Study into solar-still performance under sealed and unsealed conditions

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Abstract

Safe water is fundamental to life and sustainable development. Despite modern civilization pacing into the 21st century, global access to safe water is disparate and inadequate particularly in south Asia and Africa. The need of the hour is to promote appropriate technologies, such as desalination, which are economically viable and environmentally conducive. With increasing stress on renewable energy use, technologies based on effectively harnessing solar energy would prove sustainable. Solar-still is a desalination technology that effectively harnesses solar energy. Solar-stills generate safe water from either contaminated and/or brackish water. They are an enabling domestic technology that can suit decentralized operation and maintenance. Their fundamental dependence on solar energy and relatively low yield has thus far impeded wide-spread adoption. The current article discusses the prospects of solar-stills as a safe-water technology. Subsequently, an innovative low internal-volume stepped solar-still has been commissioned and tested for its productivity under sealed and unsealed conditions. The results of the experimental investigation have been discussed in this article. The salient contribution in this article pertains to the performance of a stepped solar-still under sealed and unsealed conditions. Such an investigation has been found to be crucial, but hitherto unattended to.

Keywords: desalination; safe water; stepped solar-still; sealed; unsealed; water crises

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1 INTRODUCTION

1.1 Desalination: a viable option

Water is the most vital resource for any ecosystem on the earth. The availability of fresh water has a direct bearing on the socio-economic development and the standard of living. Ironically, its sustained and equitable availability is one of the most overwhelming environmental, social and political challenge facing mankind today. Globally, freshwater is increasingly scarce both in terms of quality and quantity (see Figure 1).

Fresh water is traditionally drawn from pumping ground water and surface reservoirs such as rivers and lakes. As demands for fresh water increase due to population growth and development, it is necessary for water-stressed regions to adopt unconventional methods. Isak Dinesen once remarked, 'The cure for anything is salt water: sweat, tears or the sea.' Sea water, given its geographical coverage is more easily accessible than fresh-water reservoirs. Desalination is an archaic solution for water treatment and its origin can be traced back to the days of Aristotle. It involves converting saline/brackish water into fresh water deploying a combination of mechanical, thermal and/or chemical energy. Thermal and membrane-based desalination is extensively used, but for large-scale operations. Multi-stage flash (MSF), Multi-effect humidification (MED), vacuum compression (VC), reverse osmosis (RO) and electrodialysis (ED) are few commercially established alternatives. These approaches are fossil fuel intensive with input either as steam or electricity. The choice of a desalination technique depends on critical parameters such as feed water salinity, total dissolved solids (TDS), available resources and local demand attributed to population size. On an average for any desalination technique, more than twice the quantity of feed water is required to generate 1 l of fresh water. The remaining high-salt content reject water is normally discarded, often back into the sea.

Thermal processes like MSF and MED, based on their energy requirements, are usually implemented as co-generation units in a power plant. The daily output from these plants ranges from 5000 to 20 000 l. VC-, RO- and ED-based desalination is scalable and can be utilized as small stand-alone systems. Desalination usually refers to the treatment of sea water but some techniques

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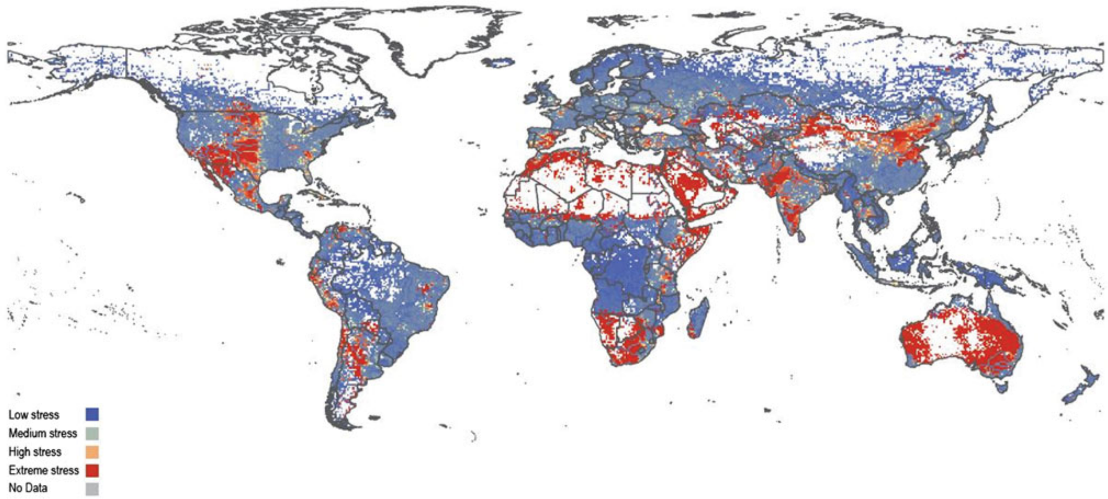

Figure 1. *Water Stress Index 2011 ([33]).*

like RO can be utilized even for domestic/industrial wastewater treatment. RO stands distinct from other desalination techniques in this regard. Lately, some chemical processes like rapid spray evaporation and ionization have been developed on a laboratory scale. While these techniques are effective, they are economically unviable and energy intensive.

Desalination is an effective technology for large-scale productivities (>20 000 l/day). They are expensive and depend heavily on conventional energy (fossil fuel and electricity) supply, thus making them unviable for scattered habitations in Asia and Africa. Consistent price hike of the fossil fuels and the resulting emissions of greenhouse gases have rendered them rather unsustainable. Further, they carry negative ramifications on the marine ecosystem too. The prospectus is to utilize the desalination techniques integrated with a sustainable renewable energy to remain viable. For sustainability, a technology would need to be effective, de-centralized, simple (easy to use/operate), consume less energy and should enable self-sufficiency among the community. A salient approach for implementing desalination has been provided in Figure 2.

