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Solar-Powered Water Purification System with Energy Storage

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Abstract

At a time when potable water, fossil fuels, and wood fuels are increasingly scarce, it is more important than ever to develop methods of purifying water with renewable energy resources. This report compares the benefits and drawbacks of various models of solar powered water pasteurizers and solar powered stills. A flow diagram is proposed for a solar powered distillation system which utilizes phase change material energy storage to extend its productive time.

1. Introduction

When presenting a complete picture of solar powered water purification systems, it is important to establish a working definition of water purification. Water purification is a very broad subject matter and can generally be defined as the removal of contaminates from water in order to make it suitable for a certain use. Water purification can include the decontamination of surface and ground water from sources such as lakes and streams but also includes reclamation from wastewater sources [1]. Around the world, various government agencies establish quality standards for different uses of water. These are important distinctions to make as standards vary from one use to another and from one geographic region to another. The U.S. Environmental Protection Agency (EPA) recommends that water used for the irrigation of food crops contain no more than 0.10 mg/L of arsenic [2]. For drinking water, however, the EPA has a current standard of 50 ppb of arsenic and is issuing a new standard of 10 ppb [3]. Water contaminates are divided into two main types: biological and chemical.

Biological contaminates include waterborne pathogens and algae. Waterborne pathogens can cause life-threatening illnesses like dysentery, which is responsible for ten million fatalities per year [4]. Pathogens such as protozoans and cryptosporidium, are obviously harmful in drinking water [1] but also pose a risk when found in water used for the irrigation of crops that are consumed raw [2]. Chemical contaminates on the other hand include heavy metals like arsenic and mercury [1-3] and substances like salt when present in high concentrations. Desalination is one branch of water purification which seeks to make brackish water safe for drinking and irrigation by removing these salts [5]. Methods of water purification include solar stills [5], water pasteurization [6], membrane filtration [1] and the use of UV lights [7, 8] to inactivate viruses and bacteria. Solar power can be applied to each of these methods. This literature survey focuses on solar pasteurization and distillation as they are the simplest and most direct means of purifying water with solar power.

2. Solar Pasteurizers

Most pasteurizers raise untreated water to a temperature that is high enough to deactivate pathogens and low enough to not require the same type of energy input as boiling. Pasteurization can be achieved with the burning of fossil fuels [9], however, this requires the consumption of large volumes of expensive resources. For this reason, many types of solar pasteurizers have been developed. It should be noted that water treated in a pasteurizer must be used within several days, as the few remaining pathogens that have not been inactivated will continue to multiply and given sufficient time, may reach dangerous levels of contamination again [2].

The simplest type of solar pasteurizer is a batch processing pasteurizer. In batch processing, a set volume of water is treated at a time. Batch processing is not the most efficient form of water pasteurization but it is inexpensive and easy to use. In 1999, Safapour and Metcalf [10] pasteurized E. coli infected water in a simple batch processing method using black painted jars in two different types of reflectors. The first type of reflector was made for the purposes of the experiment and consisted of a cardboard box lined in reflective foil. The second was a commercial solar cooker called Cookit (see figure 1). Both reflectors sped up the deactivation of E. coli compared to the same container without a reflector but. The Cookit reflector was found to be capable of completely disinfecting the contents of black-painted 1.4 L jar in 1.5-2 hours. The authors made use of thermal indicators made from a tube with wax that melts at 70 °C as an alert of when the water had been pasteurized (see figure 2).

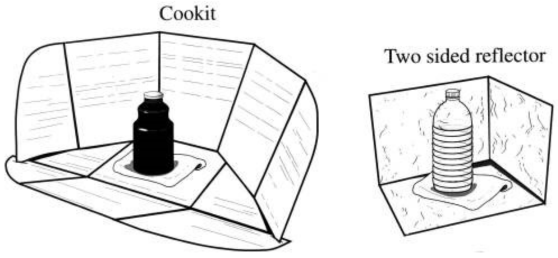


Figure 1: Batch pasteurizers with solar reflectors [10]

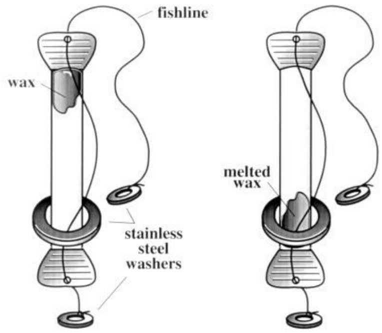


Figure 2: Wax thermal indicator [10]

A somewhat more complicated system was made by Jorgensen and Nohr [11] and can be seen in figure 3. This was a 0.7 m^2 flat plate collector with a thermostatic temperature valve that would release water when it reached 65 °Celsius. It was able to produce 25 L of water during the first half of the day. The collector contained black painted copper pipes with the water to be treated running through it. The system was designed to be manually rotated half way through the day to take advantage of the setting sun’s energy. It is unclear from the authors’ report in Tropical Doctor if the pipes were arranged in parallel or in series, although it has been shown elsewhere that arranging pipes in a flat collector in parallel is more energy efficient [12]

