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Article

Solar PV System Design for Enhancing Sustainability in SWRO Desalination: The Deir El-Balah Case Study

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Abstract: The Gaza Strip faces a dual challenge of severe freshwater scarcity and chronic electricity shortages, constraining the operation of critical infrastructure such as seawater desalination plants. This study investigates the design and feasibility of integrating a solar photovoltaic (PV) system into the Deir El-Balah seawater reverse osmosis (SWRO) desalination plant to enhance sustainability, reduce dependency on external electricity supplies, and minimize environmental impacts. Using the Helioscope simulation tool, both on-grid and off-grid scenarios were evaluated to assess system performance under local solar conditions. The optimized design requires 2,663 Canadian Solar HiKu CS3W-415P modules with Enphase M250 inverters, yielding a total installed capacity of 1.11 MWp and an AC output of 639 kW. Modules were allocated across rooftop structures and ground-mounted plots to maximize land-use efficiency. The system can meet the plant's daily demand of approximately 1,100 kWh, thereby reducing reliance on fossil fuels and mitigating greenhouse gas emissions. Beyond technical performance, the integration of solar PV offers strategic benefits, including cost savings, improved energy security, and alignment with global sustainability agendas. The findings highlight the potential of renewable-powered desalination to contribute to Sustainable Development Goals (SDGs 6, 7, and 13) while advancing resilience and energy–water security in resource-constrained regions.

Keywords: Solar Photovoltaic; Desalination; Sustainability; Gaza Strip; Reverse Osmosis; Helioscope Simulation; Energy–Water Nexus

1. Introduction

The issue of freshwater scarcity has become a major global challenge, driven by increasing consumption and rapid population growth. This challenge is particularly acute in arid and semi-arid regions such as the Middle East and North Africa, where limited natural water resources are under increasing pressure due to climate change, population growth, and unsustainable extraction practices [1]. Several countries in the region have already adopted desalination as a strategic response to these pressures. In the Gaza Strip, the water sector is often described as being in a humanitarian crisis, with the underlying coastal aquifer—the region's sole water source—heavily overexploited to meet domestic, agricultural, and industrial demands [2].

Specifically, Gaza faces challenges in both water quantity and quality. The coastal aquifer, stretching approximately 42 km along the shoreline, is the primary source of freshwater. However, seawater intrusion has caused high salinity levels in most wells, rendering the extracted water unsuitable for human consumption according to World Health Organization (WHO) standards and Palestinian Water Authority (PWA) guidelines. As a result, the PWA has identified desalination as a strategic solution for the Gaza Strip [3,4].

From an environmental perspective, desalination has relatively fewer negative impacts compared to alternative options. In reverse osmosis (RO) desalination, energy consumption plays a central role in operational performance and costs [5]. Consequently, from an economic standpoint, energy expenses are a critical factor in Gaza's desalination operations. Given the persistent energy crisis, renewable energy sources have been strongly recommended for desalination. Among the available alternatives, solar energy stands out as the most feasible choice under Gaza's climatic conditions in the Middle East [6].

The Gaza Strip is characterized by hot summers and mild winters, with a population growth rate of 2.7% annually. This rapid growth increases both water and energy demand, leading to greater pressure on already scarce resources and contributing to rising pollution levels [7]. At present, Gaza suffers from a severe electricity shortage, largely due to reliance on fossil fuels and externally controlled supply lines. This shortage has had direct economic and social impacts, worsening living conditions. Although the electricity crisis has persisted since 2005, responses have been mostly limited to scientific recommendations rather than practical implementation. These studies consistently highlight renewable energy as a potential solution to Gaza's energy challenges [8].

Energy is crucial for both economic growth and social well-being, but it also poses environmental challenges that threaten sustainable development. Rapid technological advancements and improvements in living standards have driven a sharp increase in energy demand. In the context of desalination, reverse osmosis (RO) is widely considered the most cost-effective method in the Gaza Strip [9]. However, energy accounts for 30–50% of the total desalination cost, depending on the power source used. Therefore, reducing energy consumption is key to lowering water production costs [10]. In Gaza, however, energy resources are largely controlled externally, with Israeli policies restricting local electricity generation capacity. From a sustainability perspective, renewable energy—particularly solar—has been recommended to power desalination systems [11]. This situation underscores the importance of developing a clean and independent energy supply, with solar PV emerging as a central focus for future research and planning in Gaza [8].

