NUMERICAL SIMULATION OF THE DIRECT APPLICATION OF COMPOUND PARABOLIC CONCENTRATORS TO A SINGLE EFFECT BASIN SOLAR STILL

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ABSTRACT

As regional shortages of fresh water become more prevalent, solar distillation using a single-effect basin holds promise as a method to bring low-cost, clean, and ecologically-responsible water to remote area dwellers. Compound parabolic concentrators (CPCs) can be used to direct more light onto the still increasing the throughput and efficiency of these passive solar devices. A computer program has been developed that uses the properties of materials and the solar energy characteristics of the site to calculate the increase in output of water due to reflectors of different height. For reflector 2.5 times the width of the still, the output per unit area per day roughly triples with only ~10% increase in cost and moderate maintenance (weekly tilts), indicating that CPCs have a significant economic advantage in producing solar distilled water.

Keywords: compound parabolic concentrator, numerical simulation, solar still

1. INTRODUCTION

Water desalination and distillation is becoming increasingly important in an expanding inventory of geographical locations because of regional shortages in the supply of drinking water of acceptable quality (1, 2). There are now a multitude of methods to produce fresh water from brackish water including: distillation by compression of vapor, multi-stage flash, ion exchange, electrodialysis, capillary film, and reverse osmosis (3) These methods are generally high consumers of energy and thus fossil fuels because of the current energy mix. A promising option for eliminating the detrimental effects of fossil fuel combustion (some of which contribute to the global water problems) (4,5,6) and major operating costs of distillation systems is the direct use of solar energy. High efficiencies have been obtained with large multiple effect distillation plants but are inappropriate for small-scale use. On a small scale the most commonly used device in solar desalination is the single-effect basin still or Mexican still. This device, however, has the disadvantage of having low operating efficiency and a low production rate of fresh water.

By incorporating compound parabolic concentrators (CPCs) for augmenting the light collection of the still, the efficiency and throughput of single effect basin still can be improved. This class of concentrators consist of rotated parabolic sections which have a concentration factor for planar receivers which is the thermodynamic limit: 1/sin $?_a$, where $?_a$ is one-half of the angle within which the reflectors direct all the light incident onto the aperture down to the receiver (see details in Denkenberger and Pearce this conference). One class of past solar distillation work involving CPCs used them to concentrate light to heat water within a pipe that was then circulated through the basin (7,8,9). This system has the disadvantages that it requires a pumping system and that it loses heat from the pipe. The advantage is that, because the receiver (pipe) is narrow, the CPC can be made relatively small. The other class of CPC-augmented stills concentrates light onto the bottom of the still (10,11). The application simulated here involves concentrating the light on the front glass cover of the still and overcomes the size disadvantage by severely truncating the CPC.

For an ideal untruncated CPC and isotropic illumination within the acceptance angle, the radiation leaving the bottom of the CPC is isotropic over 180°. Isotropic illumination is a reasonable approximation for the entire year. For a truncated CPC, there will be less radiation at intermediate angles of incidence, which would have been coming from the top of an untruncated CPC. But since there would be more radiation coming at small (directly from the sun) and large (reflected) incidence angles, the effect on the receiver will be approximately isotropic over 180°. Therefore, because the still is inclined from the bottom of the CPC, the intensity can be adjusted the same way a tilted plane is that is undergoing isotropic 180° illumination (diffuse light), i.e., $I = I_0(\cos(\theta_t))^2$, where $?_t$ is the tilt angle.

