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Techno-Economic Analysis of Selected PV-BWRO Desalination Plants in the Context of the Water–Energy Nexus for Low–Medium-Income Countries

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Abstract: Jordan was late in adopting seawater and brackish water desalination as a source until the late 1990s and early 2000s. However, ongoing studies are still discussing the technical, economic, and socio-political aspects of brackish water reverse osmosis (BWRO) desalination plants. In this study, the water–energy nexus was considered, in order to highlight the main challenges facing BWRO desalination. We discuss the use of photovoltaic (PV) technology, together with BWRO desalination, as an approach to compensate for ecological, financial, and social challenges in Jordan. For this purpose, the performance of nine existing BWRO desalination plants in the agricultural, domestic, and industrial sectors is assessed. The water performance is assessed based on water consumption, safe yield extraction, plant recovery rate (R, %), and compliance to local and international water quality standards; the Specific Energy Consumption (SEC, kWh/m^3) is taken as the main evaluation criterion to assess the energy performance of the BWRO desalination plants; and economic performance is assessed based on the overall cost of water produced per cubic meter (USD/m^3). The main environmental component is the brine disposal management practice utilized by each plant. Based on this assessment, the main challenges in BWRO desalination are the unsustainable patterns of water production, mismanaged energy performance, low recovery rates, and improper brine disposal. The challenges in domestic and industrial BWRO desalination, which are completely dependent on the electricity grid, are associated with critical energy and costs losses, as reflected by the high SEC values (in the range of 2.7–5.6 kWh/m^3) and high water costs per cubic meter (0.60–1.18 USD/m^3). As such, the use of PV solar panels is suggested, in order to reduce the electricity consumption of the assessed BWRO plants. The installation of PV panels resulted in significantly reduced energy costs (by 69–74%) and total costs (by 50–54%), compared with energy costs from the electricity grid, over the lifetime of the assessed BWRO desalination plants.

Keywords: water–energy nexus; brackish water reverse osmosis desalination; solar energy; photovoltaic panels; recovery rate; brine discharge management; water conservation; economic feasibility; specific energy consumption

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1. Introduction

Water scarcity is a challenge in Jordan that has been aggravated over the past few decades, placing it on the list of most water-scarce countries. The severity of water shortages in Jordan can be attributed to the rapid increase in population, refugee crisis, the poor management and high non-revenue water, frequent and prolonged droughts, and groundwater over-abstraction [1]. Most recently, several official reports have been published, warning Jordanian citizens about the severity of water shortages during the summer seasons, as well as the anticipated impacts that different sectors will subsequently face [2].

The Government of Jordan (GoJ) has been seeking alternatives to secure water supply, but these alternatives are rather short-term and will not satisfy the long-term growth demand of the different sectors in Jordan [3]. In 2017, the GoJ launched the National Green Growth Plan (NGGP), aiming to shift the economic growth in Jordan toward a greener and more resilient pathway [3]. The water sector is one of the six priority sectors for green growth, and, according to the NGGP, it is imperative to seek green projects and initiatives which ultimately provide affordable and equitable access to clean water for all societal groups, as well as securing sufficient water to support the growth of various economic sectors. In particular, the agricultural sector is one of the key economic sectors in Jordan, due to its role in food supply as well as the social character associated with farming in Jordanian society [4]. One promising solution to green the water sector and deal with water scarcity and drought is the desalination of seawater and ground brackish water; however, there are several techno-economic and environmental barriers to large-scale desalination in Jordan, such as the use of energy for desalination and the discharge of brine resulting in environmental impacts on land, air, and water [5,6]. Therefore, it is necessary to determine the environmental performance of BWRO plants in this country.

1.1. Water and Energy Challenges

The severity of the water crisis in Jordan has led to the necessity of adopting desalination plants, although they are energy-intensive and associated with critical environmental effects, attributed mainly to their high carbon footprint and brine disposal. Therefore, many studies have shown that, while desalination might be the only option to compensate for the disastrous water situation in the country, they also indicated the critical importance of suggesting techno-economically feasible remedies for the associated energy, cost, and environmental problems. Therefore, it is important to highlight the main energy, economic, and environmental performance indicators associated with the existing desalination plants in the country, specifically those for BWRO desalination. The annual renewable water resources are less than 100 m^3 per capita, much below the 500 m^3 per capita threshold limit [7]. The lack of water in Jordan threatens the health of the population, especially for vulnerable groups in under-served communities [6]. In addition, the predicted decrease in precipitation due to global warming and climate change accompanied by unsustainable urbanization has led to a tremendous decline in the available natural water supplies in Jordan [8]. According to the Ministry of Water and Irrigation (MWI) statistics of 2015, the water sources in Jordan were estimated to be around 79% from renewable freshwater sources, including 239 MCM from surface water and about 433 MCM from renewable groundwater. The rest of the water comes from non-renewable groundwater sources (75 MCM) and treated wastewater (102 MCM) [7]. This demonstrates that renewable groundwater sources are the primary source of water supply in Jordan; meanwhile, the primary brackish groundwater sources in Jordan come from the Jordan Valley, Red Sea, Wadi Araba, Azraq, Sirhan, and Hammad. However, the abstraction of groundwater sources, especially in Azraq, has increased beyond the safe yield, causing water quality degradation in the aquifers [8,9]. Thus, water scarcity in Jordan can be considered the most significant challenge to achieving sustainable development goals by 2030 [10].

According to MWI and the World Bank, the water deficit for the drinking water in Jordan can be estimated as 45 MCM while the water deficit for all water needs could be more than 450 MCM. This is critically alarming and, by 2040, at least 90% of the low-income population is expected to suffer from drastic water insecurity [11]. In addition, the progression in water deficit accompanied by the rapid increase in water demands due to population growth has created intensive pressure on energy demands, mainly for electricity.

Electricity is considered a primary factor for the country's economic growth, including the domestic, agricultural, and industrial sectors [12]. This threatens the country's economic growth, as most of the electricity generation in Jordan is dependent on fossil fuels, mainly oil and gas. Jordan imports about 97% of its fossil fuels for energy supply, and imported energy prices are drastically changing due to the unstable political situation in the Middle East and North Africa (MENA) region [11]. This has contributed to rapid inflation of electricity tariffs in response to the financial crisis facing the energy sector in Jordan [13]. Thus, the energy sector has become deleterious to the country's GDP, due to the heavy reliance on imported fossil fuels; on the other hand, it is supposed to be a vital component of the country's economic and social development [14]. In the food–water–energy nexus, population growth and the intensifying pressure on the country's resources, especially food and water, has led to a continuous increase in electricity demand, reflecting the prolonged inflation in electricity prices. Electricity prices have increased by at least 60% since 2005. In 2022, the price of electricity per kWh reached 0.12 USD for the domestic sector, 0.24 USD for the industrial sector, and 0.08 USD for the agricultural sector [15]. In fact, the water sector is considered one of the most electricity-demanding sectors, due to the water pumping systems. The Water Authority of Jordan (WAJ) has been assessed as the largest electricity consumer in Jordan [16]. Therefore, it can be concluded that water and energy are crucial components such that, in the context of the intensifying pressure created on the Jordanian water sector—where the water demand has highly exceeded the supply—the pressure on the energy sector is of equal importance [17]. The limited collaboration between Jordan's water and energy sectors represents a main challenge to achieving sustainable development; specifically, Sustainable Development Goals 6 and 7 (SDG7 and SDG6), which are most closely related to ensuring access, affordable, reliable, and sustainable water and energy dimensions. This necessitates changing the current water and energy systems, shifting towards sustainable approaches such as substituting conventional energy with renewable energy sources [18].

1.2. Future Perspectives of Renewable Energy Policies

The use of renewable energy sources has become much more critical, especially in countries such as Jordan, which has depended on imported fuels for many decades [14]. Technologies that use renewable energy have become a necessity to compensate for the effects of climate change and to reduce GHG emissions, while improving energy security at the same time [14]. As stated earlier, Jordan is surrounded by countries that suffer from an unstable political situation, impacting energy security in the country, as has been shown in terms of a remarkable increase in electricity prices [19]. To respond to this crisis, which worsened especially after the influx of Syrian refugees following the Syrian crisis, the Jordanian government has acknowledged the critical importance of establishing policies that promote the use of renewable energy sources and influence local energy production [14]. Many calls have been made to start utilizing renewable energy sources to repair the drastic increase in the electricity tariffs that threatened the country's economic development by hindering the survival of many industrial businesses in Jordan.

Over the past few decades, the acknowledgment of renewable energy legislation and policies has become global. In this regard, the first law concerning Renewable Energy and Energy Efficiency—Jordanian law No. 13 of 2012—was enacted in 2012 [18]. This law emphasizes the use of renewable energy, especially solar energy, which is the most abundant renewable energy source in Jordan, in order to achieve a safe energy supply, especially for energy-intensive sectors such as the industrial sector, to sustain their water and energy needs sustainably and environmentally [18]. The use of renewable energy has improved in Jordan since 2010, increasing from less than 1% in 2010 to 7% in 2018 in the total energy supply. Yet, the energy demand continues to grow, and the current efforts are not enough to reduce the energy consumption and patterns while simultaneously meeting the demands of the population [20]. Therefore, the question arises whether Jordan's energy law needs to be revised or if its implementation is effective regarding renewable energy projects.