1.2 Solar energy and sustainable safe water

It is important to note that almost all energy accessible to modern civilization, except nuclear and oceanic, is solar. Non-renewable fossil fuel is also stored solar energy. A sustainable future can rely on incident solar energy available at varying intensities globally. Distribution of reliable safe water and contamination is geographically varied and so is the consequent health distress on the dependent population. The progressing regions of south Asia and Africa have much to worry as these carry a very high distributed population density [1] dependent on highly stressed and increasingly unsafe water reserves, ground water in particular. The connection between inadequate water access, extreme distress and poverty is well established. However, these are also the regions gifted with amply distributed and reliable solar energy (4–7 kWh/day/m^2). Domestic mechanisms of harnessing solar energy for safe water in the widely distributed habitations of India and Africa will ensure sustainability. Solar still is one such viable solar energy technology [2] for generating safe water.

An integrated map indicating global solar potential, poverty and water scarcity is illustrated in Figure 3. The connection between solar energy and sustainability potential for safe water, particularly in south Asia and India, is evident. It is also generally observed that the solar irradiance is at its peak during adversities (famine) related to water shortage thus making solar-still a much viable desalination technology. A solar-still is a simple device primarily used to obtain potable water from saline/brackish water. Its applicability for treating biological and chemical contaminants (including heavy metals) is also promising. A solar-still generally comprises no moving parts and requires little maintenance. The underlying working mechanism is similar to occurrence of rainfall, viz. solar-induced evaporation with subsequent condensation of vapour yielding clean water. Usually, the construction of a basic solar still is robust and easy. It further adds value given the fact that people can make-do with even locally available materials.

While solar-stills provide the advantage of being simple, easy to operate and maintain, requiring no conventional energy for operation, their adoption has remained poor due to low and inconsistent productivity ranging from 2 to 5 l/m^2/day [3]. The current article provides a preliminary review on the current status of solar-stills including results from a maiden investigation into solar-still performance under sealed and unsealed conditions.

2 SOLAR-STILLS: A REVIEW

Solar-stills have been used effectively, for centuries, to treat highly contaminated water and as a means of generating water in extremely arid and water-scarce regions. The prime driver of research into solar-stills has been aimed at improving the productivity, as determined by solar-still design and ambient

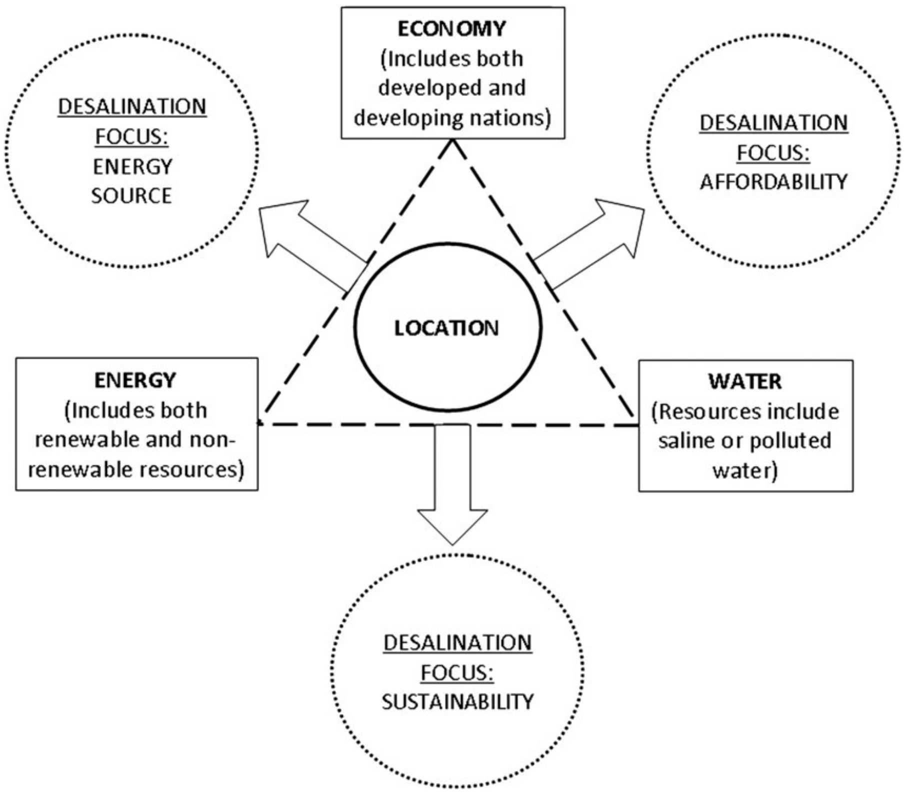

Figure 2. *Desalination approach in the present scenario.*

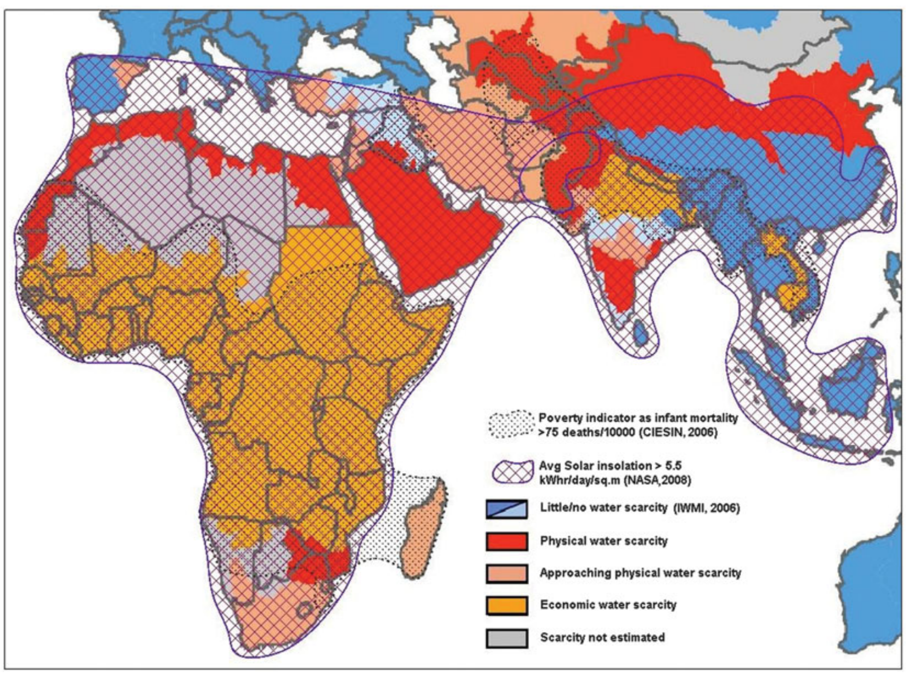

Figure 3. *Integrated (south Asia–Africa) map indicating solar energy and sustainable safe-water potential (analysis based on data from CIESIN, 2006; IWMI, 2006; [34]).*

environmental (meteorological) factors. While research is still going on to improve system productivity, available solar-still designs are yet to make a breakthrough in significantly enhancing system productivity and/or efficiency for practical use. While Cooper [4] indicates a 60% achievable practical efficiency for basin-type solar-still, most available designs barely exceed 30%. On the contrary, active and advanced mechanisms of improving system efficiency renders the system to be expensive, bulky, complex, difficult to maintain and not practicable for domestic applications. Simple innovations in passive solar-still designs are likely to be more viable in providing an affordable and effective means of obtaining fresh water.

