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Management strategies for the efficient energy production of brackish water desalination to ensure reliability, cost reduction, and sustainability

A. Bdour[1,*], A. Hejab[2], L. Almakhadmah[3], M. Hawwa[4]

[1] *Department of Civil Engineering, Faculty of Engineering, Hashemite University, P.O. Box 330127, Zarqa 13133, Jordan*
[2] *Energy Unit, Water Authority of Jordan, Amman 11181, Jordan*
[3] *Laboratories and Quality Unit, Ministry of Energy and Mineral Resources, Amman 11814, Jordan*
[4] *Water Authority of Jordan, Amman 11181, Jordan*

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ABSTRACT

BACKGROUND AND OBJECTIVES: Energy efficiency plays a crucial role in the success and sustainability of desalination technologies. Energy considerations are intricately linked with every aspect of planning, management, and operation in water desalination. This study aims to evaluate and enhance energy requirements, energy efficiency, and the economic feasibility of the Hashemite University photovoltaic brackish water reverse osmosis desalination plant at Hashemite University.
METHODS: This study's aims were achieved by conducting an energy audit and detailed assessment to identify the energy efficiency considerations that should be integrated into the facility's planning, management, and operation strategies. To ensure accurate and reliable data collection and enable a comprehensive analysis of the plant's energy performance, portable energy analyzers and loggers were employed to measure energy consumption, and measurements and verification techniques were recommended and implemented to establish the required baseline. A regression model was utilized to determine the potential energy savings resulting from energy conservation measures. This involved determining the expected savings by calculating the area between two curves: the new actual consumption of the brackish water reverse osmosis plant after implementing energy conservation measures and the curve generated by the model representing the usual consumption in the absence of energy conservation measures.
FINDINGS: This study underscores the challenges faced by desalination, particularly regarding intensive energy consumption. It also presents innovative ways to achieve sustainability by emphasizing energy efficiency, integrating renewable energy, and advocating for a holistic water management approach. It was determined that the maximum specific energy consumption of the Hashemite University photovoltaic brackish water reverse osmosis plant was 0.625 kilowatts per cubic meter. This reflects the actual consumption and energy performance of the plant, which was found to be 192 percent more efficient than the estimated specific energy and 144 percent more efficient than the calculated specific energy. No energy conservation measures were implemented at this stage, as the plant was already operating efficiently. The measured data shall be considered as a baseline for future investigations and monitoring and evaluation of the plant. Many challenges were identified during the current work, including the low quality of raw water and minimal demand for freshwater, which resulted in lower operation hours outside of sun peak hours, while the direct utilization of photovoltaic energy is recommended.
CONCLUSION: Renewable energy and energy recovery were recognized as potential sources for energy savings to achieve sustainable and long-term feasible operation and cost recovery at the Hashemite University photovoltaic brackish water reverse osmosis plant. The feasibility of the plant showed a fast payback period of up to 1.1 years. Utilizing clean solar photovoltaic energy to power the brackish water reverse osmosis plant led to a considerable reduction of greenhouse gases (mainly carbon dioxide). The estimated amount of carbon dioxide reduction during the project's lifetime was 1,289,600 kilograms. The integration of solar energy showed promise for further enhancing energy efficiency and sustainability. This study contributes to making the desalination sector more environmentally friendly and economically viable, which is of paramount importance in addressing global water scarcity concerns.

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8

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8

*Corresponding Author:
Email: *bdour@hu.edu.jo*
Phone: +079 676 9534
ORCID: 0000-0001-6244-9530

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INTRODUCTION

Jordan's government is attempting to meet the future demand for energy through several actions: increased dependence on renewable energy, energy management, use efficiency, finding new energy supplies, financial incentives, and tax exemption to attract investors. Still, some challenges should be taken into account to sustain development, such as the incapability of the current grid to handle the power expansion required by the proposed projects in the near future (Abu-Rumman *et al.,* 2020). According to a Bloomberg report, Jordan has the potential for solar and wind energy use and is one of the leading countries in the adoption of clean energy. So far, the implementation of renewable energy has been successful due to financial incentives, tax and customs exemptions, technical and financial assistance from foreign aid and international agencies, and political and economic stability (Sandri *et al.,* 2020; Drobyazko *et al.,* 2021; Ramli *et al.,* 2022). In 2015, 20 percent (%) of the national budget was consumed by the energy sector, but it was reduced to 10% in 2018 due to the adoption of energy efficiency measures and the increased contribution of renewable energy to the national power mix (Abu-Rumman *et al*., 2020). Fig. 1 shows that in 2020, 21% (about 2,400 megawatts, MW) of electricity was generated from renewable energy resources. To encourage households' installation of renewable energy systems, the Ministry of Energy and Mineral Resources (MEMR) subsidized installation costs by 30%. As a result, 500 thermal solar systems and 1,888 photovoltaic (PV) systems were installed. Moreover, 200 solar systems were installed in rural areas for free, and the cost was equally covered by the MEMR and the International Union for Conservation of Nature (MEMR, 2021). The growing adoption of renewable energy reflects a positive trend toward sustainability and reduced reliance on fossil fuels for power generation (Elsaid *et al.,* 2020; Bogachov *et al.,* 2022; Sivakumar *et al.,* 2022). It also highlights the progress made in transitioning toward a cleaner and more environmentally friendly energy sector.

Solar radiation is widely utilized for water heating purposes and PV electricity generation systems (Ahmad and Schmid, 2002). PV systems have some advantages that make them preferable, such as an absence of moving parts, ease of installation and operation, low maintenance costs, pollution-free operation, and long operation life (Qiblawey *et al*., 2011). The amount of power produced by PV systems depends on the panels' performance and the availability of solar radiation (Alrwashdeh, 2018). In Jordan, direct solar radiation intensity ranges from 5 to 7 kilowatt-hours per square meter (kWh/m^2), with an average of 310 sunny days (Abu-Rumman *et al*., 2020). Jones *et al.* (2016) conducted a simulation model of a PV system in a water pumping and desalination plant for agriculture purposes in selected areas in Jordan Valley and then compared this system with diesel-powered and grid-powered systems. The result was that PV-powered systems were more economical than diesel-powered systems but less economical than off-grid-powered systems based on assumed electricity costs. It was found that PV-powered pumping and desalination plants become profitable with high-return crops when pumping from a shallow well with low water salinity and a low water requirement in areas where solar insolation is high. According to a study by Alrwashdeh (2018), in which solar energy generation was evaluated in different major Jordan governorates (Irbid in the north, Amman in the center, and Aqaba in the south), the annual solar radiation was 1,876 kWh/m^2 in Irbid, 1,967 kWh/m^2 in Amman, and 2,151 kWh/m^2 in Aqaba, and the generated electricity for a fixed configuration per a certain single PV module during the year in Irbid, Amman, and Aqaba is 359.3, 443.1, and 502.0 kWh. Another use for solar radiation is solar ponds, per the study by Saleh *et al.* (2011). The study investigated the performance of a salt ingredient solar pond coupled with desalination plants near the Dead Sea. It was found that the plant could produce 4.3 L/min on average. In conclusion, this type of thermal desalination seems feasible and appropriate under Dead Sea conditions. There is no doubt that Jordan urgently needs desalination to meet the growing demand, and Jordan can utilize renewable energy resources, especially solar and wind energy (MoEnv, 2020a; MoEnv, 2020b). As a water- and energy-scarce country, Jordan must work on brackish and seawater desalination in conjunction with renewable energy resources to supply such technology with the power needed (MWI, 2021; Al-Kharabsheh, 2020). A comprehensive database is needed to be able to utilize them properly. Such energy sources could supply Jordan with its daily electricity requirements and reduce GHG emissions (Baniyounes, 2017). Jaber