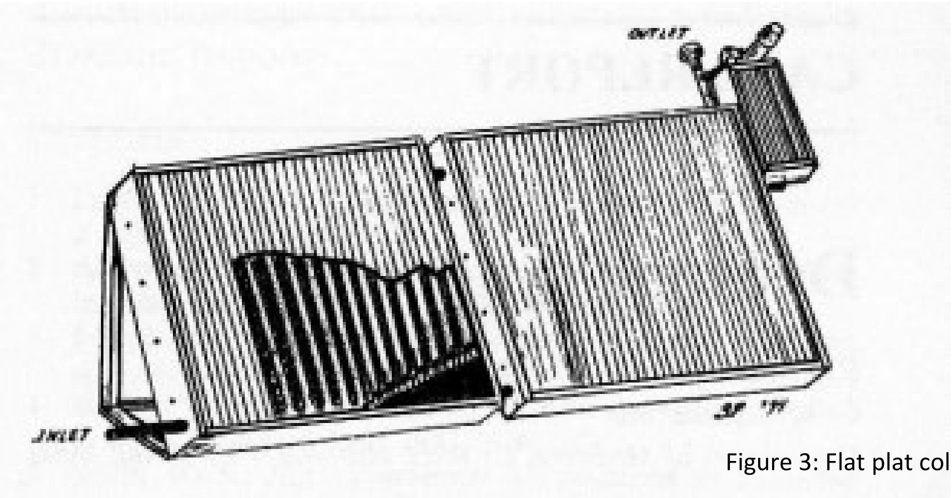


Figure 3: Flat plat collector pasteurizer [11]

Cobb [13] built and tested a density driven pasteurizer (figure 4). The system consisted of an external tube that acted as an inlet for untreated water and an internal tube that acted as an exit path for treated water. Because the internal tube contains the treated, hotter water, it also acted as a shell-tube heat exchanger, preheating the incoming, un-treated water. A flat plate thermal collector on the front of the system was the driving force in heating the water. The system had a maximum output of 70 mL per minute around noon at 85 °C. Drawbacks of this design were mostly based on wintertime poor performance. The water would freeze during the night and require additional time to thaw during the day before becoming productive again.

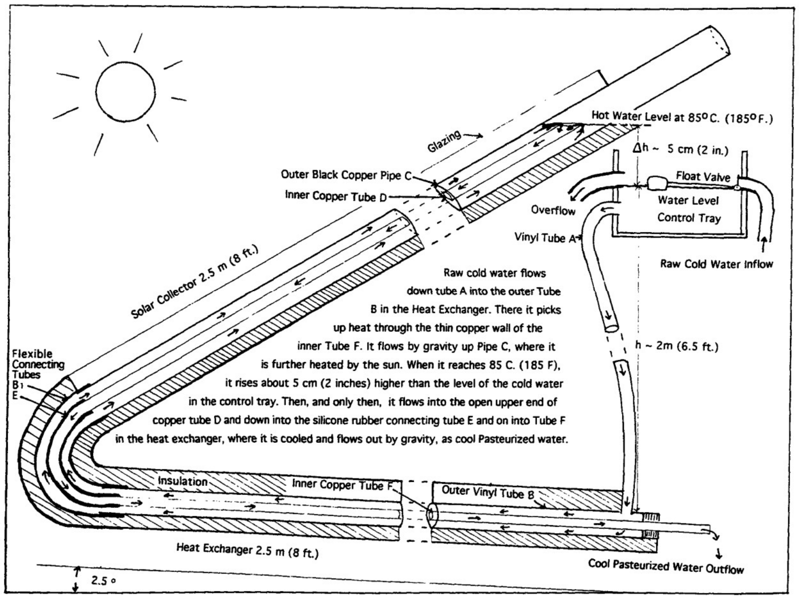


Figure 4: Density driven, self-regulating solar pasteurizer [13]

3. Solar Stills

Distillation is a method of water purification which encourages the natural process of evaporation [14]. Stills act as miniature replicas of the water cycle; where water evaporates into the air to condense in the form of clouds and return to the earth's surface in the form of precipitation. Evaporation of water happens naturally at all temperatures. Even ice evaporates to a certain extent in a process called sublimation. The rate of evaporation of water increases with an increase in temperature [15]. This raises the energy in water molecules, allowing them to overcome the cohesive attraction that exist between each water molecule in its liquid state. Evaporated water leaves behind contaminates. In a still, water vapor forms droplets on a condensing surface. When sufficiently heavy, these droplets begin to roll down the condensing surface towards whatever channel has been designated for the removal of treated water. In a still, this channel is intentionally separated from the untreated water to prevent recontamination [16]. Distillation is an effective method of removing most contaminates from water, although certain types of pesticides have been shown to remain in the distillate [17].

Spiridona and Bizerea [18] produced a greenhouse type passive solar still in 1991 and monitored its mean daily output and efficiency until 2005 (figures 5-7). The still had a peak mean daily flow of about 3.5 L/day of distilled water. The authors reasoned that a larger version of the same still could produce 5 L/day which would be enough for one person to use. Their study only examined the performance of the still during summer months, most likely due to poor performance during the winter months. Efficiency of the still declined towards the end of the study due to degradation of the insulating liner in the basin and vapor escaping through parts of the still that were no longer water-fast.