Research over the past few decades have identified major factors like the system thermal inertia, heat recovery and improvised geometric configurations in the solar-still to enhance its productivity. Theoretical investigations have by far superseded experimental investigations with increasing research being concentrated towards theoretical and simulation studies. Djebedjian and Rayan [5] developed a Navier–Stokes equation-based mathematical model which emphasized the need for numerical-analysis based sizing of the solar-still for practical applications. A mathematical model developed by Mowla and Karimi [6], to produce fresh water from saline water, recommends maintaining a minimum water-depth inside the solar-still, to maximize productivity. On the other hand, Murugavel *et al.* [7] recommend the adoption of deep-basin solar-still in locations of consistently high solar radiation and shallow-basin still in locations with low solar radiation. Eibling *et al.* [8] and Singh and Tiwari [9] conducted numerous studies to forecast the productivity of the solar-still, and stressed the importance of the basin-water temperature and the temperature difference between the water surface and the glass cover as crucial factors governing system productivity.

Many researchers have attempted to minimize the thermal losses from the solar-still to improve productivity. Extensive experimental and simulation-based studies have been carried out to understand the various thermal processes governing solar-still productivity. Onyegegbu [10] studied the factors influencing the onset of thermal convection in a basin type solar-still using the linear stability theory based on the transparency of the fluid inside the solar-still. The study concluded that convection process manifested in the form of stationary instability, since water being a transparent fluid, permitted the penetration of solar radiation to the bottom of the solar-still. By conducting experiments on two solar-stills, one with a black bottom and the other with a mirrored bottom, the study revealed that increasing the fluid thickness delayed the onset of thermal convection in the former, whereas in the latter, this resulted in an enhanced, but limited, thermal convection. Dimri *et al.* [11] evaluated the influence of the inner and outer glass-surface temperatures on the solar-still productivity and observed that the inner glass-surface temperature played an imperative role in determining system productivity. In addition, they also observed that the thermal conductivity of the condensing surface (glass cover) also influenced system productivity. Tsilingiris [12] conducted a rigorous theoretical investigation based on the Dunkle's [13], solar-still model, to verify and validate system performance under extreme conditions of high ambient temperature (that resulted in higher productivity). In addition, experimental/field investigations validated the reliability of the theoretical model. Sartori [14] conducted a theoretical comparison between the thermal performance of a basin-type solar-still and a solar evaporator. This study revealed the evaporation in a solar evaporator to be greater than that in a solar-still with a glass cover, despite the temperature inside the solar still being higher (due to the green-house effect). This behaviour was attributed to the forced convection occurring within a solar evaporator.

Limited, but crucial innovation-driven research has been pursued to arrive at novel solar-still designs. This included hybrid solar-still systems. Badran and Al-Tahaineh [15] studied the effect of coupling a solar collector with a solar still. This permitted a preheating of the basin water in the solar-still. They found a 36% productivity increase in comparison with stand-alone systems. This increase was attributed to the higher basin-water temperature. Tiris *et al.* [16] showed that by integrating collectors with solar-stills, the yield increased by 194%. Sampath kumar *et al.* [17] similarly showed an increase in the productivity by further coupling collectors with active systems. Gaur and Tiwari [18] attempted to optimize the number of collectors for an integrated PV hybrid active solar-still. The study concluded that the heat transfer co-efficient for evaporation was greater than that of convection and radiation. The yield from active systems was higher than passive solar-stills with the number of coupled collectors proportional to the mass of basin water. Voropoulos *et al.* [19] found that coupling a solar-still with a flat plate collector doubled the productivity over a 24-h period with a concurrent increase in night-time productivity. Voropoulos *et al.* [20] also studied the behaviour of a conventional greenhouse type solar-still coupled with a solar-collector based hot-water storage tank. Badran *et al.* [21] found that with tap-water input the productivity of a collector coupled solar-still increased by 231% with a decreased 2.5% efficiency. Similarly with saline-water input, the productivity increased by 52% over a 24-h period. Yadav and Yadav [22] developed an analytical expression to study the transient response of an active system. Murase *et al.* [23] devised a concept to solve both water and energy problems by substituting a PV panel as a heat receiving plate for the still and thereby attaining a high water/power ratio. Experimental investigations revealed that an insulated solar-still basin covered with a 2.5-cm-thick soot-layer yielded maximum productivity. Hybrid solar-still systems achieve higher yield by pre-heating the input water by connecting it to a solar/PV collector. However, such systems are expensive and complex to operate and maintain, as scaling is highly prevalent in such systems.

The need of the hour, thus, is to promote research into passive solar-stills for enhanced productivity while keeping the design simple and economical for domestic adoptability. Many researchers also adopted novel ideas to enhance the solar-still productivity. Hay [24] provides a complete review of plastic solar stills. Nafey *et al.* [25] studied the solar-still performance by covering the basin with black gravel to increase thermal storage capacity with an enhanced 20% productivity. On similar lines, Szulmayer's [26] experiment with floating solar absorbers (surface of the basin water) yielded an enhanced efficiency due to lower system thermal inertia. Khalifa and Hamood [27] studied the influence of insulation thickness (covering solar-still base) on productivity and found that an increased insulation thickness significantly increased productivity (up to 80%) including off-sunshine productivity. Further, the study revealed an increased productivity with decreased basin-water thickness. Murugavel *et al.* [7], through experiments, identified glass and black rubber as suitable solar-still materials for enhancing productivity—glass for the cover (condensation surface) and black rubber for the basin. The study recommends application of a black dye for the basin water to increase solar absorption and the use of internal mirrors on the side walls to reduce system thermal losses. El-Sebaii *et al.* [28] experimented with a thin layer of stearic acid as a phase change material, beneath the basin, to enhance the overnight productivity.