TABLE 1: PHYSICAL INPUT PARAMETERS[1] AND SENSITIVITIES

Para-Meter	Explanation	Assumed value [range]	Unit	% Output change No CPC winter desert	% Output change CPC winter desert	% Output change No CPC tropics	% Output change CPC tropics
θ_g	Glass angle from horizontal	15 [5,30]	°	6.2 -8.7	3.6 -6.4	3.0 -4.8	1.3 -2.7
R_{ins}	Thermal resistance of the insulation layer	2.5 [1,4]	°C/ (W/m^2)	-13.1 3.8	-14.1 4.0	-9.8 2.7	-9.6 2.6
V	Average wind velocity[3]	2 [0,10]	m/s	18.2 -12.1	0.0 0.0	9.4 -11.6	0.0 0.0
F_{sat}	Salt concentration as a fraction of saturated[4]	0.1 [0,1]		3.8 -29.3	2.5 -19.8	2.8 -22.5	2.2 -18.0
n_g	Glass index of refraction	1.5 [1.4-1.6]		3.5 -3.1	3.4 -2.8	3.0 -3.0	2.9 -2.7
T_{air}	Daily average air temperature near the ground	10 winter [0,20]; 30 tropics [20,40]	°C	-23.3 23.7	-10.2 9.3	-9.4 8.3	-3.4 3.2
I_{dif}	Diffuse intensity	100 [50, 150]	W/m^2	-16.5 17.5	-7.5 7.7	-8.6 8.8	-3.9 3.9
A_g	Glass solar absorptivity	0.06 [0.02,0.1]		4.5 -4.5	3.8 -3.9	4.4 -4.4	4.3 -4.3
A_{bas}	Basin solar absorptivity (black matte)	0.97 [0.94,1.0]		-1.4 1.4	-1.4 1.4	-1.2 1.2	-1.2 1.2
m_{HT}	Internal convective heat transfer multiplier	1.0 [0.8, 1.2]		-7.0 5.4	-3.8 2.8	-3.4 2.5	-1.3 0.9
R_{ref}	Reflector solar reflectivity[5]	0.85 [0.8,0.93]		0.0 0.0	-3.4 5.4	0.0 0.0	-3.5 5.6

[1] The properties of humid air were taken from (12). These properties were also assumed for external air because at the film temperature (average T_{air} and top of glass), the amount of water vapor in humid air is relatively small.
[2] The output change is calculated at a reflector height 2.5X the width of the stills.
[3] For reflectors greater than 0.5 m high, the wind velocity is assumed to be zero. In actuality, there would be some wind, but the natural convection is also impeded by the reflector, so these effects are assumed to counteract each other.
[4] Saturated is: 27g NaCl / 100 g water
[5] Evaporated aluminum [stainless steel-evaporated silver]

2. NUMERICAL SIMULATION OF SOLAR STILLS

A computer program in Matlab has been developed that allows a designer to input the properties of materials and the solar energy characteristics of the site, and calculate the increase in output due to reflectors of different height. The physical input parameters are listed in the first four columns of Table 1. Fig. 1 shows the mass and heat transfer processes for a standard single-effect basin still with a CPC, which is simulated in this study.

We used a relative convergence criterion of 0.1% so that all the figures in the sensitivity table above are significant. We reduced the integration time step by a factor 10 each iteration, which indicates that the final result is very close to the actual value.

The following assumptions for the input parameters were made. The heat of vaporization of the water varies according to Belessiotis, Voropoulos, and Delyannis (13). It is assumed to be independent of salt concentration. The vapor pressure of the water varies (12). It is multiplied by one minus the mole fraction of salt in a salt solution. The reflectivity of the glass-water system was calculated for parallel and perpendicular polarization, and the arithmetic mean of the two was taken, as solar radiation is randomly polarized. The assumed reflectivity was calculated as the sum of primary and secondary reflections as seen in Fig. 1b. Tertiary reflections were ignored. The slope of the glass was assumed to be zero for reflectivity calculations. In actuality, for two-glass pane stills, the reflectivity off the far side of the glass will increase more than the reflectivity off the near side of the glass will decrease, but the fraction of the incoming radiation hitting the near side will be greater, so it is assumed that these two effects cancel each other. The light hitting the glass directly and the light that hits the reflector first (indirect) are treated separately. The incidence angle of the latter is estimated by assuming: 1) a single facet for the reflector, 2) the glass is oriented as the virtual receiver of the CPC is, which underestimates the reflectivity for light hitting the equator-ward reflector and vice versa, and 3) the light is coming from the axis of the CPC on average.

The thermal resistance of the water condensed on the glass has been disregarded. The controlling variables are listed in Table 2. For this paper we explore the effects of only the reflector height in detail.

