Sun-powered solutions: Investigating productivity and economics of small-scale solar desalination system

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3 authors:

Ahmad Manasrah
Al-Zaytoonah University of Jordan

Mai Bani Younes
Al-Zaytoonah University of Jordan

Eman Abdelhafez
Al-Zaytoonah University of Jordan

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Sun-powered solutions: Investigating productivity and economics of small-scale solar desalination system

Ahmad Manasrah [a,*], Mai Bani Younes [a], Eman Abdelhafez [b]

[a] Faculty of Engineering, Mechanical Engineering Dept., AL Zaytoonah University, Amman, Jordan
[b] Faculty of Engineering, Alternative Energy Dept., AL Zaytoonah University, Amman, Jordan

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ABSTRACT

Freshwater demand is one of the most critical challenges facing many countries in the world. Jordan is a country in the middle east that is considered one of the poorest countries for renewable freshwater supplies in the world. Though desalination may be one of the solutions to the problem, the cost and energy expenses could be an obstruction. However, with an abundance of annual solar irradiance in Jordan, solar desalination systems, particularly small-scale ones, are considered better alternatives. In this study, a residential-scale solar desalination system is investigated. The design includes evacuated-tube solar heaters with a heat pipe, and flashing units comprising three desalination stages. The experiments included single-stage, double-stage, and triple-stage desalination. The results showed that production rates of 2.2 kg/m^2 using single-stage, 4.7 kg/m^2 using double-stage, and 6.4 kg/m^2 using triple-stage desalination were obtained from the system. The solar water heater used in the system exhibited an average thermal efficiency of 73 %. The economic analysis revealed that the payback period for the triple-stage desalination system is 8 years. The annualized rate of return was calculated to be 2.2 %, assuming the system operates for 4 h per day and 300 days per year.

1. Introduction

Freshwater plays an essential part in every aspect of our lives. Yet, freshwater sources are dangerously scarce in many regions of the world including the middle east. Jordan is a country in the middle east that entirely relies on precipitation and groundwater to cover its freshwater demand [1]. It is projected that freshwater shortage in Jordan might exceed 1.5 million cubic meters per year in 2050 [2]. Meanwhile, Jordan is facing a drastic increase in freshwater demands under high population growth which puts more pressure on its limited water resources. Additionally, the quality of freshwater sources has decreased dramatically due to pollution and over-abstraction [3].

However, substantial amounts of freshwater sources are being used for agricultural purposes in Jordan [4]. Typically, water treatment is needed to provide safe irrigation processes which adds more expenses to the initial and running costs. Often times, treatments are limited to removing excess salts [5] and contaminants [6] from water. To achieve that, many water desalination technologies, illustrated in Fig. 1, can be applied to effectively remove dissolved salts and minerals from water. Two of the most famous desalination technologies are thermal desalination [7] and membrane desalination [8]. Both technologies demand substantial amounts of energy to operate [9]. Solar power offers a promising alternative to electricity and fossil fuels on which water desalination technologies rely [10]. However, solar desalination systems are typically built on large scales and situated near seawater or significant water sources.

* Corresponding author.
E-mail address: ahmad.mansrah@zuj.edu.jo (A. Manasrah).

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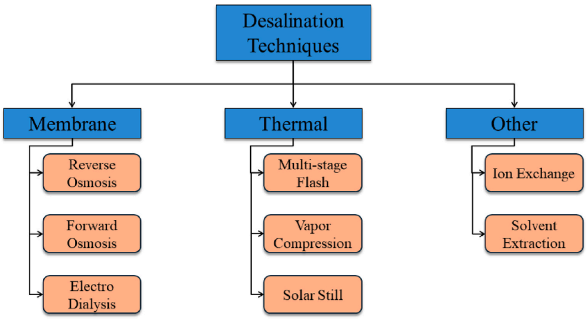

Fig. 1. Desalination Methods [12].

These systems may not be beneficial to Jordanian farmers who own their private water wells and water sources. Smaller, more economical, solar water desalination systems could provide local farmers and homeowners with a sustainable source of freshwater to irrigate their crops and also for domestic use as well [11].