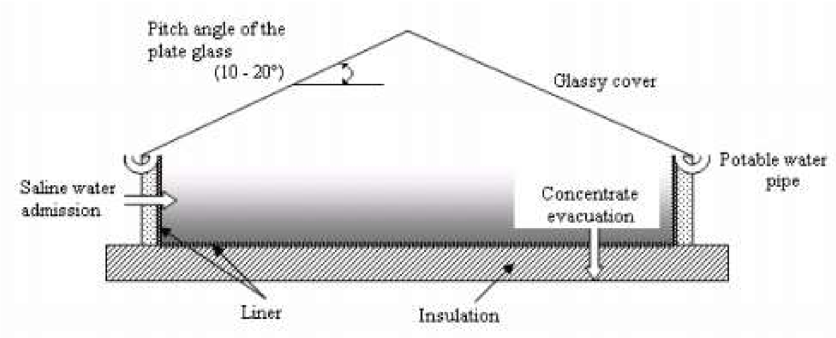


Figure 5: Passive solar greenhouse still [18]

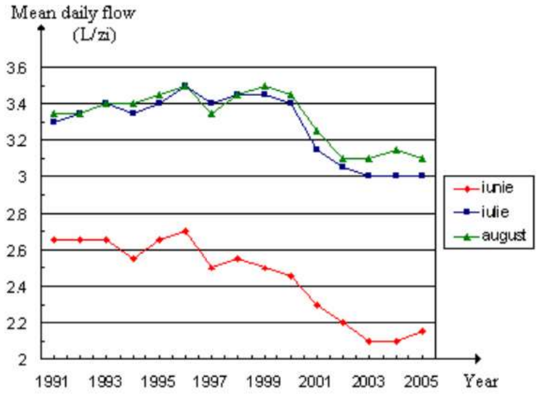


Figure 6: Mean daily flow of water during the summer months [18]

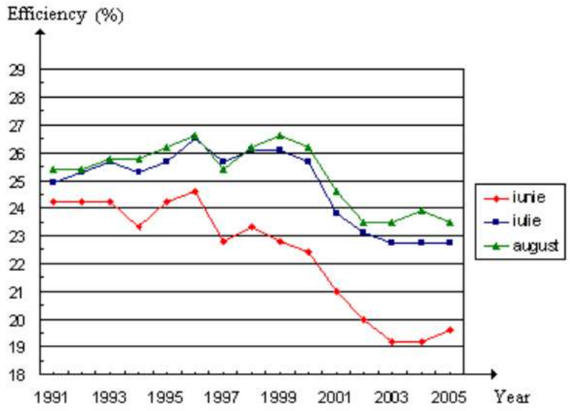


Figure 7: Efficiency of still during summer months [18]

Kumar and Arvind [19] compared the operation of a passive basin still and an active/passive hybrid (photovoltaic/thermal) still (as seen in figures 8 and 9) of the same size and geometry. The passive still was a single slope, passive solar reservoir still and the passive-active still had the addition of a pump powered by a hybrid photovoltaic and thermal (PV/T) solar collector. The pump moved water through the back of the hybrid PV/T collector, heating it before it entered the main basin. The active/passive still was able to produce 3.2-5.5 times more water than the passive still. The active still was also much more effective during the winter than the passive still. The authors tested each model with three different depths of water in the main basin and found that for both the passive and active-passive model, water yield was much higher for shallower depths.

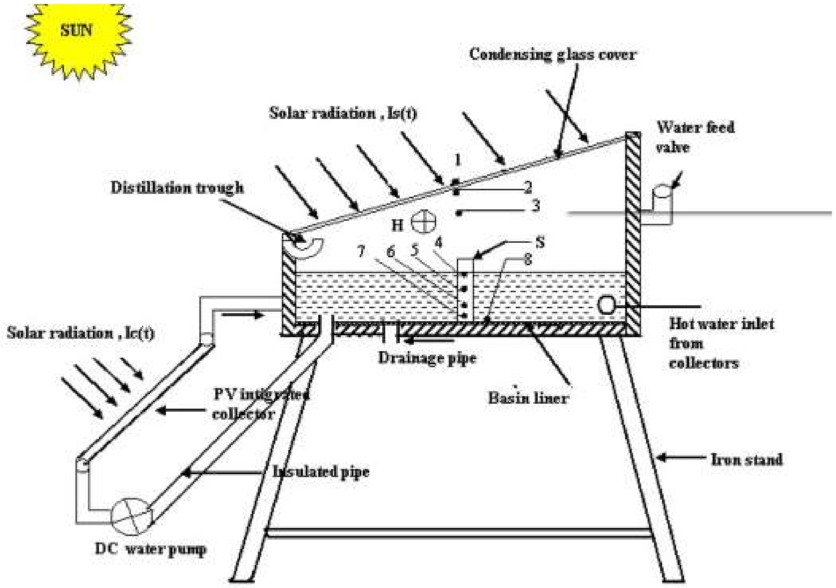


Figure 8: Schematic of the active/passive still [19]

Figure 9: Photo of the constructed active/passive still [19]

There are far more complicated models of active stills. Abakr and Ismail [20] created a solar powered multistage still, shown in figure 10, capable of producing 14.2 kg/m^2/day (see figure 10). The multistage still possessed three different levels of water (see figure 11) stacked one on top of the other. The bottom layer is actively heated by a solar thermal collector and a heat exchanger. The top two layers are heated by the latent heat released from the water condensing in the container underneath them. The system uses a photo-voltaic powered pump to remove non-condensable vapor. This lowers the pressure within the system and increases the rate of distillation. As with some of the previously mentioned units, this was only tested during the summer months. One of the drawbacks to this system was that cloudiness drastically lessened the production of distilled water.