TABLE 2: OTHER VARIABLES AND PARAMETERS

Variable/ Parameter	**Explanation [Value]**
T_{sky}	Effective radiation temperature of the sky (emissivity = 1): $0.0552*(T_{air})^{1.5}$ [K]
E_{basin}	Basin emissivity (lampblack) [0.95]
E_{gl}	Glass emissivity [0.925]
L_{gl}	Thickness of the glass
E_{vap}	Emissivity and absorptivity of the air-vapor mixture (inside the still) [0.17]
$m_{rad,conv,liq}$	Transparency of the liquor to operating-temperature radiation [0.15]
w_{rec}	Width of the basin (receiver)
h_{refl}	Height of the reflector
$T_{top,g}$	Temperature of the top of the glass
T_{liq}	Temperature of the liquor

When no insulation is used beneath the basin, there are wide temperature fluctuations in the soil temperature beneath the still (14). However, with the use of insulation and deep liquor, the soil temperature fluctuations should be much smaller. Therefore, a constant soil temperature, equal to the average temperature of the day, is assumed in this study. The thermal resistance in the soil should be considered, but this is an involved calculation, so we use an equivalent thermal resistance which sums the effect of insulation and soil thermal resistance.

The program integrates the solar energy over the day and finds the average. This steady state analysis is correct in the limit of large liquor depth. In reality, more of the heat is transferred at a higher temperature. A greater temperature dramatically increases the latent heat transferred because the vapor pressure of water increases exponentially with temperature, while the heat transferred by sensible and radiant transfer increases only slowly. Therefore, the efficiency (water produced per total heat transferred) is greater at higher temperature. This is counteracted by the fact that there are greater conduction losses, but these losses are small for a well-insulated still, which is our base case. Therefore, the average efficiency will be greater than the steady state analysis predicts. However, we are primarily interested in the increase in output due to the CPC, so the fact that the no-CPC case would actually produce more water, and the CPC case would also produce more water, does not change the increase in output due to the CPC. And there are cases when deep liquor would be advantageous, such as in a cold climate with little sun and no CPC, to prevent freezing. Also, in a warm climate with much sun and with a CPC, one would want to have deep liquor to prevent boiling. Furthermore, deeper liquor reduces the labor of refilling.

The program assumes an initial temperature for the components of the system: glass, liquor, and basin. It calculates the heat transfer rates between the different components and iterates until the fluxes are equal to what is required by the calculated averages. When $T_{liq} - T_{bot,gl}$ or $T_{air} - T_{top,g}$ became negative, the temperature difference was set to zero because the convective heat transfer would have been imaginary. This situation does not occur in most scenarios so the error in this assumption is small. The heat internal transfer equations are valid from T_{liq} = 60 to 80°C (12) and summarized by:

$$h_{in} = \frac{0.4178 m_{HT} k_{in} (Ra_{in}(1+\cos(\theta_g))/2)^{0.2106}}{l_c}$$

Where k_{in} is the thermal conductivity of humid air, Ra_{in} is the Rayleigh number based on l_c, which is the characteristic length: the average distance between the liquor and glass. In the baseline scenario, winter desert T_{liq} = 30 and 56°C without CPC and with, respectively. Tropics T_{liq} = 63°C and 100°C without CPC and with, respectively.

Examining table 1, changing this heat transfer at all temperatures by 20% up and down has a small effect on output. This is important because the operating temperature is often outside the accurate range. This provides a good estimate of the output if a series of adjacent days have similar characteristics. A more advanced simulation would allow the inputting of the differing characteristics of sequential days.

The CPC will need to be tilted to follow the progression of the sun in the sky with the seasons as seen in Fig 2. In the summer the sun is directly overhead (Fig 2a) and during the winter it is lower in the sky (Fig. 2b). In the figure the dotted line represents the virtual receiver and the black “house” is the actual receiver. The angle between the CPC axis in winter and summer is 57°. This is due to the sun’s zenith moving 47°, and aiming the CPC 5° below zenith in winter and 5° above the zenith in summer. The cost of labor will determine the number of tilt changes that are economical to undertake, but we have assumed weekly tilts which keeps the CPC aligned within a few degrees. This allows us to use

?$_a$ = 5° (see Denkenberger and Pearce this conference).