Palestine, particularly the Gaza Strip, has substantial solar energy potential. The region receives nearly 3,000 hours of sunshine annually, with average daily solar radiation of about 3.7 kWh/m^2 on horizontal surfaces and up to 6.2 kWh/m^2 on south-facing tilted surfaces. The lowest radiation levels occur in December (3.7 kWh/m^2/day in Jabalia), while the highest are in June (7.5 kWh/m^2/day in Rafah). These favorable conditions strongly support the integration of solar PV into electricity generation and water desalination [8,12]. Accordingly, this study examines the feasibility of integrating solar PV into the Deir El-Balah SWRO desalination plant. While previous studies have generally emphasized the potential of renewable energy in Gaza or provided theoretical recommendations for solar adoption, few have developed a detailed design and performance assessment tailored to the operational requirements of an existing desalination facility. This gap is particularly relevant given the plant's critical role in addressing Gaza's water crisis and its dependence on an unreliable electricity supply.

This study extends previous research by coupling Helioscope-based photovoltaic (PV) simulation with a sustainability-oriented policy framework customized for Gaza's post-crisis water–energy context. Unlike earlier works that focused mainly on system sizing or techno-economic optimization, the present study integrates technical modeling, environmental assessment, and policy implications into a unified design approach. This combined perspective provides both methodological innovation and practical guidance for PV-SWRO integration in resource-scarce and conflict-affected regions.

The analysis in this study, therefore, focuses on calculating the optimal PV system size and configuration required to meet the plant's daily energy demand, while also evaluating its economic viability using the Helioscope simulation tool. By linking technical design with environmental and sustainability considerations, the study provides a practical model for renewable-powered desalination that can inform both local decision-making and broader regional strategies in water-scarce, energy-constrained contexts.

2. Materials and Methods

2.1. Study Area and SWRO Deir El-Balah Plant

The Deir El-Balah seawater reverse osmosis (SWRO) desalination plant is located in the central Gaza Strip and was originally funded by the Austrian Government in collaboration with the Palestinian National Authority. The project was established to supply potable water to the densely populated areas of Deir El-Balah and Al-Zwaydah, as shown in **Figure 1**.

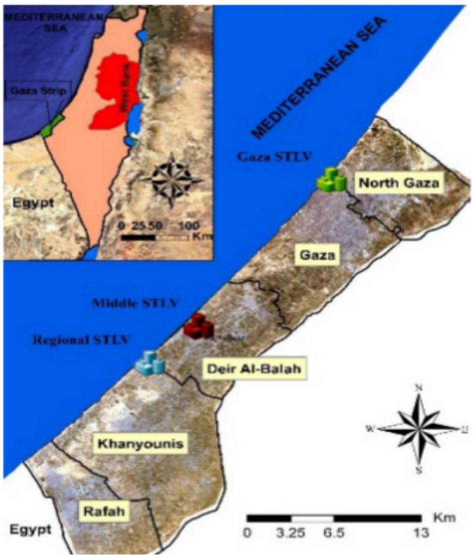

Figure 1. Location of SWRO desalination plant in the Gaza Strip [1].

The plant was constructed in phases, beginning in 2000, with an initial design capacity of 600 m^3/day. Over time, the facility underwent several expansions, and its current operational capacity has reached 6,000 m^3/day of potable water. The seawater intake system consists of five beach wells, from which raw water is pumped for treatment. The brine generated by the process is discharged back into the sea [11].

The produced water is distributed through a dedicated pipeline network to Deir El-Balah and Al-Zwaydah, while additional quantities are transported by tankers to surrounding areas. The desalinated water meets high-quality standards, with a total dissolved solids (TDS) concentration of approximately 80 ppm after treatment.

2.2. Technical Description

The desalination plant sources seawater from five beach wells located near the shoreline, of which three are operational and two are on standby. Each well is designed to deliver 250 m^3/h of raw water, giving the plant a maximum production capacity of 6000 m^3/day when operated continuously. The pumps and electromechanical equipment are sized to handle this capacity.

After intake, the seawater passes through 5-micron cartridge filters equipped with differential pressure transmitters (max. 1.5 bar). It is then pressurized by high-pressure pumps to the required operational level of 65–70 bar before entering the RO unit. The system utilizes spiral-wound thin-film composite (TFC) membranes with an 8-inch diameter and 40-inch length, arranged in pressure vessels that can accommodate up to 654 elements. Under typical operating conditions, the feedwater flow rate is 250 m^3/h, producing a permeate flow of 100 m^3/h and a brine flow of 150 m^3/h, corresponding to a water recovery rate of about 40%. The brine is discharged back into the sea [13].