Current solar desalination technologies frequently encounter several shortcomings. These include high initial costs for deployment, energy inefficiencies in smaller-scale applications, and limited adaptability to different local water conditions [43]. In addition, the majority of studies and implementations focus on large-scale or industrial purposes, leading to a substantial lack of exploration and progress for small, residential-sized systems that could benefit individual farmers and homeowners [44].

This paper addresses these gaps by introducing a multi-stage, residential-scale solar-powered desalination system designed to operate in Mediterranean conditions. A solar thermal collector equipped with a heat pipe is deployed to preheat water before the desalination process. Three insulated water tanks are utilized as water evaporation stages to produce desalinated water. The designed system can be deployed as a single stage with one tank, two stages, or three stages with all three tanks connected in series, adapting to various needs and conditions. By focusing on a smaller, more economical design, this study aims to provide a sustainable solution for local farmers and homeowners who have private water sources but face significant desalination challenges.

The primary objectives of this research are to evaluate the efficiency and productivity of this novel solar-powered desalination system, and to assess its financial viability through calculations of the return on investment and payback period. This study not only seeks to fill the existing gaps in solar desalination research but also to demonstrate the feasibility and benefits of small-scale, solar-powered systems in addressing freshwater scarcity in Jordan. The remainder of this paper includes a literature review, design and methodology, experimental approach, results, and conclusion.

2. Background

Fig. 1 showed several examples of water desalination methods that are currently used or investigated. Many of these methods require extensive amounts of energy to operate. For instance, the electrical energy needed for the reverse osmosis method can reach 5 kWh/m^3 for a large sized water desalination plant [13] while as a multi-stage flash desalination plant consumes 3–5 kWh/m^3 [14]. These numbers will definitely increase on small to medium scale plants. This section reviews membrane and thermal technologies used in desalination.

2.1. Membrane technologies

This technology is widely used in large and medium-scale desalination plants. More than half of the global capacity of desalination plants is produced using different membrane technologies [15], the most famous of them is reverse osmosis (RO). In the reverse osmosis process, external pressure is applied to a membrane system to force water to move against its natural osmosis [16]. However, in this technology there is no need to apply a phase change to water. High quality membrane systems can withstand pressures up to 80 bars and can operate efficiently from 2 to 5 years depending on the salinity of water [17]. Such membrane systems are not cheap, which adds more expenses to the running cost of the plant. However, researchers are investigating ways to produce cheaper and more efficient membranes. For example, a recent study introduced an improved polyester membrane system with chlorine resistance that has 99 % salt rejection [18]. Nanofilms and nanofiltration materials are also being investigated these days [19].

2.2. Thermal technologies

Thermal desalination technologies are based on increasing the temperature of water until it reaches phase change status (i.e. evaporation). Water is then condensed to obtain a purified product. Usually, fossil fuels or electricity are used in the evaporation process, hence, the relatively high running costs. The most commonly used thermal desalination technology is the multi-stage flash (MSF) [14]. In this method water is evaporated and condensed in multiple stages. The excess water in each stage will be sent to the next stage and so on until the cycle is completed. The evaporation process in each stage is called flashing. Commonly, this process is accompanied by pressure reduction in each stage to initiate the flash at relatively low temperatures. Heat recovery subsystems are also commonly used in MSF. The remaining water with high salinity is usually discharged out of the system. Many recent studies have presented improvements to MSF either by increasing the efficiency of the process or reducing the cost. For instance, a compressed air energy storage system was integrated with MSF to improve the efficiency of the process [20]. Another study introduced MSF integration with membrane desalination [21]. The results showed a decrease in brine water and an improvement in freshwater production. Energy and economic analysis were also conducted on MSF when integrated with steam power plants [22] which resulted in reductions in CO_2 emissions from the facility.

Solar energy has been integrated with MSF as a provider of electrical power or as a direct source of heat. A previous study introduced solar chimney system with MSF to produce freshwater [23]. The system was also coupled with a water turbine to generate electricity. The results showed that the integrated system can produce about 8 kg/s of freshwater. Parabolic trough collectors (PTC) were also integrated with MSF and desalination plants in general. Aboelmaaref et al., reviewed different configurations between concentrated solar power systems and thermal desalination systems [24]. They showed that utilizing PTC systems with desalination plants can improve efficiency and productivity more than other solar systems. Most of these technologies, however, are built on a large scale with productions suitable for small cities.