While many researchers have extensively investigated various solar-stills to enhance productivity, most studies have not been explicit, in adopting a sealed solar-still system for analysis and experimental investigation. The possible reasons could be to prevent loss of dense vapour-rich air and/or to rule out the possibility of any external contamination inside the solar-still. El-Bassuoni and Tayeb [29] experimentally investigated five solar-still designs to comprehensively study methods to enhance productivity by maximizing solar capture, and by increasing the rate of (vapour) condensation. The study particularly noted enhanced solar-still productivity in an unsealed system over a sealed one. Figure 4 provides an overview of research into solar-stills identifying various aspects influencing system yield that have been dealt with in literature to varying degrees. Table 1 provides a comparative overview of available desalination and wastewater treatment technologies.

3 INVESTIGATION INTO PERFORMANCE OF STEPPED SOLAR-STILL UNDER SEALED AND UNSEALED CONDITIONS

Many attempts in improving the performance of solar-stills have incorporated mechanisms of heat recovery, i.e. recapture/recover the heat lost during condensation to evaporate more water. This has only lead to designs that are expensive, bulky, complex and difficult to practically operate and maintain. Designs incorporating features to reduce the internal volume are few and have not been adequately investigated experimentally. Further, designs have rarely been compared for their performance under unsealed and sealed conditions. Studies, explicitly looking into unsealed solar-still performance are insufficient. The highlighted parameters (Figure 4) have been investigated in the current article through an innovative design adopting a stepped profile to maintain the water-basin close to the condensation surface and minimizing internal volume.

3.1 System design

A stepped solar-still (Figure 5) comprising of semi-circular pipe sections welded progressively one next to the other so as to maintain a constant slope was fabricated to serve as the water-channel basin. To minimize thermal losses from the base of the solar-still, an air-tight (vacuum capable) jacket has been provided. Air being a good insulator, the jacket was kept sealed to prevent thermal losses from the base of the system. An inlet at

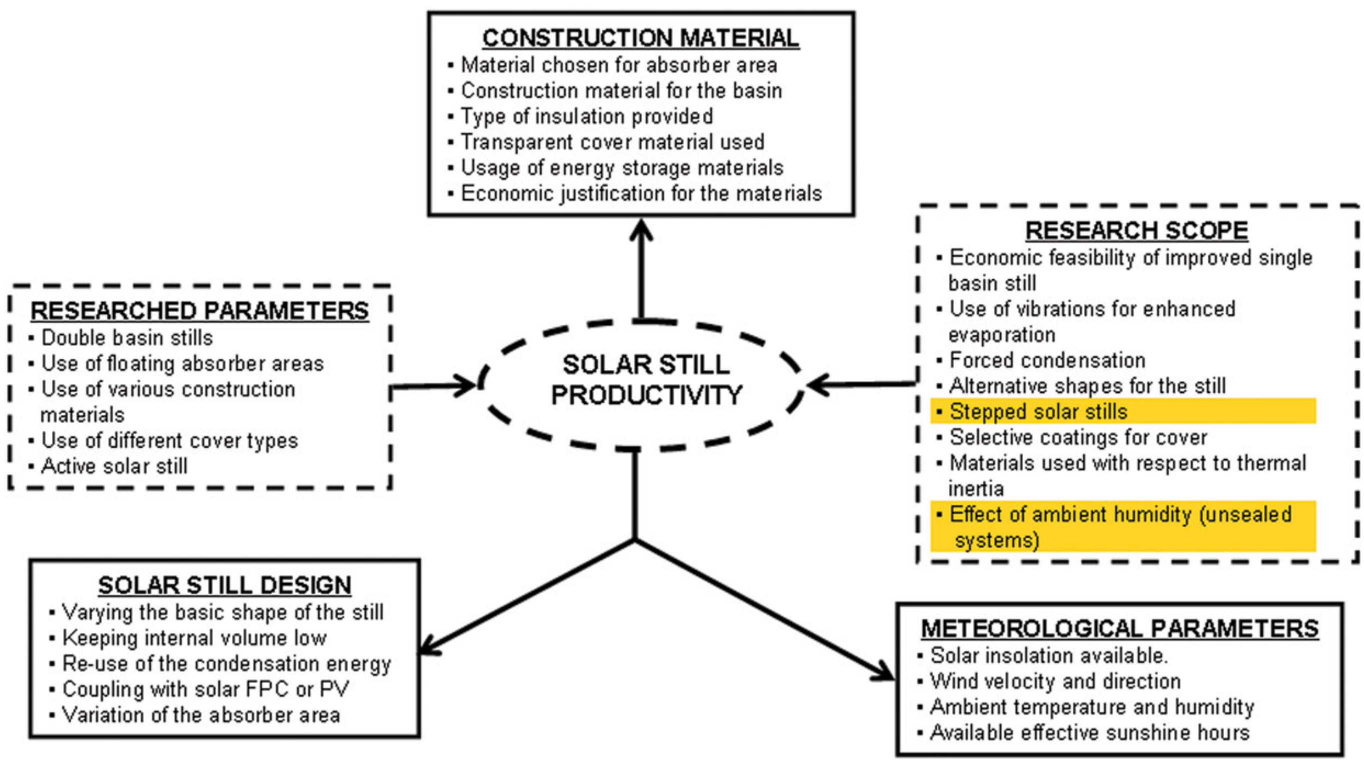

Figure 4. *Factors influencing solar-still productivity.*

Table 1. *Comparison between various desalination and water treatment techniques.*

