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Economic feasibility of a solar still desalination system with enhanced productivity

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HIGHLIGHTS

- Rotating cylinder increases solar still yield by 200–300%.
- Calculated cost is comparable to that of renewable desalination methods.
- Comparison with fuel-based desalination requires adjustment for externalities.
- Environmental degradation and carbon-trading schemes are included.
- Justified economic feasibility especially for seawater desalination

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ABSTRACT

Solar still desalination systems offer sustainable tools for fresh water production. However, their widespread application is often hindered by their relatively low production rates compared to other desalination methods. In this study, a simple amendment, in the form of a slowly-rotating hollow cylinder, was introduced within the solar still, significantly increasing the evaporative surface area. This new modified still was analyzed in terms of both operation and economic feasibility. The introduced cylinder resulted in a 200–300% increase in water output relative to a control, which did not include the cylinder. The resulting percent improvement far exceeds that obtained by other modifications. Unit production cost estimates varied between 6 and 60 $/m^3 depending on discount rates, productivity, service lifetime and initial capital costs. These projections are well within reported cost ranges for renewable-based technologies. In order to evaluate the system's feasibility in real market value, different scenarios that introduce carbon-trading schemes and environmental degradation costs for fuel-based desalination, were performed. Reported costs for fuel-based brackish water and seawater desalination were thus adjusted to include unaccounted-for costs related to environmental damage. This analysis yielded results that further justify the economic feasibility of the new modified solar still, particularly for seawater desalination.

1. Introduction

With the advent of climate change issues, the economic importance of environmental degradation has increased. Renewable-energy-based desalination technologies offer a promising solution to both water shortage and environmental pollution problems. Their relatively lower productivity compared with fuel-based desalination, however, attributes to their higher costs and the need for larger installation areas [1]. On the other hand, acknowledging the environmental damage costs associated with fuel/gas energy sources, the market access of desalination based on renewable energy becomes justified [2]. The economical viability of renewable-based systems is even higher in countries with the greatest water needs and where the cost of other alternatives such as the pipe work to supply an arid area with water or the cost of fuels is high [3–5]. Today, the world economy steadily shifts from a hydrocarbon basis to one that is based on more sustainable energy forms [6].

In the field of solar desalination, an interest in solar still systems revives to develop these devices into a more efficient technology for sustainable water production. Solar stills have been used for many decades to produce potable water particularly in remote arid areas. In their simplest form, they comprise a transparently-roofed basin containing the sea-, waste- or brackish water to be evaporated. This water is heated under solar radiation, evaporates and condenses as it hits the cooler cover and trickles down into a channel as distillate. Increasing the productivity of solar stills has been the focus of intensive research. Some studies add heat absorbers such as gravel [7,8], sponge cubes [9–11], rubber [12], glass balls [13], charcoal [14,15], floating absorber aluminum sheets [16], dyes and inks [12,17,18] among others [19]. Solar stills coupled to reflectors [20–24], flat-plate-collectors [25–27] or separate condensers [28–33] as well as multiple-effect stills [34–41], wicks

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Nomenclature

CRF	capital recovery factor
i	interest rate
M	first annual cost
N	annual salvage value
O	annual operation cost
P	capital cost
S	salvage value
SFF	sinking fund factor

[42–44], vacuum technologies [45,46] and thermoelectric technology [47,48], excess solar energy storage [49,50], and computerized sun tracking devices [51] have also been used. In some cases, a new design of the still is employed e.g. using a hemi-spherical dome-shaped still [52], tubular still [53] or horizontal transparent tubes instead of basins [54]. The success of these developments in increasing the water output of the still varies [1] and since some of the improvements rely on introducing complex or expensive components, the introduced modifications may not match the low-tech level characterizing places with severe water stress. Other installations such as solar panels, collectors, ponds, condensers, and sun-tracking devices moreover require considerable additional space, which entails further cost increments. It is therefore beneficial to develop a compact, low-cost and easy-to-operate system that lends itself to areas where the solar still is most applicable.