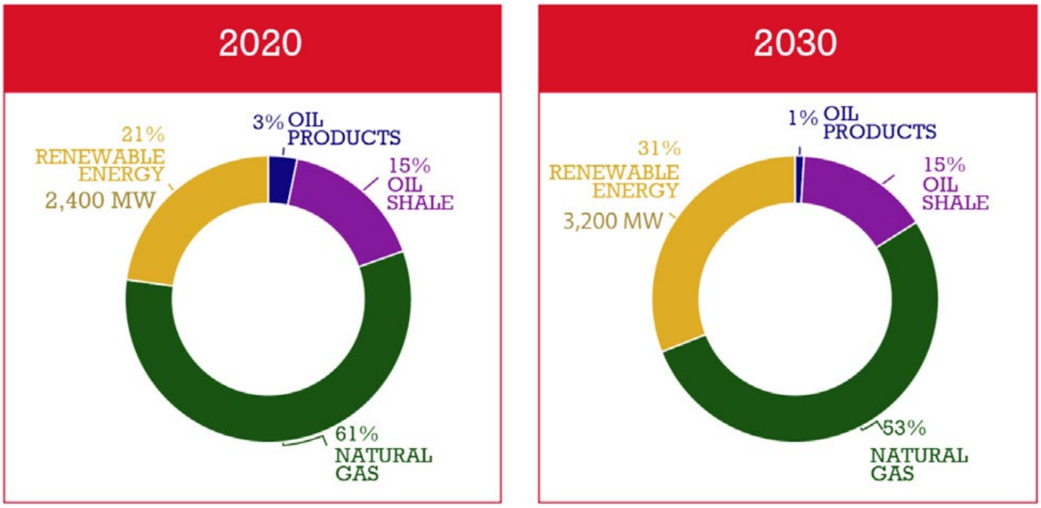

Fig. 1: Renewable energy contribution ratio to electricity generation (2020–2030) (MEMR, 2021)

et al. (2015) conducted a SWOT analysis showing the strengths and weaknesses of Jordan's renewable energy market and illustrated the opportunities and threats. Compain (2012) presented different solutions to the most used desalination processes—reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED)—coupled with solar energy production technology compatible with desalination. The goal is to assess the feasibility and profitability of the substitution of fuel energy used for desalination plants with renewable energy. A review of various technologies broadly defined features associated with each technology and the range of cost that is expected and included a review of various projects detailed the practical aspects of floor space and the actual production costs of fresh water. Luo *et al.* (2021) presented solar-thermal evaporation as a traditional steam generation method for solar desalination, which has received much attention in recent years due to the significant increase in efficiency achieved by adopting interfacial evaporation. While most previous studies have focused on improving evaporation efficiency through material innovation and system design, the underlying mechanisms of energy efficiency are underexplored, leading to much confusion and many misunderstandings. It was found that, overall, the solar desalination efficiency of interfacial evaporation in a solar system is still not as high as expected; further improvement is possible from the system design perspective. The analysis provides insights into the thermal processes involved in interfacial solar evaporation and offers perspectives on the further development of interfacial solar desalination technology. Naderipour *et al.* (2021) introduced a framework for designing a photovoltaic-based water pumping system to supply customers in remote areas with drinking water. Their approach minimizes net present cost (NPC) and ensures reliability while using an intelligent water drops algorithm to optimize the system. Simulation results demonstrated the effective sizing of components and storage, achieving optimal reliability and minimal NPC of 3.17%. Goosen *et al.* (2023) provided a review of recent developments in solar desalination from the viewpoint of environmental, regulatory, and economic aspects. Their analysis attempted to give better insight into the larger question of why more solar desalination plants are not being established by reviewing different technologies, drivers, barriers, and markets. Critical barriers that are dependent on the level of regional development were found to be an uncertainty of government subsidies and a lack of regulatory policies. The overall trend was a shift toward the integration of renewable energy with conventional sources and energy storage systems. The primary objective of this study is to optimize energy consumption and enhance the energy efficiency of a hybrid BWRO plant through the integration of energy efficiency considerations into the planning, management, and operation strategies of the facility. Also, this study will investigate the techno-economic feasibility and financial analysis of the plant. Ultimately, this will reduce operational costs and improve the overall sustainability of the plant. Also, it will improve reliability, sustainability, and environmental performance through the more efficient utilization of resources for meeting water demands. This study was carried out at the Hashemite University (HU) desalination plant, Jordan, from 2021–2022. Also, it demonstrates the linkages of water availability and energy supply with production, which are vital needs to ensure a healthy life for communities' livelihoods and represent the basis of the country's socioeconomic and ecological resilience.

Optimizing energy efficiency and sustainability in hybrid BWRO desalination plants

Brackish water desalination has become a crucial necessity, but its success hinges on meticulous planning and effective management to avoid systemic deficiencies that undermine performance, increase costs, and cause unexpected downtime (Usman *et al.,* 2021). Failure to address these deficiencies can lead to critical shortcomings in the realization and operation of desalination facilities, compromising their ability to meet local and regional water demand requirements (Okampo and Nwulu, 2021). During operation, the abstraction scheme may prove incapable of delivering the intended quality and quantity of raw water (Wang *et al.*, 2019). Comprehensive planning must encompass various key elements (Fig. 2) to mitigate these challenges.

By emphasizing adequate planning and operation, costs can be reduced, as planning expenses constitute only a fraction of the total investment in desalination facilities (Al-Karaghouli and Kazmerski, 2013). Optimized tendering documents, aligned with market conditions, can yield significant savings if all necessary planning steps are executed properly. System failures and the limited availability of source water disrupt water supply stability and inflate costs, necessitating sustainable and stable operations (Pugsley *et al.*, 2016; Moghadam and Samimi, 2022). High plant reliability requires substantial investments to be made in process equipment, automation, and control systems, minimizing power outages, unsafe operations, and equipment damage (Tao *et al.*, 2018). Regardless of the desalination technology employed, whether thermal or membrane-based, desalination remains an energy-intensive process, as it impacts the overall cost, reliability, sustainability,

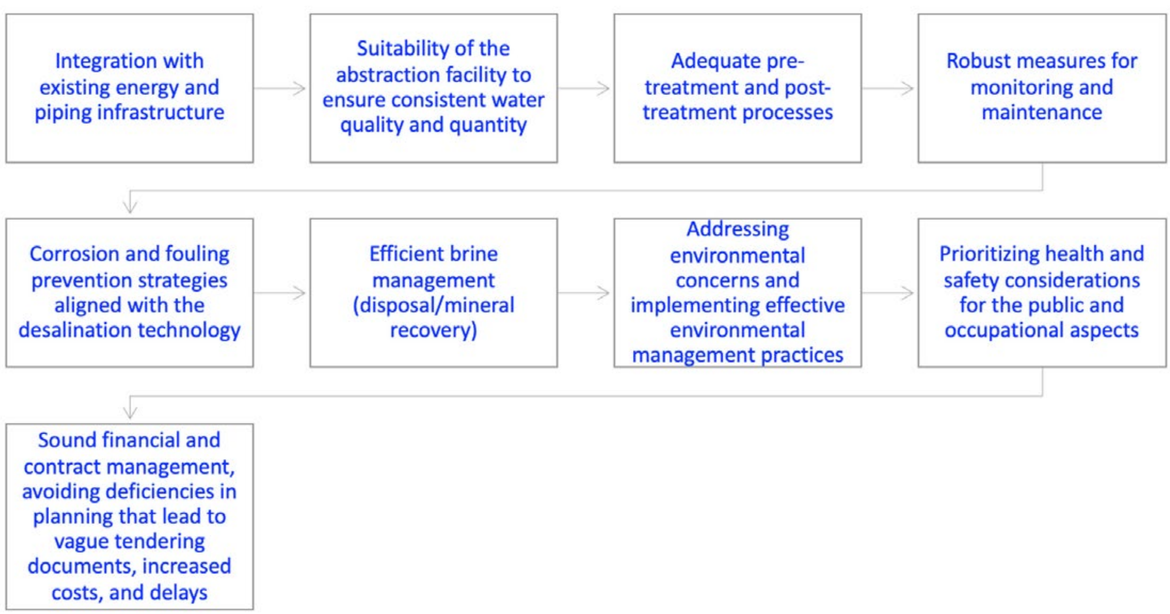

Fig. 2: Key elements in planning and management for efficient and reliable brackish water desalination