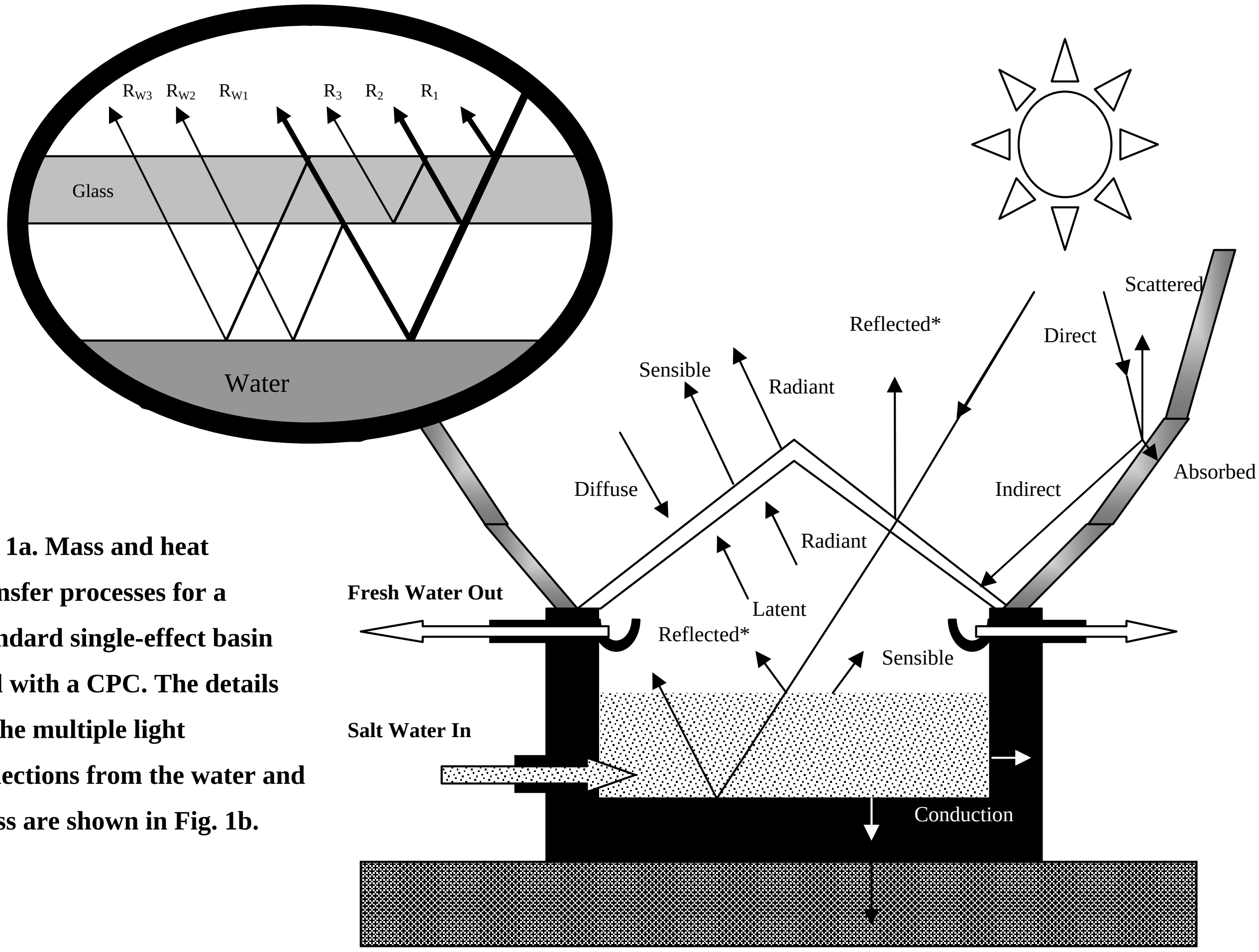

Fig 1a. Mass and heat transfer processes for a standard single-effect basin still with a CPC. The details of the multiple light reflections from the water and glass are shown in Fig. 1b.

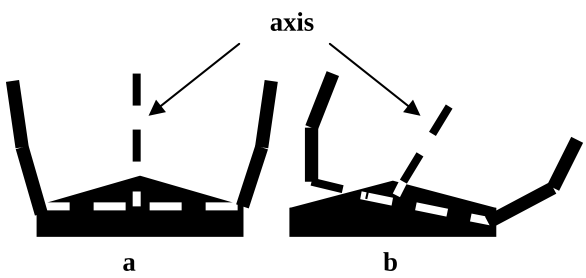

Fig. 2 a) Summer and b) Winter positions for CPC

In this preliminary study we also neglect the increase in solution concentration at the surface of the liquor due to water loss there and we assumed a point sun. We also assume that no fresh water falls back into the liquor, and that there is no gas exchange with the outside.