In this regard, the UN Economic and Social Commission for Western Asia (ESCWA) has stated the need for more studies on policy reforms to promote renewable energy in Jordan. Under the Jordan vision 2025, the NES 2015–2025 aims for the 11% renewable energy target by 2025, with increasing energy supply from local energy sources [20].

1.3. Background of BWRO Desalination in the MENA Region

Desalination technology is considered one of the central options to meet the growing water demands in water-scarce countries, such as those in the MENA region. The MENA region holds about 48% of the total global desalination capacity, especially in the Gulf countries [21]. These pioneer countries in desalination are typically allocated in coastal sea areas, except for Jordan, with only one coast (Red Sea coast), which is located 400 km from its capital, Amman. Due to the extensive future pressure in demands and supplies challenged by the prolonged decline in freshwater sources, local and international studies have shown that BWRO desalination can be considered a primary management approach in countries such as Jordan [21,22]. Hence, Jordan relies on brackish water (BW) desalination as its primary conventional water source, and is ranked fifth in this aspect, compared with the 19 other countries in the MENA region; particularly, Saudi Arabia has the largest capacity for BW desalination, followed by Iraq, Iran, Algeria, Jordan, Egypt, the UAE, and others. RO is the most common desalination technology used in Jordan [21,22].

1.4. Potential of PV-BWRO Desalination in Jordan

Jordan is significantly dependent on the importation (around 97%) of fossil fuels for the production of electricity. This represents a high cost for different sectors (e.g., 30% of cost for some industrial operations), adding to the pressure to increase wind and solar technology to meet energy demands and targets for emissions reductions [3]. This is a barrier, for example, to increasing the water supply though desalination, and also affects development and food security. BWRO desalination is less energy-intensive and, thus, less costly than other forms of desalination technologies such as seawater desalination [23]. Still, many challenges regarding BWRO desalination remain, related to the high electricity consumption and prices, as well as operational costs [24]. It has been assessed that about 95–100 MCM/year comes from brackish water desalination. The average specific energy consumption of RO desalination in Jordan has been estimated as 3.5 kWh/m^3 on average. This is associated with at least 35 M USD of annual cost losses due to the energy consumption of the few operating desalination plants in Jordan, which is significantly high concerning the relatively small–medium economy of Jordan [7].

Another concern that exists regarding the current desalination plants in Jordan is poor brine discharge management [21]. At present, approaches for proper brine disposal remain unclear for many ongoing BW desalination plants. In the context of the water–energy nexus, the poor spotlight on proper brine management approaches related to desalination plants constitutes a central environmental concern in Jordan, which can harm the soil, flora, and the quality of nearby water resources [3,21]. To address these challenges, a previous study has shown that implementing PV energy in energy-intensive technologies such as desalination could represent a great solution to improve energy and economic efficiency for various economic sectors and industries in Jordan [21]. Based on the results of this study, PV panels were installed at multiple BW desalination plants in Jordan, especially those related to the agricultural sector, contributing to favorable reductions in overall water and energy losses and costs. Solar energy is considered plentiful in Jordan, as shown in Figure 1.

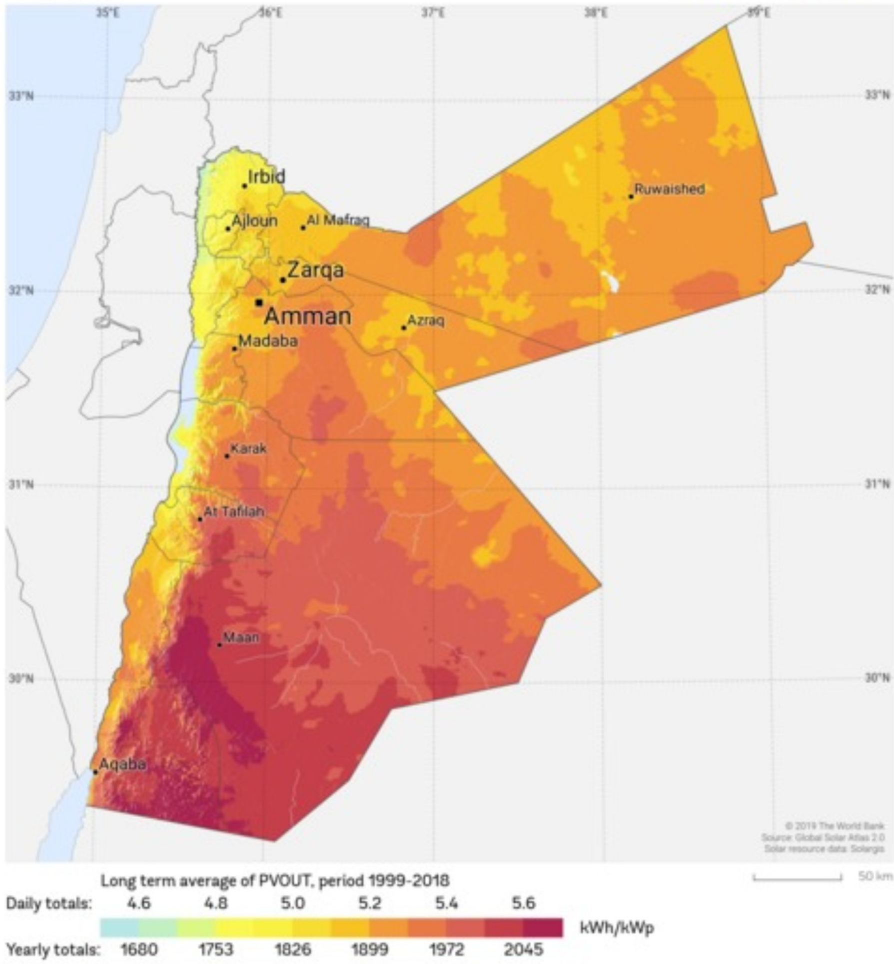

Figure 1. Jordan Photovoltaic Power Potential [20].

The average solar radiation has been estimated to reach 6.8 kWh/m^2/day, one of the highest globally [21]. As such, the implementation of PV solar panels to meet the energy demands of the BWRO desalination plants may be an optimal solution, in terms of lessening water scarcity in the domestic, industrial, and agricultural sectors, in order to ensure water and food security for the country.

1.5. Generated Brine Quantities and Disposal Methods

It was estimated that the combined daily amount of generated brine for all operating plants in the country is 61,148 m^3/d (about 22.3 MCM/yr), with the average salinity of the brine being 8274 ppm, measured as TDS. Figure 2 depicts the brine disposal practices of desalination plants in Jordan. Basically, 30% of plants discharge their generated brine into valleys or nearby seas, 8.4% of the plants use the brine for irrigation (with or without blending it with low-salinity water), 4.7% of the plants have evaporation ponds, 14% of the plants dispose of their brine into an on-site wastewater treatment facility, and about 40% of the plants did not offer any data in this regard.

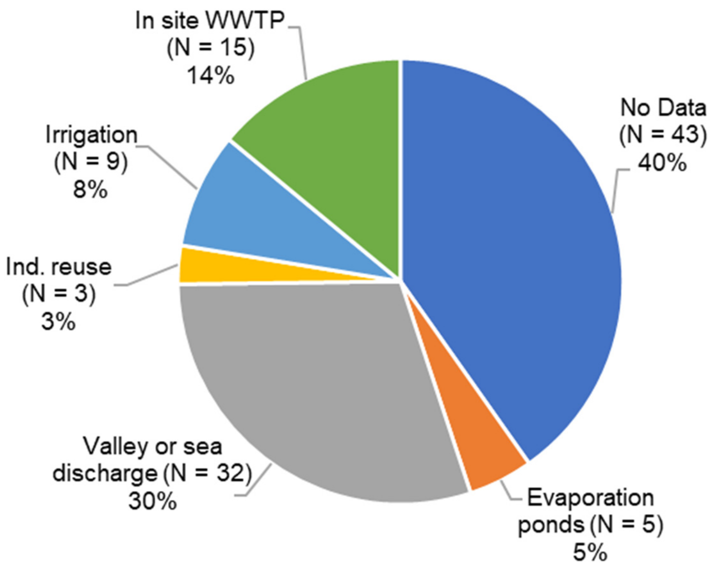

Figure 2. Brine disposal practices in Jordan.

1.6. Study Scope and Main Objectives

This study aims to discuss the challenges that some of the selected BWRO desalination plants face in different sectors in Jordan, including the agricultural, domestic, and industrial sectors, in the context of the water–energy nexus. We aim to propose a process for techno-economic analysis of BWRO desalination plants in Jordan, considering water consumption and production, energy use, operation costs, and environmental performance (e.g., brine generation management). The process takes into consideration the recovery rate, practical brine management approaches and, most importantly, reducing energy and costs by integrating the assessed BWRO plants with PV solar panels. The successful planning, design, and implementation of PV-BWRO desalination in all sectors requires governmental support and the collaboration of WAJ, MWI, and the Ministry of Energy. Thus, the main objective of this study is to show the techno-economic feasibility of PV-BWRO desalination in Jordan, in terms of increasing water supply while reducing the associated energy consumption and costs at the same time [7].