In this study, a simple and sustainable modification is introduced within the solar still cavity comprised of a slowly-rotating hollow cylinder. This low-tech amendment proves to enhance the productivity of the solar still by limits far exceeding that of more complex modifications introduced before. Although a number of previous studies have introduced a shaft within the still for the purpose of breaking the water surface and induce better evaporation [13,55], the adoption of the rotating large hollow drum is far more reaching than a simple shaft. The rotating cylinder, in addition to continually breaking the water surface, significantly increases the evaporation area and allows thin water films to rapidly evaporate. To our knowledge, no previous study has proposed a similar process or a concept close to it. For all conducted experiments, the new solar still with the rotating cylinder gave considerably higher yield than the control still (without the cylinder). The enhancement in water productivity reached an average of 200–300%, depending on the specific weather and operational conditions. This percentage notably exceeds that obtained using other modifications such as the use of heat absorbers (10–38% improvement in water productivity) [7–19], reflectors (15–41%) [20–24], collectors (24–35%) [25–27], or separate condensers (15–55%) [29,33].

In this paper, the new modified solar still is studied in terms of both operation and economic feasibility. A direct comparison with available renewable-based desalination technologies is presented taking into account specific locations and designs. For evaluating the feasibility of the modified still and other renewable-based desalination technologies against fuel-based alternatives, which still apparently take over in terms of lower cost advantages, an introduction of carbon trading schemes and discussion of environmental degradation costs is included. Reported cost estimates for fuel-based desalination are adjusted based on a range of minimum and maximum values that considers the unaccounted-for costs giving more reasonable economic estimates that further justify the feasibility of renewable-based desalination alternatives.

2. System description

2.1. The modified solar still

The basic principle of the introduced modification in this study is to expose a considerably larger amount of water to sunlight than that usually exposed in conventional stills. It is well known that increasing the evaporating surface increases the output of the solar still. Previous studies have addressed this fact by increasing the evaporative surface area through the use of sponges, wicks or fins or by adding certain materials in the brine water to increase the surface area available for evaporation; however, the design introduced in this study has a different concept. A partly submerged slowly-rotating low-cost hollow cylinder is introduced into the still and as it rotates, the cylinder grabs a thin water film around its circumference. The cylinder is hollow on both of its vertical edges so that the collected brine water forms thin films on both the inner and outer sides of the cylinder.

The thin water films evaporate at a fast rate as opposed to the much deeper water brine found in the basin of conventional stills. This rapid evaporation is also attributed to the high heat of the rotating cylinder, which is painted in black to maximize solar heat absorption and which receives more direct sunlight than the basin water. Only a low rotational speed of the cylinder is needed, hence the required rotational energy can be provided by a renewable source e.g. solar or wind. One side-benefit of this design is solving the stagnation problem that usually develops in conventional basin solar stills. The rotating cylinder continues to break the brine surface layer, which is otherwise known to form a shielding surface in conventional stills. Fig. 1 shows a schematic diagram of the modified solar still with the installed cylinder. A summary of the governing heat and mass balance equations for this modified system is given in the appendix.

2.2. Experimental Setup

Two stills for this project were constructed using local materials. One still acted as a control with no rotating cylinder while the other still had a rotating cylinder. Water basins (0.67 m × 1.5 m, giving a unit squared meter of surface area) were made of plywood (18 mm thickness) and coated with black fiberglass, which has a relatively long life expectancy, is easy to handle and does not require insulation. Grooved edges were at the sides to allow for ease of placement and removal of the covers. Aluminum sheets (3 m × 1.5 m × 1.0 mm) were wrapped to form the cylinder (0.6 m diameter, 1.4 m length), which was mounted on low-carbon steel shafts (20 mm diameter × 1.7 m length) using 20 mm ball-bearings. The rotating motor for the cylinder was similar to that used for windshield wipers and was operated using a small photovoltaic (PV) panel during sunshine hours. These panels were connected to storage batteries in order to operate the systems during the night. The current intensity required to run one motor was 0.1 A. The added evaporative surface area due to the presence of the rotating drum or cylinder is 5.2 times that of the conventional still for the dimensions used in this experiment (unit squared meter).