and environmental footprint of the desalination technology (Mahmoudi *et al.,* 2009). Fig. 3 illustrates the linkage between energy efficiency and various aspects of planning, management, and operation strategies in water desalination. Obviously, energy is critical and connected with all six strategic planning and management phases (Mohammad *et al.,* 2021). For example, comprehensive planning involves the selection of desalination technologies that prioritize energy efficiency. Engineers can optimize the plant's energy efficiency for the initial stages by assessing design considerations that are relevant to energy consumption (Manju and Sagar, 2017; Amani *et al.,* 2021). Meanwhile, optimal system design includes the layout and configuration of the plant to minimize losses and improve the plant's performance. Advanced process control continuously monitors and optimizes plant operations by modifying key parameters while maintaining produced water quality according to standards (Bdour *et al.,* 2022). Maintenance and optimization address issues of proactive maintenance practices, implementing energy audits to identify energy drops to ensure operation at optimum efficiency levels. Lastly, the training and knowledge transfer phase is related to providing adequate training and knowledge for operators to ensure optimum operation, identify energy-saving opportunities, and employ energy-efficient measures properly (Edris *et al*., 2022).

Most existing active desalination plants in Jordan are reverse osmosis systems with advanced membranes and energy recovery devices (Al-Obaidi *et al.,* 2023). These technologies are energy-efficient, resulting in reduced energy consumption during the desalination process (Saeed *et al.,* 2023). Recent advancements in desalination strive to enhance energy efficiency by reducing the energy consumption per unit of freshwater produced (Bundschuh *et al.,* 2021). One of these attempts includes the coupling of renewable energy sources to drive desalination plants. There is a need to enhance the technical and thermal performance of these technologies through comprehensive analysis and industrialization. The integration of renewable energy sources with a traditional desalination system requires continuous research and development to improve their market penetration and cost-effectiveness (Shokri and Fard, 2022).

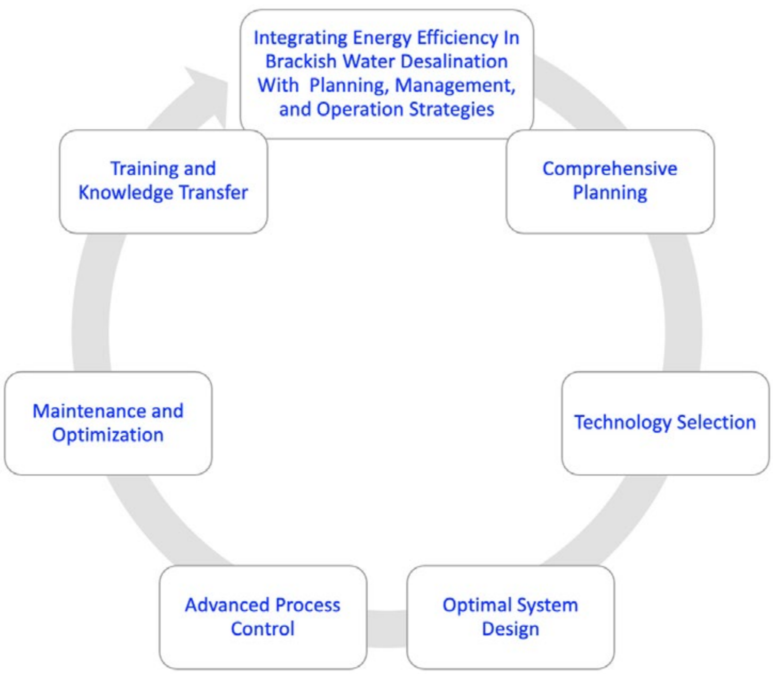

Fig. 3: Illustration of the linkages between energy efficiency and various aspects of planning, management, and operation strategies in water desalination

Description and pre-assessment of the HU PV-BWRO plant

Plant design and general layout

The Hashemite University photovoltaic brackish water reverse osmosis (HU PV-BWRO) desalination plant has been designed to have a total capacity of 1,992 cubic meters (m^3) based on full operational hours. It has been assessed that the domestic water consumption of the HU campus, determined during the summer season, is approximately 270–300 cube meter per day (m^3/d), representing the total daily water demand for various domestic on-campus purposes. Also, there has been a shortage of underground water in the HU campus to cover domestic and agricultural water demands. The prolonged deterioration of the Amman-Zarqa basin has affected the water quality of its associated aquifers. In the HU campus, the two main groundwater wells had total dissolved solids (TDS) levels in the range of 1,200–3,500 milligrams per liter (mg/L), which does not comply with Jordan's drinking water standards. An on-grid 53-kilowatt PV solar system has been placed on the rooftop and car park of the desalination building to supply the HU PV-BWRO desalination plant with the required electrical energy. The main BWRO desalination compartments include a raw water tank (100 m^3), a feed pump, five- and 25-micron bag filters (series filtration), an antiscalant tank, a hydrochloric acid (HCL) tank, a high-pressure pump (HPP), a three-stage reverse osmosis (RO) system, an inter-stage high-pressure pump allocated between stage 2 and stage 3 of the RO system, a mixing pump, an aeration tower, a 50-m^3 equalizer tank (treated water tank), a treated water pump, and a caustic soda tank. The system has a three-stage RO configuration, which is designed to have a high recovery of approximately 88% by attaining a permeate flow of about 59 m^3/h, and the reject water is about 8 m^3/h. Permeate is mixed with raw water to obtain a final product of 83 m^3/h with an applicable TDS for domestic use. Flow rate, pressure, potential of hydrogen (pH), electrical conductivity (EC), and TDS sensors are used to measure and monitor feed, permeate, final product, and even the brine reject water before being disposed of in the associated evaporation ponds. The evaporation ponds were estimated to have a surface area of over 5,000 m^2 and a depth of 1.5 m. Table 1 shows the performance parameters assumed by HU BWRO at the total design capacity of the plant.

The quality and quantity of product water and the plant recovery ratio are crucial performance indicators for the desalination plant. However, they are not the sole factors that determine the plant's overall performance and sustainability. Another critical indicator to consider is electrical consumption, as energy usage (electricity) constitutes a significant portion of the operational cost of any desalination plant. Ensuring efficient electricity consumption is of utmost importance to maintain control over the actual specific water production cost of the plant. This guarantee of power consumption is often expressed as a "specific energy consumption," measured in kWh/m^3, which includes all power consumed from the raw water pumps through the final storage tank. The electrical consumption should be carefully evaluated across various components, including the pre-treatment system, desalination system, post-treatment system, and associated infrastructure. Since electrical energy is a significant part of the operational cost of a BWRO plant, it is crucial to optimize the energy consumption of each plant component. Achieving this requires the identification and definition of the various energy consumers within the plant, considering the operating hours of each individual component. By understanding the energy requirements and usage patterns of these components, it becomes possible to implement measures that enhance energy efficiency and reduce operational costs in the BWRO plant. The estimated specific energy consumption (kWh/m^3) for the BWRO station at the HU, as indicated in Table 1, is found to be relatively high. Therefore, it is necessary to propose measures aimed at improving energy efficiency in the BWRO plant and reducing the specific energy consumption (kWh/m^3). It is essential to clearly define the scope and boundaries of the study to achieve

Table 1: HU BWRO performance parameters

Feed (m^3/h)	Permeate (m^3/h)	Final product (m^3/h)	Reject brine (m^3/h)	Plant recovery ratio (%)	Plant Capacity (m^3/d)	Estimated energy consumption (kWh/m^3)
67	59	83	8	88%	1,992	1.2

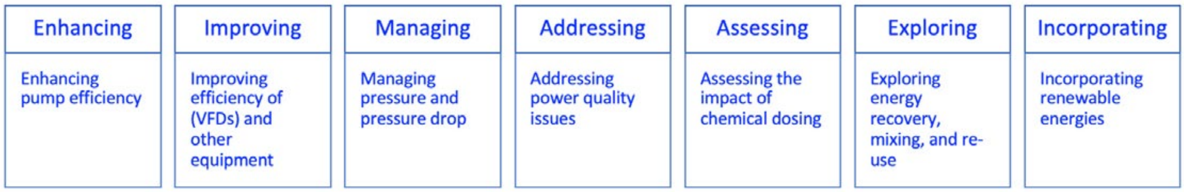

Fig. 4: Opportunities for energy savings in the context of the BWRO plant

these outcomes. This investigation will help identify areas that require improvements and allow for a targeted approach to optimizing energy consumption in the BWRO plant. This study was carried out at the Hashemite University (HU) desalination plant, Jordan, from 2021–2022.