PARAMETERS	DESALINATION TECHNIQUES					WATER TREATMENT TECHNIQUES				
	RENEWABLES BASED (SOLAR)			NON-RENEWABLES BASED		RENEWABLE BASED (SOLAR)			NON-RENEWABLES BASED	
	SIMPLE STILL	ACTIVE STILL	STEPPED STILL	REVERSE OSMOSIS	DISTILLATION	SIMPLE STILL	ACTIVE STILL	STEPPED STILL	REVERSE OSMOSIS	FILTRATION
ROBUSTNESS	VERY GOOD / HIGH	AVERAGE / MEDIUM	GOOD / HIGH	POOR / LOW	GOOD / HIGH	VERY GOOD / HIGH	AVERAGE / MEDIUM	GOOD / HIGH	POOR / LOW	AVERAGE / MEDIUM
MAINTENANCE	POOR / LOW	AVERAGE / MEDIUM	POOR / LOW	VERY GOOD / HIGH	VERY GOOD / HIGH	POOR / LOW	AVERAGE / MEDIUM	POOR / LOW	VERY GOOD / HIGH	GOOD / HIGH
RELIABILITY	POOR / LOW	AVERAGE / MEDIUM	POOR / LOW	VERY GOOD / HIGH	GOOD / HIGH	POOR / LOW	AVERAGE / MEDIUM	POOR / LOW	VERY GOOD / HIGH	GOOD / HIGH
PRODUCTIVITY	POOR / LOW	AVERAGE / MEDIUM	AVERAGE / MEDIUM	VERY GOOD / HIGH	VERY GOOD / HIGH	POOR / LOW	AVERAGE / MEDIUM	AVERAGE / MEDIUM	VERY GOOD / HIGH	GOOD / HIGH
USAGE LIFE	VERY GOOD / HIGH	AVERAGE / MEDIUM	GOOD / HIGH	AVERAGE / MEDIUM	AVERAGE / MEDIUM	VERY GOOD / HIGH	AVERAGE / MEDIUM	GOOD / HIGH	AVERAGE / MEDIUM	POOR / LOW
ELECTRICAL (kWhr/m3) ENERGY REQUIREMENTS	0.35	0.65	0.1	4.5	13	0.35	0.65	0.1	4.5	5.3
FLOW RATE (WATER)	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	GOOD / HIGH	VERY GOOD / HIGH	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	GOOD / HIGH	AVERAGE / MEDIUM
INPUT WATER QUALITY	ANY	ANY	ANY	SALINE/BRACKISH	SALINE/BRACKISH	ANY	ANY	ANY	PRETREATED	CONTAMINATED
COST PER LITRE	GOOD / HIGH	VERY GOOD / HIGH	AVERAGE / MEDIUM	AVERAGE / MEDIUM	POOR / LOW	GOOD / HIGH	VERY GOOD / HIGH	AVERAGE / MEDIUM	AVERAGE / MEDIUM	AVERAGE / MEDIUM
CONTAMINANTS REMOVED	VERY GOOD / HIGH	VERY GOOD / HIGH	VERY GOOD / HIGH	NOT APPLICABLE	NOT APPLICABLE	VERY GOOD / HIGH	VERY GOOD / HIGH	VERY GOOD / HIGH	VERY GOOD / HIGH	AVERAGE / MEDIUM
CLEAN (DIRECT & INDIRECT)	VERY GOOD / HIGH	VERY GOOD / HIGH	VERY GOOD / HIGH	AVERAGE / MEDIUM	POOR / LOW	VERY GOOD / HIGH	VERY GOOD / HIGH	VERY GOOD / HIGH	GOOD / HIGH	AVERAGE / MEDIUM
COST PER LITRE ($/m3)	0.06	0.118	0.02	1	1.15	0.06	0.118	0.02	0.7	NA
LEGEND:	POOR / LOW	(dotted)	AVERAGE / MEDIUM	(grey)	GOOD / HIGH	(hatched)	VERY GOOD / HIGH	(dark)	NOT APPLICABLE	(grid)

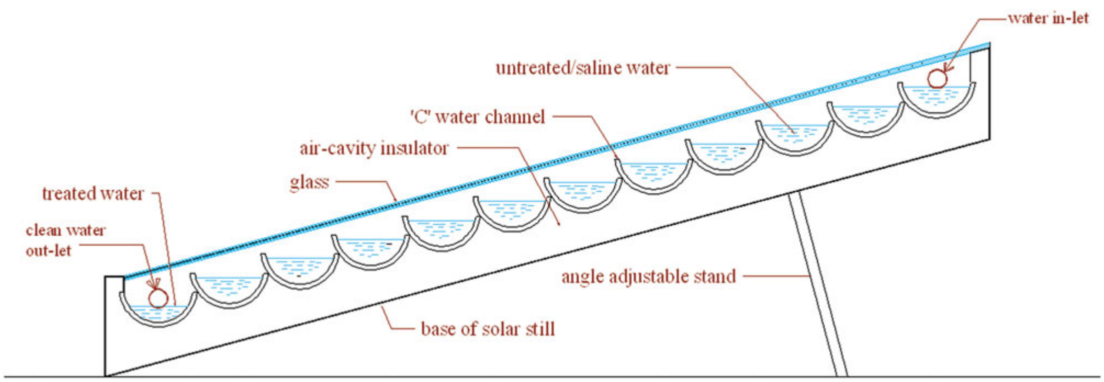

Figure 5. *Stepped solar-still design.*

the top and outlet at the bottom serve to refill and empty the solar still of treated water, respectively. The design also incorporates an adjustable slope which can be varied depending on the corresponding latitude and solar altitude (to maximize solar gain) and can hold between 3 and 4 l of water for treatment. The internal air volume of the solar-still is limited to <40% of the total solar-still volume. Libin *et al.* [30] provides a sealed-system performance appraisal of the solar-still.

The solar-still is primarily made from cold-rolled mild steel, with water channels made from galvanized iron pipes (cut into half). To prevent excessive corrosion, the water channels (basin) were spray galvanized and subsequently coated with matt-black paint to increase thermal absorptivity. The rest of the exposed surface of the solar-still was given a coat of red oxide followed by a coat of white enamel paint. The glass cover was cleaned daily to prevent assimilation of dust. The solar-still once placed inclined to the requisite angle was then levelled using a spirit level to ensure that the water completely filled the water channels. To ensure complete air-tightness, rubber gaskets were used on the edges of the solar- still on which the glass rested. As a secondary measure to ensure air-tightness, silicone based RTV (Room Temperature Vulcanizing) adhesive was applied externally on the seams between the glass and the base. The outlet tube was also immersed in a measured quantity of water in the distillate collection bottle. An air-tight cap was also devised to seal the water-inlet (see Figure 6), which for unsealed experimental conditions was left open, but covered with a filter cloth.

