Redirecting Sunlight with Polar Tracking in Developing Countries… and Elsewhere

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Abstract

A correctly oriented mirror rotating anti-parallel with the earth's rotation will reflect incident sunlight parallel to the rotation axis in either direction onto a stationary target. The mirror's orientation on the rotation axis (declination) must be adjusted for the seasonal variation in the sun's altitude but throughout the day the mirror tracks on a single axis. While this system may not improve tracking for industrial solar electricity production, it could be a game-changer in developing countries where concentrator construction and seasonal declination adjustment could be done by hand. The easily constructed, functionally single axis polar tracking may greatly increase accessibility to effective solar cooking and other small-scale industries requiring intense heat; assisting developing economies in leap-frogging the increasingly unavailable or undesirable carbon-intensive step that industrial societies took.

Introduction

Harnessing solar energy would be much easier if the sun didn't move. For low-precision concentration, the complexity of construction could be reduced by an order of magnitude if sunlight came from a fixed direction. However, in order to achieve sustained solar concentrations greater than 2 "suns" throughout the day, the reflector surface must track the sun's apparent motion. Complexity increases not only because of the tracking mechanism itself, but also due to the structural rigidity, lightness, and precision necessary for a structure to track on two axis. We present a single-axis, polar-tracking, flat mirror heliostat that simply and inexpensively redirects sunlight to a stationary location where it can be subsequently concentrated, redirected, or otherwise utilized. Daily tracking can be done by a simple comparator circuit, a clockwork mechanism, or by hand. The trade-offs of having only one tracking axis are that the mirror's declination must be adjusted weekly (or daily near equinox when the sun's altitude changes at the greatest rate), and that the orientation of the stationary target and the mirror must be along the earth's rotation axis.

Our innovation fits between conventional tracking heliostats and the Scheffler Concentrators. A flat mirror on a dual axis tracker can redirect sunlight to a stationary concentrator, such as the high-flux solar furnaces[1] at the National Renewable Energy Laboratory and the Institute of Solar Research in Cologne, Figure 1a. The dual-axis tracking requires sophisticated computer controlled

[1] High Flux Solar Furnace at National Renewable Energy Laboratory (NREL) in Golden Colorado, DLR Institute for Solar Research in Cologne, Germany

coordination, which is not a drawback for this already expensive and precise system. However, dual axis tracking would greatly increase the cost of a low precision, hand-made solar concentrator. Polar or planetary mount tracking is common in astronomy, where counter rotating a telescope parallel to the earth's rotation allows the telescope to remain fixed on the same celestial direction. Polar tracking for solar energy has so far been used only in Scheffler Concentrators,[2] where a parabolic mirror rotates on a polar axis, concentrating sunlight to between 50 and 500 suns onto a stationary target, Figure 1b. There are about 10,000 such devices in use, mostly for cooking in Asia and Africa. Seasonal adjustment of the polar tracking Scheffler Concentrator requires that the flexible parabolic mirror change in both declination and curvature. The construction of a movable, deformable mirror requires moderate training, time and resources.

The Scheffler reflector *concentrates and directs* sunlight with one curved reflector while in our design a polar tracker *directs* the sunlight with a flat mirror to a stationary location for subsequent *concentration* or redirection by a secondary device, Figure 1c. Doing so decouples tracking from concentration, making possible a wide variety of stationary concentrating geometries, some of which may be less complicated or more appropriate for a given project than other solar concentration or redirection techniques. The advantage of our polar tracking dual mirror concentrator (1c) is a potential decrease in cost because both single axis tracking of a flat mirror, and stationary concentration technologies are inexpensive. The comparative advantage of the Scheffler design (1b) is that they either have no secondary mirror, reducing reflective losses, or have a smaller secondary that is easier to accommodate geometrically. The comparative advantage of the dual axis high flux solar furnace (1a) is freedom to place the two mirrors not on the earth's rotational axis. Thus, our polar tracking dual mirror solar concentrator geometry (1c) is unique with its own advantages and disadvantages, and could be particularly compelling where cost is very important and a person could conveniently do seasonal declination adjustments.

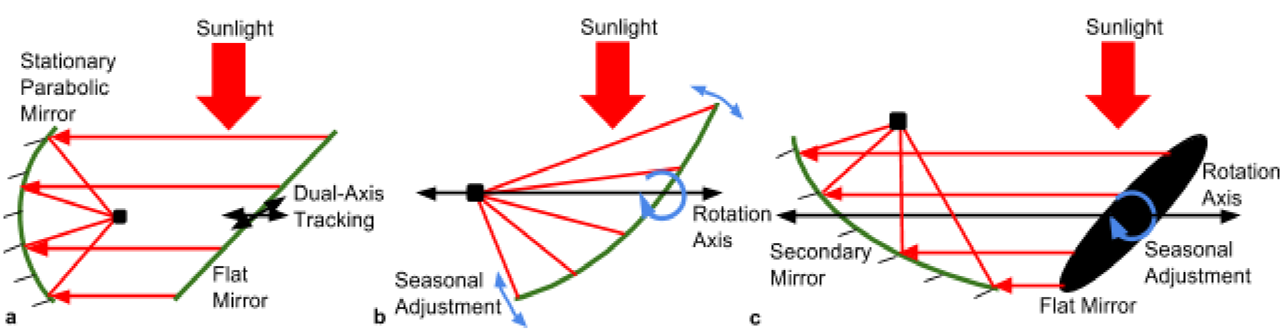

Figure 1 Illustration of three solar concentrators and tracking methods: **a)** NREL high flux solar furnace with 2-axis flat heliostat and stationary parabolic concentrator, **b)** Scheffler solar concentrator with single axis deformable parabolic mirror (tracking seasonally by rotating declination and flexing, blue arrows) **c)** polar axis dual mirror concentrator with a single axis flat primary mirror and a parabolic secondary mirror (tracking seasonally by rotating declination of primary mirror, blue arrow)