Small scale solar desalination technologies have also been studied in the literature, with less enthusiasm, however. A previous study investigated the integration of solar parabolic dish collector with MSF. The solar collector provided hot saline water to two flashing stages equipped with a vacuum pump. The proposed system showed a productivity of more than 3 L per day with specific flow rates [25]. A similar system was proposed with a regular solar collector and storage tanks [26]. The small system could produce about 20 kg of freshwater a day. Photovoltaic solar panels were also utilized in small scale desalination plants. A multi-effect desalination plant (MED) was integrated with a solar photovoltaic system as an electrical power source in a previous study [27]. The results showed a reduction in the operating costs of freshwater as opposed to diesel generators.

The system presented in this study introduces a residential scale, multi-stage flash system integrated with solar evacuated tubes and a heat pipe. The proposed system is distinctively different than previous systems since it is comprised of market-available components and is only dedicated to being used for agricultural and domestic purposes. Further, very few studies have investigated residential-scale solar desalination plants in Jordan.

3. Materials and methods

In this study, a residential-scale solar thermal desalination system was designed and built. The unit consists of two main subsystems. The first subsystem is a solar water heater equipped with evacuated tubes, and a heat pipe. The second subsystem consists of three desalination tanks connected together in series, equipped with a vacuum pump and three feeding tanks. Manual on/off valves were installed across the system to enable users to operate the desalination system with different configurations. Fig. 2 represents the schematics of the entire desalination system. The desalination system's size was determined by the tank sizes available in the local market. This method was selected to reduce expenses and achieve the best possible outcomes. The system is designed such that it can be scaled up or down to an appropriate size according to needs.

3.1. Solar heater

The solar water heater was designed and selected from the local market. The heater consisted of 18 evacuated tubes that were connected to a heat pipe. The total effective area of the solar heater was 2.28 m^2 and the full length of the heat pipe 170 cm with a maximum operating pressure at 10 bars. Table 1 shows the specifications of the evacuated tubes. The inlet of the solar water heater is connected to the cold saline water and the outlet of the heater is connected to the first stage of the desalination unit.

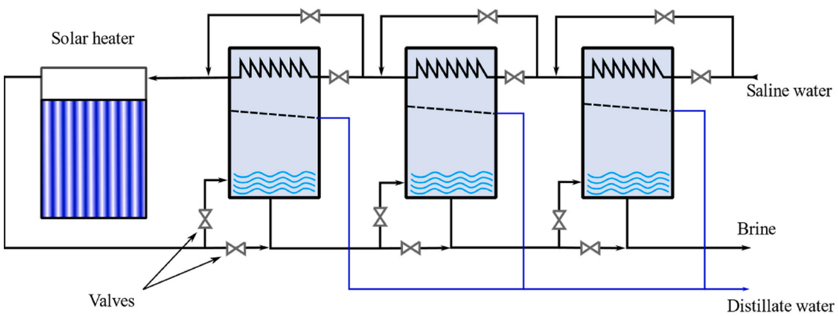

Fig. 2. The proposed desalination system.

Table 1
The specifications of the evacuated tubes.

Evacuated tube	Details
Length	1800 mm
Outer tube diameter	58 mm
Inner tube diameter	48 mm
Absorptance	0.92
Emittance	0.06

The thermal efficiency of the solar heater is affected by several factors: the effective area exposed to sun radiation, the average irradiance, the flow rate and thermal specifications of water, and the difference between the inlet temperature and outlet temperature of water. Hence, the solar heater's efficiency can be represented as follows [28]:

$$\zeta_{th} = \frac{Q_{heater}}{A\ .\ G} \tag{1}$$

where.

- Q is the energy needed to heat water in [W].
- A is the total effective area of the heater in [m^2].
- G is the solar irradiance in [W/m^2].

Q is calculated using the following equation [29]:

$$Q_{heater} = \dot{m}\, C_p \Delta T \tag{2}$$

where.

- $\dot{m}$ is the mass flowrate of water in the system in [Kg/s].
- C_p is the average thermal coefficient of water [4181 J/kg.K].
- ΔT is the difference between the inlet temperature and the outlet temperature of water in [K]

Additionally, to model the fluid flow through the evacuated tubes, Bernoulli's equation (Equation (3)) and the continuity equation (Equation (4)) were applied, assuming one dimensional, steady-state, incompressible flow in the desalination tanks.