3.2 Experimental set-up

The solar still was designed and commissioned at the Centre for Sustainable Technologies, Indian Institute of Science, Bangalore. The experiments were conducted for both conditions, unsealed and sealed; experiment under unsealed condition was carried out between 10 and 18 June 2009, and under sealed condition between 19 and 27 June 2009. The still was kept at a tilt angle of 12.5°, which was close to the latitude of Bangalore and also permitted the condensed water to drain to the collection channel (without dripping into the water basin) [31]. For the given latitude, the solar-still was oriented north to maximize solar-gain

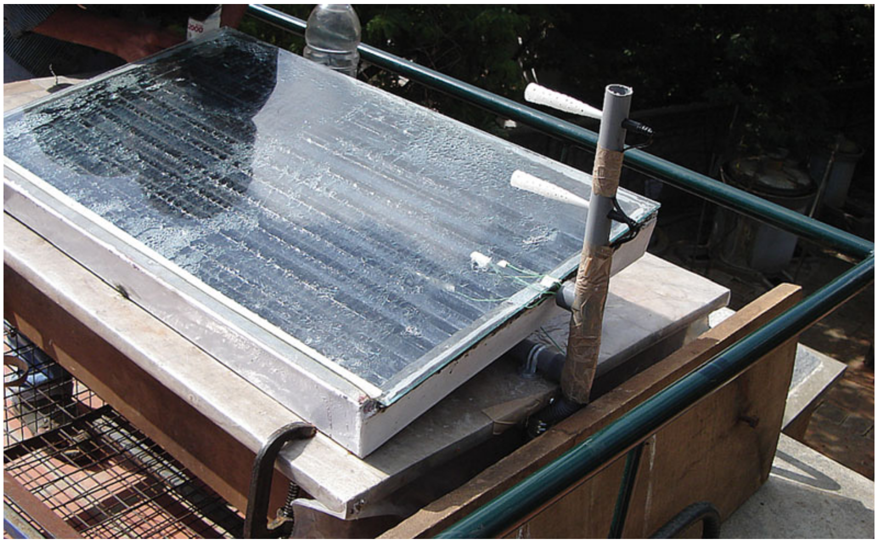

Figure 6. *Experimental set-up.*

during the month of June. Plain float glass (3 mm thick) was used as the solar-still cover, which was kept at an average height of 25 mm from the water surface. The weather conditions (9 am to 3 pm) that prevailed during the solar-still experiment are in the following Table 2.

The experiment (see Figure 6) was carried out between 9 am and 3 pm due to extensive tree cover on the eastern and western sides. To maintain experimental consistency, data collected between 9 am and 3pm has been used for the study (to eliminate the effects of shade from surrounding vegetation). A graduated bottle measured the hourly yield.

Ambient weather parameters were recorded at 5 min intervals by a weather station located within 10 m from the solar-still. Relevant parameters measured include air temperature, relative humidity and solar insolation. The comparative solar-still performance between an unsealed and sealed solar-still was carried out for the same prototype for 2 consecutive weeks. As the experimental investigations under unsealed and sealed conditions were not performed in tandem, the comparative performance evaluation needs careful investigation.

Table 2. *Prevalent weather conditions during the experiment.*

Sn	Weather parameter	Average conditions	Standard deviation
1	Solar intensity	718.76 W/m^2	276.7[a]
2	Ambient temperature	27.5°C	1.2
3	Relative humidity	76.4%	5.6

[a]This (high) standard deviation can be attributed to the diurnal variation in solar intensity.

4 RESULTS AND DISCUSSIONS

4.1 Temperature and humidity conditions: unsealed and sealed system

The rate of evaporation and condensation critically influence solar-still productivity. Evaporation and condensation being converse to each other, their coefficients determine system productivity. Evaporation (in case of water) is prevalent even at ambient temperature but is significantly accelerated at higher temperatures; condensation occurs when water vapour attains dew-point temperature. In a solar-still, condensation occurs on the underside of the glass cover and its temperature is considered to be the dew point temperature. Owing to the greenhouse effect occurring inside a solar still, the temperatures inside are much higher than ambient conditions. An ideal condition for high yield is a high basin-water temperature (to enhance evaporation) and a low temperature at the condensation surface (glass cover underside). The role of vapour temperature is also crucial as a lower temperature difference between that of vapour and glass cover (underside) results in rapid condensation. The resulting temperature gradient inside the solar-still influences the internal relative humidity of the system. For water, the coefficients for evaporation and condensation depend on temperature and pressure. Although, a generalized governing equation was difficult to predict in the current context, experiments have concurred that these coefficients decrease with an increase in temperature and pressure [32].

The possible reasons/postulates for significant variations in the system productivities between unsealed and sealed conditions, during the experimental period, are listed below. These need to be taken up for further research for validation.

- With the temperature at the glass cover underside being considered as the dew-point temperature, the relative humidity inside the solar-still, for unsealed and sealed conditions, was computed based on psychrometric calculations. The relative humidity inside the unsealed system was found to be higher than that of the sealed system. The non-existence of

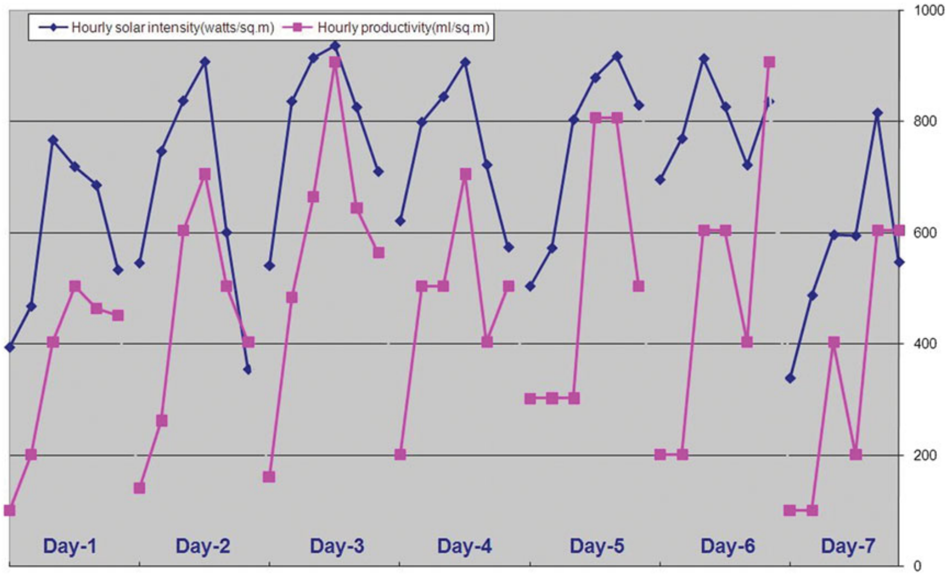

Figure 7. *Hourly (unsealed) solar-still productivity in response to solar radiation.*