HU-PV BWRO pre-assessment evaluation

After conducting the pre-assessment at the HU-PV BWRO plant, several opportunities for energy savings were identified, as illustrated in Fig. 4. These opportunities include the following areas within the plant.

1. Enhancing pump efficiency: This can be achieved through the utilization of more efficient pumps or by replacing existing pumps with more efficient models. Also, the re-selection of pump sizes based on factors such as power and the best efficiency point can contribute to energy savings (Mohammadi *et al.,* 2021). In some cases, modifications to existing pumps, such as removing stages from multi-stage pumps or using/activating variable frequency drives (VFDs), can also improve efficiency (Razi and Dincer, 2022).

2. Improving the efficiency of variable frequency drives (VFDs) and other equipment: Optimizing the performance of VFDs and other auxiliary equipment can lead to energy savings.

3. Managing pressure and pressure drops: Addressing energy losses caused by friction, mechanical losses, hydraulic energy losses, and water leaks can significantly reduce energy consumption (Gude and Fthenakis, 2020).

4. Addressing power quality issues: Energy losses resulting from power quality issues are to be identified and mitigated to minimize their impact on overall energy efficiency (Goh *et al.,* 2017). Also, measures to reduce heat dissipation, such as improving insulation and optimizing HVAC, lighting, and electrical cable systems, can help conserve energy (Dashtpour and Al-Zubaidy, 2012).

5. Assessing the impact of chemical dosing: Evaluating the influence of chemical dosing in the pre-treatment stage on scaling and fouling of membranes can help optimize the dosing process and reduce energy requirements (Patel *et al.,* 2020).

6. Exploring energy recovery, mixing, and re-use: Implementing strategies for energy recovery, efficient mixing processes, and the re-use of treated water can contribute to energy savings (Alawad *et al.,* 2023).

7. Incorporating renewable energies: Increasing the use of renewable energy sources, such as solar or wind power, can supplement the energy requirements of the BWRO plant and improve overall energy performance (Ghaffour *et al.*, 2014). Also, optimizing operating times and considering energy storage solutions can enhance the efficiency of renewable energy integration (Ahmadi *et al.,* 2020).

By considering these energy-saving opportunities, the BWRO plant can achieve improved energy efficiency and reduce its specific energy consumption (Tayyeban *et al.*, 2022). The SEC of the BWRO unit per hour, indicated in Table 2, was calculated based on the summation of the nominal powers of the pumps within the unit. In practical water applications, pump-motor sets are typically partially loaded, resulting in lower discharge pressures for the same water quantities, as indicated in Table 2. Measurements are necessary to determine the actual specific energy consumption. The BWRO unit is not always operational due to quality issues with the raw groundwater. Also, it is recommended to sustain the operation of the BWRO station at full capacity, especially during peak sun hours, to optimize and balance energy requirements from renewable sources, such as solar energy. Energy meters with energy loggers should be installed for the BWRO unit and the PV system. Displaying energy data on the monitoring system is advised.

Table 2: Monthly energy and water data for the year 2021

2021 month	Treated water (m^3)	Operating hours (h)	PV-produced energy [kWh]	Calculated energy consumption (kWh)	Calculated energy cost (kWh/m^3)	Total power (kW)
JAN	5,072	100	4,250	6,900	1.36	69
FEB	4,482	89	4,982	6,107	1.36	69
MAR	5,443	116	7,142	8,004	1.47	69
APR	6,001	108	8,025	7,452	1.24	69
MAY	5,566	92	9,417	6,362	1.14	69
JUN	4,728	78	9,950	5,351	1.13	69
JUL	5,477	90	9,909	6,213	1.13	69
AUG	4,175	70	9,134	4,820	1.15	69
SEP	5,391	87	7,095	5,986	1.11	69
OCT	5,664	90	6,191	6,189	1.09	69
NOV	4,864	81	4,791	5,568	1.14	69
DEC	5,657	91	3,841	6,262	1.11	69
SUM/AVG	62,520	1,090	84,727	75,213	1.2	69

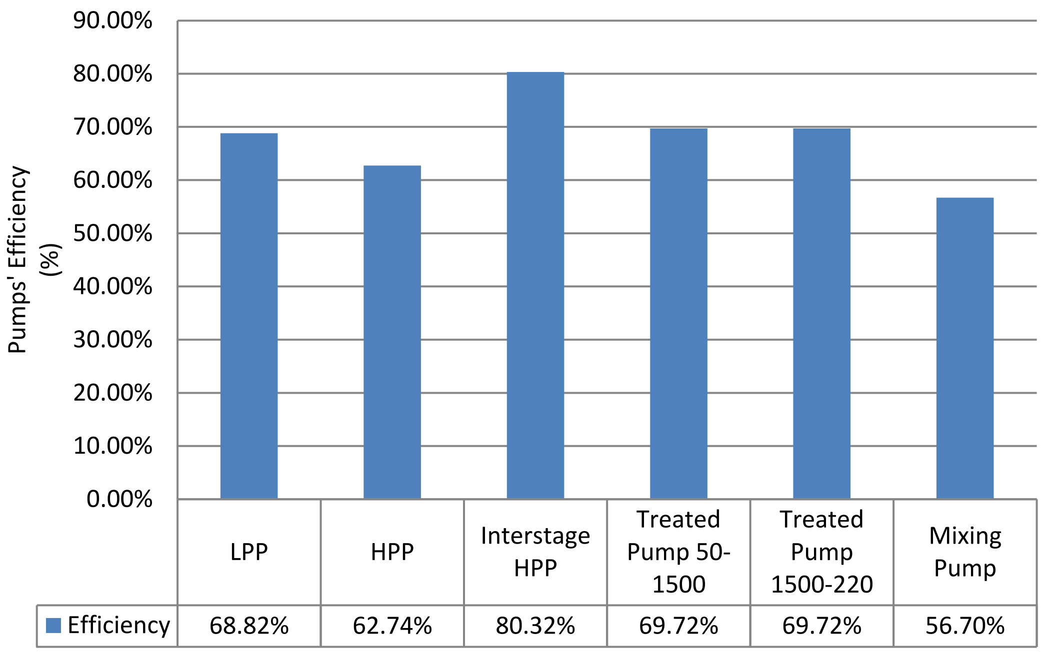

Fig. 5: Pumps' efficiencies at the HU-BWRO desalination plant.

The use of variable speed drives (VSDs) is recommended as an energy-saving measure instead of wasting energy through throttling. The energy consumption of each pump should be measured and monitored to verify the potential for energy saving. Initially, it was observed that the efficiency varies among pumping units. Further investigation is needed to assess the efficiency of each unit individually. Fig. 5 shows the efficiency of the BWRO pumps. It was found that the inter-stage high-pressure pump is the most efficient pump and has 80.32% efficiency, while the mixing pump has the lowest efficiency of the pumps in the BWRO plant (56.7%), assuming that both the inter-stage high-pressure pump and the mixing pump have the same power (4 kW). It is possible to eliminate certain pumps, such as the mixing pump, which would result in power savings. The power of other pumps could be reduced compared to their

Table 3: Calculations of the specific energy consumption for different assumed scenarios in 2021

Pumps	Duty point			Operational		
	Power (kW)	Q (m^3/h)	H (m)	Q (m^3/h)	H (m)	Power (kW)
LPP	9.2	67	30	67	25	7.67
High-pressure pump	37	67	110	67	90	30.27
Inter-stage HPP	4	17	60	17	50	3.33
Treated pump 50–1,500	15	83	40	81	20	7.32
Treated Pump 1,500–220	15	83	40	83	40	15
Mixing Pump	4	24	30	22	25	3.06
Total loads (assumed scenarios):	Total nominal power (kW)	SEC (kWh/m^3)	TW* (m^3)	OH** (h)	Total operational power (kW)	SEC (kWh/m^3)
Loads + Pump 1,500–220	84.2	1.45			66.65	1.16
RO Loads (Pumps) only	69.2	1.21	62,520	1,090	51.65	0.90
Loads – Mixing Pump	65.2	1.14			48.59	0.85

*TW: Treated water for the year 2021
**OH: Operating hours for the year 2021

nominal values.