To ensure reliable operation, the plant performs automatic flushing during shutdowns using permeate water and a dedicated flushing pump to clean the RO membranes, pumps, and pipes. The high-pressure feed system includes two pumps connected in series: the first pump is coupled with a Pelton turbine for energy recovery from the high-pressure brine stream, while the second is driven by a variable-speed electric motor to reach the final required pressure.

2.3. Energy Demand of the Plant

The design capacity of the Deir El-Balah SWRO desalination plant is 6000 m^3/day of potable water. Accordingly, the mechanical and electromechanical equipment of the RO unit has been sized to handle this production rate. The power consumption was calculated based on feedwater with a TDS of 42,000 ppm and a recovery rate of 40%. The total electrical load required to operate the RO unit over 24 hours is estimated at approximately 1100 kWh/day, which includes the demand of high-pressure pumps and other auxiliary systems within the plant [11].

2.4. Methodology of PV System Design

The research methodology was structured in three stages. In the first stage, detailed data on the desalination plant's electricity consumption were gathered from operational records, technical reports, and on-site visits. These included specifications of pumps, membranes, and auxiliary systems, as well as historical performance data. In parallel, solar radiation and climate data for the Gaza Strip were obtained from regional meteorological datasets and satellite-based solar resource databases. The collected data were then processed to estimate the daily and annual energy demand of the plant under standard operating conditions.

In the second stage, a solar photovoltaic (PV) system was designed for the SWRO desalination plant, considering both off-grid and on-grid configurations, using the Helioscope simulation tool [14]. The model provided design outputs, energy calculations, and site-specific solar maps. Finally, the third stage involved evaluating the feasibility of the PV system size, assessing whether the system could supply the required voltage and current ratings for the plant's components, and meet the overall electricity demand. The results were also compared with conventional grid electricity.

Off-Grid PV System: In the first scenario, the SWRO plant was designed to operate on a stand-alone solar energy system (off-grid). Such systems are not connected to the utility grid, and their performance depends entirely on solar irradiation and storage capacity. **Figure 2a** presents the conceptual design of the proposed off-grid PV system, which was evaluated to determine its ability to supply the full daily energy demand.

On-Grid PV System: The second scenario considered an on-grid PV system, in which the solar installation is connected to the public electricity grid. The advantage of this configuration is its flexibility to balance supply and demand. When the PV system generates more electricity than required, the excess energy can be exported to the grid through net metering. Conversely, when solar generation is insufficient, the plant can draw electricity from the grid to maintain continuous operation. **Figure 2b** illustrates the conceptual design of the proposed on-grid PV system.

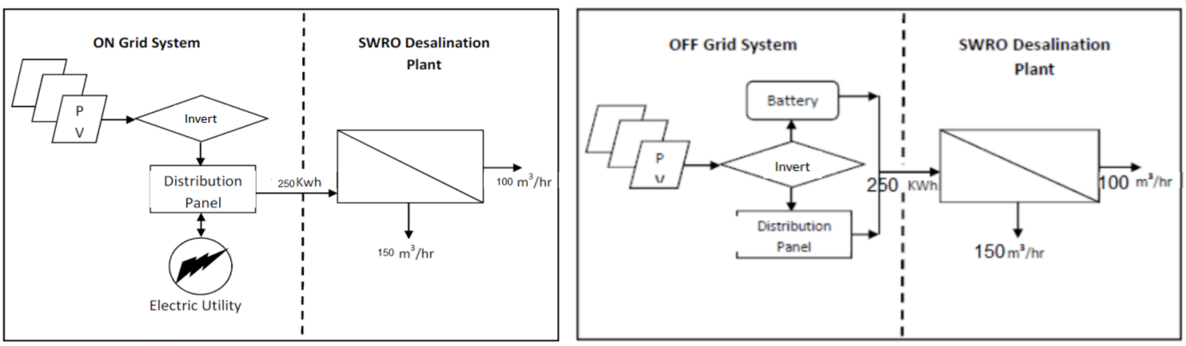

Figure 2. (**a**) Conceptual layouts of the proposed PV-powered SWRO desalination plant: On-grid configuration; (**b**) Conceptual layouts of the proposed PV-powered SWRO desalination plant: Off-grid configuration.

The Helioscope simulations were conducted using Typical Meteorological Year (TMY) data from the PVGIS database for the 2018–2020 period. The temporal resolution of solar radiation input was hourly, enabling accurate estimation of diurnal performance variations.