Our ultimate goal is to suggest economically feasible solutions to improve the overall water, energy, and environmental performance of the assessed desalination plants. This study of the water–energy nexus in Jordan represents a holistic view of the BWRO desalination process, which is essential for achieving sustainability. As such, the main objectives of this report are to: (1) Evaluate the water consumption trends of the assessed BW desalination plants in the context of water conservation and the water recovery rate; (2) evaluate the operation performance of the BW desalination plants in terms of water and energy production and consumption; and (3) propose effective methods to optimize the performance of the assessed RO plants for the purpose of reducing the energy consumption by integrating the RO plants with renewable energy sources, such as PV panels.

2. Materials and Methods

A quantitative methodological approach was used to evaluate the performance of existing BW desalination plants in the Hashemite Kingdom of Jordan, in the context of water–energy nexus components. The data collection methods used in this study included the following: (1) Audit data for the domestic BWRO desalination plants, obtained from WAJ; (2) monthly water quality monitoring reports from several domestic RO plants; (3) farmer responses to survey questionnaires were computed for RO agricultural plant assessments; and (4) performance operating data on multiple BWRO desalination plants in the domestic, agricultural, and industrial sectors. In this sense, data related to about 100 BWRO desalination plants were collected in Jordan during the period of 2019–2021.

However, most of the collected data were scattered and lacked accuracy, which could be related to the fact that desalination technology is still limited in Jordan; therefore, the data obtained for this assessment were associated with some uncertainties, mainly related to the accessibility of data in all sectors, including the agricultural, domestic, and industrial sectors.

In the agricultural sector, many farmers denied having desalination plants, likely due to their violation by exceeding the allowable water quantities allocated to their farms. The domestic and industrial sectors lack proper technical and water quality monitoring systems, so the collected data related to water quality monitoring were minimal. Data screening was conducted to inspect the missing data, remove errors, and select the BWRO desalination plants that were most viable to assess in the context of this study, in terms of the water–energy nexus. Accordingly, three BWRO desalination plants from each sector, including those intended for drinking, agricultural, and industrial water, were selected for the analysis.

The main parameters that were used to represent the overall performance of the BWRO desalination plants in Jordan, in terms of economic/cost and environmental aspects, were: (1) plant recovery rate (R%); (2) specific energy consumption (SEC); (3) Jordanian Water Quality Standards (JWQS) [6], MWI water irrigation, and JS 893/2006 reclaimed domestic wastewater standards; and (4) brine characteristics and disposal. The costs and financial benefits related to optimizing the energy consumption patterns for the existing RO plants were considered by assessing the overall operational costs before and after installing the PV solar renewable energy source. Costs of electricity supplied by the national grid were calculated based on the Jordan electricity tariff which ranged between 0.069 USD/kWh and 0.33 USD/kWh for households, industrial, and agricultural users [5]. Assuming the average solar irradiation of Jordan as 7 kWh/m^2/day and a maximum power capacity of 350 W for one PV panel, the techno-economic feasibility of the BWRO plants in each of the agricultural, domestic, and industrial sectors was assessed.

2.1. The Surveyed BWRO Desalination Plants

All of the assessed BWRO desalination plants were configured as two-stage RO units. Table 1 details the locations, size, and the associated sector of the surveyed BWRO desalination plants considered in this study.

Table 1. Details of the Surveyed BWRO Desalination Plants.

Station	Location	Plant Size	Groundwater Basin	Sector
Al-Jawasra BWRO plant	Balqaa govern	Large	Dead sea basin	Agricultural
Al-Kafrain (Banana) BWRO plant	Balqaa govern	Small	Dead sea basin	Agricultural
Al-Kafrain (Banana and Vegetables) BWRO plant	Balqaa govern	Small	Dead sea basin	Agricultural
Mudawwara border BWRO plant	Mudawwara borders, south Jordan	Small	Disi and Mudawarah	Domestic
Meshtal Fasial BWRO plant	Jerash, northern Jordan	Large	Amman-Zarqa Basin	Domestic
Abu Zeighan BWRO plant	Zarqa Governorate, northeast Jordan	Very Large	Amman-Zarqa Basin	Domestic
Aquaduva BWRO plant	Aljeeza, Amman, Jordan	Small	Amman-Zarqa Basin	Industrial
Arab Potash BWRO plant	Karak governorate, southeast Jordan	Small	Dead sea basin	Industrial
Zarqa Power BWRO plant	Zarqa, northeast of the capital (Amman)	Small	Amman-Zarqa Basin	Industrial

The desalination plants are typically classified into very large-scale industrial use, large capacities/small operations, and very small-scale in-home applications; however, in order to obtain a broader and deeper view of the size of the plants, the following classification was proposed (see Table 2).

Table 2. Desalination plant size classification.

Plant Size	Production Capacity (m^3/d)
Very small	10–100
Small	100–1000
Large	1000–10,000
Very large	10,000–100,000
Super large	≥100,000

The locations of the assessed BWRO desalination plants are identified on the map shown in Figure 3.

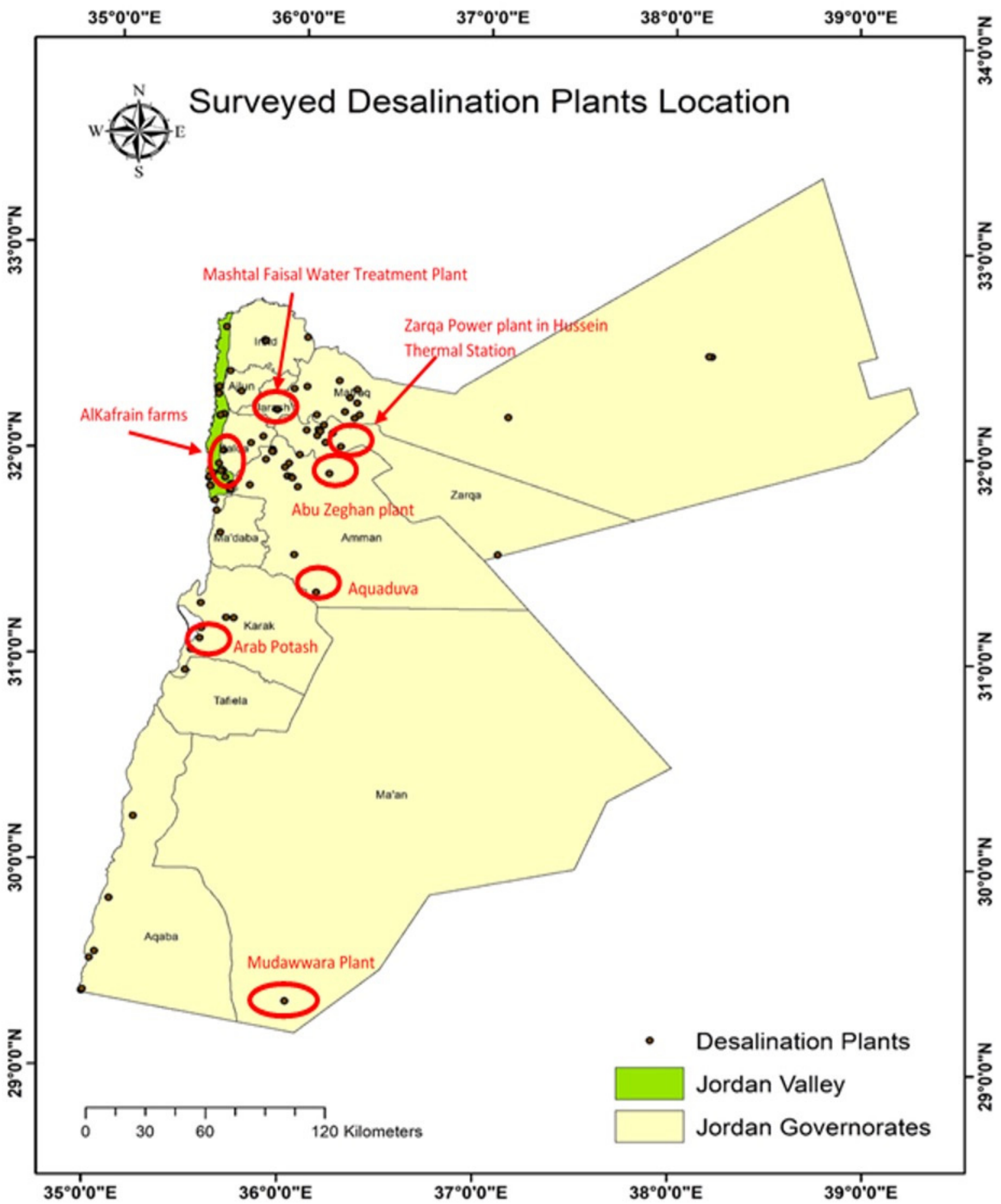

Figure 3. Locations of the Surveyed BWRO Desalination Plants.