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{3}$$

$$\rho\, v_1 A_1 = \rho\, v_2 A_2 \tag{4}$$

where.

- P is the pressure of fluid in [KPa].
- ρ is the density of fluid in [Kg/m^3].
- v is the velocity of fluid in [m/s].
- h is the elevation of fluid in [m].

3.2. Desalination units

Three identical desalination stages were designed and fabricated in the local market. Each stage consisted of 120 cm tall, closed steel cylinder which had an outer diameter of 50 cm. Each unit was isolated with a 5 cm layer of foam and covered with 5 cm white painted stainless steel. Inside the desalination unit, a 20-turn, helical copper tube was installed near the top that acted as a condenser, and a flat meshed tray was installed 20 cm under the copper tube that collected the distilled water. Fig. 3 shows the internal components of a desalination unit.

The desalination process in each unit can be described as follows: hot water coming from the heat pipe enters the unit from the bottom where it flashes under vacuum and condenses on the copper tube that carries relatively cold feed saline water. The vacuum pump creates pressures below atmospheric pressure allowing saline water to evaporate well below the normal boiling temperature of water. The condensed distillate water is collected on the flat tray under the tube where it will be removed outside. The rest of the hot saline water moves to the next desalination unit. At the last stage warm high salinity brine is left at the bottom and will be discharged at the end of the process.

3.3. Experimental setup and procedure

Fig. 4 shows the final setup of the experiment. The outlet of the solar heater is connected to the desalination tanks which are connected together in series. Saline water feeds the system from nearby water tanks via a variable speed pump. The distillate water outlets are connected to a small freshwater tank located behind the desalination unit. Seven k-type thermocouples are installed in the system at different locations: one for the saline water supply tank, three for the outlets copper tubes, and three for the feed inlets of the desalination tanks.

The experiment was conducted in three phases over 15 days, each phase dedicated to a different desalination setup: single-stage, double-stage, and triple-stage. Operating hours were from 11:00 a.m. to 3:00 p.m. daily, accumulating 20 h per phase. Saline water, sourced from a nearby well, was consistently supplied using a variable-speed pump, with daily replenishments to maintain uniform water quality.

Throughout the experiment, key water quality parameters such as turbidity, salinity, and pH were measured before and after each run using precise digital instruments. Seven k-type thermocouples were strategically placed to monitor temperature changes at 5-min intervals, with data captured by a 10-channel logger to ensure accurate tracking of the thermal performance of both the solar heater and desalination units. Solar irradiance, an important factor in the experiment, was measured daily using a TENMARS TN-207 solar

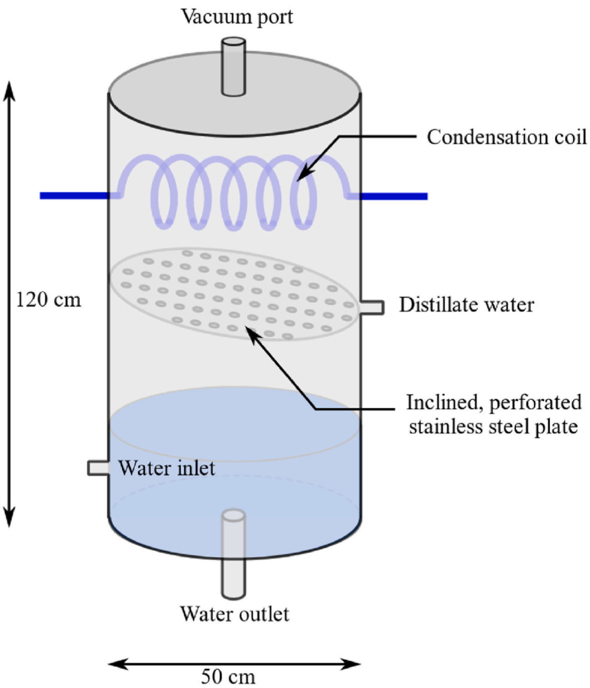

Fig. 3. Internal components of a desalination unit.