The current membranes used in the BWRO system are low-energy membranes with negligible energy-saving potential. Energy recovery from the brine can be achieved under specific parameters: namely, a flow rate of 8 m^3/h and a pressure of 11.5 Bar. More data and on-site investigations are required to evaluate the feasibility of implementing such a system. Contrarily, optimizing the use of renewable energy can be achieved through the addition of PV panels and increasing the direct current to alternating current (DC/AC) ratio to enhance energy production. Also, changing the operation time of the BWRO unit to align with sun peak hours and ensuring the regular and efficient cleaning of the PV modules can contribute to improved energy efficiency (Naderipour *et al.*, 2021). Due to the absence of power and energy meters in the plant, the data presented in Table 2 were derived using the nominal power of the pumping units in the BWRO plant, resulting in a specific energy consumption of 1.2 kWh/m^3. An alternative approach was followed to calculate the specific energy using operational data provided by the plant operator, as shown in Table 3. According to this method, the specific energy consumption was found to be 0.9 kWh/m^3. It was discovered that there are other loads associated with the pumping units, with the sum of the nominal powers of the pumps amounting to 69.2 kW, excluding the second treated water pump from the 1,500-m^3 reservoir to the 220-m^3 reservoir. Taking this pump into account, the total power of all pumps in the BWRO plant is 84.2 kW. It is important to consider the scope and boundaries of the study when analyzing the data, which may involve deciding whether to include or exclude the groundwater submersible pump and the treated water pump from the 1,500-m^3 tank to the 220-m^3 tank based on the objectives and focus of the research.

The study methodology

Detailed assessment and energy auditing (EA) require examining the overall efficiency of the plant before implementing any measures toward an energy-efficient RO plant. In the case of HU-BWRO, the energy input can be directly measured from the electrical component, while measuring the energy output requires a specific setup. One method to measure the output energy of the motors, which represents the mechanical energy, is to install two measurement devices at the shaft coupling the motor and the pumps. These devices are capable of measuring and recording the rotational speed and torque to calculate the mechanical energy. The output power equals the torque multiplied by the angular speed. These measurements are helpful when assessing a motor's efficiency. Power measurements can be conducted without following this procedure by measuring the hydraulic data, such as water flows and water pressures, especially when the couplers are not easily accessible. The overall efficiency could be calculated based on the input electrical power and the output hydraulic power. In this study, an energy analyzer was used to measure and analyze power and energy consumption. The initial setup of the

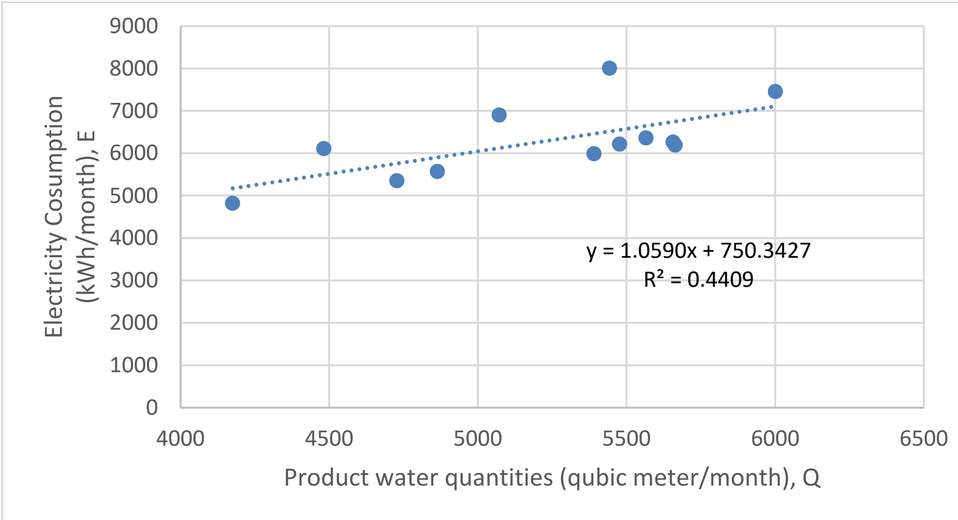

Fig. 6: Baseline model for monthly energy and water data for the year 2021

power and energy analyzer device was conducted to identify various parameters, including details of the electrical system and other measurement and Logger specifications and parameters. Power and energy were measured using a Fluke 438-ii power quality and energy analyzer. Since direct access to the electrical terminals of each pumping unit was not feasible, power and energy measurements were performed on the main power circuit breaker of the BWRO station instead of each pumping unit. The power measurements included were the energy loss calculator, the scope, and the logger. The energy loss calculator provided a summary of losses caused by power quality issues, which were found to be minor in terms of power losses (< 1 kW), with no major poor power quality issues. The scope functioned as an oscilloscope, while the logger was used to record predetermined parameters. This study primarily focuses on measuring the energy and active power consumption of the BWRO to investigate the specific energy consumption at the HU station. The logger, scope, and other collected data are available for further elaboration on specific measurement details and the overall situation. A baseline was established using a regression model implemented in an Excel sheet. Monthly data on energy consumption and treated water quantities from Table 2 were utilized, yielding the results illustrated in Fig. 6.

As shown in Fig. 6, there are different operation characteristics for the months of January to April, which were not correlated or consistent with the data of the remaining months of the year 2021, as R^2 equals 0.4409. Fig. 7 illustrates this gap clearly. Knowing that the BWRO was operated starting from January, it is expected that in the first four months that the plant was operated, the efficiency was improved, and the data became steady.

By excluding the data from the first four months and considering the data from May to December of the year 2021, the data become more correlated, and R^2 equals 0.9747. Fig. 8 illustrates the baseline model for the BWRO plant.

This study focuses on investigating the techno-economic feasibility and financial analysis of the HU BWRO plant, considering self-financing and operation and maintenance (O&M) deduction. The cost savings resulting from this project can be categorized into two parts. The first is savings in water demand costs for the water supplied by the water services company to the HU, amounting to 1.76 USD/m^3 (sewer services provided by the water services company to the HU still incur a cost of 1.2 USD/m^3). The second is the additional savings generated through the electricity produced by the 52.8-kWp on-grid PV system. This study evaluates the total savings attained from PV energy generation and reduced water costs.