3. Results and Discussions

3.1. Photovoltaic (PV) Module

The Helioscope simulation identified the HiKu CS3W-415P module (Canadian Solar) as the most suitable unit for the system design. The module provides a rated output power of 415 W, with a maximum power point voltage

(Vmp) of 39.3 V and a maximum power point current (Imp) of 10.56 A. Under standard test conditions (STC: 1000 W/m^2, 25 °C, AM 1.5 spectrum), the module achieved a conversion efficiency of approximately 20.4%, consistent with manufacturer specifications.

The key electrical and physical parameters of the selected module are summarized in **Table 1**, which served as the basis for calculating the total number of modules required in the plant's PV system.

Table 1. Key specifications of the HiKu CS3W-415P PV module (Canadian Solar).

Parameter	Value
Rated Power (Pmax)	415 W
Voltage at Maximum Power (Vmp)	39.3 V
Current at Maximum Power (Imp)	10.56 A
Open-Circuit Voltage (Voc)	47.8 V
Short-Circuit Current (Isc)	11.14 A
Technology	Si-Poly (144 cells)
Dimensions	1.048 m × 2.108 m
Temp. Coefficient (Pmax)	−0.37%/°C
Temp. Coefficient (Voc)	−0.29%/°C
Temp. Coefficient (Isc)	+0.05%/°C

These results confirm that the module's high efficiency, favorable voltage/current ratings, and robustness under varying climatic conditions make it suitable for large-scale deployment in the Gaza Strip. The parameters obtained formed the input for sizing the complete PV system presented in the following sections.

3.2. Inverter

The Helioscope simulation selected the Enphase M250 (240 V) microinverter as the most suitable option for the PV system configuration. Each inverter provides a maximum AC power output of 240 W (single-phase) and operates within a maximum power point tracking (MPPT) range of 27–39 V, which matches the voltage characteristics of the selected PV modules.

The efficiency curve of the inverter, shown in **Figure 3**, indicates stable performance across the rated operating voltage range, with peak efficiencies above 95%. The detailed electrical specifications are summarized in **Table 2**, which formed the basis for calculating the total number of inverters required in the system.

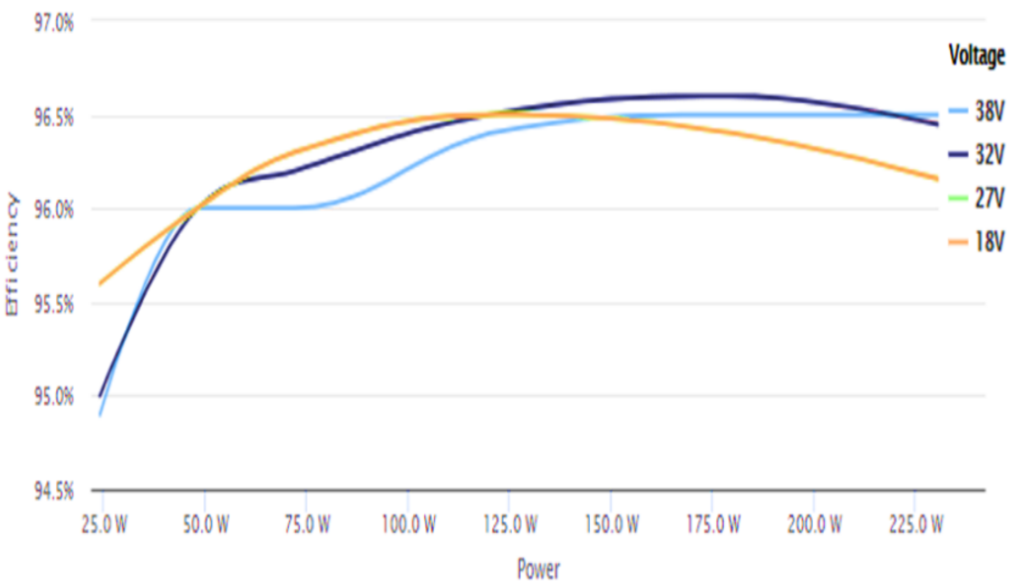

Figure 3. Modeled efficiency curve of the Enphase M250 inverter at different power levels.

Table 2. Key specifications of the Enphase M250 microinverter.

Parameter	Value
Maximum Power Output	240 W
Maximum MPPT Voltage	39 V
Minimum MPPT Voltage	27 V
Maximum DC Voltage	48 V
Minimum DC Voltage	16 V
AC Output	240 V, single-phase

For installation, the simulation determined that the AC network requires 134 copper branch circuits (8 AWG conductors) to ensure safe transmission and proper load balancing across the array. These design outputs confirm the suitability of the Enphase M250 for large-scale deployment in the desalination plant, both in terms of technical compatibility and system reliability.