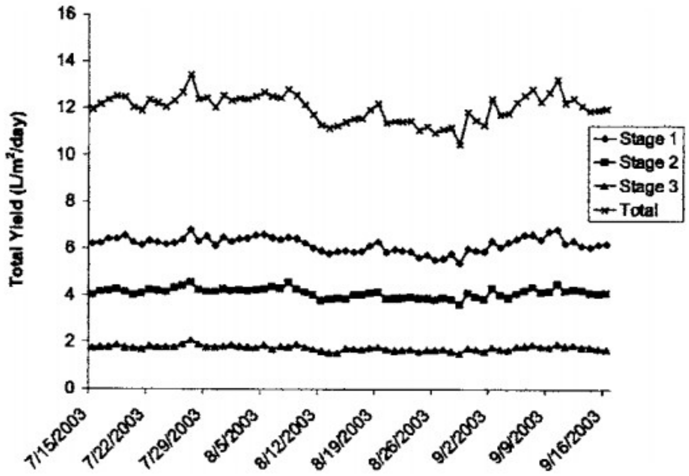


Figure 10: Total daily yield of the multistage still [20]

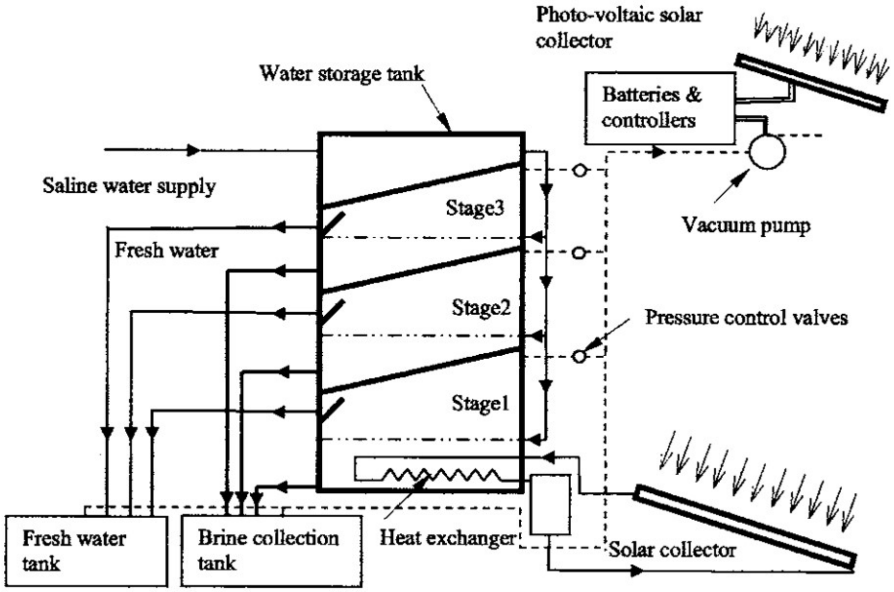


Figure 11: Diagram of multistage still [20]

K. Hameed et al. [15] designed and constructed a solar-powered water distillation unit which combines a filtration system, concentrated solar power (CSP) and solar tracking (see figure 12). The filtration system was made using a 3 ft long pvc pipe with a 4 in diameter. Concentrated solar power was delivered to the system using a parabolic mirror. Solar tracking was accomplished using two gear motors, one moved the dish of the mirror north and south and the other moved east and west. This was a low cost unit, made from pieces found in scrap yards and local stores. Output of water was not mentioned in the authors’ report but water temperature was between 600 and 800 °C. Unlike the previously described stills, the effect of this model was to boil the water to steam, rather than simply evaporate it. One drawback is that the

Figure 12: Parabolic mirror water distiller [15]

system must be programmed to follow the sun. A person operating a unit like this for a significant amount of time must have sufficient programming knowledge to fix any issues that arise. Another issue is that the complexity of the moving parts introduce more opportunities for the still to break and need repair.

One key component to producing a higher volume of purified water with a still is to increase the evaporating surface area and to reduce the depth of the water being evaporated. As Khalifa and Hamood [21] have shown, there is a direct relationship between depth of water being evaporated and the rate of evaporation. A tried and true method of increasing said surface area is with the use of a wick. In a wick-based still, water is poured at a prescribed rate along an absorbent fiber surface which ensures that only a very thin layer of water is being evaporated at any given time. Concentrated, untreated water that has not evaporated leaves the system by the wick as well. This concentrated solution can then be recycled through the still.

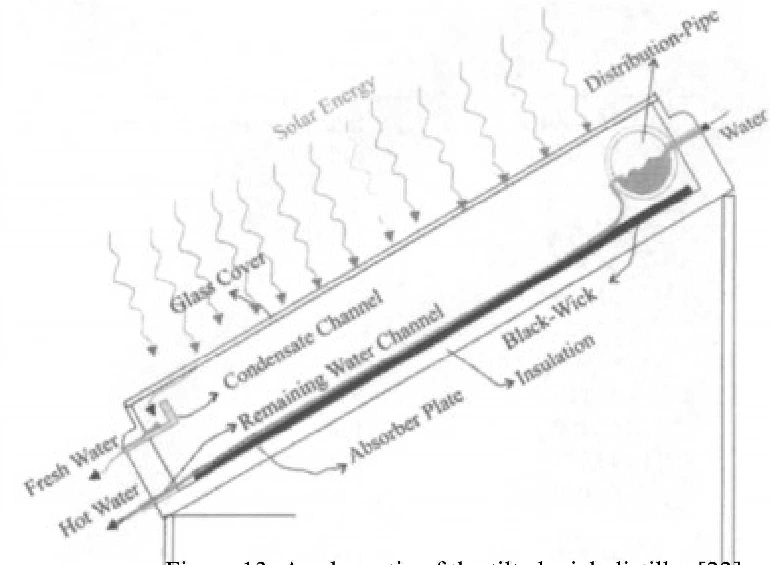


Figure 13: A schematic of the tilted wick distiller [22]