2.2. Water and Energy Assessment

Table 3 summarizes the collected data, which were used to conduct the water and energy audits of the selected BWRO desalination plants in the agricultural, domestic, and industrial sectors.

Table 3. Surveyed data for the assessment of BWRO desalination plants/stations.

Station	Feed (m^3/h)	Permeate (m^3/h)	Brine (m^3/h)	Delta P (bar)	Water Unit Cost (USD/m^3)	Operational Costs (USD/year)	Feed TDS (ppm)	Permeate TDS (ppm)	Brine TDS (ppm)
Al-Jawasra BWRO plant	83	52	31	1.8	0.32	150,921	4000–5000	300	10,206
Al-Kafrain (Banana) BWRO plant	33	20	13	1.2	0.21	37,729	4000	300–500	9384
Al-Kafrain (Banana and Vegetables) BWRO plant	35	27	8	1	0.18	43,099	2500–4600	<600	8912
Mudawwara border BWRO plant	45–48	34–36	12–13	2.6	0.37	114,598	256	63–94	684
Meshtal Fasial BWRO plant	58	49	8.7	2.5	0.32	164,585	3053	177	19,356
Abu Zeighan BWRO plant	1800	1350	450	2.5	0.37	4,430,402	3673	145–500	13,192
Aquaduva BWRO plant	27	19.2	8.3	3.9	0.68	80,732	850	125	2475
Arab Potash BWRO plant	50	33	17.2	3	0.56	113,868	1098	198	2811
Zarqa Power BWRO plant	24	19.2	4.8	2.4	0.42	98,861	512	230	1640

One of the main water assessment criteria is to ensure the water conservation and water quality components within the assessed BWRO desalination plants. The performance of the selected BWRO desalination plants, in terms of water demand patterns, was assessed with respect to the associated groundwater basin safe yield (shown in Table 4) and the recovery rate. The water recovery rate is one of the main components to improve the efficiency of any desalination plant. The recovery in desalination plants is the amount of water produced or permeated per unit time, as shown in Equation (1).

$$\text{Recovery Rate } \% = F - \frac{B}{F} * 100\% = \frac{P}{F} * 100\%, \quad (1)$$

where F is the feed flow (m^3/h), B is the brine (concentrate) flow (m^3/h), and P is the permeate or product flow (m^3/h). The quality of the product water from the BWRO desalination plants from all sectors was assessed according to the Jordan Drinking Water Standards (JDWS) [7], while the water quality of the discharged brine was assessed according to MWI's water reuse standards for irrigation and Jordanian standards for reclaimed domestic wastewater (JS 893/2006) [12]. In addition, multiple Jordanian water laws, policies, and standards were used in the water assessment conducted for this study, including the Water Authority Law of 1988 and its Amendment for 2014, Groundwater Control Regulation No. (85) of 2002, Brine Disposal Regulations, and Wastewater Standards in Jordan, which include the JS893/2006 related to reclaimed wastewater [25–27].

Table 4. Abstraction from groundwater basins in Jordan and their safe yields in 2019 [3].

Groundwater Basin	Abstraction (MCM)								Safe Yield (MCM)	Balance (MCM)	Safe Yield %	Number of Wells
	Domestic		Livestock Remote Areas	Industrial	Agriculture		Recreation	Total				
	Private	Governmental			Private	Governmental						
Disi and Mudawarah	0	116.18	0	0	25.93	2.84	0	144.95	125	−19.95	116.0	112
Dead Sea	1.2	44.94	7.33	0.56	25.14	4.57	0.25	83.99	57	−26.99	147.4	467
Amman Zarqa	4.79	81.83	4.22	1.05	71.65	0	0.05	163.59	87.5	−76.09	187.0	1022
	9.27	345.41	25.41	1.96	209.38	26.27	0.33	618.03	413.5	−204.53	149.5	3183

One of the main motives of this study was to evaluate the current energy consumption trends of the operating plants, in order to suggest renewable energy sources for the reduction in water production costs. The energy consumption trends of the assessed BWRO plants were calculated based on the total specific energy consumption (*SEC*, kWh/m^3), as shown in Equation (2) [21], which includes the hydraulic work conducted by the pump and the total electric energy consumed. Most of the electric consumption comes from the pumps, as shown in Equation (3) [21], while the rest comes from other utilities, such as energy losses, wasted energy, and lighting system, which can be estimated in the range of 30–35% (based on personal communication with the operators/engineers of the assessed BWRO desalination plants). The ideal thermodynamic minimum *SEC* was used as a reference. The ideal thermodynamic *SEC* gives a rough estimate for the least energy needed to produce one cubic meter of water without any energy losses, calculated using Equation (4) [21].

$$SEC = \frac{EHP}{QP} + 0.35 * SEC\ , \tag{2}$$

$$EHP = QF\frac{Po - Pi}{\mu}, \tag{3}$$

$$SEC\ ideal = Posmotic\left(\frac{1}{R}\right)\ln\left(\frac{1}{1-R}\right), \tag{4}$$

where *SEC* is the specific energy consumption (kWh/m^3), *EHP* is the power consumed by the high-pressure pump (kW), *QP* is the permeate flow rate (m^3/h), *QF* is the feed flow rate (m^3/h), P_o is the reject (output) pressure (bar), P_i is the feed (inlet) pressure (bar), μ is the pump efficiency (assuming the use of HPP, μ = 90%), *SEC* ideal is the minimum SEC (kWh/m^3), $P_{osmotic}$ is the osmotic pressure of the feed water, and *R* is the recovery ratio.

The *SEC* benchmark was set as 1.3 kWh/m^3 for this study, as determined based on previous studies in the literature review [21].

The PV Philadelphia Solar panels were considered a good option, which are manufactured locally in Jordan. The average solar irradiation of Jordan in regions such as Zarqa and Amman is about 4 kWh/m^2/day in winter, reaching 8 kWh/m^2/day in summer. The techno-economic feasibility of the combined PV-BWRO desalination was assessed assuming an average solar irradiation in Jordan of 6.8 kWh/m^2/day (direct normal irradiation) and a maximum power capacity of 350 W per PV panel. Previous studies have shown that the lifetime of a BWRO desalination plant could reach 20 years, if the specific energy consumption were between 1.5 and 3 kWh/m^3 [28]. Thus, the estimated lifetime of BWRO plants in the agricultural and domestic sectors was taken as 20 years, while that for those in the industrial sector was set as 15 years, due to their higher SEC values. The PV system lifetime could be up to 25 years, based on Philadelphia's manufacturing specifications for a 350 W PV panel system. Philadelphia's PV system operational and maintenance costs are approximately 13.8–21.4 USD/kW/year.

3. Results and Discussion

3.1. Water and Energy Assessment

Using the data presented in Tables 1–4, the performance of the selected BWRO desalination plants in the agricultural, domestic, and industrial sectors was assessed. Table 5 presents the output variables that were used to investigate the water, energy, and environmental performance of these plants. The water and energy audits were carried out based on the performance results for the assessed BWRO desalination plants. The water performance was assessed based on the recovery rate and compliance to Jordanian Water Standards. As mentioned earlier, the recovery ratio represents the primary indicator for water losses and brine discharge; meanwhile, the energy performance was assessed based on the SEC, which directly indicates the amount of energy required in the desalination process.

Table 5. Water and Energy Performance of the Assessed BWRO Plants.

Station	Recovery (%)	Production Capacity (m^3/day)	SEC (kWh/m^3)	Overall Water Unit Cost (USD/m^3)	Total Plant Costs (USD/Lifetime)
		Agricultural Sector			
Al-Jawasra	62%	1248	2.7	0.62	5,615,275
Alkafrain (banana)	60%	480	1.7	0.21	1,415,958
Alkafrain (banana and vegetables)	77%	648	1.5	0.18	1,204,317
		Domestic Sector			
Mudawarra	75%	840	3	0.65	3,985,632
Mashtal Faisal	85%	1176	2.7	0.6	5,204,393
Abu Zeighan	75%	32,400	3	0.65	153,832,995
		Industrial Sector			
Aquaduva	70%	460.8	5.6	1.18	2,976,470
Arab Potash	65%	787	4.5	0.95	4,111,259
Zarqa Power Plant (RO2),	80%	576	3.6	0.8	2,497,300

3.1.1. Water Assessment

Water Consumption and Safe Extraction Yield Comparison

Among the assessed BWRO desalination plants, the Abu-Zeighan plant—considered a prominent water consumer for the domestic sector—showed the most alarming consumption trends from the associated groundwater basin. It was estimated to consume about 22.4% of the Amman-Zarqa basin's annual safe extraction yield. This is justifiable, based on the location of the basin and the huge number of people this plant served. On the other hand, it could be concluded that the agricultural sector showed the most unsustainable water consumption practices, as reflected by the low recovery rates shown in Table 4. This was achieved by scaling up of water consumption percentages from the assessed agricultural BWRO desalination near the Dead Sea groundwater basin (3% of the safe yield), assuming similar rates for the rest of the farms in the Jordan Valley, which is significant for the Jordanian agricultural activities. An over-extraction pattern was indicated, reaching 212% on average of the Dead Sea basin safe yield for the desalination plants in the Balqa region. Indeed, this is considered a primary challenge threatening the ecosystems in the Jordan Valley. In fact, the over-extraction of water accompanied by water pollution and mismanaged agricultural development has been affecting food security in the country by leading to a substantial reduction in cultivation activation, determined based on statistical data for irrigated crop production in the Jordan Valley [12].

