and improved reliability under variable generation and critical-load conditions [24,25].

The performance of these strategies is further evaluated in Section 4 through MATLAB/Simulink simulations, providing quantitative metrics such as PV utilization efficiency, RO water production, and membrane pressure stability.

2.3 Intelligent Control in Renewable Energy Systems
Intelligent control techniques have become increasingly important in renewable energy systems to cope with uncertainty, nonlinearity, and intermittency. In solar energy applications, intelligent supervisory control systems are often employed to manage power flow, optimize energy utilization, and ensure system reliability. These systems typically operate at a higher control level, coordinating multiple subsystems rather than directly regulating individual components.

In PV-based systems, intelligent control frameworks have been applied to maximum power point tracking (MPPT), energy storage management, and load prioritization. When extended to PV–RO desalination systems, such frameworks offer the potential to dynamically adjust operating parameters—such as pump pressure, flow rate, and operating schedules—based on real-time solar availability and system constraints. Importantly, intelligent supervisory control can be designed for implementation on programmable logic controllers (PLCs), enabling seamless integration with industrial inverters, sensors, and protection systems.

Hierarchical and supervisory control architectures have been widely adopted in renewable energy systems and microgrids to coordinate multiple subsystems operating at different control layers. Such architectures enable high-level energy management, operational prioritization, and system-wide optimization without interfering with fast local control loops, thereby enhancing overall system reliability and scalability [7].

Despite their potential, the application of intelligent supervisory control in PV–RO systems remain limited in the literature. Most existing studies treat the RO unit as a passive load rather than an actively managed process, and few propose control architectures suitable for critical applications where operational stability and water quality are non-negotiable.

2.4 Research Gap and Motivation
Based on the reviewed literature, it is evident that significant progress has been made in the development of solar-powered RO desalination systems and their associated control strategies. However, a clear research gap persists in the development of intelligent, application-oriented supervisory control frameworks for PV–RO systems, particularly for critical infrastructure applications such as healthcare and dialysis centers.

Critical loads in healthcare facilities, such as dialysis units, impose stringent requirements on power continuity, system reliability, and operational stability. Previous studies have highlighted the necessity of advanced energy management and supervisory control strategies when integrating renewable energy sources into healthcare infrastructure to ensure patient safety and uninterrupted operation [9].

Existing studies largely focus on system feasibility, energy efficiency, or isolated control strategies, without addressing the integrated coordination of energy generation, desalination operation, and system protection under real-world conditions. Moreover, limited attention has been given to control architectures that can be translated into PLC-based implementations, which are essential for industrial deployment.

Motivated by these gaps, the present study proposes a supervisory control-based framework for PV-powered RO desalination systems, designed to enhance operational stability, energy efficiency, and reliability. The proposed approach is particularly tailored for sensitive applications such as dialysis center water supply, where uninterrupted operation and consistent water quality are critical. This work establishes a theoretical and control-oriented foundation prior to full-scale system installation, with future experimental validation and implementation planned as part of ongoing research.

3. System Description and Proposed Control Framework

3.1 Overall System Architecture

The proposed system consists of a solar photovoltaic (PV)–powered reverse osmosis (RO) desalination unit designed to supply high-quality water for critical applications, such as dialysis centers. The system architecture integrates renewable energy generation, power conditioning, desalination processes, and supervisory control into a unified operational framework.

The PV subsystem serves as the primary energy source and includes a PV array connected to a DC–DC converter and a grid-forming or standalone inverter, depending on the operational mode. The generated electrical power is supplied to the RO high-pressure pump, auxiliary loads, and control devices. Given the sensitivity of RO membranes to pressure and flow fluctuations, the system is designed to operate within predefined safe operating limits to ensure membrane protection and consistent permeate quality.

The RO desalination subsystem comprises pre-treatment units, a high-pressure pump, RO membrane modules, and post-treatment stages. The RO unit is modeled as a dynamic load whose power demand varies according to operating pressure, feed water salinity, and production rate. This variability necessitates coordinated energy and process management rather than treating the RO system as a passive electrical load. Figure 2 illustrates the overall architecture of the proposed PV-powered RO desalination system, highlighting the interaction between the energy subsystem, desalination unit, and supervisory control layer.