Aybar, Egelioglu, and Atikol [22] created a wick-based unit that acted as both a still and a water heater (shown in figure 13). Two different types of wicks were tested; black cloth and black fleece. Each wick was draped over a galvanized steel absorber plate that was painted black. The authors made note that it would have been better for the absorber plate to be made of a more food-safe metal that was not prone to corroding. The wick and absorber plate were tilted to 30 degrees, which had the added benefit of maximizing exposure to the sun's rays. Note that this angle of inclination is well suited to the location in which the system was tested: Cyprus, Turkey. Solar insolence varies based on geographic location [12]. As the water was poured over the wick, some of it evaporated and condensed on the glass condensing surface of the still. The rest of the water continued to travel over the wick and absorber plate, which raised the water's temperature. The heated water was then collected rather than recycled through the still. The surface area of the absorber plate and wick was 1 m^2. Between 9 AM and 4PM, distilled water and heated water were collected and measured at four even intervals of time. The black fleece wick produced the greatest volume of distilled water with a peak of 2995 mL. Hot water in the model without a wick was consistently hotter than the hot water collected from the wick models. The maximum temperature of hot water achieved was 57.6 °C. This temperature falls shy of the minimum temperature required to deactivate most pathogens (80 °C for 30 seconds) [6]. Another drawback of the system was that the absorber plate deformed from the heat of the still, causing the exposure to the sun to be irregular along its surface.

Abdallah, Badran and Abu-Khader [23] tested three different additions to the classic single slope still model. The authors experimented with the inclusion of mirrors inside of the still on its back and side walls, including a stepwise evaporating surface and finally, a solar tracking feature (see figure 14) similar to that used by K. Hameed et al. The mirrors helped to limit the energy loss within the still. The stepwise basin serves the same purpose as a wick-based still, which is to increase the surface area of evaporation. There is an added benefit to the stepwise basin in that it decreased the amount of trapped air in the still. The authors noted that the reduction of trapped air allowed the air to heat up faster and to a higher temperature than the classic still model. Each addition to the single slope still, increased the production of treated water. Mirrors alone added an additional 30% output, the stepwise basin added a 180% increase and the solar tracker with mirrors nearly quadrupled output with a 380% increase.

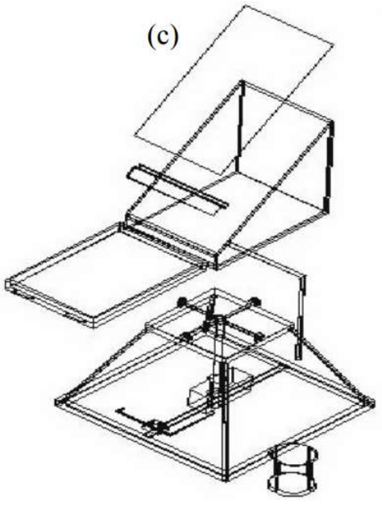


Figure 14: A schematic of a still that utilizes solar tracking, a stepwise surface and reflective mirrors [23]

El-Agouz showed that combining the use of a step-wise feature with wick technology would additionally increase the production of treated water [24] (see figure 15). The author compared the output of a traditional single slope still (figure 16), a stepped still and a stepped

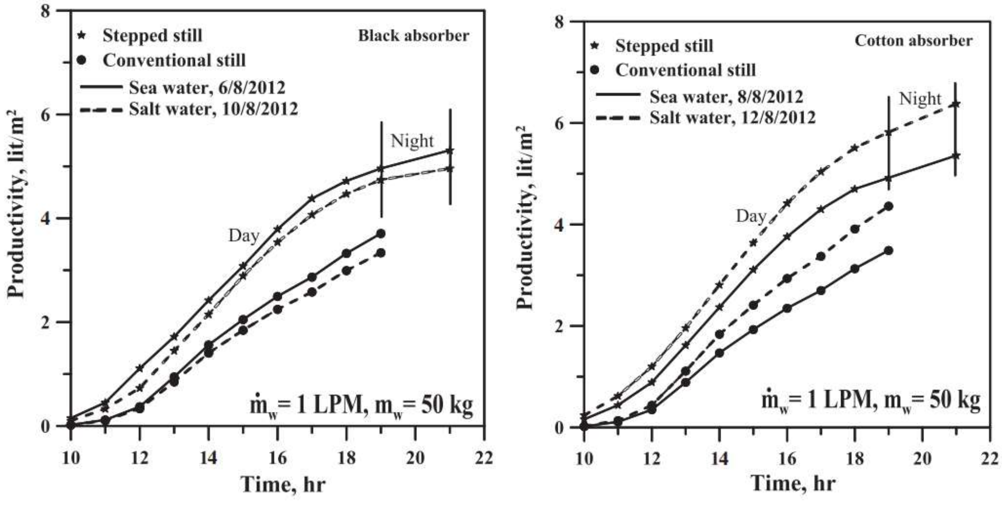


Figure 15: A step-wise solar still

“Schematic diagram of the experimental setup. (1) Solar still frame, (2) glass cover, (3) absorber plate, (4) digital thermometer, (5) water vessel, (6, 12) control valve, (7) water drain, (8) graduate level, (9) flow meter, (10) water pump and (11) control timer.” [24]

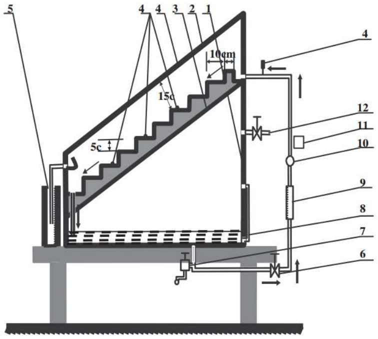


Figure 16: The productivity of the step-wise still for the model with black paint and the model with a black wick [24]

still in which each step was covered in a black cloth wick. The stepped still with black cloth wick consistently out-performed the other two models.