convective currents and higher pressure inside a sealed system, results in higher internal temperatures. This raises the saturation vapour pressure (maximum vapour pressure reached before condensation begins) inside the solar-still and consequently lowers the internal relative humidity (ratio of vapour pressure to saturation pressure) under sealed conditions. This lower relative humidity restricts higher solar-still productivity in a sealed system.

- The convective currents occurring inside the unsealed system facilitates heat removal which consequently induces rapid attainment of dew-point temperature (and thereby increasing condensation).
- Moreover, an internal high pressure in a sealed system, with low air-gap (<25 mm), is likely to suppress the phase-change (water to vapour) rate by inhibiting the interface (water to water vapour) barrier. This could also explain the lower productivity in the sealed system. Explicit discussion on this behaviour is however lacking in available literature.
- The external relative humidity has been found to influence the unsealed system productivity in particular. It has been observed that the system productivity is inversely proportional to ambient relative humidity. This can be attributed to the fact that drier air (low relative humidity) is likely to enhance the evaporation potential, which in the case of an unsealed system (with equalized external–internal pressure) operating at high internal relative humidity is likely to result in higher condensation rates (and thereby higher system productivity).

4.2 Solar-still productivity in response to solar radiation

Being the primary energy source, solar radiation is the singlemost factor dictating solar-still productivity. Thus, total system yield increases with higher net solar radiation. However, it is interesting to note the hourly system thermal response and productivity for both conditions (see Figures 7 and 8 for unsealed system and Figures 9 and 10 for sealed system) in response to incident solar radiation. It is important to note the higher response of the unsealed system in comparison with the sealed system. For an unsealed system, the maximum productivity was obtained during the peak solar-intensity hour (12 noon–1 pm), while for the sealed system the maximum productivity was obtained with a time lag of 1 h from the peak solar-intensity hour. This time lag in productivity can be attributed to the increased thermal inertia of the sealed system due to the prevalent higher internal temperature and pressure. The productivity of the solar-still under both conditions more-or-less follows the incident solar-radiation trend.

Table 3 provides a comparative summary of the solar-still performance, under unsealed and sealed conditions, in response to varying system and ambient parameter trends.

4.3 Water quality

While extensive studies have been conducted to evaluate the performance of solar-stills, little is known on the quality of water produced. Three water quality parameters are crucial indicators of safe water, viz. TDS, pH and electrical conductivity (Salinity). Higher conductivity values indicate presence of dissolved salts. These parameters were tested for both the untreated and treated water from the solar-still (under both unsealed and sealed conditions). The treated water from both the unsealed and sealed solar-still were found to be safe for consumption (see Table 4).

5 CONCLUSION

The role of solar energy for sustainability in safe water is particularly noteworthy given the fact that the world's densest regions

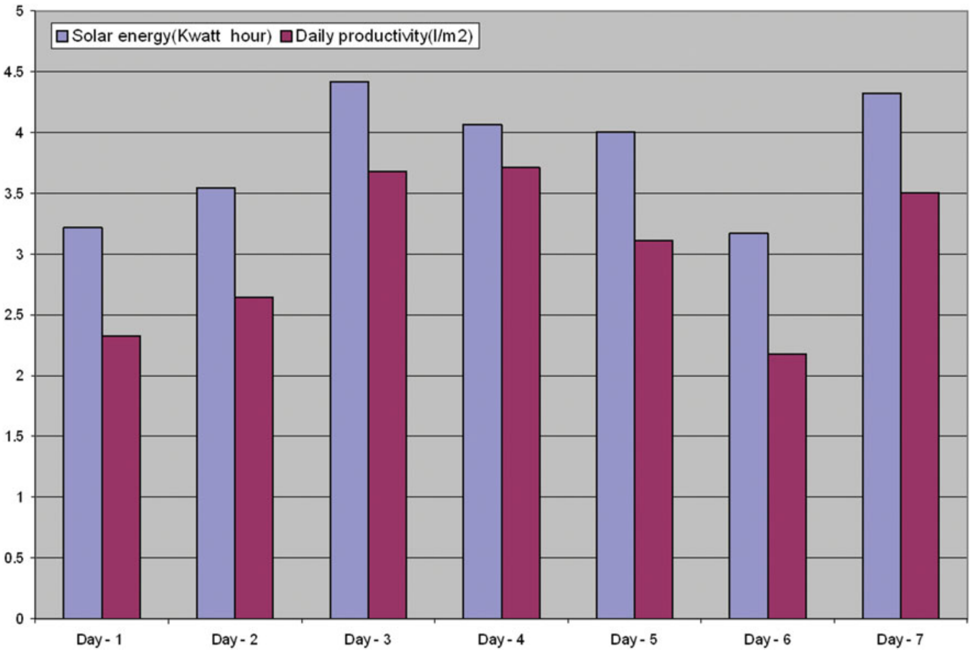

Figure 8. *Daily (unsealed) solar-still productivity with respect to solar radiation.*