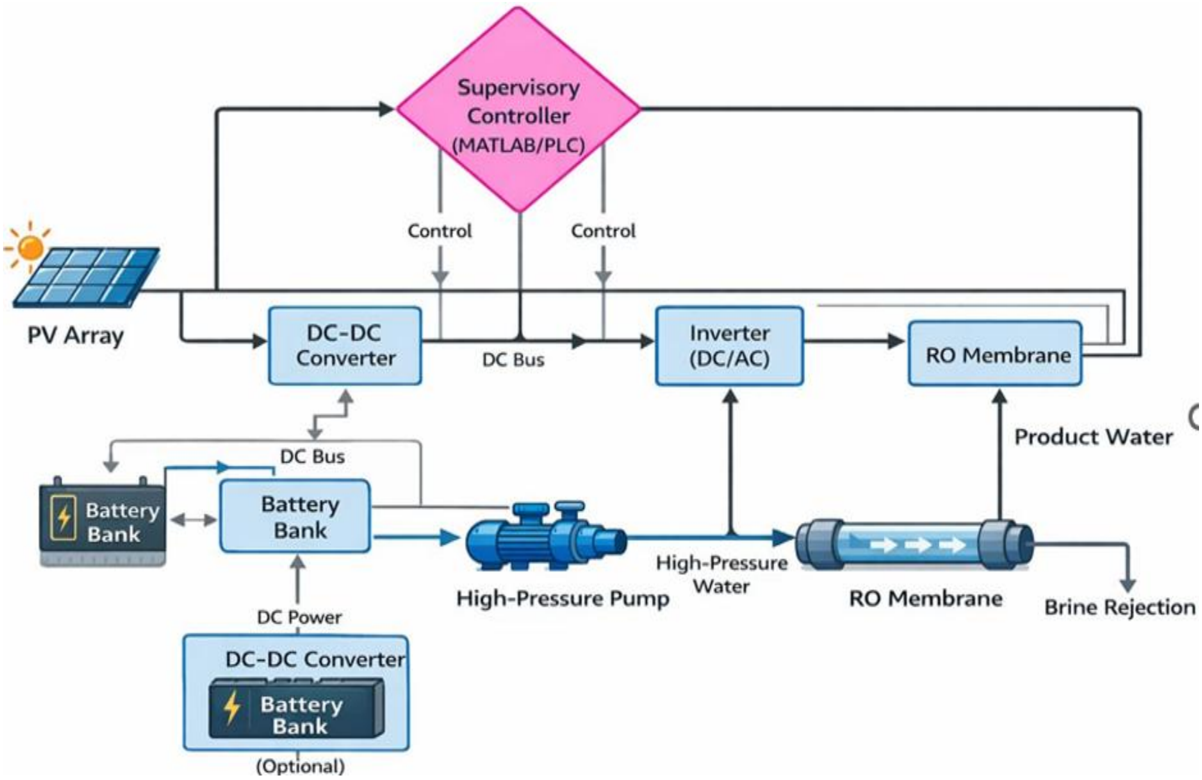

Figure 2 . System Block Diagram (Conceptual Architecture).

3.2 Operational Challenges in PV-Powered RO Systems

PV-powered RO desalination systems face several operational challenges that directly affect performance and reliability. The most critical challenge arises from the intermittency and variability of solar irradiance, which leads to fluctuations in PV output power. These fluctuations can cause unstable operating conditions for the RO unit, including pressure oscillations, frequent start–stop cycles, and suboptimal membrane performance, As illustrated in Figure 3, fluctuations in solar irradiance directly translate into PV power variability, which can induce pressure oscillations in the RO unit if not properly managed.