Changing the shape of a still in an effort to increase its output is by no means a new idea. Both Arunkumar et al [25] and Ismail [26] built hemispherical models of solar stills. The model built by Arunkumar et al was a stationary hemisphere with a shallow cylindrical basin with a 71 in^2 area and a height of 0.1 m (see figure 17). Alone, it had a 34% efficiency but when coupled with a film of water that was run over the exterior of the dome, the still's efficiency rose to 42%. The effect of the water on the exterior of the dome was to cool the condensation surface, increasing the rate of condensation inside of the still. The Ismail model was a transportable model seen in figure 18. This consisted of a hemispherical dome over a conical, thermal absorber. This model had an efficiency as high as 33% and yielded 2.8-5.7 L/m^2 of treated water. Kabeel [27] produced yet another geometry of solar still, this time with a pyramidal cover. Inside of the still was a concave wick (figure 19). The still was capable of producing up to 4 L/m^2/day and had a 45% thermal efficiency.

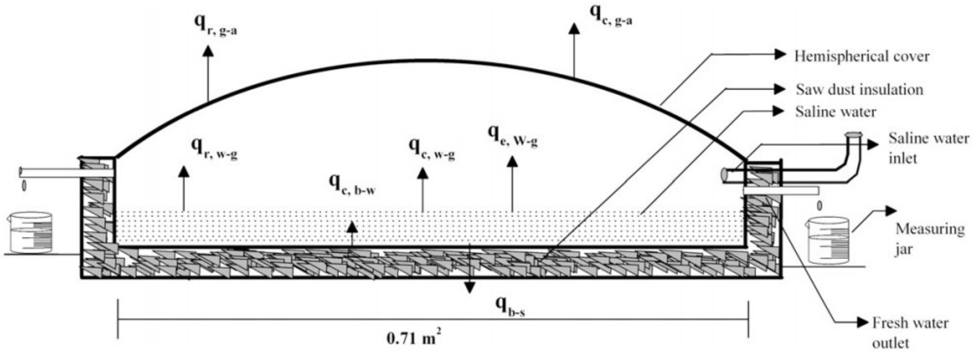


Figure 17: A stationary hemispherical solar still [25]

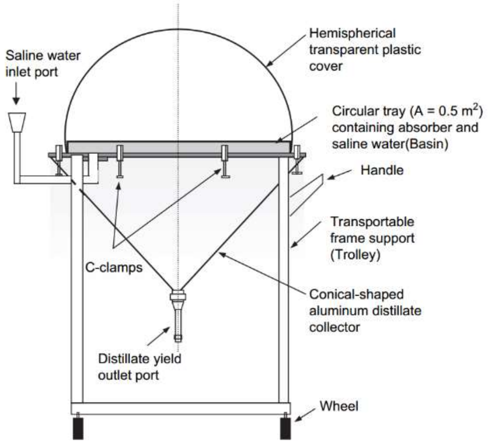


Figure 18: A transportable hemispherical solar still [26]

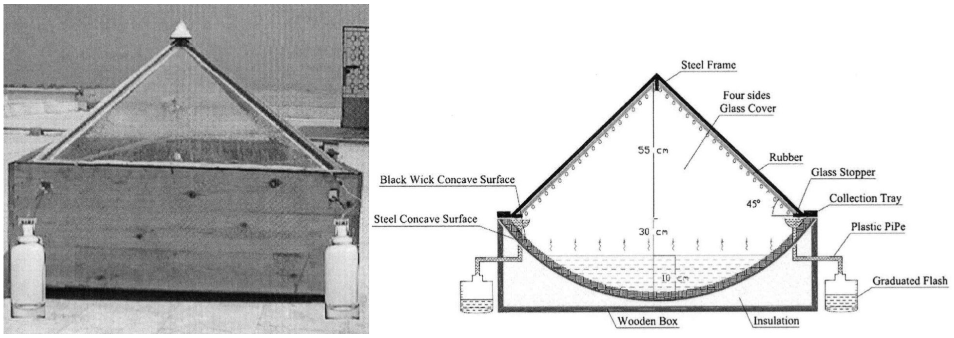


Figure 19: A photo and schematic of a pyramidal still with a convex wick [27]

4. Energy Storage

In each of the previously mentioned systems, a major issue arises as the sun sets. Solar power is obviously not possible when there is no sunshine. Some methods have been developed as a means of storing solar energy to increase a system's productivity of purified water during the night. One such method is the use of phase change materials. Chaichan and Kazem [28] used paraffin wax as a phase change material for their solar still. During the day the sun melts the paraffin wax, keeping it in a liquid state. At night, as the temperature lowers, the wax becomes a solid releasing latent heat which warms the water around it. The system devised by the authors combined a parametric solar concentrator, a conical distiller and solar tracking (see figure 20). The parametric solar concentrator was used to preheat the water before it was moved to the still. This is also where the paraffin wax was stored in a shell-tube heat exchanger surrounding the water. The addition of the phase change material added another 5 hours of productive time per day for the still.