Figure 3 highlights consistently strong inverter performance across a wide range of operating conditions. Conversion efficiency remains stable, with only minor dips during very high temperatures or at low-power operating points, which is typical for modern inverters. The stability of the conversion stage indicates that system losses at this point are limited and predictable, helping to maintain reliable AC output to the desalination facility. This behavior supports the use of standard grid-tied configurations without specialized mitigation measures, provided that thermal management, ventilation, and routine maintenance are preserved according to manufacturer recommendations.

3.3. Helioscope Simulation Results

The Helioscope simulation produced the final configuration of the PV system required to meet the daily energy demand of the Deir El-Balah SWRO desalination plant. The optimized design consists of 2663 Canadian Solar HiKu CS3W-415P modules, each rated at 415 W, corresponding to a total installed DC capacity of 1.11 MWp. The system uses 2663 Enphase M250 microinverters (240 V), which together provide a total AC output of 639.1 kW. The AC network was modeled to include 134 copper branch circuits (8 AWG) with a cumulative wiring length of approximately 2.36×10^6 ft, ensuring safe load distribution across the installation.

The modules were arranged into five field segments, each with a fixed tilt angle of 18.4° and an azimuth of 180° (south-facing). One segment was mounted on existing rooftop structures within the facility, while the remaining four were distributed across open plots of land located on the northern and western sides of the plant. This hybrid layout maximizes solar exposure while minimizing land occupation within the facility. **Table 3** summarizes the key design outputs generated by Helioscope.

Table 3. Key design parameters of the PV system from Helioscope simulation.

Parameter	Value
Number of Modules	2663
Module Type	Canadian Solar HiKu CS3W-415P
Total DC Capacity	1.11 MWp
Number of Inverters	2663 (Enphase M250, 240 V)
Total AC Capacity	639.1 kW
AC Branch Circuits	134 (8 AWG copper)
Tilt/Azimuth	18.4°/180° (south-facing)
Largest Field Segment	2035 modules, 844.5 kW
Rooftop Mounted Panels	Installed on arbors inside the facility
Ground-Mounted Panels	Installed on northern and western plots adjacent to the plant

To further illustrate the benefits of solar photovoltaic integration, a comparative assessment was carried out between diesel-based electricity and solar-powered desalination. Conventional diesel generation in Gaza is associated with significant emissions of carbon dioxide (CO_2), sulfur oxides (SO_x), and nitrogen oxides (NO_x), as well as higher operational costs. In contrast, solar PV systems eliminate direct emissions and substantially reduce operating expenses. **Figure 4** compares key indicators, demonstrating the substantial reduction in greenhouse gas emissions and air pollutants when replacing fossil-fuel–based electricity with solar energy. The analysis highlights that solar-powered desalination can cut CO_2 emissions by more than 90% and reduce operating costs by approximately half, thereby reinforcing both the environmental and economic sustainability of the Deir El-Balah SWRO plant. While exact life-cycle metrics depend on component sourcing and local operating profiles, the qualitative outcome is robust: displacing fossil-based electricity with solar generation leads to a sustained reduction in emissions over time. These environmental gains complement the operational advantages, particularly the reduced exposure to fuel disruptions and the improved predictability of long-term energy costs.