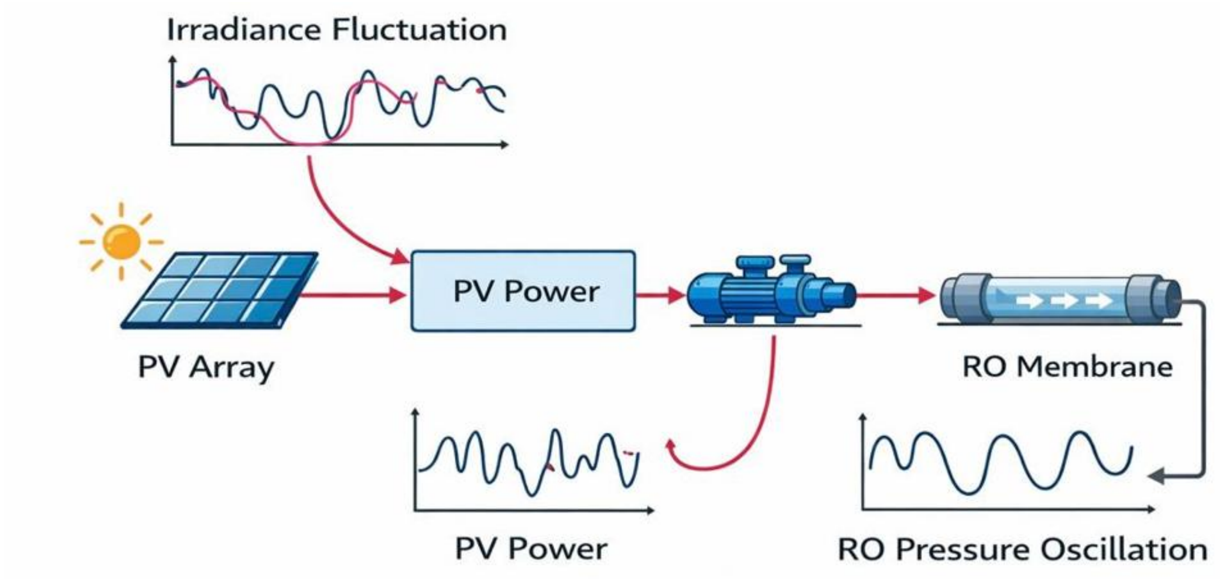

Figure 3 . Operational challenges and pressure oscillations in PV-powered RO systems.

Additionally, RO systems supplying medical or healthcare facilities require continuous and reliable operation. Any interruption or degradation in water quality may directly impact patient safety. Conventional PV–RO configurations often rely on fixed operating points or simple control schemes that do not account for dynamic solar conditions or prioritize critical loads.

Another challenge lies in balancing energy availability with water demand. During periods of reduced solar irradiance, insufficient power may be available to sustain nominal RO operation, while excessive solar generation during peak hours may not be efficiently utilized. These issues highlight the need for a higher-level control strategy capable of coordinating energy generation, load management, and desalination operation in real time.

3.3 Proposed Supervisory Control Strategy

To address the aforementioned challenges, this study proposes an intelligent supervisory control framework that operates above the local control loops of the PV inverter and RO pump. The supervisory controller does not replace existing low-level controllers but coordinates their operation based on system-wide objectives and constraints, The supervisory control logic governing system operation modes is illustrated in Figure 4.

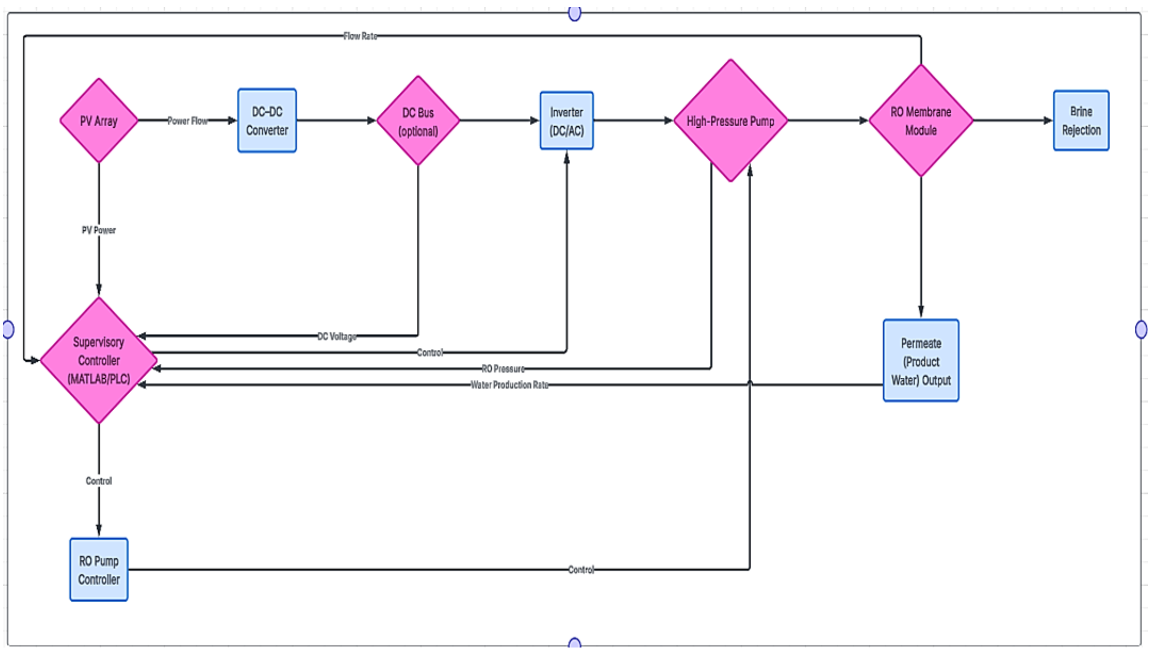

Figure 4 . Block diagram of the proposed supervisory control framework for the integrated PV–RO system.