Fig. 4. The experimental setup of the desalination unit (front and side view).

meter. After each phase, the collected distilled water was tested for quality, and production rates were recorded for each desalination stage. This comprehensive and detailed approach ensures the experiment's validity and reproducibility, providing robust data to support the results.

4. Results

The results section is divided into three subsections: the experimental and technical findings, the annualized rate of return and payback period of the system, and uncertainty and device errors.

4.1. Experimental results

In this study, the experiments were categorized into three phases: single-stage, double-stage, and triple-stage desalination. Each phase was executed over a span of five days with a total of 20 operating hours. The average solar irradiance was recorded for the entire experiment as shown in Fig. 5. The operating hours were between 11:00 and 15:00 as highlighted in red. The average solar irradiance during this period was 966.4 W/m^2 for all three phases. Based on these readings, the average daily solar irradiance in KWh/m^2 was calculated for each day in all three phases as presented in Fig. 6. Day 3 from the double-stage phase and day 5 from the triple-stage phase recorded the lowest solar irradiation readings. However, the differences between the lowest and highest readings are considered insignificant considering that the average solar irradiance is between 5 and 7 KWh/m^2 during that period in this area according to Ref. [30].

Based on the average solar irradiance reading, the thermal efficiency of the evacuated tube solar heater with a heat pipe was calculated each day during all phases. Fig. 7 shows the average results of the thermal efficiency based on Equation (1) and Equation (2).

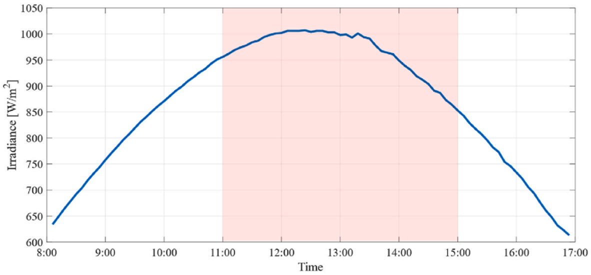

Fig. 5. Average irradiance in [W/m^2] during the experiments period (dataset was smoothed). Operation times highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

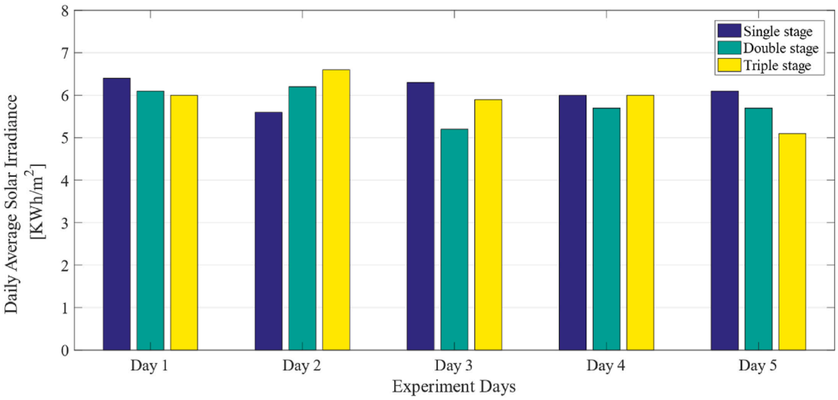

Fig. 6. Average irradiance in [kWh/m^2] in all three phases of the experiment.

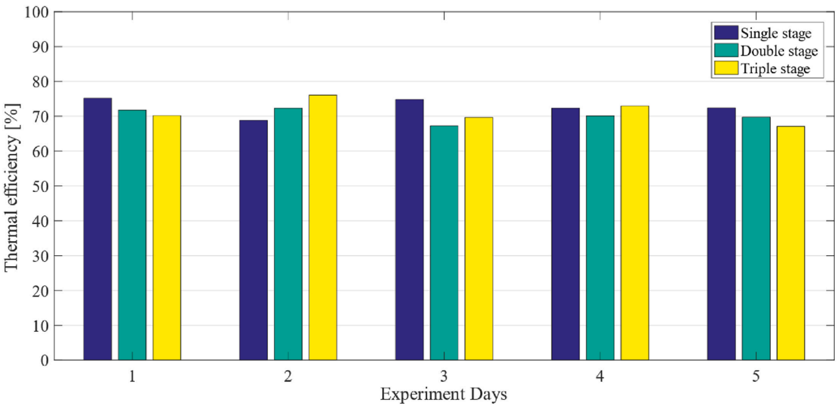

Fig. 7. Average thermal efficiency in all three phases of the experiment.