On the other hand, the other assessed BWRO desalination plants in the domestic and industrial sectors showed medium water consumption patterns from the associated groundwater basins. The average plant capacity of the Mudawwara and Mashtal Faisal water treatment plants in the domestic sector was much smaller than that of the Abu-Zeighan plant, which thus does not constitute a real threat, in terms of over-pumping from the nearby groundwater aquifers, as these plants are supplying water to many fewer people. As for the industrial sector, the capacities of the assessed BWRO desalination plants were small, with an average of 576–1200 m^3/day. The average capacity of industrial plants, indicated in Table 4, indicates that their estimated safe yield in water utilization was less than 1% for the three industrial BWRO stations; however, this suggests that the industrial sector is being challenged by a shortage in water supply, which may hinder the establishment of new industries due to increased costs related to water and energy utilities. Thus, there is a critical need to develop non-conventional water resources for the industrial sector, which requires sustainable water management approaches.

Water Quality

The data analysis conducted on the collected monthly water quality monitoring data showed that the produced water quality for all the assessed BWRO desalination plants in the agricultural, domestic, and industrial sectors complied with the MWI water irrigation standards and the Drinking Water Jordanian Standards. However, it was noted that most of the assessed BWRO desalination stations did not have a rigorous water quality monitoring system. This represents a central challenge, especially for the domestic sector, as it falls under the drinking water category; therefore, more precautions should be taken in terms of maintenance and monitoring, and strict regulations must be promoted for monitoring of the produced water quality. On the other hand, referring to the feed TDS values given in Table 3, it can be concluded that the quality of the associated groundwater basins is threatened by the high salinity records shown, especially in the Dead Sea basin. Table 3 indicates that the salinity of the Dead Sea groundwater at the site locations of the farms was about 4000–5000 ppm. Groundwater quality data for Jordan in 2009 showed that the TDS value for the Dead Sea groundwater basin was only about 755 ppm, which even complied with the Jordanian Standards for Drinking Water [29]. Meanwhile, the TDS for the Amman-Zarqa basin at the location of plants was estimated at 3053–3673 ppm. Based on the 2015 groundwater quality data for the Amman-Zarqa basin, the maximum recorded TDS value was about 1200 ppm [30]. This demonstrates that the TDS in the Amman-Zarqa basin has increased by about three times since 2015, indicating an alarming salinization trend for the Dead Sea groundwater. The recorded high salinity for the assessed groundwater sources in this study further confirm the continuing groundwater over-abstraction in Jordan and the deterioration of its quality. This is in line with previous assessment studies conducted on groundwater sources in Jordan and desalination technology. Those studies have also indicated a significant degradation in groundwater sources, in terms of quantity and quality, which constitutes a significant threat to Jordan's future water supply and demand [1].

In the long- and short-term perspectives, BWRO desalination could represent a competitive solution to this dilemma, considering its reduced costs compared to seawater RO and other desalination technologies [19,31]. Although BWRO desalination is still considered an energy-intensive water treatment method associated with energy and economic losses, there are various opportunities for improvements, in terms of energy and cost reduction, that can be highly recommended in Jordan. PV solar energy has shown high potential, in terms of powering Jordan's assessed BWRO desalination plants. Solar energy represents an economically and environmentally sustainable electric power source in Jordan, due to its abundant availability [18,20].

Brine Disposal Management

The TDS analysis trends obtained in this study indicated that brine disposal is seriously problematic for the assessed BWRO desalination plants, especially in the agricultural sector. Unfortunately, it was noted that most of the assessed BWRO desalination plants disposed of brine into nearby terrestrial and aquatic ecosystems. The recorded TDS concentrations of the agricultural BWRO desalination brine discharge were alarmingly high, as indicated in Table 3; in three cases exceeding 8000 mg/L—this is higher than the groundwater source TDS by at least two times. Although no specific Jordanian regulations have been set for brine discharge quality, these high-salinity discharges would violate Environment Protection Law No. 1 of 2003, according to article 9, due to their hazardous impacts on the land and nearby aquatic surfaces. Based on the responses of farmers to the assessed agricultural BWRO desalination plants, there has been a decline in cropland areas surrounding them. The farmers related this problem to the prolonged water deficit from the nearby watersheds, such as the Jordan River and reduced rainfall patterns; however, these farmers were unaware that unsustainable brine management also represents a direct cause for deterioration in the soil's capability to produce sufficient amounts of fruits, vegetables, and crops. In the context of the food–water–energy nexus, the poor brine management that has been witnessed in the agricultural sector, accompanied by water shortages, and decreased rainfall patterns, has led to the creation of more threats to crop production capacity in the Jordan Valley. On the other hand, the salinity records shown for discharged brine in the domestic and industrial BWRO stations did not constitute an adverse problem, compared to the agricultural sector. Still, the overall TDS analysis trend for most of the assessed agricultural, domestic, and industrial BWRO desalination plants indicates the necessity of developing effective brine management methods.

The situation in Jordan is becoming more critical, in terms of water, energy, and food security. Therefore, the Jordanian Environmental, Climate, and Sustainable Development laws and legislations should consider preventing brine disposal into surrounding terrestrial or aquatic ecosystems [1]. Considering the relationships between food, water, and energy, brine disposal from the agricultural sector poses a threat to the cultivation capacity in Jordan, influencing desertification through high soil salinity levels and damaging the soil structure, as shown below (see Figure 4) [1].

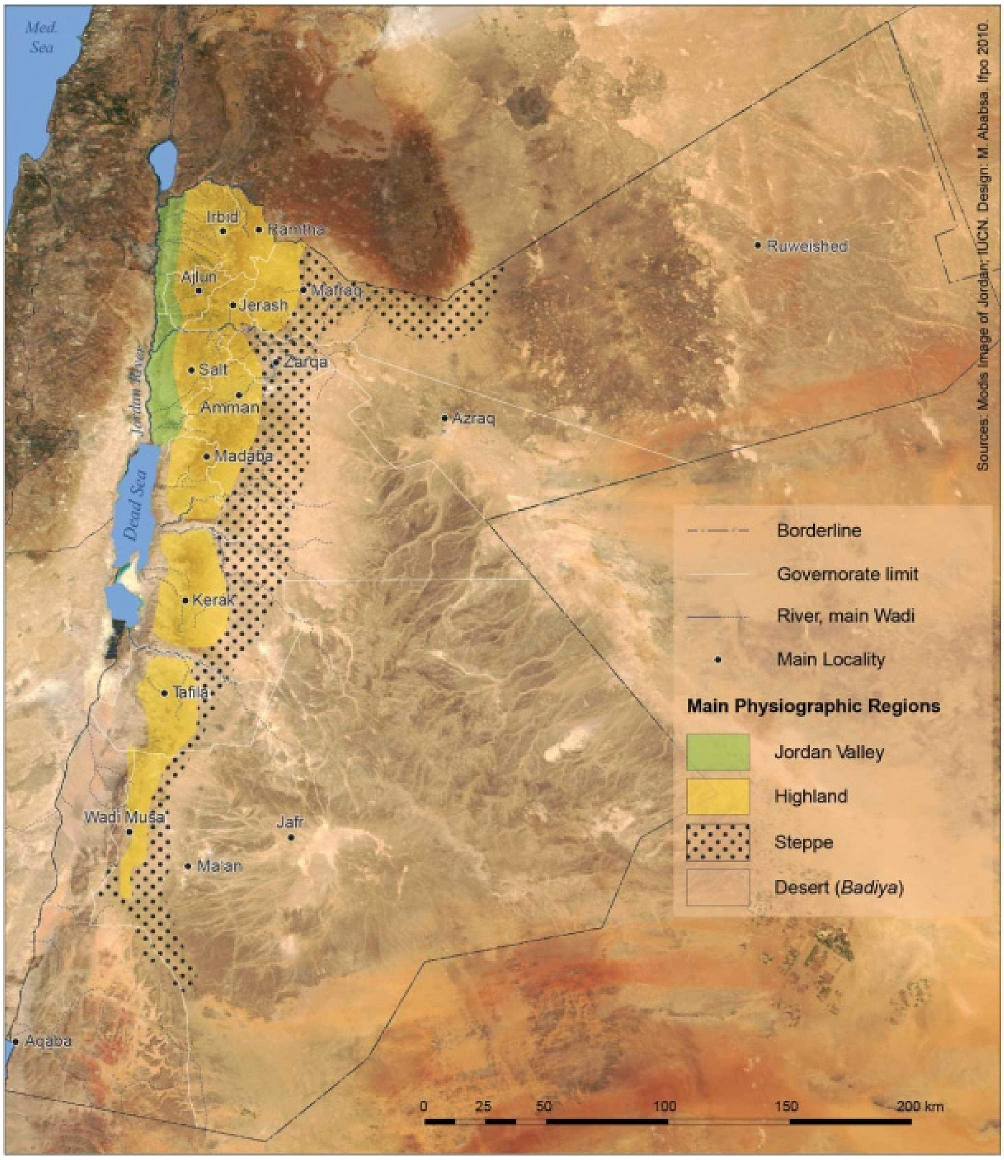

Figure 4. Jordan Four Main Physiographic Region [1].