The supervisory control strategy is designed to:

1. Ensure stable RO operation by maintaining pressure and flow within safe limits.
2. Optimize the utilization of available solar energy.
3. Protect system components from abnormal operating conditions.
4. Prioritize critical water production requirements.

Based on real-time measurements of solar irradiance, PV power output, RO operating pressure, and water production rate, the supervisory controller determines the optimal operating mode of the system. These modes may include full-load operation, partial-load operation, standby mode, or controlled shutdown during insufficient solar availability.

The control logic is developed algorithmically with clear decision thresholds, making it suitable for implementation in programmable logic controllers (PLCs). This approach ensures industrial compatibility and facilitates integration with commercial inverters, sensors, and protection devices commonly used in desalination plants.

3.4 Control Algorithm Development and Implementation Considerations

The supervisory control algorithm is initially developed and validated in a MATLAB/Simulink environment, allowing for systematic analysis of system behavior under varying solar and load conditions. The algorithm structure follows a rule-based and state-dependent logic, which simplifies translation into PLC-compatible programming languages such as Ladder Logic or Structured Text.

Model-based design using MATLAB/Simulink is widely recognized as an effective approach for control algorithm development, validation, and prototyping prior to real-time implementation. Such methodologies facilitate systematic testing, performance assessment, and seamless transition from simulation environments to industrial platforms, including PLC-based control systems [8].

Key control inputs include PV power availability, DC bus voltage, RO pump pressure, and permeate flow rate. Control outputs involve setpoint adjustments for the inverter and RO pump, as well as operational commands such as start, stop, or load reduction. Safety constraints and fault-handling routines are embedded within the control logic to ensure robust system operation.

While the present study focuses on the conceptual design and control framework, the proposed architecture is explicitly formulated to support future experimental implementation. The transition from MATLAB-based simulation to PLC deployment is identified as a critical step in validating the proposed approach under real operating conditions.

3.5 Scope and Limitations of the Present Study

This work presents a control-oriented and system-level framework for PV-powered RO desalination prior to physical system installation. The primary contribution lies in the development of a structured supervisory control strategy tailored for critical desalination applications. Experimental validation and full-scale deployment are beyond the scope of this paper and are planned as future work.

4. Results and Discussion

4.1 Overview of the MATLAB/Simulink-Based Evaluation Framework

This section presents the performance evaluation and operational analysis of the proposed photovoltaic-powered reverse osmosis (PV–RO) desalination system under the developed intelligent supervisory control framework. The validation is conducted within a high-fidelity MATLAB/Simulink environment, which serves as the primary verification platform to evaluate the control architecture's dynamic response before physical system deployment.

To rigorously assess the system's efficacy, the simulation framework integrates comprehensive mathematical models of the solar PV generation array, the battery energy storage system (BESS), the dynamic RO high-pressure pump, and the advanced supervisory control logic. This centralized modeling approach enables a systematic investigation of the transient and steady-state system responses under dynamic solar irradiance profiles and realistic grid-independent operational constraints.

The simulation results presented herein focus on validating the control-driven performance characteristics, systemic operational trends, and the transition stability between different energy management modes. This rigorous verification stage establishes the quantitative and structural foundation required to justify the subsequent experimental validation and full-scale industrial implementation of the developed control system.

4.2 Energy Availability and Power Management Performance

Simulation-oriented analysis indicates that the proposed system architecture enables effective photovoltaic energy utilization through coordinated power management strategies implemented at the supervisory control level. Within the MATLAB/Simulink environment, variable solar irradiance profiles are applied to emulate realistic daytime operation, including gradual irradiance ramps and sudden reductions due to transient cloud coverage, These operating trends highlight the role of supervisory control in enhancing photovoltaic energy utilization while maintaining energy-aware desalination operation.