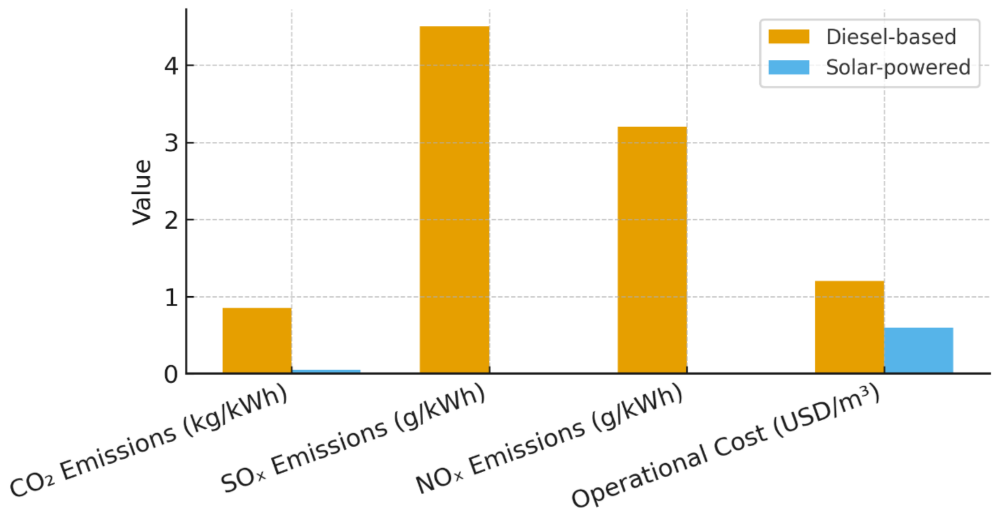

Figure 4. Comparison of diesel-based versus solar-powered desalination in terms of emissions and operational costs for the Deir El-Balah SWRO plant.

A simplified economic assessment was conducted to evaluate the financial feasibility of the proposed PV system. While detailed cost figures are procurement- and tariff-dependent in Gaza's rapidly changing market, the analysis indicates that PV-assisted operation offers markedly lower lifecycle energy costs than grid- or diesel-based supply. In addition, the PV system reduces exposure to fuel price volatility, lowers routine operating expenditures, and provides a predictable long-term cost profile over the system's expected lifetime. These advantages collectively support the economic sustainability of PV integration for SWRO desalination under the study conditions. Moreover, qualitative benchmarking against typical diesel and grid supply scenarios in comparable settings consistently shows superior cost stability for PV over the project lifetime, particularly when factoring in fuel price shocks and supply disruptions.

3.4. PV Module Location

The spatial distribution of the photovoltaic (PV) modules was optimized to balance energy generation requirements with land-use constraints around the desalination facility. A total of 2663 PV modules were allocated across both rooftop structures and adjacent land areas.

To minimize land occupation, part of the system was installed on the roofs and gazebos within the facility, thereby utilizing existing built-up surfaces. The remaining modules were distributed over two ground-mounted plots located on the northern and western sides of the desalination plant, which are owned by the facility. This hybrid approach—combining rooftop and ground-mounted installations—ensures efficient land use while maximizing solar exposure.

This spatial allocation enables the PV system to be integrated without significant land-use conflicts while maintaining optimal conditions for solar capture, thereby supporting the plant's long-term operational sustainability.

An hourly load-matching analysis was performed to evaluate the temporal alignment between PV generation and desalination demand. The results indicate that the PV system supplies approximately 70% of daily energy needs during daylight hours, with residual demand covered by the grid at night or during low irradiance periods. Due to financial and logistical constraints, no battery storage was included in the current design; however, the grid connection provides stability during shortfalls. Future integration of lithium-ion storage could reduce grid reliance by 25–30 %, improving autonomy and resilience under Gaza's intermittent grid conditions.

4. Environmental and Sustainability Implications

The integration of solar photovoltaic (PV) systems into desalination facilities not only addresses the technical and economic challenges of energy supply but also carries profound implications for the environment, sustainability, and policy planning. While section 3 presented the technical design and performance results of the proposed PV system for the Deir El-Balah SWRO plant, this section examines the broader impacts of such integration. It explores the environmental benefits of replacing fossil-fuel-based electricity with solar energy, the contribution of this transition to sustainability and climate goals at both local and global levels, and the policy and strategic perspectives necessary to enable renewable-powered desalination in Gaza. Together, these discussions provide a comprehensive understanding of how solar energy adoption can strengthen the long-term viability and resilience of water infrastructure in resource-constrained contexts.

4.1. Environmental Impact of Solar PV Integration

The integration of solar photovoltaic (PV) systems into the Deir El-Balah SWRO desalination plant has significant environmental advantages compared to reliance on fossil-fuel-based electricity. Conventional energy sources in Gaza are primarily diesel- and heavy-fuel–based, which release greenhouse gases (GHGs) such as carbon dioxide (CO_2) as well as harmful air pollutants including sulfur oxides (SO_x) and nitrogen oxides (NO_x). These emissions contribute to air pollution, acid rain, and climate change, with direct impacts on both environmental quality and human health.

By contrast, PV systems generate electricity without combustion processes, thereby eliminating direct emissions of GHGs and air pollutants [15]. This transition not only reduces the facility's carbon footprint but also contributes to improved air quality and lower health risks in surrounding communities. Moreover, unlike conventional power plants, PV systems do not require water-intensive cooling processes, which helps preserve scarce water resources and prevents thermal or chemical pollution of aquatic ecosystems [16].