The solar still covers were made of plexi-glass and Aluminum channels were added to collect the distillate (Fig. 1). Inlets for basin filling, outlets for distillate collection and outlets for brine discharge were installed and controlled with ball-type valves. Thermocouples (Type K) were installed to measure temperature at four locations for each of the experimental stills: inside and outside cover, inside still and in the basin water. The thermocouples were attached to a USB board connected to a PC for continual reading of temperature using a LabView program. Digital scales (CPWplus) to measure the distillate water output were supplied by AdamEquipment[1] and were equipped with software that allows continual reading of the collected weights. Distillate was collected in 6-liter pyrex Erlenmeyer flasks. The stills were operated in batch mode whereby the inlets were used to fill in the feed water for each experiment in the morning with a water level in the basin of 5 cm. Experiments were conducted at the American University of Beirut, Lebanon between May and October.

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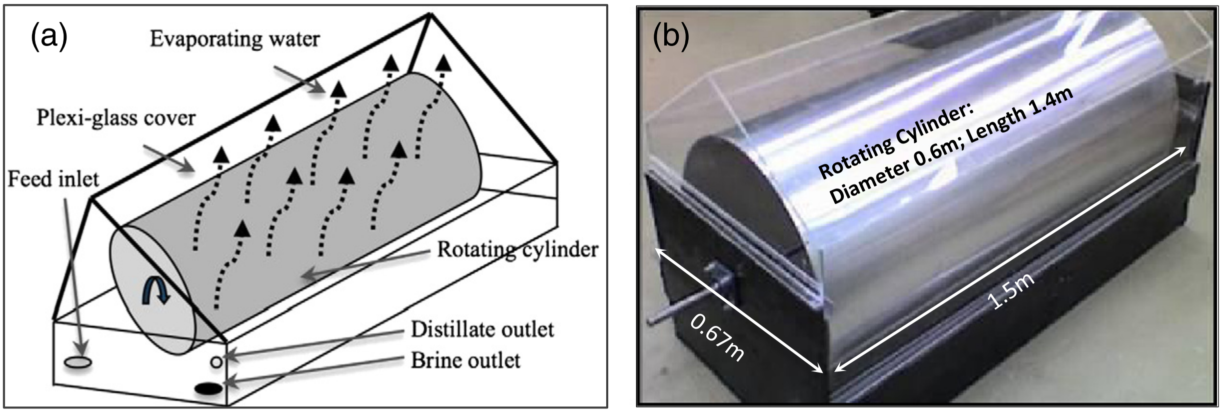

Fig. 1. (a) Modified solar still with introduced drum; (b) Photo of the system during construction.

3. Results and discussion

Throughout the experiment, the new system with the drum gave considerably higher yield than the control, i.e. the solar still without the rotating cylinder. Fig. 2 shows sample results for the productivity of the new system with the drum and the conventional solar still, which is used as a control, for a typical day in May (Mean ± SD; 5 replicates). It can be observed from these results that the new setup had an average increase in daily yield of 190% ($p\text{-value} < 0.05$) and could reach a peak enhancement of 260% depending on the hour of the day considered (Fig. 2). Experimental results for other months (data not shown) showed that the overall enhancement in productivity for the modified still varied between 200 and 300%.