Thermal efficiencies of the solar heater ranged between 70 % and 80 % on average during the experiments. These results are similar to results from previous studies like [31,32].

Temperatures of the saline water at the outlet of the solar heater are presented in Fig. 8. The temperature drop presents the thermal discharge of the heat pipe in the solar heater. However, 50 kPa vacuum pressure was applied to the desalination units which dropped the saturation temperature of water to around 81C [33], allowing flashing to occur at the illustrated temperatures in Fig. 8.

The amounts of produced distilled water depended on the number of stages used in the desalination process. Fig. 9 shows the production of distilled water in all three phases during the experiments. The average production of distilled water with a single-stage desalination unit was 2.2 kg per square meter a day. Production improved significantly using two stages with an average of 4.7 kg/m^2 of distilled water per day. However, the distilled water production maxed at 6.4 kg/m^2 a day using triple-stage desalination. The total daily distillate production was heavily influenced by the average daily irradiance discussed in Fig. 6. For instance, day 2 from the triple-stage desalination experiment recorded the highest average irradiance in the experiments at 6.6 kWh/m^2. The total daily distillate production reached 6.4 kg/m^2 on that day. Similar results were obtained in Refs. [34,35] using small scale solar desalination units. However, a full comparison of distillate production with previous studies could be hard to perform mainly since each study was

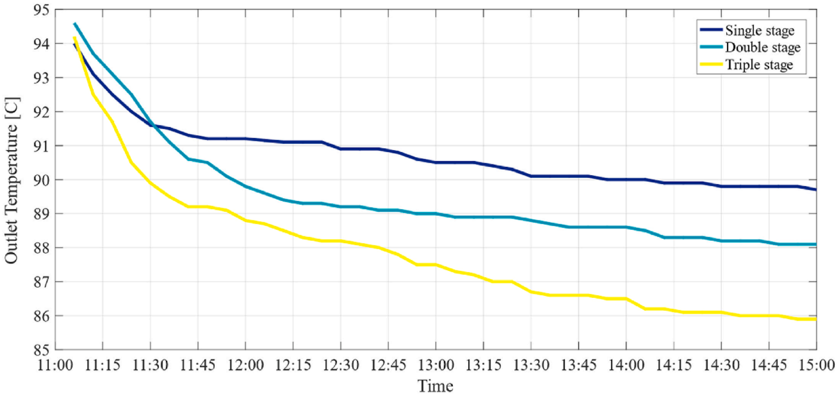

Fig. 8. Temperatures of saline water at the outlet of each stage.

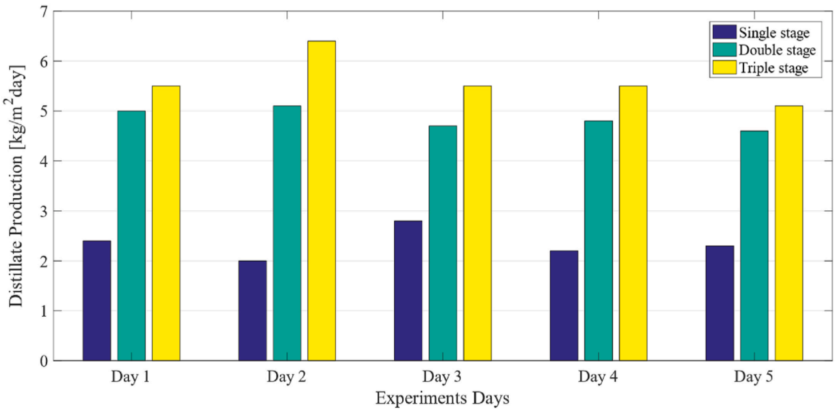

Fig. 9. Total daily distillate production in [kg] in all three phases of the experiment.

conducted at different weather conditions, and with different solar heater areas. Further, the process presented here only worked for 4 h a day for testing purposes. Table 2 shows a comparison of similar small-scale solar desalination systems from the literature.