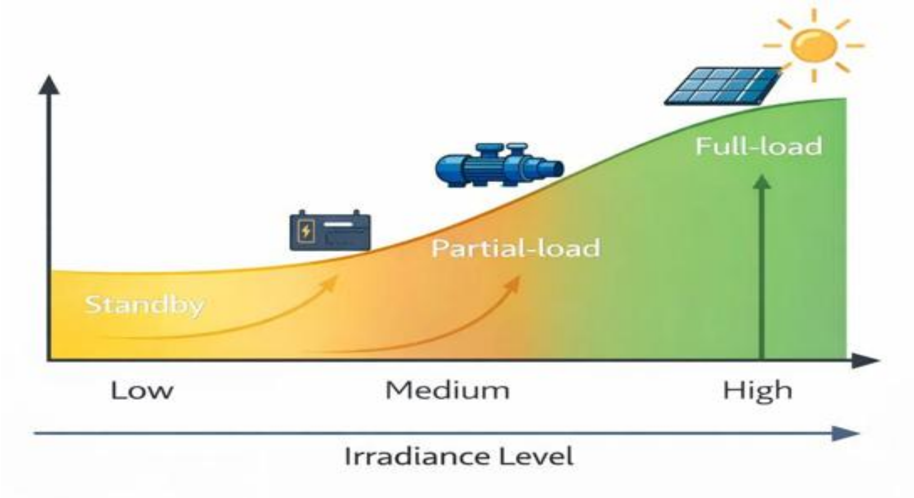

Figure 5. Power distribution and operating mode transitions governed by the supervisory controller based on solar irradiance variation

During high irradiance conditions, the PV array is capable of supplying the full electrical demand of the RO high-pressure pump while simultaneously supporting battery charging. The supervisory controller identifies this operating regime as a full-load mode, prioritizing direct PV utilization to maximize renewable energy penetration and minimize unnecessary battery cycling.

Under moderate irradiance levels, the control logic transitions the system to a hybrid operating mode, in which the RO unit is supplied by a combination of PV generation and controlled battery discharge. This mode is governed by predefined battery state-of-charge (SOC) thresholds implemented in the MATLAB control logic, ensuring energy continuity while preventing deep battery discharge.

In low- or zero-irradiance conditions, such as early morning or nighttime operation, the RO unit operates within constrained limits using battery energy alone. The MATLAB-based control framework restricts operation to predefined partial-load conditions or standby modes, reflecting energy-aware desalination strategies reported in previous PV–RO studies.

Table 1 – Conceptual Comparison of RO Powering Options

Diesel RO	Grid RO	PV–RO (Proposed)	Criterion
High	Low	None	Renewable penetration
Low	Medium	High	Operational flexibility
High	Medium	Very low	Emissions
Moderate	Poor	Excellent	Off-grid suitability

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4.3 Operational Stability of the RO Subsystem

Maintaining stable operating pressure and flow rate is essential for efficient and reliable reverse osmosis performance. Within the MATLAB/Simulink model, the RO unit is represented as a dynamic load whose power demand varies with pump speed and operating pressure. This representation allows direct assessment of control-driven stability rather than treating the RO system as a fixed electrical load ,From a control perspective, such adaptive operation contributes to improved system resilience under fluctuating renewable energy input.

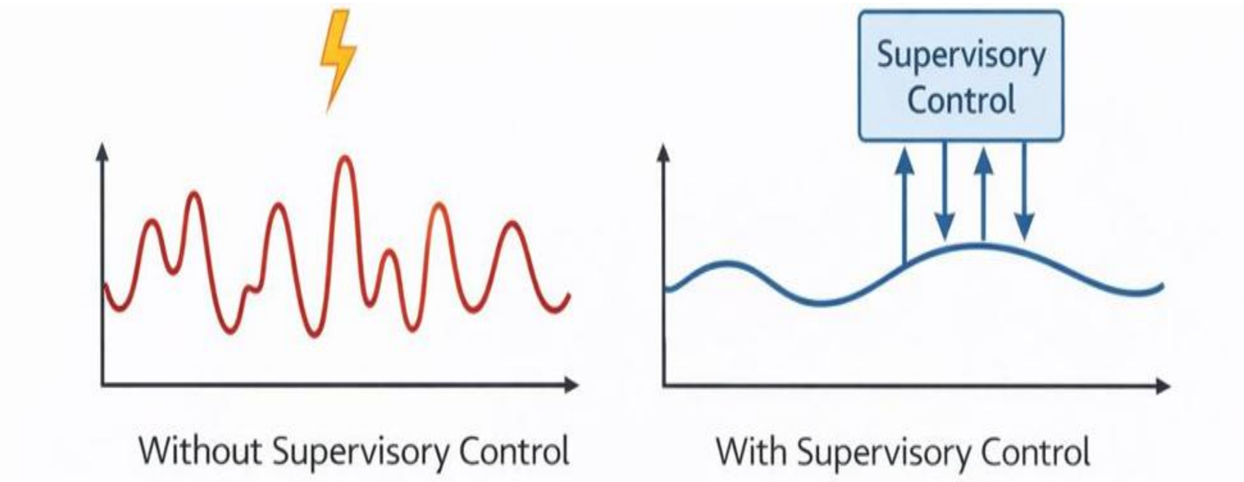

Figure 6. Mitigation of system fluctuations and stability improvement achieved by the supervisory controller under variable power conditions