For the Deir El-Balah SWRO plant, the adoption of solar energy therefore represents a dual environmental benefit: mitigating the adverse impacts of fossil fuel consumption while supporting cleaner and more sustainable water production.

Beyond the direct reduction of atmospheric emissions, PV adoption minimizes a range of localized environmental externalities. The elimination of fuel deliveries and on-site storage reduces the risk of leaks, spills, and soil contamination near the plant premises—a relevant factor in Gaza's densely populated coastal areas. The reduced use of combustion generators also lessens noise and vibration levels, improving the environmental quality for nearby communities and plant personnel [17].

From an operational standpoint, solar PV offers a cleaner and quieter working environment, which indirectly enhances occupational safety. Furthermore, the absence of fuel storage and exhaust systems simplifies waste management and reduces hazardous residues typically associated with diesel-based operations.

Routine maintenance practices can further strengthen environmental performance. Regular module cleaning using optimized low-water or dry methods limits dust accumulation without imposing additional stress on scarce freshwater resources. Likewise, careful array siting and cable routing can minimize land disturbance and avoid sensitive habitats, ensuring ecological compatibility with the coastal environment of Deir El-Balah [18].

Finally, responsible end-of-life (EoL) planning is essential for maintaining the long-term environmental integrity of PV-based systems. Establishing protocols for recycling and recovery of PV modules, inverters, and metallic components can prevent waste accumulation and enable material circularity. Early integration of EoL strategies into procurement and maintenance contracts will extend equipment life and minimize environmental burdens across the system's lifecycle.

4.2. Contribution to Sustainability and Climate Goals

The integration of solar PV into the Deir El-Balah SWRO desalination plant contributes not only to local environmental protection but also to broader sustainability and climate objectives [19]. Gaza currently faces a severe energy deficit, as illustrated in **Figure 5**, which shows electricity production and imports compared with the steadily rising demand. The figure highlights a persistent gap between supply and demand, aggravated by dependence on external sources, fuel shortages, and political constraints.

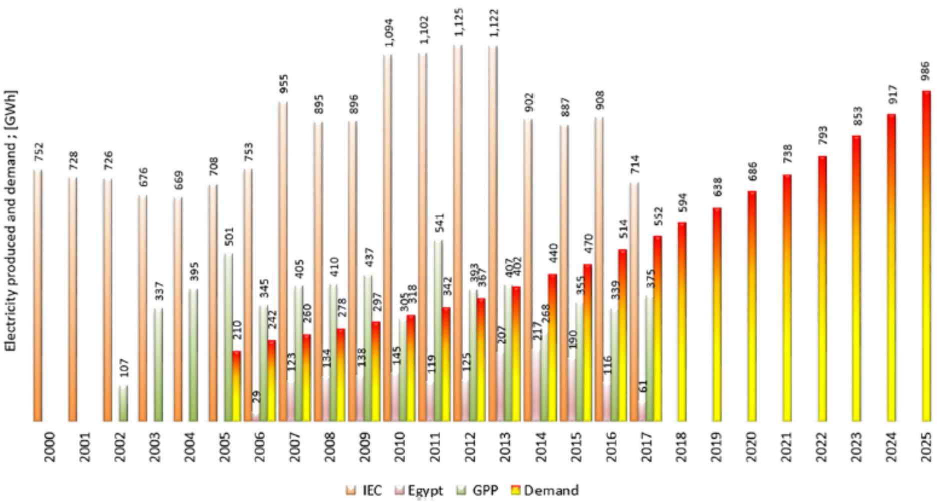

Figure 5. Energy balance in the Gaza Strip and demand forecast (adapted from Palestinian Energy Authority, 2018).

By deploying a 1.1 MWp PV system to power the desalination facility, part of this gap can be alleviated through clean, locally generated electricity. This enhances energy security, reduces vulnerability to external disruptions, and provides a more stable basis for water and energy services.

From a sustainability perspective, the adoption of PV systems directly supports several United Nations Sustainable Development Goals (SDGs), including:

- SDG 6 (Clean Water and Sanitation): ensuring reliable access to potable water through sustainable desalination.
- SDG 7 (Affordable and Clean Energy): increasing the share of renewable energy in the energy mix.
- SDG 13 (Climate Action): reducing carbon emissions and building resilience against climate-related challenges.

The alignment of the desalination project with these goals demonstrates the potential of renewable energy integration as a pathway toward long-term ecological and socio-economic stability in resource-constrained regions.