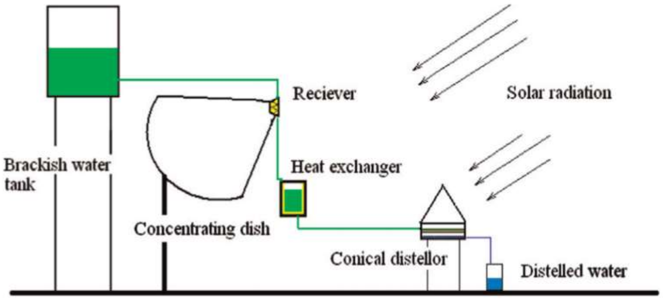
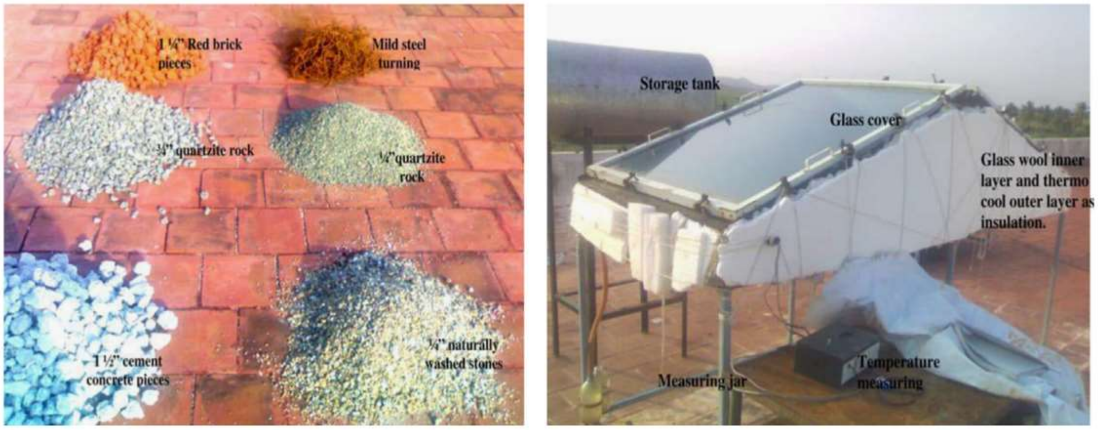


Figure 20: A distiller system employing both a paraffin wax phase change material and a parabolic concentrator [28]

Thermal storage can also be accomplished with sensible heat. Sensible heat is measureable heat and is not associated with a phase change (unlike latent heat). This can be stored in certain materials that hold heat well. Concrete is a good example. Murugavel et al. [29] tested several sensible heat storage materials in their double slope solar still seen in fig. 21. These included concrete, brick, quartzite, stones and iron. Each medium was used in broken pieces of a certain average size. The authors determined that the ¾ in pieces of quartzite worked the best for heat storage and had a daily production of distilled water of 3.66 L.

Figure 21: Double slope still with multiple types of sensible heat storage mediums [29]



Reversible chemical energy storage makes use of endothermic chemical reactions which occur at certain temperatures and are reversible to exothermic reactions. When the temperature drops (as it does when the sun sets), the chemical reaction is reversed, releasing stored energy in the form of heat. This is very similar to how the PCM's function but there is no phase change. Levy et al. [30] used chemical heat storage from the transformation of methane to CO2 and back again to heat a solar furnace during overcast days. This method could also be adapted to water pasteurization.

A cooling tower is a device that rejects heat from hot water into the surrounding air. Cooling towers are used on an industrial level, as in energy plants, and on a consumer level as a component in HVAC systems. A common example of a cooling tower is the "swamp cooler", an inexpensive form of air-conditioner. Cooling towers vary widely in design but all cooling towers include several basic components; an inlet for hot water and some method of distribution for that water, a fill layer, a basin for cooled water, an inlet for air and an outlet for air (see figure 22).

Hot water enters the cooling tower and is sprayed or otherwise evenly distributed over the fill layer. The fill layer is a means of increasing the surface area of water evaporation. The fill layer can take many forms including sponges and meshes of various materials. As the hot water passes over the fill, air is also moved over the fill from the air inlet. The air is either induced, meaning that one or more fans pull the air into the tower from above, or forced, meaning that the fans push the air into the tower from below. The combination of the moving air and increased evaporation surface area encourages some of the water to evaporate. The evaporated water, along with heat released from the phase change, mix with the moving air and exit the tower through the top. The remaining, unevaporated water precipitates through the system, losing heat on its way down. It eventually collects in the basin at the bottom, where it can be recycled through the cooling tower [31].

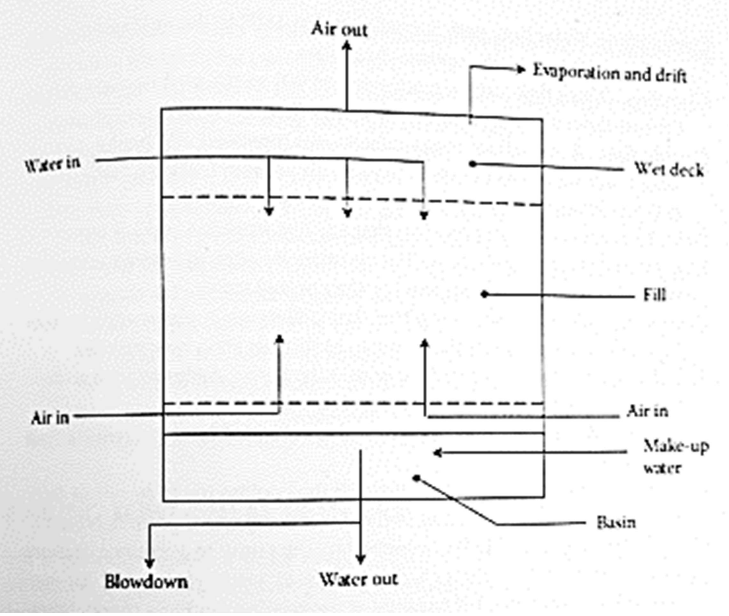


Figure 22: Cooling tower elements [31]