In this study, the adoption of evaporation ponds was considered the primary option for all of the assessed BWRO desalination plants that produce brine with high levels of TDS content (i.e., exceeding the 1700 ppm range). The allowable limit for irrigation reuse is 1700 ppm and that for sewer discharge is 1500 ppm, according to the Jordanian MWI water irrigation, JS 893/2006 reclaimed domestic wastewater standards [5,32]. Thus, referring to the TDS analysis trend shown in Table 3, the use of an evaporation pond was considered the primary brine management option for most the BWRO plants, except for the Mudawwara border BWRO plant in the domestic sector and Al-Zarqa's Power station in the industrial sector. The brine of Al-Zarqa's Power station can be reused for irrigation; however, looking into the prolonged soil erosion in Jordan, it would be better to utilize an evaporation basin for brine disposal. On the other hand, the lower salinity records (<1500 ppm) shown for the discharged brine from the Mudawwara domestic BWRO and Aquaduva's industrial BWRO stations make it applicable for sewer discharge or irrigation reuse [32,33].

In addition, increasing the recovery ratio has been studied, in order to obtain a favorable reduction in the disposed brine and increase the rate of produced treated water [34]. However, optimizing the RO performance by increasing the recovery rate will be equated with lower energy losses and reduced water losses. In general, a desalination plant's larger capacity, accompanied by a proper monitoring and maintenance system, would technically influence maximization of the recovery rate [23,24,34]. It has been noted that the RO units in the agricultural sector lacked the appropriate maintenance and monitoring systems. Thus, this study suggests aiming for >75% recovery in the assessed BWRO desalination plants in the agricultural sector, which is suitable for their current off-grid operational capabilities, as indicated by operational engineers who have previously assessed the performance of plants in the agricultural sector. On the other hand, the BWRO desalination stations in the domestic sector showed the best performance, compared to the industrial and agricultural sectors. Thus, our proposed aim is an 85–90% recovery rate for the domestic sector, which is suitable to their off-grid operation, as indicated by relevant operational and design engineers of those plants. In fact, obtaining a high recovery rate in the assessed BWRO desalination plants in the domestic sector is vital to improving the produced drinking water quality. As for the industrial sector, maximizing the recovery rate is vital for two main reasons: (1) It has minimal water consumption, compared to the domestic and agricultural sectors, making it necessary to conserve water and reduce water losses; and (2) brine disposal from industrial BWRO desalination plants may be associated with the production of chemical and minerals, especially in industries such as Arab Potash. For small-scale industries, it would be feasible to aim for an 80–85% recovery; this also depends on the feed water quality, which can be considered fair, looking at the TDS analysis shown for the industrial sector in Table 3.

3.1.2. Energy and Economic Assessment

Looking at the energy and economic analysis trends displayed in Table 4, it can be concluded that desalination plants in the industrial sector showed the highest specific energy consumption, followed by the domestic sector and, finally, the agricultural sector. Although the feed TDS was higher for the agricultural sector, as shown previously in Table 3, it was assessed that the BWRO desalination in the agricultural sector were typically supported with PV solar panels, allowing them to attain lower SEC values, compared with the other plants in other sectors. The actual specific energy consumption ranges of domestic and industrial BWRO desalination units exceeded our energy benchmark (i.e., 1.3 kWh/m^3) by 3–5 times [21,22]. Significant costs accompanied the high energy consumption of these two-pass systems, reflected in the overall water unit price, which was the highest for the industrial sector (as shown in Table 4). This could be related to the high electricity consumption for water pumping considering the current situation of groundwater resource depletion and the minimal share of water supply reaching small- and medium-scale industries. Still, many factors contribute to the increased energy expenditure of the assessed desalination plants. Based on the computed energy and economic analysis in this study, we concluded that optimization of the operation of the plants, with regard to total recovery, is necessary.

Although the highest energy consumption was observed for the BWRO desalination plants in the industrial sector, some of the assessed BWRO plants in other sectors had a recovery lower than 70%, leading to similarly high energy consumption. According to the responses of engineers related to the assessment of BWRO desalination, the reduced efficiency of the operating pumps contributed to higher energy losses. This was explicitly noted for the BWRO desalination systems in Al-Jawasra farm constructed in 2010 (agricultural sector), Aquaduva industry constructed in 2014 (industrial sector), and Arab Potash constructed in 2017 (industrial sector). This could also be related to an isobaric energy problem accompanied by technical flaws in the RO membranes, associated with the low quality of the water feed entering the system. Finally, referring to Table 4, the lowest energy and costs were observed for Al-Kafrain (banana and vegetables) followed by Al-Kafrain (banana). It was assessed that both solar energy and electricity were used to operate BWRO desalination in Al-Kafrain farms, unlike the rest of the assessed BWRO desalination stations, which depended on the electricity from the public network as the primary source for energy supply. In addition, the Meshtal Faisal plant also showed a lower specific energy consumption value than the other domestic BWRO desalination plants, despite having the highest recovery rate of 85%. The energy audit assessment showed that the most recent BWRO desalination units for the Mashtal Faisal were powered by PV solar energy, which lowered the electricity consumption patterns, compared to the other assessed BWRO desalination plants in the domestic and industrial sectors. Thus, the techno-economic feasibility of implementing photovoltaic solar energy for the assessed BWRO desalination plants was studied, with the primary purpose of demonstrating a valuable energy and cost optimization approach for countries that suffer from trans-boundary water conflicts and a mismanaged energy sector such as Jordan.

3.2. Photovoltaic Solar Energy for the BWRO Desalination

Previous studies have shown that significant cost reduction in electricity generation can be achieved by installing solar energy technologies in combination with water pumping systems. The cost reduction was associated with reduced water losses through improving the water pump efficiency and supplying the needed electric power for the operation of the pumps by solar energy [34]. In Jordan, which has some of the highest solar radiation values globally, PV energy represents a solution with great potential to improve energy and economic efficiency in various economic sectors and industries [31]. Due to the significant electricity consumption in Jordan, PV solar panels have already been applied and implemented in many economic activities, mainly for water pumping systems [14,35]. It was also found, in this study, that the PV panels have been installed in multiple BW desalination plants in Jordan, especially in the agricultural sector, contributing to a favorable reduction in overall water costs, as has been demonstrated. The techno-economic feasibility of PV-BWRO systems was assessed, in order to reach our energy benchmark target, by reducing the energy consumption and costs associated with the electricity grid. Figure 4 shows the estimated energy and economic reduction ranges obtained with the PV solar energy, compared with the electricity grid, for the assessed BWRO desalination plants in the agricultural sector, domestic sector, and industrial sectors over their estimated lifetime. Table 6 shows the economic and energy assessment in the case of implementing the PV as the primary energy source for the assessed BWRO desalination plants.

Table 6. Economic Feasibility of PV-BWRO desalination for the Agricultural, Domestic, and Industrial Sectors.

Station	SEC (kWh/m^3)	Overall Water Unit Cost (USD/m^3)	Total Plant Costs (USD/Lifetime)
Al-Jawasra	1.3	0.32	3,007,922
Alkafrain (banana)	1.7	0.21	1,415,958
Alkafrain (banana and vegetables)	1.5	0.18	1,204,317
Mudawarra	1.5	0.32	2,028,165

Table 6. *Cont.*

Station	SEC (kWh/m^3)	Overall Water Unit Cost (USD/m^3)	Total Plant Costs (USD/Lifetime)
Mashtal Faisal	1.35	0.32	2,799,371
Abu Zeighan	1.5	0.32	78,330,676
Aquaduva	2.47	0.61	1,532,515
Arab Potash	2.25	0.5	211,5696
Zarqa Power Plant (RO2)	1.87	0.42	1,353,124

By looking at the PV specific energy consumption analysis trend shown in Table 6 and Figure 5, it can be deduced that some of the assessed BWRO desalination plants still need some improvements to reach our targeted energy benchmark (1.3 kWh/m^3). This is mainly for the BWRO stations in the industrial sector, followed by Al-Kafrain (banana) in the agricultural sector, which showed an elevated energy consumption even though it was already supported by PV panels. It can be concluded, from Table 4, that the most significant financial and energy losses were observed for the assessed BWRO plants in the industrial sectors. The high energy and cost losses reported for the assessed BWRO stations in the industrial sector in this study are a reflective situation for all of the industries in Jordan. High energy costs represent the greatest threat to the sustainable capability of industrial businesses in Jordan [12]. The lack of sustainable management planning in the energy sector and the substantial reliance on imported fossil fuels have crippled many industries in Jordan due to increased energy costs, which have led to severe inflation in the electricity tariff, as elaborated earlier [12,36]. Thus, it is critically important to call for energy minimization improvements and long-term energy strategies, such as the use of renewable energy sources, which several business owners have already suggested in Jordan. In this study, PV solar energy showed favorable energy cost reduction ability for the industrial sector, as shown in Figure 6. However, even with the PV-BWRO configuration, the SEC obtained by plants in the industrial sector, especially those of Aquaduva (2.47 kWh/m^3) and Arab Potash (2.25 kWh/m^3), were still far from our target of 1.3 kWh/m^3. Thus, the conducted assessment for the industrial sector indicates a need to develop additional efforts beyond the sole use of PV solar energy, in order to minimize water/energy losses and the accompanying financial losses. In general, it can be concluded that the PV solar energy obtained favorable energy consumption and cost reductions, comparing the values shown in Tables 5 and 6 for all the BWRO desalination plants from different sectors. The PV solar energy reduced energy costs by 69–74%, compared to electricity from the grid, for the assessed agricultural, domestic, and industrial BWRO desalination plants. This resulted in a more than 50% total cost reduction for the assessed BWRO desalination plants over their estimated lifetimes.