4.3. Policy and Strategic Perspectives

The transition toward solar-powered desalination at the Deir El-Balah SWRO plant has important policy and strategic implications for Gaza and the broader Palestinian territories. At present, the energy sector is highly dependent on imported electricity and fuel, leaving water and energy services vulnerable to external restrictions. The deployment of solar PV systems for critical infrastructure such as desalination plants can therefore be considered a strategic priority in national planning.

At the policy level, several measures are essential to support this transition:

- Institutional support and regulation: Establishing clear policies that facilitate the integration of renewable energy into public utilities, including water facilities [20].
- Financial mechanisms: Mobilizing international donor support, concessional financing, and public–private partnerships (PPPs) to overcome the high upfront costs of PV installation.
- Land-use and permitting frameworks: Providing streamlined procedures for allocating land and rooftops for solar projects, ensuring minimal conflict with agricultural or urban development.
- Capacity building: Enhancing local technical expertise in solar system design, installation, and maintenance to reduce reliance on external contractors.
- In addition to the water sector, the agricultural sector—the primary consumer of groundwater in Gaza—offers an important avenue for policy innovation. Encouraging farmers to adopt solar-powered irrigation systems and solar-driven pumping for wells could reduce operational costs, alleviate pressure on the electricity grid, and promote more efficient use of scarce resources. When coupled with modern agricultural practices such as

drip irrigation and precision farming, this approach would advance both water conservation and renewable energy adoption as declared in Mizyed et al. studies [21,22].

Strategically, integrating renewable energy into the water sector creates co-benefits:

- It strengthens energy–water security, reducing dependence on external suppliers, which aligns with the Mahdi study [23].
- It contributes to climate resilience, enabling desalination plants to operate even during fuel shortages or political disruptions [24].
- It aligns with regional and international sustainability agendas, positioning Palestine to benefit from climate finance opportunities and global renewable energy initiatives.

In this context, the Deir El-Balah case study demonstrates the feasibility of coupling renewable energy policies with water sector development, offering a replicable model for other regions facing similar challenges of scarcity, dependency, and vulnerability.

The practical implementation of PV-desalination systems in Gaza faces three main barriers: (1) limited access to concessional financing, (2) shortage of specialized maintenance personnel, and (3) intermittent grid stability. Addressing these challenges requires multi-level interventions—blended finance schemes involving international donors, capacity-building for local technicians, and incremental hybrid-grid integration. Establishing a unified energy–water regulatory framework could further enhance long-term scalability and operational reliability. This is aligned with a study conducted in Egypt [25].

5. Conclusions

This study presented the design and feasibility assessment of a 1.1 MWp solar photovoltaic (PV) system to power the Deir El-Balah seawater reverse osmosis (SWRO) desalination plant in the Gaza Strip. The plant, with a capacity of 6,000 m^3/day, faces high operational energy demands and is constrained by chronic electricity shortages and reliance on externally supplied fossil fuels. By integrating PV technology, the facility can significantly reduce its dependence on conventional energy sources, thereby improving operational reliability and lowering long-term costs.

The Helioscope-based simulation demonstrated that a system consisting of 2,663 PV modules and corresponding inverters could adequately supply the plant's energy needs through both on-grid and off-grid configurations. The hybrid use of rooftop and ground-mounted installations further optimizes land utilization while ensuring sufficient solar exposure.

Beyond the technical outcomes, the transition to solar energy has broader environmental and policy implications. It mitigates greenhouse gas emissions and air pollutants, contributes to Sustainable Development Goals (SDGs) related to clean water, clean energy, and climate action, and enhances Gaza's energy and water security. At the policy level, the study highlights the need for supportive institutional frameworks, financial incentives, and capacity-building programs to scale up renewable energy adoption in critical infrastructure.

In conclusion, the integration of PV systems into desalination facilities represents a strategic pathway for sustainable development in resource-constrained and politically vulnerable regions. The Deir El-Balah case study demonstrates not only the technical feasibility but also the environmental and socio-economic value of renewable-powered desalination. Replicating such models can play a pivotal role in addressing the global water–energy nexus, ensuring resilience, and advancing sustainability in the face of growing climatic and demographic pressures.

Funding

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Institutional Review Board Statement

Ethical review and approval were waived for this study because no human or animal subjects were involved. All operational data and technical information were obtained with the official approval of the desalination plant management.

Informed Consent Statement

Not applicable. The study did not involve humans. All operational data were obtained with official approval from the desalination plant management.

Data Availability Statement

All data supporting the findings of this study are available within the manuscript, including the calculation methods and analysis procedures.

Conflicts of Interest

The author declares no conflict of interest.

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