The above results show that the rotating cylinder has therefore contributed significantly in increasing the productivity of the simple solar still due to several reasons. The most important factor is having an increased surface area available for evaporation and the layer of water available for evaporation is thin relative to the water depth in the basin of a conventional still. In comparing the performance of the control solar still used in this study to conventional solar stills, the water output of the control tends to fall on the lower range (0.9–1.4 L/m^2/day) of reported values, which varies from 0.98–1.5 L/m^2/day [56,18] up to 3.5–4.15 L/m^2/day [21,36] mainly depending on the climatic and geographic conditions of the experimental location. For more favorable weather conditions, the control, which does not include the rotating cylinder, in this study is expected to give a higher water output and accordingly the productivity of the new modified solar still (2.5–4.2 L/m^2/day in this study, depending on the specific weather and operational conditions) is also anticipated to shift upwards with higher temperatures and more abundant sunshine as well as more extended sunshine hours. In fact, the productivity of a solar still is a function of many factors, the most important of which is solar radiation so that the same unit or design when tested in one region could give totally different results than when tested under another environmental condition. A detailed benchmarking of the conventional and modified solar stills used in this study against other stills is given in [57] where it is shown that under the Lebanese conditions (average 19 MJ/m^2/day for the duration of this experiment), the level of output that is obtained herein for the conventional still is acceptable compared to values for conventional solar stills that are reported in the literature. Thus, an even higher yield is expected for the proposed modified still under more favorable weather conditions.

4. System cost and feasibility

4.1. Cost estimation of proposed system

Reported costs of produced distillate using conventional and renewable energy vary widely due to the many variables and uncertainties involved and depending on the system design, location, and year of investigation. Fig. 3 shows the cost estimates for different conventional i.e. fuel-based and renewable desalination technologies treating

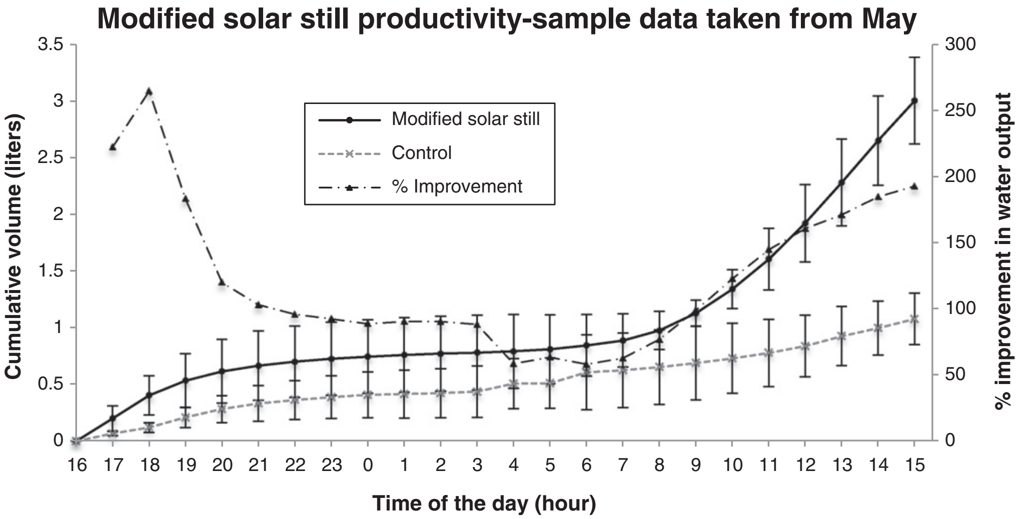

Fig. 2. Productivity of modified solar still versus control.

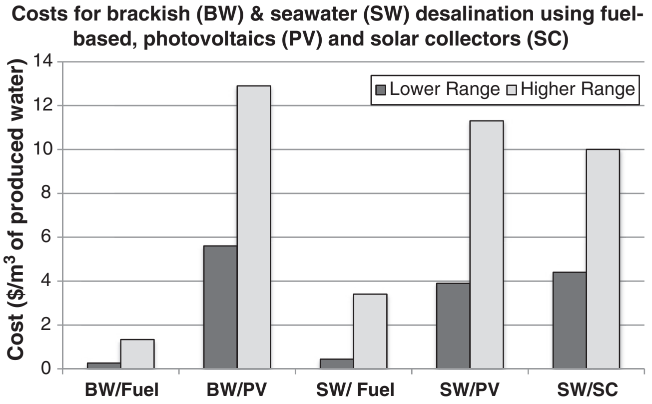

Fig. 3. Cost estimate ranges (low and high) for conventional and renewable desalination methods (data adopted from [57]): brackish (BW) & seawater (SW) desalination using fuel-based, photovoltaics (PV) and solar collectors (SC).