Specific energy consumption results

Tables 4 and 5 show a summary of the field

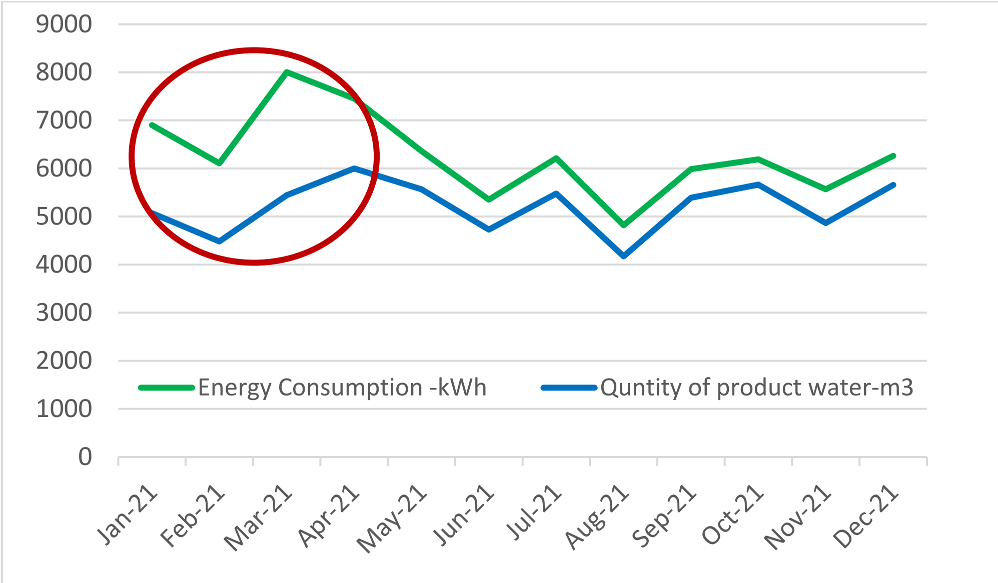

Fig. 7: Baseline model for the monthly energy and water data for the year 2021

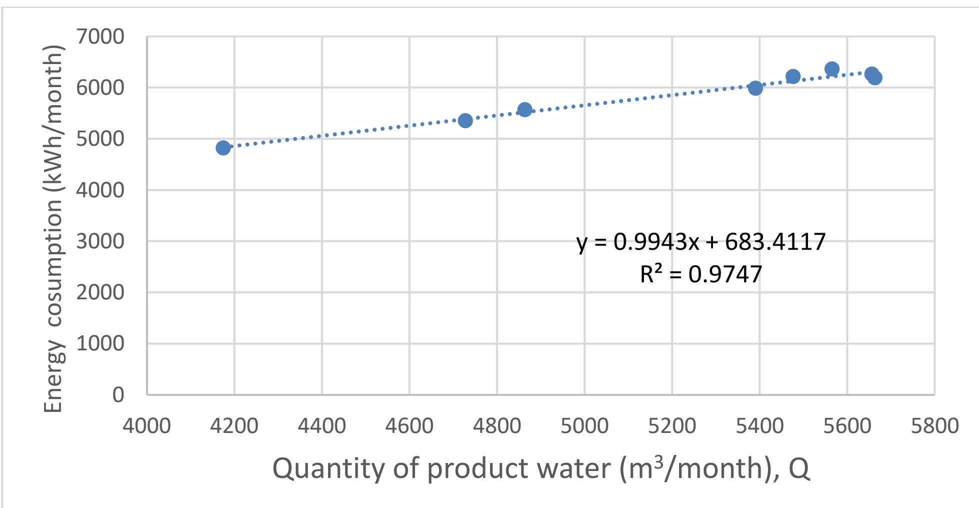

Fig. 8: Baseline model for the monthly energy and water data for the year 2021 (May to December). A simple scatter diagram for one variable and regression analysis for multi-variables for the monthly energy and water data for the year 2021

measurements at the HU BWRO plant. Data were obtained from the installed fixed meters within the BWRO station; the power and energy measurements were obtained from the power and energy analyzer. There was a challenge faced during the measurements while operating the BWRO station to take the required measurements due to the fact that the operation time was limited to the available water at the raw water storage tank due to the current shutdown of the groundwater well.

During the measurement period, the water quantities were fixed, and the pressures were found to be lower than the nominal values of the pumps due to the usage of the VFDs. The following readings in Table 6 show the power consumption. These values consist of two parts: the consumption of the

Table 4: Summary of the field measurements at the HU BWRO station

No.	Meter	Parameter	Unit	Reading 1	Reading 2	Reading 3	Reading 4
1	Feed flow meter	Flow rate	m^3/h	0	62.98	62.5	0
2		Totalizer	m^3	164,750.13	164,753.08	164,767.05	164,802.28
3	Reject flow meter	Flow rate	m^3/h	0	9.03	8.8	0
4		Totalizer	m^3	21,336.11	213,36.74	21,338.74	21,343.75
5	Mixing flow meter	Flow rate	m^3/h	0	11.47	28.94	0
6		Totalizer	m^3	93,272.39	93,272.57	93,276.9	93,293.58
7	Treated flow meter	Flow rate	m^3/h	0	0	80.31	0
8		Totalizer	m3	247,180.66	247,180.66	247,181.92	247,223.09
9	Quality of raw water	EC	µS/cm	2.352	2,709	2,682	5.016
10		TDS	ppm	1	1,138	1,139	2
11		pH	unity	7.49	7.95	7.96	5.33
12		TEMP	deg C	12.3	19.2	19.3	17.4
13		CL_2	mg/L	0	0.01	-0.01	0
14	Quality of product water	EC	µS/cm	1.481	1.485	1445	1659
15		TDS	ppm	1	1	545	704
16		pH	unity	8.75	8.75	8.73	8.74
17		TEMP	deg C	12.2	12.2	16.6	17.9
18		CL_2	mg/L	-0.084	-0.082	0.366	0.522

Table 5: Measurements Records at the BWRO station at the HU

Date	01-Sep-2022	Sample time	2:22 pm
No.	Reading	Unit	Value
1	Raw water quantity	m^3/h	63
2	Desalinated RO water quantity	m^3/h	54
3	Final treated water quantity	m^3/h	81
4	Rejected water quantity	m^3/h	8.9
5	Water pressure before protection filters	bar	3.2
6	Water pressure after protection filters	bar	2.8
7	Water pressure of stage #1	bar	9.9
8	Water pressure of stage #2	bar	7.5
9	Water pressure before inter-stage pump	bar	6.5
10	Water pressure after inter-stage pump	bar	9.7
11	Rejected water pressure	bar	9.4
12	Desalinated RO water pressure/stage #1	bar	0.5
13	Desalinated RO water EC	µS/cm	988
14	Final treated water EC	µS/cm	1,658
15	Final treated water excess chlorine	mg/L	0
16	pH	unity	8.7

Table 6: Active total power measurements from the BWRO station at the HU

Basic power		Power with TP15 kW off		Power with TP15 kW	
Reading #	Power (W)	Reading #	Power (W)	Reading #	Power (W)
Average	5,216.67	Average	32,145.79	Average	47,166.52
Net average power without basic loads (W):					41,949.86
Net average power without basic loads and treated water pump (W):					26,929.12
Measured specific energy with respect to treated water 83 m^3/h (kWh/m^3):					0.505
Measured specific energy with respect to RO water 67 m^3/h (kWh/m^3):					0.402

treated water pump from the 50-m^3 tank to the 1500-m^3 reservoir and the basic load for the BWRO station, including the ACs, internal lighting, etc. The average net power value was 47,166.5 W, while the maximum average recorded value was 50,760 W and the maximum specific energy was 0.625 kWh/m^3. These

Table 7: Comparison of specific energy consumption and cost of product water with similar desalination plants in the MENA countries.

Country	Specific Energy Consumption (kWh/m^3)	Cost of desalinated water USD/ m^3	Sources
Morocco	4.0	1.0	Kettani and Bandelier, 2020
Saudi Arabia	3.5–3.75	0.825	Sayed *et al.,* 2022
Bordering the Red and Mediterranean Seas	2–4	1.52–1.74	Maftouh *et al.,* 2023
Jordan	2.7–5.6	0.60–1.18	Bdour *et al.*, 2022
India	4.0	2.4–3.6	He *et al.*, 2020
Egypt	4–5	1.25	Shouman *et al.,* 2015
Palestine	2.33	0.95	Hussam H. A., 2013
Hashemite University, Jordan	0.62	0.36	The current study

details are shown in Table 6. Given that the average basic load before operating the BWRO station was 5,216.67 W, the treated water pump with a nominal power of 15 kW was not operational at the beginning of the operation of the BWRO station because the treated water tank was empty.