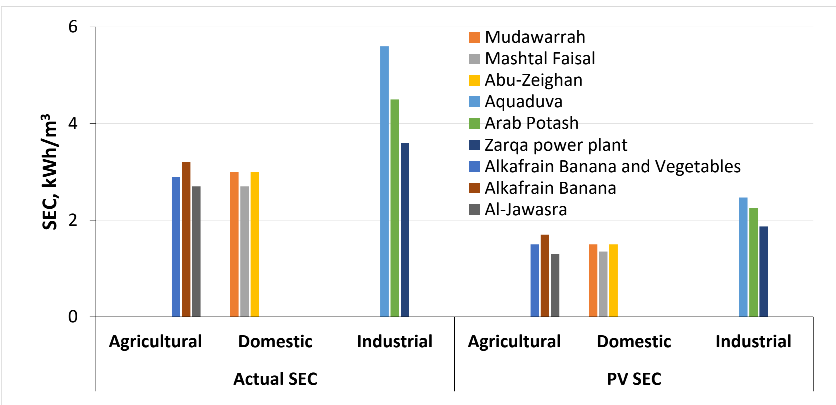

Figure 5. SEC in actual situation and when using PV solar energy by sector (kWh/m^3).

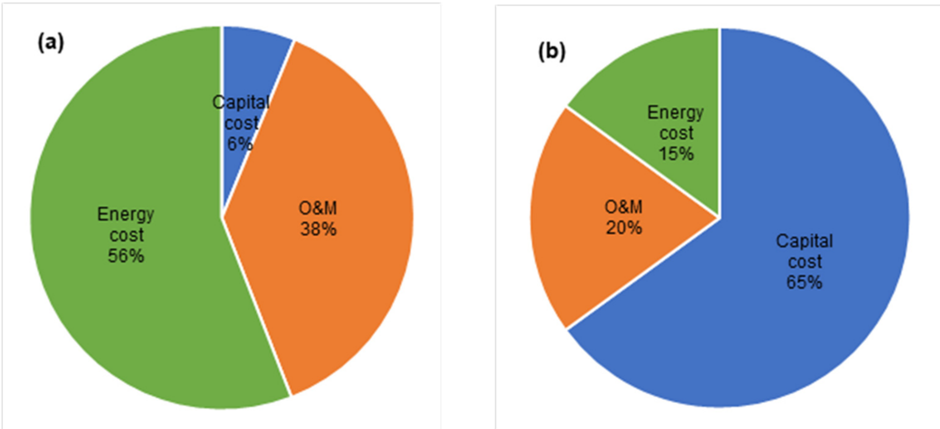

Figure 6. Cost comparison per energy source for the industrial BWRO desalination plants. (**a**) Electricity network; (**b**) PV solar energy.

However, there is a need to optimize the energy reduction efforts for the BWRO desalination plants that were slightly elevated, compared to our energy benchmark target. It is crucial to reconsider the operational scheme of the RO systems in the industrial sector, and to check the areas contributing to the most extensive amounts of energy consumption and losses. On the other hand, in the case of the Al-Kafrain (banana) BWRO station, improving the SEC by reducing water and energy losses could be achieved by adequately maintaining the BWRO system and improving technical education on PV solar panels, which was one of the main challenges portrayed in the survey responses. To further confirm the economic feasibility of PV-BWRO desalination, it is essential to refer to previous financial analysis studies in Jordan in the literature, in order to obtain a cost comparison. According to the study of Al-Jayyousi, the average desalination costs in Jordan in the agricultural sector is 0.35 USD/m^3, when powered by the electricity network [23]. In this study, the desalination costs in the agricultural sector, when powered by the electricity network, were about 0.62 USD/m^3. This shows that the water cost has increased by 1.7 times over a two-decade period, in line with the water and electricity price inflation conflict addressed in this study. On the other hand, it was challenging to find previous data on desalination costs in Jordan's domestic and industrial sectors. In the MENA region, the average costs of brackish water desalination using conventional energy are in the range of 0.23–1.17 USD/m^3 [22]. However, California's average brackish water desalination costs are about 0.4–0.75 USD/m^3 for the domestic and industrial sectors [36]. Meanwhile, the desalination costs of the domestic and industrial sectors in this study were 0.6–1.18 USD/m^3. These are alarmingly high prices in Jordan, a middle-income country, when compared to those in California, the largest economy in the United States. It can be concluded that reducing the costs associated with water production from brackish water desalination plants is critical in Jordan, which can be facilitated by installing PV solar power systems. However, energy remains one of Jordan's top challenges. Thus, it is important to implement proper management action plans to address these challenges, in order to increase the dependence on PV solar energy as a substitute for the conventional fuel used for electricity production. Many challenges are still faced, due to the lack of cooperation between Jordan's water and energy sectors. Still, these challenges could be addressed and accomplished through effective communication with experts and specialists, strengthening the collaboration between the water and energy sectors. Furthermore, it is essential to ensure that applicable stakeholders in the country deal professionally with such challenges, from the perspectives of complexity in water and energy governance in Jordan and the MENA region overall.

4. Conclusions

Water scarcity represents one of the greatest challenges facing the Hashemite Kingdom of Jordan, which has been projected to increase with the rapid progression of water demand associated with unsustainable population and economic growth patterns. In this context, brackish water desalination is considered one of the central options to meet the growing water demands and might become a primary source of water supply in water-scarce countries such as Jordan. Yet, BWRO desalination in Jordan faces several environmental and economic constraints, mainly related to the high energy consumption, associated with GHG emissions and high electricity bills. The water challenges in Jordan are primarily associated with issues related to securing energy sources, as the country imports about 97% of its energy supply. The only solution to lessen the major stresses created on the energy sector is to shift toward renewable energy sources, such as solar energy. In this study, we revealed that solar-powered BWRO desalination has the potential to become a major flashpoint between environmental and economic conflicts, providing a primary solution for water-scarce countries such as Jordan.

The water–energy nexus approach employed herein highlighted the main challenges facing BWRO desalination in Jordan, including: (1) The mismanaged water and energy performance, low recovery rate, and improper brine disposal, especially in the agricultural sector, leading to unsustainable patterns of water production and negative impacts on agricultural activities in the Jordan Valley; and (2) high energy costs, constituting a significant threat to multiple economic activities in Jordan, especially in the industrial sector. These challenges induce direct environmental impacts related to brine disposal and indirect effects associated with the high energy consumption and heat losses. In this study, we proposed the use of combined PV-BWRO desalination as an approach to compensate for the ecological, financial, and social challenges associated with BWRO desalination technology in Jordan in the context of the water–energy nexus.

The estimated water costs for a BWRO desalination plant powered by PV from any of the assessed (agricultural, domestic, and industrial) sectors in Jordan were estimated to be around 0.18–0.6 USD/m^3, while the water costs of the BWRO plants powered by the electricity grid were estimated to be 0.6–1.18 USD/m^3. As such, integrating the BWRO desalination plants in Jordan with renewable energy sources and considering energy recovery technologies, as well as adopting practical and well-designed evaporation ponds for brine disposal, would surely compensate for the various environmental impacts while ensuring energy and cost reductions [15,37–39]. However, the renewable energy sector in Jordan still faces various challenges, such as those related to political agreements and the country's over-supply of conventional energy sources [11]. Thus, two main recommendations can be made to overcome the challenges and support the sponsoring of PV solar energy: (1) construct demonstrative plans and schemes to show how using PV solar plants is profitable in the long-term, by reducing the unsustainable consumption trends from imported fossil fuels, while reducing the financial losses associated with energy insecurity in Jordan, and (2) implement educational programs to understand how solar energy could be integrated efficiently for water and electricity production in energy-intensive technological situations such as desalination plants, in order to reduce water losses, energy losses, and the associated environmental impacts. This would further encourage the dependence on local and sustainable energy sources, pushing the country's economic progress.