3. RESULTS AND DISCUSSION

Sensitivity studies were run for the percent change in output as a function of the input parameters in both winter desert (30° latitude, low solar flux and low T_{air}) and tropics (0° latitude, high solar flux and high T_{air}) conditions for stills with and without CPCs. As can be seen in Figures 3 and 4, summer desert behaves similarly to tropics, so a separate sensitivity was not performed on summer desert. This is shown in Tables 1 (columns 5-8), where the change in daily output that corresponds to varying the parameters within the range in brackets, when all other parameters have their typical value.

The sensitivity study found the following. A lower glass angle yields less area to release heat to the atmosphere, which translates into a higher operating temperature, so higher efficiency. The CPC is less sensitive to this effect. Lower thermal resistance to the ground results in greater output, with the CPC responding similarly. Slower wind results in higher operating temperature, so greater efficiency for no CPC. For CPC cases, we assumed that the reflector blocks the wind, so the wind is already zero, so no change results. Greater salt concentration decreases output significantly, but the CPC is less sensitive to this. A lower index of refraction of glass increases output by reducing reflection losses for all cases. Lower ambient temperature translates to lower operating temperature, thus reducing efficiency, but this effect is less pronounced for a CPC. Also, this is less pronounced if the temperature is initially warmer (e.g. tropics). An increase in diffuse intensity increases output, but less so for the CPC because CPCs cannot concentrate diffuse light. A change in glass solar absorptivity of 4% yields a change in output of about 4% for all configurations. Basin solar absorptivity behaves similarly (reflectivity is 1/3 the apparent value because water decreases the incidence angles, so it is a 1% change reflectivity), but the effect is magnified by the fact that greater basin absorption means a greater increase in operating temperature. Increasing reflector reflectivity does not increase output proportionately because, despite the increase in efficiency, increased reflectivity does not increase the direct light falling on the still. Obviously, if there is no CPC, reflector reflectivity has no effect. Convective heat transfer coefficients often have uncertainties of +/- 20%; however, the effect on output is much less because when the coefficient decreases, the operating temperature increases, tending to offset the efficiency loss. Other parameters had only a minor effect on output, such as the glass thermal resistance.

In Figures 3 and 4 below the effect of the CPC reflector height on the energy input and clean water output are explored. The three climate scenarios are i) winter desert, ii) tropics, and iii) summer desert.

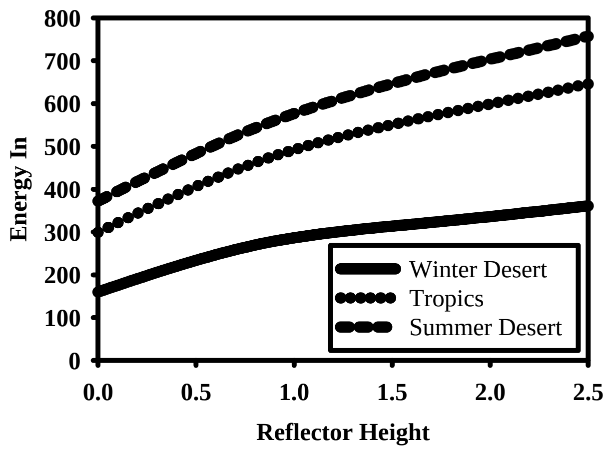

Figure 3. Energy directed into the solar still as a function of reflector height

As can be seen in Fig. 3, a reflector that is 2.5X as high as the still is wide directs 126% more light onto the still for winter desert, 116% more for tropics and 103% more for summer desert conditions.

The CPC increases operating temperature, which increases the internal efficiency, defined as the latent heat transferred from the liquor to the glass as a fraction of the total heat transferred from the liquor to the glass. A reflector that is 2.5X as high as the still is wide has an internal efficiency that is 53% greater for winter desert, 17% greater for tropics and 28% greater for summer desert.
However, there are increased reflection losses because the light from CPC is more oblique, so the overall efficiency does not increase as much as the internal efficiency. A reflector that is 2.5X as high as the still is wide has an overall efficiency that is 47% greater for winter desert, 15% greater for tropics and 28% for summer desert.

Combining the increased light hitting the still and the increased overall efficiency yields the increase in output (Fig. 4). This output is for sunny days. As can be seen in Fig. 4, the reflector that is 2.5X as high as the still is wide increases output by 242% for winter desert, by 159% for tropics and by 174% for summer desert conditions.