Based on the above results, the net average power without basic loads is 41,949.855 W, while the net average power without basic loads and a treated water pump is 26,929.123 W. The measured specific energy with respect to treated water (83 m^3/h) is around 0.505 kWh/m^3, while the measured specific energy with respect to RO water (67 m^3/h) is around 0.402 kWh/m^3. The above findings reveal a highly efficient BWRO plant, opposite to the first assumption of a 1.2 kWh/m^3 specific energy. This could be justified due to the following reasons: 1) The use of high-efficiency reverse osmosis (RO) membranes (low energy membranes), 2) the use of VFDs for all pumping units, and 3) the blending of the desalinated water product with a portion of the raw water using a small pump. The raw and treated water tanks are concrete tanks that are adjacent to each other. The idea of the cancellation of the mixing pump may require an adjustment and modification to the BWRO station, which seems to be an infeasible option for a 4-kW pump versus the required investments and works to cancel the mixing pump. By comparing the findings of the current study with other desalination plants in the Middle East and North Africa (MENA) countries regarding specific energy consumption values and cost of desalinated water, the results in Table 7 reveal that the HU-PV BWRO plant exhibits exceptional performance in terms of energy costs, energy efficiency, and energy consumption. This achievement can be attributed to effective plant management, meticulous operation practices, and the integration of renewable energy sources to power the plant. The findings of this comparison highlight the potential for substantial cost reduction and enhanced sustainability, achieved through lowered greenhouse gas emissions. By integrating renewable energy, the economic feasibility of desalination can be greatly improved, contributing to both environmental preservation and economic efficiency. A noteworthy aspect of this study is its recognition of the synergy between brackish water desalination and groundwater utilization. By considering the integration of these water sources, this study offers insights into how the pressing water scarcity issue in Jordan can be alleviated. This underscores the pivotal role that desalination can play within a comprehensive water management strategy, providing a multifaceted solution to water shortage challenges.

Regarding the comparison of the technology used, a multi-stage flash distillation (MSF) brackish water desalination technology tends to be less energy-efficient compared to advanced RO with an energy recovery device. The requirement for heating and evaporation at varying stages consumes more energy, leading to higher operational costs. Also, RO technology offers a more convenient and effective solution for various capacities (Tayyeban *et al.,* 2022). Contrarily, there are potential barriers and limitations that could hinder the widespread adoption of the proposed strategies for brackish water desalination energy production. These barriers are important to consider, as they provide a more comprehensive understanding of the challenges that need to be addressed to make the strategies viable. Some common barriers are 1) the high initial cost due to implementing advanced membrane technology, energy recovery devices, and solar energy; 2) low electricity tariff structures and fragmented energy policies; and 3) technical challenges and operational complexity, which might require trained and specialized expertise.

Energy recovery by hydropower micro-turbines.

Another possible energy efficiency option is to recover energy from the brine water for the 8-m^3/h flow and around 11 bar excess pressure. The estimated power recovered by this figure is around 1.6 kW, which translates to an estimated savings of around 3–4%. This was calculated using the following hydropower using Eq. 1 (Blackburn, 1993).

$$P = mg * Hnet * \eta \quad (1)$$

Where

P: Power, measured in Watts (W).

m: Mass flow rate in kg/s (numerically the same as the flow rate in liters/second because 1 liter of water weighs 1 kg).

g: TGravitational constant, which is 9.81 m/s^2.

H_{net}: Net head, which is the gross head physically measured at the site less than any head losses. Head losses can be assumed to be 10%, so $H_{net}=H_{gross}$ x 0.9.

η: The product of all components' efficiencies, which are normally the turbine, drive system, and generator.

For a typical small hydro system, the turbine efficiency would be 85%, the drive efficiency would be 95%, and the generator efficiency would be 93%, so the overall system efficiency would be calculated as follows:

0.85 x 0.95 x 0.93 = 0.751 (i.e., 75.1%)

If the gross head is relatively low, the gross head is 110 meters (11 bar). As in this study, the gross head is considered relatively low, a turbine could take a maximum flow rate of 8 m^3/h (0.0022 m^3/s), and the maximum power output of the system would be the gross head converted into the net head, multiplied by 0.9 as follows:

$H_{net} = H_{gross}$ x 0.9 = 110 x 0.9 = 99 m

Then, the flow rate in m^3/s is converted into liters/second by multiplying it by 1,000 as follows:

0.0022 m^3/s = 2.222 *l/sec*

Knowing that 1 liter of water weighs 1 kg, kg/s is the same numerically as the flow rate in liters/second (in this case, 2.22 kg/s). Then, the hydropower power is determined as follows:

P = 2.22 x 9.81 x 99 x 0.751 = 1,621 W = 1.621 kW

An additional avenue for improving energy efficiency is the potential recovery of energy by addressing poor power quality issues. After identifying and measuring the possible energy waste due to poor power quality, it was determined that the maximum power that can be recovered in our case falls within the range of 0.8–1.6 kW. This recovery could lead to estimated savings of up to 3%. It is important to note that for both energy recovery processes through hydropower micro-turbines and curing poor power quality issues, comprehensive studies are necessary to assess their feasibility and the potential energy savings they may offer. Such studies will provide a better understanding of the practicality and effectiveness of these options in achieving significant energy efficiency improvements.

Techno-economic modeling and financial analysis results

Regarding the feasibility of the HU BWRO desalination configuration, including the on-grid PV BWRO with a 100% operating capacity of 1,992 m^3/d, the capital investment of constructing this plant was 1,393,935 United States dollars (USD). The average maintenance and operational costs equal 54,280 USD/year, and the normalized initial and running costs per kWp PV installed capacity are 26,400 USD and 1,028 USD per year. For the PV system alone, the capital investment was approximately 47,887 USD for the 52.8-kWp on-grid PV system, while the estimated average operation and maintenance cost is estimated at 14 USD/kWp/year. Based on the above data, the feasibility of the plant was investigated for the following two scenarios:

1. Techno-economic feasibility, including only savings from PV system (PV scenario).

With solar PV system capacity, system cost, electrical consumption, estimated energy to be generated by the solar PV system, % of energy bill coverage by the solar PV system, and solar system productivity, the total energy savings over 25 years is 2,193,198 kWh (727,407 USD). The system costs were based on

Table 8: Financial parameters for techno-economic modeling of HU PV-BWRO plant feasibility (Self-financing with O and M deduction)

No.	Parameter	52.8 kWp on-grid PV system	BWRO+52.8 kWp PV
1	System capacity-kWp or m^3/h	52.8	83 m^3/h
2	Energy yield-kWh/kWp	1,814	1,814
3	System cost (CAPEX)-USD/kWp	907.04	26,400
4	Investment CAPEX [USD]	(47,891.55)	-1,393,935
5	Water yield-m3/day	1,992	1,992
6	Energy/water cost savings [USD/kWh or USD/m^3] – energy/water tariff	0.36	1.76 USD/m^3
7	O and M cost oPEX [USD/y]	14.08	1,026
8	Simple payback period (SPB)	1.4	1.1
9	Net present value (NPV) [USD]	724,304.23	29,603,232
10	Internal rate of return (IRR)	70%	89%
11	Total costs over systems life (CAPEX + OPEX) [USD]	(66,483.10)	-1,953,164
12	Total energy production over 25-year project life span (kWh)	2,193,198	2,193,198
13	Level zed cost of energy (LCoE) [USD/kWh]	0.03	1.25
14	Price to current tariff price (% kWh)	8%	348%
15	Positive benefit-cost ratio (B/C ratio)	13.26	15.69

the constructed plant considering all costs such as solar PV system components, preconstruction, civil, electromechanical works, O and M, duties, and all related construction costs.

2. Techno-economic feasibility, including the savings from the PV system and reduced water demand costs (BWRO+PV scenario).

This scheme seemed to be the most probable financing model for the project and was used to proceed with the financial analysis of the feasibility of the project. Desalinated water production capacity, the solar PV system's capacity, system costs, electrical consumption, estimated water to be produced by the BWRO system, estimated energy to be generated by the solar PV system, water tariff, electricity tariff, % of energy bill coverage by the solar PV system and solar system productivity. The system's costs were based on the constructed plant considering all costs, such as RO, solar PV systems components, preconstruction, civil, electromechanical works, transmission lines, O&M, duties, and all related construction costs. The financial and cash flow analysis for this plant is summarized in Table 8, representing the base scenario (self-financing) by the plant owner (the HU).