brackish or seawater based on data in reference [58]. A full cost analysis requires a long term evaluation of the desalination system to reliably assess all costs involved including local materials, manufacturing, marketing, distribution, training, operation and maintenance, lifespan, payment of micro-loans, depreciation, land and labor costs among others [59].

If P is the initial investment in the solar still system, r the interest rate, n the number of useful years and S the salvage value, then the system annual cost is determined as [60]:

$$C = M + O - N \tag{1}$$

where M is the first annual cost, O is the annual maintenance costs and N is the annual salvage value. The first annual cost of the system M can be determined as:

$$M = P.CRF \tag{2}$$

where P is the capital cost of the system ($300 for the new solar still with rotating cylinder) and CRF is the capital recovery factor, given in terms of the interest rate i as follows:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}. \tag{3}$$

The salvage value is considered as 50% cost of usable material saved even after the system life is over. If S is the salvage value, the first annual salvage value N can be determined as:

$$N = S.SFF \tag{4}$$

$$SSF = \frac{i}{(1+i)^n - 1}. \tag{5}$$

The annual cost of the modified solar still for various interest rates i and expected lifetime or number of operational years n is given in Table 1. The unit production cost per cubic meter varies between 6 and 60 $ depending on the different factors such as service lifetime, interest rate, productivity and initial capital costs, which can decrease significantly for mass production/manufacturing and the time as well as place of operation.

The influence of these parameters is shown in the diagram plotted in Fig. 4 that reflects the extent of impact for each parameter on the calculated cost [61]. The cost range for the modified solar still in this study therefore falls within the limits reported in the literature [1,62].

Table 1
Annual cost variation with interest rate and operational life.

i[a]	*n*	*CRF*	*SFF*	*M*	*N*	*O*	*Annual cost ($)*
0.02	30	0.04	0.02	13.39	3.70	1.34	11.04
0.04	30	0.06	0.02	17.35	2.67	1.73	16.41
0.06	30	0.07	0.01	21.79	1.90	2.18	22.08
0.08	30	0.09	0.01	26.65	1.32	2.66	27.99
0.1	30	0.11	0.01	31.82	0.91	3.18	34.09
0.06	10	0.14	0.08	40.76	11.38	4.08	33.46
0.06	20	0.09	0.03	26.16	4.08	2.62	24.69
0.06	30	0.07	0.01	21.79	1.90	2.18	22.08
0.06	40	0.07	0.01	19.94	0.97	1.99	20.96

[a] *i*: interest rate, *n*: number of years, *CRF*: capital recovery factor, *SFF*: sinking fund factor, *M*: first annual cost of the system, *N*: annual salvage value, *O*: annual operation cost.

4.2. Cost comparison with renewable-based desalination technologies

According to World Bank Review in 2000, about 700,000 deaths result each year from emitted toxic pollutants when fossil fuels burn. On the other hand, 1 kW photovoltaic system producing 150 kWh/month prevents 75 kg of fossil fuel being mined, 150 kg of CO_2 from entering the atmosphere and keeps 473 L of water from being consumed [2]. Accordingly, the need for more efficient and cost-effective sustainable water production methods grows. A number of studies have addressed the economical aspects of solar stills [61–74]. Reported values vary from $71/m³ of produced water for a stepped still with sun-tracking [63], $53/m³ for a weir-type still [64] and double-cover still with condenser [65], $30/m³ for a large size plant with pyramid stills [66], down to $20/m³ for a large size plant of stills [67], $10–12/m³ for conventional solar stills [68,69], $3–5.7/m³ for solar stills coupled with PV-powered reverse osmosis (RO) [70] and $2.4/m³ for 50 m³ water production facility using porous basin stills [71]. In fact, larger systems tend to decrease the overhead costs of auxiliary components [72].

