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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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