The results shown in Table 8 suggest that both scenarios are financially feasible, but the BWRO+PV scenario appears to have more favorable financial outcomes, including a higher net present value (NPV), internal rate of return (IRR), and positive benefit-cost (B/C) ratio. The PV scenario has a payback period of 1.4 years, while the BWRO+PV scenario has a slightly shorter payback period of 1.1 years. Also, the PV scenario indicates a positive NPV of 724,304 USD, whereas the BWRO+PV scenario shows a significantly higher positive NPV of 29,603,232 USD. Also, both scenarios demonstrate favorable IRR values (70% for the PV scenario and 89% for the BWRO+PV scenario). Also, by utilizing renewable solar PV energy sources to power the BWRO plant, a considerable amount of GHG reductions, mainly CO_2 reductions, were achieved, resulting in an estimated CO_2 reduction of around 1,289,600 kg during the 25-year project lifetime.

CONCLUSIONS

In conclusion, energy efficiency plays a crucial role in the success and sustainability of desalination technologies. Energy considerations are intricately linked with every aspect of the planning, management, and operation of water desalination. The strategic planning phases include critical decisions, such as selecting energy-efficient desalination tools and optimizing the plant's energy efficiency during the initial design stages. Efficient system design, advanced process control, and proactive maintenance practices contribute to minimizing energy consumption and maximizing plant performance. Addressing energy efficiency throughout all stages of the desalination process is crucial to achieving cost reductions, reliability, and environmental sustainability. Also, integrating energy-efficient measures into plant operations not only reduces operational costs but also minimizes the environmental footprint of desalination technologies. This study involved a comprehensive evaluation of the sustainability of the HU-PV BWRO desalination plant, focusing on several key dimensions. Addressing the energy efficiency challenge remains a significant hurdle in desalination technology due to high energy consumption. Using energy-efficient technologies, such as reverse osmosis membranes and energy recovery devices, yields promising results by substantially decreasing energy consumption and reducing the energy footprint of desalination plants. Also, the economic implications of integrating solar energy sources significantly reduce the cost of desalination and make the desalination technology more sustainable by lowering GHG emissions, contributing to both environmental preservation and economic efficiency. Furthermore, brackish water desalination in combination with groundwater offers insights into alleviating the pressing water scarcity in Jordan and highlights the importance of integrating desalination into a broader water management strategy. It was found that the net average power for the BWRO plant was 41,949.855 W, while the net average power for the BWRO plant without including the treated water pump was 26,929.123 W, and the measured specific energy with respect to treated water of 83 m^3/h was around 0.505 kWh/m^3, while the measured specific energy with respect to RO water of 67 m^3/h was around 0.402 kWh/m^3. The above findings reveal that the BWRO station is highly efficient, which is mainly attributed to the use of high-efficiency RO membranes (low-energy membranes) and the employment of VFDs for all pumping units. A potential option for improving energy efficiency is to recover energy from brine water. The estimated power recovered is around 1.6 kW, representing a potential energy savings of approximately 3–4%. Another opportunity to enhance energy efficiency is to address poor power quality issues and recover wasted energy. Measurements revealed that the maximum power that can be recovered by resolving these issues falls within the range of 0.8–1.6 kW, translating into an estimated savings of up to 3%. The installation of renewable PV energy for the BWRO plant presents further opportunities for optimization. The following steps are recommended to maximize the use of renewable energy: 1) Increasing the number of PV panels to improve the DC/AC ratio and enhance energy production from the solar PV system; 2) adjusting the operation time of the BWRO to coincide with the sun's peak hours, typically around noon, to capitalize on the highest solar energy availability; and 3) frequently and efficiently cleaning PV modules to ensure their optimal performance and energy generation. By implementing these measures, the BWRO plant can enhance its energy efficiency, reduce energy wastage, and improve the overall sustainability of its operations. The feasibility of the HU PV-BWRO plant was investigated, and the results indicate a fast payback period of up to 1.1 years. This represents the base scenario of the self-financing scheme by the project owner (the HU). The results reflect the good feasibility of the project and an acceptable rate of return. Utilizing clean solar PV energy to power the BWRO plant led to considerable reductions in GHGs, mainly CO_2; the estimated amount of CO_2 savings during the project lifetime is around 1,289,600 $kgCO_2$. As advancements in desalination continue, the integration of solar energy sources shows promise in further enhancing energy efficiency and sustainability. An additional comprehensive analysis and industrialization of these technologies are essential to optimizing their performance and cost-effectiveness. The findings of this research contribute to a more environmentally friendly and economically viable desalination sector, which is of paramount importance in addressing global water scarcity concerns.

AUTHOR CONTRIBUTIONS

A. Bdour performed the research work plan, data interpretation, and manuscript edition. A. Hijab performed the field measurements and research experimentation and prepared the manuscript text. L. Almakhadmeh helped with the data analysis and organized the manuscript text. M. Hawa performed the literature review and helped in field measurements and research experimentation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS	DEFINITION
%	Percent
AC	Air conditioning
B/C ratio	Benefit-cost ratio
BWRO	Brackish water reverse osmosis
CAPEX	Capital expenditure
CL_2	Chlorine
CO_2	Carbon dioxide
DC/AC	Direct current to alternating current ratio
EA	Energy auditing
EC	Electrical conductivity
ECMs	Energy conservation measures
GHGs	Greenhouse gases
HCL	Hydrochloric acid
HPP	High-pressure pump
HU	Hashemite University
IRR	Internal rate of return
kW	Kilowatts
kW/m^3	Kilowatts per cubic meter
kWh	Kilowatt-hours
kWh/m^2	Kilowatt-hours per square meter
kWp	Kilowatt peak (a measure of solar panel capacity)
LCoE	Levelized cost of energy
LPP	Low-pressure pump
m^3	Cubic meter
m^3/d	cube meter per day (
m^3/h	Cubic meters per hour
MEMR	Ministry of Energy and Mineral Resources
MENA	Middle East and North Africa
MED	Multi-effect distillation
MSF	Multi-stage flash distillation
MW	Megawatts
NPV	Net present value
OH	Operating hours
O&M	Operation and maintenance
OPEX	Operational expenditure
pH	Potential of hydrogen
PV	Photovoltaic
RO	Reverse osmosis
SEC	Specific energy consumption
SWOT	Strengths, weaknesses, opportunities, threats
TDS	Total dissolved solids
TEMP	Temperature
TW	Treated water
USD	United States dollars
VFDs	Variable frequency drives
Y	Year

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AUTHOR (S) BIOSKETCHES

Bdour, A., Ph.D., Professor, Department of Civil Engineering, Faculty of Engineering, The Hashemite University, Zerqa, Jordan.
- Email: *bdour@hu.edu.jo*
- ORCID: 0000-0001-6244-9530
- Web of Science ResearcherID: GYJ-7283-2022
- Scopus Author ID: 16063036900
- Homepage: https://hu.edu.jo/en/facnew/dept/Academic.aspx?deptid=55010000#

Hejab, A., M.Sc., Director of Energy Unit, Water Authority of Jordan.
P.O. Box 5012, Amman 11181, Jordan.
- Email: *Abdallah_Hejab@mwi.gov.jo*
- ORCID: 0009-0001-7978-2724
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.mwi.gov.jo/Default/Ar

Almakhadmah, L., M.Sc., Engineer, Laboratories and Quality Directorate, Ministry of Energy and Mineral Resources.
P.O. Box 140027, Amman 11814, Jordan.
- Email: *Linda.Almakadmeh@memr.gov.jo*
- ORCID: 0009-0003-8280-6007
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://memr.gov.jo/Default/Ar/

Hawwa, M., M.Sc., Water and Wastewater Treatment Expert, Water Authority of Jordan.
P.O. Box 5012, Amman 11181, Jordan.
- Email: *Maram_Hawa@mwi.gov.jo*
- ORCID: 0009-0007-6934-3211
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.mwi.gov.jo/Default/Ar

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