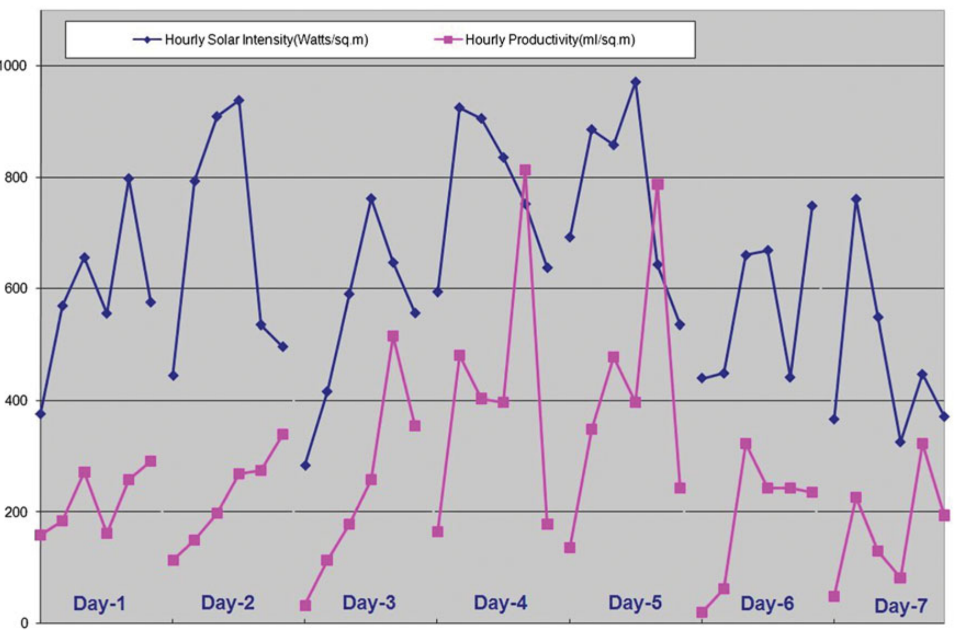

Figure 9. *Hourly (sealed) solar-still productivity in response to solar radiation.*

in south Asia and Africa are solar-rich despite being water stressed with extreme human distress and morbidity attributed to unsafe water. Desalination as a concept provides an ideal solution to safe water, but available desalination technologies are diverse and carry many limitations. These have been discussed and presented in this article. The role of solar-still as a viable desalination technology has also been discussed with a review on its current status and applicability. Solar-stills can provide a sustainable de-centralized safe-water technology for infusing domestic self-sufficiency in safe water by directly harnessing solar energy. However, its complete reliance on solar energy and low productivity hinders widespread adoption. This is despite the fact that solar stills have been providing safe drinking water for centuries in the most arid water-scarce regions of the earth. The current article substantiates the role of solar stills as a viable safe-water technology. In addition, an innovative stepped solar still

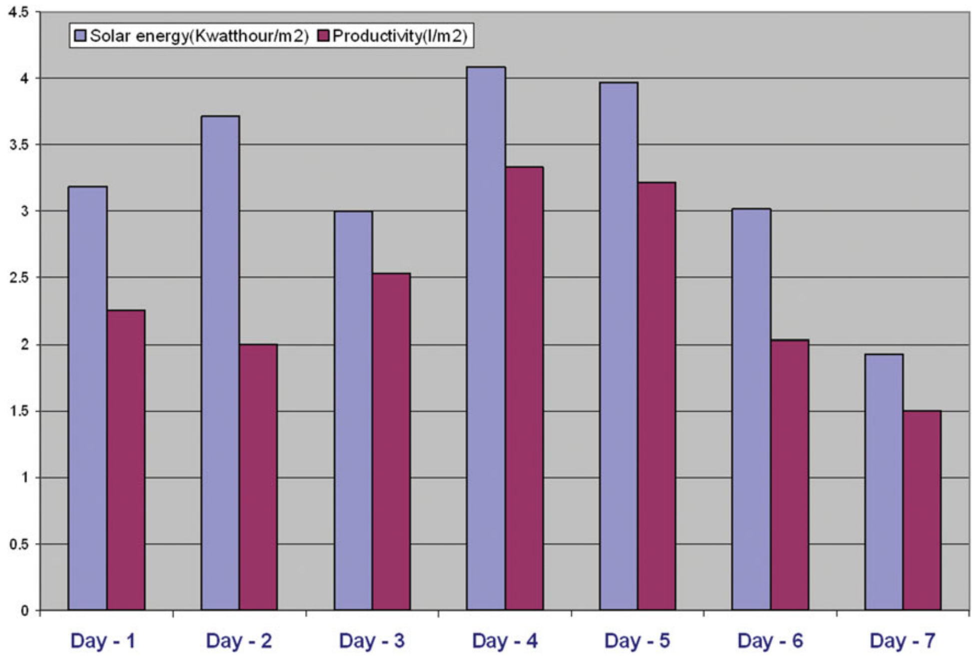

Figure 10. *Daily (sealed) solar-still productivity with respect to solar radiation.*

Table 3. *Summary—solar-still performance under unsealed and sealed.*

Sn	Determinant factor	Unsealed system	Sealed system
1	High solar radiation	High productivity	High productivity
2	Relative humidity		
	High	Low productivity	No observable impact
	Low	High productivity	
3	High ambient temperature	High productivity	Marginal decrease in productivity
4	Thermal inertia	Low	High
5	Ideal conditions for maximum productivity/ yield	High constant solar radiation High ambient temperature Low relative humidity	High solar radiation (with intermittent dips) High ambient temperature
6	Ideal climatic conditions for maximum productivity	Desert climate (high solar radiation and ambient temperature and low relative humidity)	Tropical climates (high solar radiation with intermittent dips due to cloud cover)
7	System responsiveness (time lag between rate of evaporation and condensation)	High	Low

Table 4. *Average results—water quality analysis.*

Solar-still	TDS (mg/l)		Conductivity (mS)		pH	
	Untreated	Treated	Untreated	Treated	Untreated	Treated
Unsealed	154	19.48	0.237	0.030	7.58	6.82
Sealed		7.14		0.011		7.31

with low internal volume, to marginally overcoming hitherto limitations of low productivity, has been designed and tested. The current design adopts a low internal air gap (~25 mm) when compared with much higher air gaps (in excess of 150 mm) in conventional systems.

A comprehensive evaluation into the productivity of the developed stepped solar-still under sealed and unsealed conditions has been discussed and presented in this article. The system performance evaluation has been based on efficiency, productivity and water quality. A rational explanation for the variation in system productivity, between that of the sealed and unsealed system, has also been discussed in this article.

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