The evaporation that a cooling tower relies on, produces purified water just as a still does. Cooling towers tend to recycle this evaporated water through the cooling tower after heating it up again. With a few modifications, a cooling tower can be made into a distiller by collecting the purified, condensed water as distillate. The heat that is rejected through the top of the cooling tower could be reclaimed by some form of energy storage such as a heat exchanger with a phase change material placed over the opening. Ghosh et al. have proposed something similar on an industrial level. Industrial cooling towers release a large plume of evaporated water and hot air. The authors propose capturing the fog from this plume as purified water, although they make no mention of the potential for reclaiming energy from the hot air in the plume [32].

For the purposes of this design project, a cooling tower modified as a still is too complicated. The use of fans would add cost to the running of the system and require more energy. The cooling tower itself would be difficult to assemble properly and would require too much maintenance.

5. Proposed Design

For the proposed design, pictured in figure 23, a passive wick-based solar still, paired with a solar collector was chosen for its simplicity and effectiveness. The lack of moving parts (except for one pump) limits the complexity of its construction and the need for maintenance. Water is pumped from the untreated water vessel into the bottom of the solar collector. Then, heated by the sun, the water moves upwards due to decreased density. The heated water moves out of the solar collector into the wick still where a nozzle distributes the water evenly over the wick. Some of the water evaporates and is moved into the distillate vessel by means of a distillate trough. The rest of the water is heated passively by the sun on its way down the wick. The reheated water exits the still via gravity where it passes through a heat exchanger storing its heat in a PCM. The now cooled water returns to the untreated water vessel to recirculate through the system. The PCM is ideally situated to continue heating the water when solar power is not available. This system should continue to be productive for some time into the night and during cloudy weather. The wick-based still will be very similar in design to that developed by Aybar, Egelioglu, and Atikol [22].

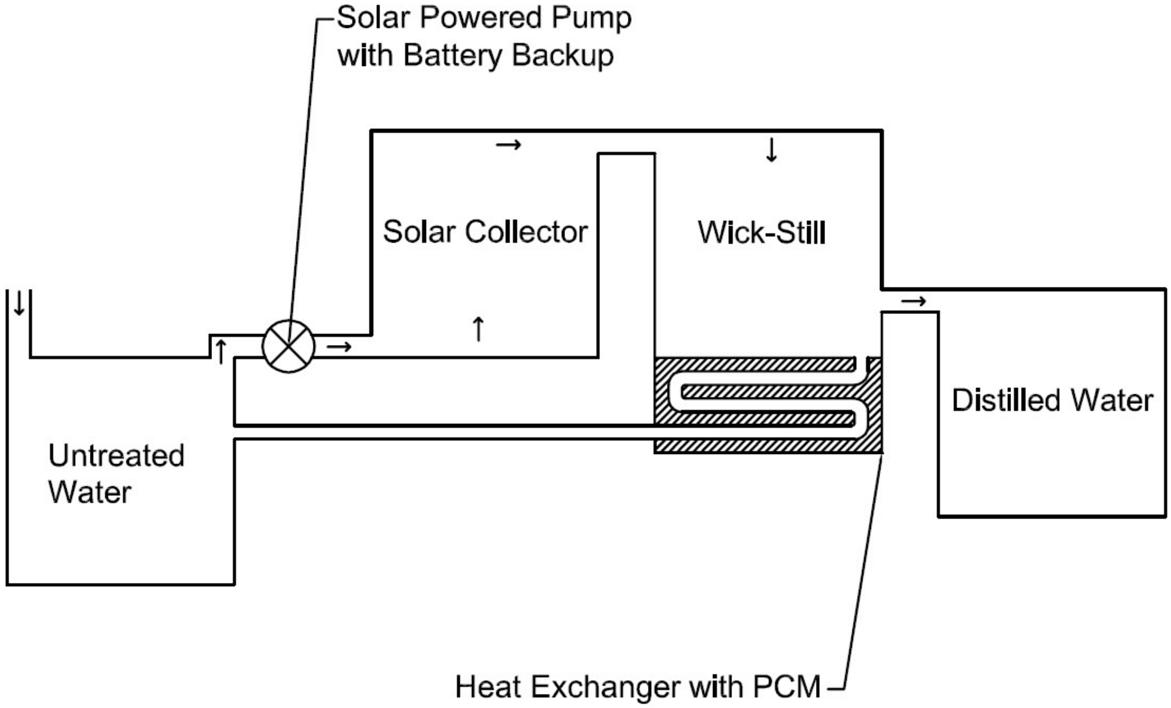


Figure 23: Flow diagram of proposed system

6. Conclusion

Solar power is a plentiful and environmentally friendly source of energy. With the increasing scarcity of drinkable water, it is only logical to pursue methods of water purification that employ solar power and other forms of renewable energy. While many forms of solar-powered water purification have been developed, one of the simplest and most reliable is distillation. The efficiency of distillation is greatly increased with the introduction of a wick, but solar-powered distillation can be further improved with the use of PCM energy storage.

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Figure List