The salinity, turbidity and PH of the saline water were recorded before the beginning of each experiment using a digital salinity refractometer, and a TDS/EC/Ph meter. The average salinity of the source was around 20 ppt with a turbidity of 28 NTU, and a 7.6 PH level. Fig. 10 shows the average salinity readings of the discharged brine after the experiments. Fig. 11, however, shows the average turbidity and PH readings of distilled water in each phase. As illustrated, turbidity was around 3 NTU and the PH levels were between 6.5 and 6.9. Naturally, the PH level of distilled water is 7, however in this experiment, the PH was slightly on the acidic side. This may be related to iron oxides coming from possible rust occurring in the pipes or inside the desalination units.

4.2. Payback period and rate of return

To calculate the payback period of the system, the initial and running costs must be calculated. Table 3 shows the costs of each component of the system according to the prices in the local market. The running costs include electrical consumptions of a circulation pump and a vacuum pump for 4 h a day which can be estimated as $40 every five years given the short operating hours and the current electricity prices in Jordan at $0.07 per kWh [36].

The payback period is calculated based on the savings provided by the desalination related to the initial and running costs of the system. The proposed system produced around 6.4 kg/m^2 day of distilled water for a triple-stage desalination process. However, the system only operated 4 h a day (i.e., between 11:00 and 15:00). Therefore, the production rate could be expressed as 6.4 kg/m^2 every 4 h or 1.6 kg/(m^2 h). The average price of fresh water in Jordan is around $3 per cubic meter which equates to $0.003 per liter [37].

Table 2
Productivity of solar desalination systems from literature.

Reference	Year	Method	Productivity
[25]	2021	Solar MSF	3.22 Kg/5h
[26]	2021	Solar MSF	19.7 Kg/day
[45]	2022	Solar flash evaporator	13.95 Kg/day
[46]	2020	Vertical multi-effect diffusion solar distiller	3.4 Kg/day
[47]	2014	Inclined solar desalination	3.25 kg/m^2 day

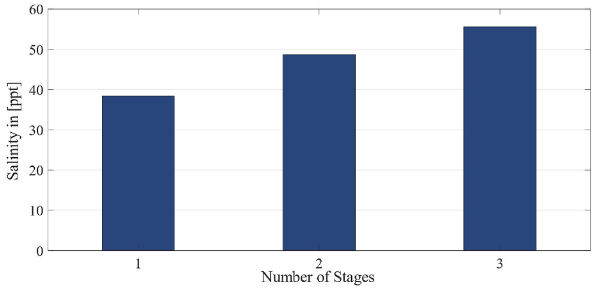

Fig. 10. Average salinity of brine after each phase.

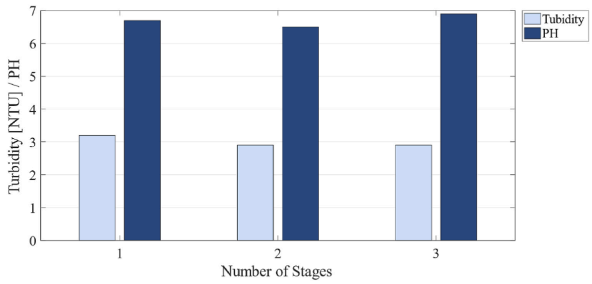

Fig. 11. Average turbidity and PH of distilled water after each phase.

Table 3
The initial and running cost of the desalination system.

System Components	Cost $
Desalination units	300.00
Solar collector with a heat pipe	450.00
Pumps and valves	180.00
Running costs	40.00

Table 4 shows the annual system savings and expenses over a 20-year period. The estimates show a payback period of eight years and annual savings of $132 of fresh water based on operating times of 4 h a day for 300 days a year. Fig. 12 shows the payback period for the system.

From Fig. 12, the annualized rate of return (RoR) of the system can be calculated using the following equation [38]:

Table 4
Annual savings and net profit over a 20-year period (five-year intervals).