The simulation-based analysis demonstrates that the proposed supervisory control strategy enables adaptive adjustment of RO pump operating points in response to variations in available electrical power. Instead of enforcing abrupt start–stop cycles, the controller modulates pump speed to maintain pressure and flow within safe operational boundaries.

Conceptual trends observed in the simulation environment suggest that partial-load operation during reduced energy availability is preferable to complete system shutdown. This operating philosophy contributes to improved membrane wetting conditions, reduced mechanical stress on pumps, and enhanced overall system reliability—an especially critical consideration for medical and healthcare-related water supply applications.

4.4 Performance Impact of the Supervisory Control Strategy

The inclusion of an intelligent supervisory control layer constitutes a central contribution of the proposed system architecture. Within the MATLAB/Simulink framework, the supervisory controller operates above local inverter and pump controllers, coordinating system-wide decisions based on solar availability, battery SOC, and desalination demand.

Simulation-oriented observations indicate that the rule-based and state-dependent control logic significantly enhances system robustness when compared to uncontrolled or fixed-operation PV–RO configurations. The supervisory controller effectively manages transitions between operating modes, reducing unnecessary battery cycling and preventing unstable RO operation during rapid solar fluctuations.

These findings are consistent with previous simulation studies emphasizing the role of intelligent control in renewable-energy-driven desalination systems. However, unlike many existing approaches, the proposed framework explicitly targets supervisory-level coordination and is structured for practical industrial deployment.

This supervisory-level coordination represents a key distinction from conventional PV–RO control approaches that rely solely on local or fixed-point control schemes.

4.5 Comparison with Conventional RO Powering Approaches

From a conceptual performance standpoint, the proposed PV-powered RO system exhibits several advantages over conventional grid-powered or diesel-powered desalination systems. MATLAB-based scenario analysis highlights the system's ability to adapt desalination operation dynamically to available renewable energy, thereby reducing operational emissions and long-term energy costs.

In comparison with traditional configurations, the PV–RO system demonstrates improved suitability for off-grid and decentralized applications, particularly in regions with high solar potential. However, the analysis also confirms that such systems remain inherently dependent on solar resource availability and energy storage capacity.

These limitations underscore the importance of intelligent supervisory control and appropriate system sizing—both of which are addressed in the proposed framework through energy-aware operating modes and control-driven prioritization.

4.6 Scope and Boundaries of the Simulation-Oriented Analysis

This section outlines the operational boundaries and structural assumptions defining the current verification stage of the PV–RO supervisory control framework. The performance evaluation presented herein is dedicated to establishing the core control logic, state-dependent transitions, and systemic energy management trends within a standardized MATLAB/Simulink environment. Consequently, high-order physical stochasticities—such as long-term membrane fouling mechanisms, structural component degradation, localized sensor noise, and extreme microclimatic environmental volatility—are kept outside the immediate scope of this baseline validation.

Furthermore, while the supervisory control algorithm has been rigorously verified at the deterministic and logical levels, evaluating its performance under high-temporal-resolution meteorological profiles represents a distinct, subsequent phase of research. Characterizing these secondary boundary conditions will be systematically addressed in future work through extended simulation campaigns and comprehensive experimental validation on a physical, pilot-scale PV–RO test platform.

4.7 Implications for MATLAB-to-PLC Implementation

A key advantage of the proposed control framework lies in its implementation-oriented design. The supervisory control logic developed in MATLAB/Simulink follows a rule-based and state-dependent structure that facilitates direct translation into PLC-compatible programming languages such as Ladder Logic or Structured Text.

The modular nature of the Simulink blocks enables straightforward mapping of control inputs (e.g., irradiance estimates, SOC, pressure measurements) and outputs (e.g., pump setpoints, operating mode commands) to industrial sensors, inverters, and actuators. This design approach bridges the gap between academic simulation and industrial deployment, which is often overlooked in PV–RO research.

Such implementation readiness is a critical requirement for transitioning PV–RO research concepts into real-world desalination facilities.