Cost data for small-scale RO systems that operate on renewable energy vary between $1.5 and 33/m³ [58,73,74] for seawater desalination and between $2.7 and 14.9/m³ [73,74] for brackish water. The prices and material performances can vary significantly depending on the place and year of project implementation [75] and hence an accurate comparison in terms of desalination costs and production is difficult. It should be noted that the production rate for solar stills is proportional to the area of the still, hence the cost per unit of water produced is nearly the same regardless of the installation size, which renders solar stills more attractive for small-sized applications. This is in contrast to fresh water supplies and to other desalination methods, where the capital cost of equipment per unit of capacity decreases as the capacity increases [4]. In comparing with RO, it should also be noted that many of the drawbacks in RO systems are not present in solar stills such as the sensitivity to variations in feed quality, noise associated with pumps, extent of pretreatment and membrane replacement, and disposal of both

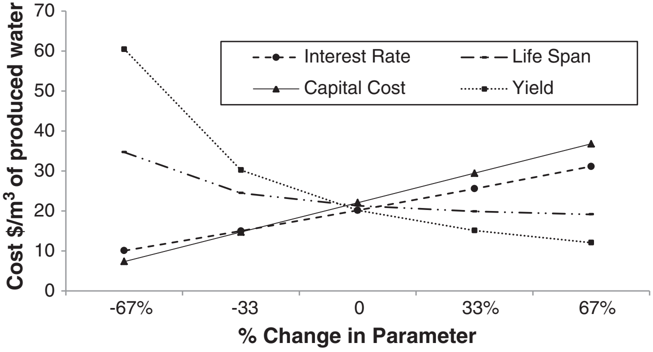

Fig. 4. Effect of different parameters on the cost of the modified still.

the concentrate and cleaning waste-streams and other related issues whose monetary value might be difficult to quantify.

4.3. Comparison with fuel-based desalination technologies

The operation of fuel-based desalination technologies such as multi-stage flash distillation (MSF) and reverse osmosis (RO) encompasses hidden costs that are often not presented in the cost ranges that are reported in the literature. About 6.6 billion metric tons carbon equivalent of greenhouse emissions is released in the atmosphere to meet today's annual world energy demand of 22 billion kWh (expected to reach 53 billion by 2020). A major cost component that has to be included in studying the economic feasibility of a desalination technology is that of environmental degradation, which is no longer restricted to being an externality.

In order to allow for a reasonable comparison of the proposed solar still in this study with fuel-based desalination technologies, the cost of the latter is adjusted to include two components: (i) an assumed carbon-trading scheme that is enforced and implemented; and (ii) external environmental degradation costs. Borsani and Rebagliati [76] estimated the cost of MSF desalination in Middle East countries at 0.52 $/m^3 while Wade [77] calculated this cost to be 1.044 $/m^3, which tends to be closer to present unit water costs [78]. It is estimated that a mid-size RO plant (250,000 m^3/day) with an energy demand of 5 kWh/m^3 can supply 48,000 persons at an assumed daily consumption of 130 L/capita while the energy used for this production could supply 10,300 4-person households with electricity assuming an average demand of 4430 kWh/year [79]. El-Fadel and Alameddine [80] estimated the energy requirements for multi-stage flash distillation (MSF) at 10 kWh/m^3 and for RO processes to vary between 0.8 and 4.2 kWh/m^3 depending on the feed salinity. Average values as well as minimum and maximum values have been adopted for the purpose of this study and used as a basis to calculate the costs of these processes including environmental degradation costs.