Year	Savings [$]	Initial & running costs [$]	Net profit [$]
1	0.00	930.00	−930.00
5	528.00	40.00	−442.00
10	660.00	40.00	178.00
15	660.00	40.00	798.00
20	660.00	40.00	1438.00

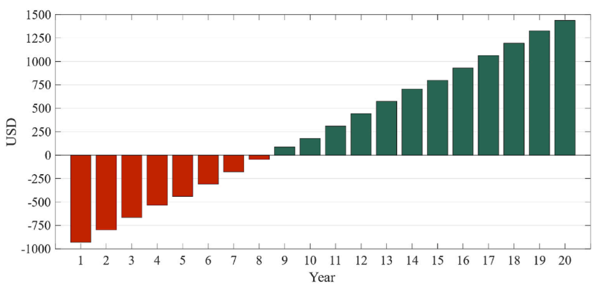

Fig. 12. Payback period of the system over 20 years.

$$RoR = \left(\frac{A_n}{A_o}\right)^{\frac{1}{n}} - 1 \tag{5}$$

where.

- A_n is the future revenue of the project (after 20 years).
- A_o is the initial cost of the project.
- n is the number of years.

Using equation (5), the annualized rate of return is determined to be 2.2 % compounded each year. Previous studies calculated an average rate of return between 12 % and 16 % [39,40]. Though, those studies investigated mid and large-scale desalination plants that did not utilize solar heating. However, studies that utilized solar heating showed similar results between 1.6 % [41] and 3.8 % [42].

4.3. Uncertainty and device errors

In this study, several measuring devices were employed, including a solar irradiance meter (TENMARS TN-207), k-type thermocouples connected to a 10-channel data logger (HIOKI LR8431-20), and a digital salinity refractometer and TDS/EC/pH meter for water quality analysis. The uncertainty associated with the solar irradiance measurements was ±2 % based on the manufacturer's specifications, and the thermocouples had an accuracy of ±1 °C. The error margin for the water quality measurements was ±0.05 ppt for salinity and ±0.1 pH units.

To quantify the overall uncertainty in the experimental results, a propagation of uncertainty analysis was performed by considering the uncertainties in each measurement device. For instance, the uncertainty in the calculated thermal efficiency was derived from the uncertainties in solar irradiance, mass flow rate, and temperature difference, which were combined using standard uncertainty propagation methods. This analysis yielded an estimated uncertainty of ±2.44 % in the thermal efficiency values. Additionally, the production rates of distilled water were affected by fluctuations in irradiance and environmental conditions, contributing to an overall uncertainty of ±2.4 % in the water output measurements.

5. Conclusions

This study investigated the performance and economic feasibility of a residential-scale, multi-stage solar desalination system in Jordan. This study investigated a residential-scale, multi-stage solar desalination process. The system comprised an evacuated-tube solar water heater with a heat pipe and three desalination units operated with a vacuum pump. Multiple experimental tests were conducted, including single-stage, double-stage, and triple-stage desalination. Experiments lasted for 20 h over 15 days. The system showed varying desalination efficiency depending on the number of stages employed. The production rates were 2.2 kg/m^2 of distilled water per day for single-stage desalination, 4.7 kg/m^2 for double-stage, and 6.4 kg/m^2 for triple-stage. This indicates that increasing the number of stages significantly enhances distilled water production. The solar water heater achieved an average thermal efficiency of 73 %, which is comparable to similar systems documented in the literature.

An economic analysis indicated that the payback period for the triple-stage desalination system is eight years, with an annualized rate of return of 2.2 %, based on an operating schedule of 4 h per day for 300 days each year. Additionally, the quality of the distilled water met the required standards, showing significant reductions in average salinity and turbidity levels within acceptable limits.

CRediT authorship contribution statement

Ahmad Manasrah: Writing – original draft, Supervision, Funding acquisition, Data curation. **Mai Bani Younes:** Resources, Methodology. **Eman Abdelhafez:** Writing – review & editing, Formal analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Nomenclature

MSF	Multi-Stage Flash
MED	Multi-Effect Desalination
ζ_{th}	Thermal efficiency
Q	Energy needed to heat fluid [W]
G	Solar irradiance [W/m^2]
$\dot{m}$	Mass flow rate [Kg/s]
C_p	Average thermal coefficient of water = 4181 [J/Kg.k]
ρ	Density of fluid [Kg/m^3]
v	Velocity of fluid [m/s]
ppt	Part per trillion
NTU	Nephelometric Turbidity Unit
RoR	Return on investment
A_n	Future revenue of the project
A_o	Initial costs of the project

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