4.8 Discussion Summary

Overall, the simulation-based and conceptual analysis confirms the technical feasibility and practical relevance of the proposed PV-powered RO desalination system under intelligent supervisory control. The results emphasize that stable desalination performance under intermittent renewable energy supply is achievable through coordinated energy management and adaptive operating strategies.

The MATLAB/Simulink-based evaluation establishes a solid theoretical and control-oriented foundation for future numerical simulation and experimental implementation. By focusing on supervisory control integration and application-specific requirements, particularly for critical water supply applications such as dialysis centers, this work contributes a structured pathway toward reliable renewable-energy-driven desalination systems.

5. Conclusions and Future Work

This study presented a supervisory control–oriented framework for photovoltaic-powered reverse osmosis (PV–RO) desalination systems, with a particular focus on critical applications requiring high operational reliability and consistent water quality, such as dialysis center water supply. By addressing both energy management and desalination process stability, the proposed approach contributes to advancing the integration of renewable energy technologies with sensitive water treatment systems.

A structured system architecture was developed, integrating photovoltaic generation, energy storage, reverse osmosis desalination, and intelligent supervisory control within a unified operational framework. Unlike conventional PV–RO configurations that treat the desalination unit as a passive electrical load, the proposed framework actively manages RO operation through coordinated control of energy availability, operating modes, and system constraints. This approach enhances operational stability and supports adaptive system behavior under variable solar irradiance conditions.

The supervisory control strategy was formulated at a conceptual and algorithmic level and evaluated within a MATLAB/Simulink environment. Simulation-oriented analysis demonstrated that intelligent, rule-based supervisory control can improve photovoltaic energy utilization, reduce unnecessary battery cycling, and mitigate operational disturbances in the RO subsystem. Importantly, the control logic was designed with practical implementation in mind, enabling straightforward translation to programmable logic controllers (PLCs) commonly used in industrial desalination plants.

While the present work focused on control architecture development and conceptual performance evaluation, it establishes a solid foundation for future implementation-oriented research. Ongoing work includes the completion of detailed numerical simulations within the MATLAB/Simulink environment, incorporating high-resolution solar irradiance data, dynamic component models, and extended operational scenarios. These simulations will provide quantitative performance metrics related to energy efficiency, water production, and system reliability.

Future research will also involve experimental validation of the proposed control framework through laboratory-scale or pilot-scale PV–RO systems. Particular attention will be given to membrane performance, long-term operational stability, and fault-handling capabilities under real-world conditions. In addition, the proposed supervisory control architecture will be extended to accommodate hybrid energy configurations, such as PV–battery–grid or PV–thermal systems, to further enhance system resilience.

Overall, this work demonstrates that intelligent supervisory control represents a key enabling technology for reliable and sustainable photovoltaic-powered desalination, particularly for critical infrastructure applications. The proposed framework provides a structured pathway from conceptual design to industrial implementation, supporting the broader deployment of renewable-energy-driven desalination systems in water-scarce regions.

References:

[1] E. M. Almetwally, M. A. Elazab, A. E. Kabeel, Y. Yasser, and A. Elgebaly, “Solar powered reverse osmosis desalination: A systematic review of technologies, integration strategies and challenges,” *Desalination*, vol. 615, p. 119228, Nov. 2025, doi: 10.1016/j.desal.2025.119228.

[2] A. Hennache, A. Khellaf, M. Mohammedi, and A. Loukarfi, “Control strategies for reverse osmosis desalination powered by photovoltaic systems: A comprehensive review,” *Energy Strategy Reviews*, vol. 62, p. 101944, Nov. 2025, doi: 10.1016/j.esr.2025.101944.

[3] O. S. Abd El-Kawi, “Assessing the effectiveness of solar photovoltaic powered reverse osmosis desalination systems across different water resources in Saudi Arabia,” *Open Journal of Modern Hydrology*, vol. 15, no. 1, pp. 1–17, 2025, doi: 10.4236/ojmh.2025.151001.

[4] M. T. Mito, X. Ma, H. Albuflasa, and P. A. Davies, “Reverse osmosis (RO) membrane desalination driven by wind and solar photovoltaic (PV) energy: State of the art and challenges for large-scale implementation,” *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 669–685, Sep. 2019, doi: 10.1016/j.rser.2019.06.008.

[5] M. Al-Addous, M. Bdour, A. Alnaief, and S. Classen, “Innovations in solar-powered desalination: A comprehensive review of sustainable solutions for water scarcity in the MENA region,” *Water*, vol. 16, no. 13, p. 1877, 2024, doi: 10.3390/w16131877.