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References

1. Brückner, F.; Bahls, R.; Alqadi, M.; Lindenmaier, F.; Hamdan, I.; Alhiyari, M.; Atieh, A. Causes and consequences of long-term groundwater overabstraction in Jordan. *Hydrogeol. J.* **2021**, *29*, 2789–2802.
2. International Union for Conservation of Nature—Regional Office for West Asia (IUCN-ROWA). (n.d.). The National Biodiversity Strategy and Action Plan 2015–2020. Available online: https://www.cbd.int/doc/world/jo/jo-nbsap-v2-en.pdf (accessed on 9 January 2022).
3. Ministry of Water and Irrigation Jordan. *Water Budget 2019*; MWI: Amman, Jordan, 2020.
4. Ministry of Environment. A National Green Growth Plan for Jordan, Amman, Hashemite Kingdom of Jordan. 2017. Available online: https://www.greengrowthknowledge.org/sites/default/files/A%20National%20Green%20Growth%20Plan%20for%20Jordan.pdf (accessed on 22 March 2022).
5. Al-Kharabsheh, A. Challenges to Sustainable Water Management in Jordan. *JJEES* **2020**, *11*, 38.
6. Al-Obaidi, M.A.; Alsarayreh, A.A.; Al-Hroub, A.M.; Alsadaie, S.; Mujtaba, I.M. Performance Analysis of a Medium-Sized Industrial Reverse Osmosis Brackish Water Desalination Plant. *Desalination* **2018**, *443*, 272–284.
7. Ministry of Water and Irrigation. *Water Year Book, Hydrological Year 2016–2017*; MWI: Amman, Jordan, 2018.
8. UNICEF. UNICEF and Ministry of Water and Irrigation Launch "Clean Water and Sanitation for All" Monitoring Framework. 2021. Available online: https://www.unicef.org/jordan/press-releases/unicef-and-ministry-water-and-irrigation-launch-clean-water-and-sanitation-all (accessed on 17 February 2022).
9. Alsarayreh, A. Overview of Brackish Water Desalination in the Jordan Valley. In Proceedings of the Solutions to Water Challenges in MENA Region, Regional Workshop, Cairo, Egypt, 25–30 April 2017; Cuvillier Verlag: Göttingen, Germany, 2017.
10. Katz, D.; Shafran, A. *Water Energy Nexus. A Prefeasibility Study for Mid-East Water-Renewable Energy Exchanges*; EcoPeace Middle East: Amman, Jordan; Konrad-Adenauer-Stiftung: Oldenburg, Germany, 2017.
11. Everett, D.L. *The Future Horizon for a Prophetic Tradition: A Missiological, Hermeneutical, and Leadership Approach to Education and Black Church Civic Engagement*; Wipf and Stock Publishers: Eugene, OR, USA, 2017.
12. Kool, J. *Sustainable Development in the Jordan Valley: Final Report of the Regional NGO Master Plan*; Springer Nature: Berlin/Heidelberg, Germany, 2016.
13. Sandri, S.; Hussein, H.; Alshyab, N. Sustainability of the Energy Sector in Jordan: Challenges and Opportunities. *Sustainability* **2020**, *12*, 10465.
14. Minister of Energy and Mineral Resources. *Annual Report 2020*; MEMR: Amman, Jordan, 2020.
15. NEPCO. Electricity Tariff in Jordan. 2022. Available online: https://www.nepco.com.jo/en/electricity_tariff_en.aspx (accessed on 26 May 2022).
16. Komendantova, N.; Marashdeh, L.; Ekenberg, L.; Danielson, M.; Dettner, F.; Hilpert, S.; Wingenbach, C.; Hassouneh, K.; Al-Salaymeh, A. Water–Energy Nexus: Addressing Stakeholder Preferences in Jordan. *Sustainability* **2020**, *12*, 6168.
17. Belda Gonzalez, A. *The Water-Energy-Agriculture Nexus in Jordan: A Case Study on As-Samra Wastewater Treatment Plant in the Lower Jordan River Basin*; Diva: Uppsala, Sweden, 2018.
18. Al Jarida Al Rasmiyya. *Law No. 13 Of 2012 concerning Renewable Energy and Energy Efficiency Law*; 2012-04-16, No. 5153; ILO: Geneva, Switzerland, 2016; pp. 1610–1618.
19. Abu-Dalo, M.; Al-Mallahi, J.; Shahrouri, Y.; Qdais, H.A. Water desalination as an option to balance the water demand and supply equation of Jordan. *Desalination Water Treat.* **2019**, *162*, 1–3.
20. ESCWA. United Nations Development Account Project on Promoting Renewable Energy Investments for Climate Change Mitigation and Sustainable Development: Case Study on Policy Reforms to Promote Renewable Energy in Jordan. 2018. Available online: https://www.unescwa.org/sites/default/files/pubs/pdf/policy-reforms-promote-renewable-energy-jordan-english.pdf (accessed on 5 May 2022).
21. Abu Ali, H.; Baronian, M.; Burlace, L.; Davies, P.A.; Halasah, S.; Hind, M.; Hossain, A.; Lipchin, C.; Majali, A.; Mark, M.; et al. Off-grid desalination for irrigation in the Jordan Valley. *Desalination Water Treat.* **2019**, *168*, 143–154.
22. Sayed, E.T.; Olabi, A.; Elsaid, K.; Al Radi, M.; Alqadi, R.; Abdelkareem, M.A. Recent Progress in Renewable Energy Based-Desalination in the Middle East and North Africa MENA Region. *J. Adv. Res.* **2022**. [CrossRef]
23. Subiela-Ortín, V.J.; Peñate-Suárez, B.; de la Fuente-Bencomo, J.A. Main Technical and Economic Guidelines to Implement Wind/Solar-Powered Reverse-Osmosis Desalination Systems. *Processes* **2022**, *10*, 653. [CrossRef]

24. García-Rodríguez, L.; Delgado-Torres, A.M. Renewable Energy-Driven Desalination: New Trends and Future Prospects of Small Capacity Systems. *Processes* **2022**, *10*, 745. [CrossRef]
25. Saidam, M.; Ibrahim, M. *Institutional and Policy Framework. Analysis of Water Sector Jordan*; Policy Paper; Royal Scientific Society: Amman, Jordan, 2006.
26. Gorjian, S.; Ghobadian, B.; Jamshidian, F.J.; Sharon, H.; Saadi, S. Performance evaluation and economics of a locally-made stand-alone hybrid photovoltaic-thermal brackish water reverse osmosis unit. *Clean. Eng. Technol.* **2021**, *2*, 100078.
27. Ibrahim, M.N. Effluent Quality Assessment of Selected Wastewater Treatment Plant in Jordan for Irrigation Purposes: Water Quality Index Approach. *J. Ecol. Eng.* **2019**, *20*, 206–216.
28. Pearson, J.L.; Michael, P.R.; Ghaffour, N.; Missimer, T.M. Economics and Energy Consumption of Brackish Water Reverse Osmosis Desalination: Innovations and Impacts of Feedwater Quality. *Membranes* **2021**, *11*, 616.
29. Goode, D.; Senior, L.A.; Subah, A.; Jaber, A. *Groundwater-Level Trends and Forecasts, and Salinity Trends, in the Azraq, Dead Sea, Hammad, Jordan Side Valleys, Yarmouk, and Zarqa Groundwater Basins, Jordan*; US Geological Survey; US Department of the Interior: Washington, DC, USA, 2013.
30. Al-Harahsheh, S.; Al-Adamat, R.; Abdullah, S. The Impact of Za'atari Refugee Camp on the Water Quality in Amman-Zarqa Basin. *J. Environ. Prot.* **2015**, *6*, 16–24.
31. Al-Jayyousi, O. Capacity building for desalination in Jordan: Necessary conditions for sustainable water management. *Desalination* **2001**, *141*, 169–179.
32. Katal, R.; Shen, T.Y.; Jafari, I.; Masudy-Panah, S.; Farahani, M.H. An overview on the treatment and management of the desalination brine solution. In *Desalination—Challenges and Opportunities*; IntechOpen: London, UK, 2020.
33. JSMO. *Water—Reclaimed Domestic Wastewater*; JSMO: Amman, Jordan, 2016.
34. McMordie Stoughton, K.; Duan, X.; Wendel, E.M. *Reverse Osmosis Optimization*; Pacific Northwest National Lab. (PNNL): Richland, WA, USA, 2013.
35. EPA USA. *Strategies for Saving Energy at Public Water Systems*; EPA: Washington, DC, USA, 2013.
36. Shahsavari, A.; Akbari, M. Potential of solar energy in developing countries for reducing energy-related emissions. *Renew. Sustain. Energy Rev.* **2018**, *90*, 275–291.
37. Al Zyoud, A.; Othman, A.; Manasrah, A.; Abdelhafez, E.A. Investment Analysis of a Solar Water Pumping System in Rural Areas in Jordan. *Int. J. Energy Clean Environ.* **2020**, *21*, 3.
38. Abu-Rumman, G.; Khdair, A.I.; Khdair, S.I. Current status and future investment potential in renewable energy in Jordan: An overview. *Heliyon* **2020**, *6*, e03346.
39. Soliman, A.M.; Alharbi, A.G.; Eldean, M.A.S. Techno-Economic Optimization of a Solar–Wind Hybrid System to Power a Large-Scale Reverse Osmosis Desalination Plant. *Sustainability* **2021**, *13*, 11508. [CrossRef]