Carbon-capture and storage have become a widely adopted practice [6]. Different CO_2 emission levels are reported for a given desalination process by different researchers e.g. [81,82]. Poullikkas [83] used a value of 42$ per ton CO_2 emitted as a trading scheme to conduct an economic analysis of power generation from parabolic trough solar thermal plants in Cyprus. Emission trading is a market-based approach that is used to control pollution by providing economic incentives for achieving reductions in emissions. A government or similar authority sets a limit or cap on the amount of a pollutant that can be emitted and this cap is sold to firms in the form of emission permits. For greenhouse gasses, the largest active trading program is the European Union Emission Trading Scheme. For the purpose of this study, values for carbon trading prices ranging from 0 to 120 $ per ton of emitted CO_2 have been adopted for developing scenarios used in comparing the costs of different desalination technologies. It should be pointed out that in comparing solar stills with other desalination methods, it is assumed that the amount of CO_2 and other pollutants emitted in the manufacturing processes of these techniques is similar.

For external costs associated with environmental degradation, estimates are based on the results of the European CASES project (Cost Assessment for Sustainable Energy Systems), which uses the methodology developed within the Extern-E project for the evaluation of the externalities of energy generation. Pollution costs on emissions per ton basis for each country in the European Union and neighboring countries are estimated using simulations taking into account climate, population density, and epidemiological studies linking pollutant concentrations and morbidity and mortality rates.

Four primary pollutants are considered: particulate matter, nitrogen oxides, sulfur oxides and carbon dioxide. General estimates for environmental damage are 3.2 cents/kWh of electricity produced using fuels for the former three pollutants whereas for carbon dioxide, the estimates vary between 0.1 and 10 cents/kWh of electricity produced. Table 2 summarizes the results for the adjusted cost analysis including externalities due to CO_2, SO_2, NO_x and particulate matter and different carbon-trading cost scenarios. It is notable that for seawater desalination and with an applied carbon-trading scheme, the cost range becomes \$4.7–5.7/m^3 of produced water, which is currently the lower range of renewable-based alternatives. Therefore, with further enhancements in the water output of these technologies and with the implementation of strict environmental regulations, the cost feasibility of renewable-based desalination systems becomes more justified.

Table 2
Estimated desalination costs including environmental damage costs.

Type of feed water into conventional desalination method			*Brackish*	*Seawater*
Reported costs without external costs and carbon trading (\$/m^3)		Low range	0.3	0.4
		High range	1.3	3.4
Average energy consumption (kWh/m^3)			2.5	10
External costs due to SO_2, NO_x & particulate matter (¢/kWh)			3.2	3.2
External costs due to CO_2 emissions (¢/kWh)			5.0	5.1
External costs due to SO_2, NO_x & particulate matter (¢/m^3)			8.2	32
External costs due to CO_2 emissions (¢/m^3)			12.5	50
Adjusted costs including externalities and carbon trading for various possible CO_2 trading schemes (\$/m^3)	0 \$/ton	Low range	0.5	1.3
		High range	1.5	4.3
	40 \$/ton	Low range	0.6	1.7
		High range	1.7	4.7
	80 \$/ton	Low range	0.7	2.2
		High range	1.8	5.2
	120 \$/ton	Low range	0.8	2.7
		High range	1.9	5.7

5. Conclusions

In this study a new design of solar still is proposed which significantly increases the water output without forsaking the key advantages of the still. Based on the experimental study and the cost analysis conducted, the following conclusions are deduced:

- The introduced rotating cylinder significantly accelerates the evaporation process and results in a 200–300% enhancement in productivity compared to the control. The enhancement in productivity due to this low-cost amendment exceeds that of many of the complex modifications introduced to the solar still before.
- An economic assessment of the proposed system reveals that the cost per unit water produced is comparable to that reported in the literature for other renewable-based desalination methods.
- Cost values for fuel-based desalination are adjusted to include externalities due to CO_2, SO_2, NO_x and particulate matter and different carbon-trading cost scenarios. This analysis shows that the economic feasibility of desalination systems based on renewable energy becomes more justified if environmental degradation costs associated with fuel-based-desalination are acknowledged.

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