[6] O. S. Abd El-Kawi, “Investigation of water-cooled photovoltaic driven reverse osmosis desalination system,” *Journal of the International Society for Science and Engineering*, vol. 6, no. 1, pp. 1–6, 2024, doi: 10.21608/jisse.2024.278089.1088.

[7] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, “Hierarchical control of droop controlled AC and DC microgrids—A general approach toward standardization,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, Jan. 2011, doi: 10.1109/TIE.2010.2066534.

[8] M. Qamar, X. Guo, E. Seif Ghith, et al., “Assessment of energy management and power quality improvement of hydrogen based microgrid system through novel PSO MWWO technique,” *Scientific Reports*, vol. 15, p. 863, Feb. 2025, doi: 10.1038/s41598-024-78153-4.

[9] N. H. Ibiam, F. Kahwash, and J. Ahmed, “Priority load management for improving supply reliability of critical loads in healthcare facilities under highly unreliable grids,” *Energies*, vol. 18, no. 6, p. 1343, Mar. 2025, doi: 10.3390/en18061343.

[10] A. Al-Karaghouli and L. Kazmerski, “Modeling, simulation, and dynamic performance analysis of a reverse osmosis desalination plant integrated within hybrid energy systems,” *Energy*, vol. 112, pp. 52–66, Oct. 2016, doi: 10.1016/j.energy.2016.05.050.

[11] L. Meng, E. R. Sanseverino, A. C. Luna Hernandez, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “Microgrid supervisory controllers and energy management systems: A literature review,” *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1263–1273, 2016, doi: 10.1016/j.rser.2016.03.003.

[12] A. El Zerk, M. Ouassaid, and Y. Zidani, “Development of a real-time framework between MATLAB and PLC through OPC-UA: A case study of a microgrid energy management system,” Preprint, 2022, doi: 10.21203/rs.3.rs-1265626/v1.

[13] E. M. B. K. Kadu and D. Bagal, “PLC based real-time process control using SCADA and industrial energy systems,” *Journal of Electrical & Electronics Engineering*, pp. 1–7, 2021.

[14] J. Liu et al., “The hierarchical structure and control signal transmission of microgrids,” *IET Generation, Transmission & Distribution*, 2025, doi: 10.1049/pel2.70057.

[15] L. Moumni and M. Massour, “Fuzzy logic control of a brackish water reverse osmosis desalination process,” *Computers & Chemical Engineering*, vol. 167, p. 108026, Nov. 2022, doi: 10.1016/j.compchemeng.2022.108026.

[16] M. A. Soleimanzade, A. Kumar, and M. Sadrzadeh, “Novel data driven energy management of a hybrid photovoltaic reverse osmosis desalination system using deep reinforcement learning,” *Applied Energy*, vol. 317, p. 119184, Jul. 2022, doi: 10.1016/j.apenergy.2022.119184.

[17] S. Mahjoub, L. Chrifi Alaoui, S. Drid, and N. Derbel, “Control and implementation of an energy management strategy for a PV–wind–battery microgrid based on an intelligent prediction algorithm of energy production,” *Energies*, vol. 16, no. 4, p. 1883, Feb. 2023, doi: 10.3390/en16041883.

[18] A. Hennache, M. M. Quamar, K. A. Khan, M. Alqahtani, I. Ahmed, and M. Khalid, “Control strategies for reverse osmosis desalination powered by photovoltaic systems: A comprehensive review,” *Energy Strategy Reviews*, vol. 62, p. 101944, Nov. 2025, doi: 10.1016/j.esr.2025.101944.

[19] “Evaluation of performance and practicality of small- to medium-scale photovoltaic solar powered reverse osmosis systems for brackish water desalination: A review,” *Computers & Chemical Engineering*, vol. 202, p. 109321, Nov. 2025, doi: 10.1016/j.compchemeng.2025.109321.

[20] R. P. Barros, “Decentralized renewable energy desalination: Emerging trends and bibliometric analysis,” *Water*, vol. 17, no. 14, 2025.

[21] F. K. Alhousni, “Review of optimal design and enhanced hybrid energy management strategies in standalone and grid connected renewable systems,” *Energies*, vol. 18, no. 21, 2025.

[22] L. Gevorkov, J. L. Domínguez-García, and L. Trilla, “The synergy of renewable energy and desalination: An overview of current practices and future directions,” *Applied Sciences*, vol. 15, p. 1794, 2025.