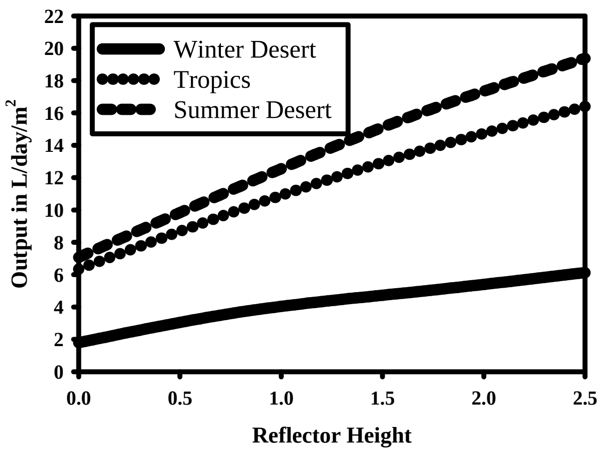

Figure 4. Output in L/day/m^2 as a function of reflector height.

Figure 4 represents ideal conditions with no clouds. The output of reflector and no reflector would be very similar if it is cloudy. In order to take cloud cover into account the average output (O_{ave}) must be calculated with the help of Figure 5 below.

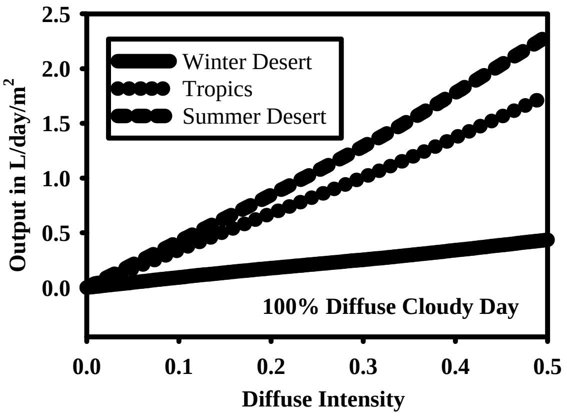

Figure 5. Output in L/day/m^2 as a function of the diffuse intensity, where the diffuse intensity is the fraction of the beam (direct from sun) intensity. This figure is for a completely cloudy day (i.e. it is 100% diffuse).

The average output can be determined from the following formula:

$$O_{ave} = O_{Cloud} \times F_{Cloud} + O_{Sun}(1 - F_{Cloud}),$$

where F_{Cloud} is the fraction of cloudy days determined for a specific site and O_{Cloud} and O_{Sun} are the output under cloudy and sunny conditions, respectively. By taking the results of O_{Sun} (Fig. 4) and combining them with the results of O_{Cloud} (Fig. 5) solar still designers can get a realistic prediction of a still's performance for a given location with a given reflector height.

There are several scenarios for rating the system output. In one scenario, fresh water would be trucked or shipped to the site when the output of the stills dropped below the need for fresh water. In this case, the rated output should be during the equinoxes because at these times and the plentiful season, the system is self-sufficient. For a system with little access to outside water, the rated output would be during the time of year when the still output was less than the need for fresh water. In areas with hot summers and people who do strenuous outdoor work during the summer, the need for fresh water can be three to four times the demand during the winter. The stills with or without produce about that much more water in the summer than the winter. However, if the need for water is relatively consistent throughout the year, then the limiting season is the winter.

Fiberglass Mexican stills cost approximately \$100/m^2 installed (15), and inexpensive reflectors cost ~\$4/m^2 (16). For reflectors that are 2.5X as tall as the width of the still and for a long row of stills which makes the reflector overhang a small fraction of the total, this yields a 10% increase in cost due to the reflectors.

4. CONCLUSIONS

The results of numerical simulation for a single effect basin still indicate that CPCs increase the energy into the still and thus raise the operating temperature, which raises the internal efficiency. The CPC also creates an increase in reflection losses so the overall efficiency is not as pronounced. However, the output of clean water per unit area per day approximately triples. Also, the cost only increases about 10%, so the cost of water decreases significantly. The application of CPCs to simple solar stills for the millions without access to clean drinking water could be a powerful lever for sustainable development, world health and poverty relief.

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