The Polar Tracking Redirects Sunlight to Stationary Target

Figure 2 illustrates the apparent path of the sun for equinox, and winter and summer solstice. In order to properly track the sun, a heliostat must rotate daily to compensate for the apparent daily

[2] a) Scheffler, W., 2006. Introduction to the revolutionary design of Scheffler. In: SCIs International Solar Cooker Conference, Granada, Spain, 2006. b) A. Munir, O. Hensel, W. Scheffler, Solar Energy 84 (2010) 1490–1502

path of the sun about the earth, and must also traverse north and south annually to account for the apparent change in altitude of the sun's daily path.

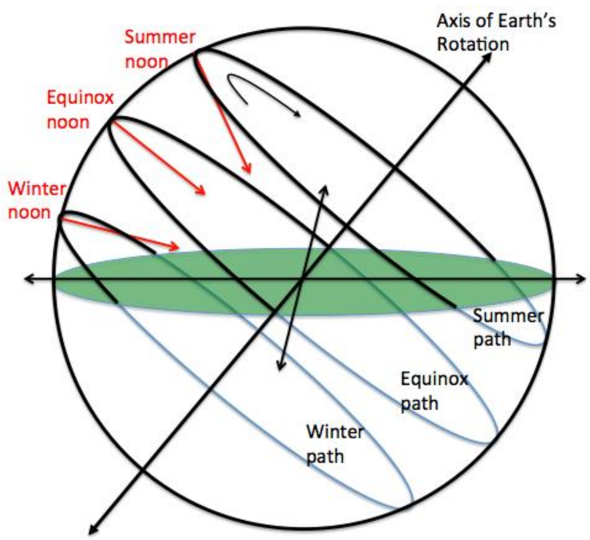

Figure 2 The sun's apparent path for a place at about 50° North Latitude. Red rays indicate direction of sunlight at noon at the season indicated.

A flat mirror rotating counter parallel to the earth's rotation will maintain the same orientation with respect to the sun and is said to be "polar tracking".[3] If the mirror is mounted such that it reflects sunlight parallel to this rotation axis (see Figure 3a), the reflected light will remain in the same place throughout the day. The mirror could reflect the sunlight upwards (Figure 3a), or downwards (Figure 3b) along the rotation axis.

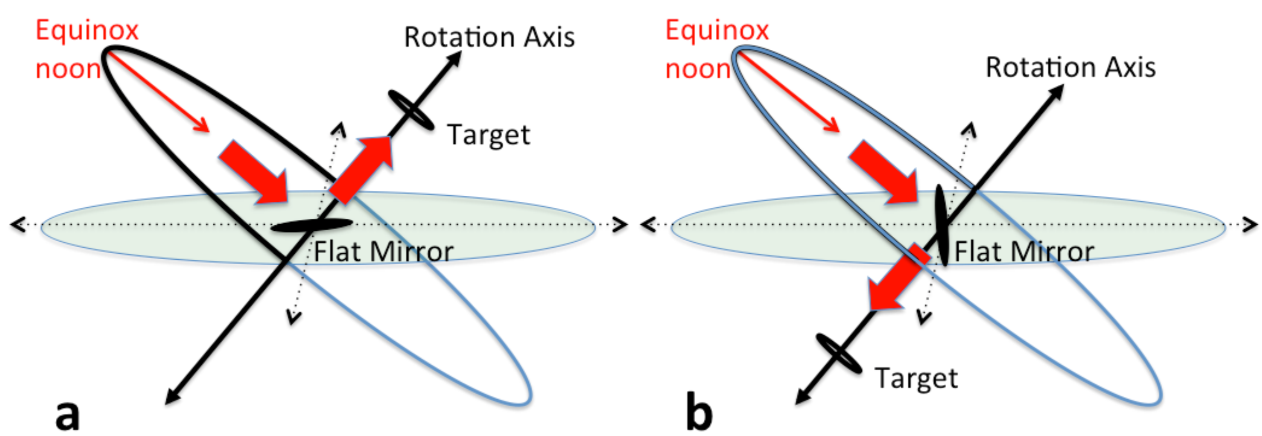

Figure 3 Mirror in the northern hemisphere at the latitude of Fig. 1 reflects sunlight along the earth's rotation axis **a)** upward to a target located to the north, and **b)** downward to a target located to the south.

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[3] Because the earth also orbits the sun once per year, the sun's apparent orbit is about 0.3% slower than the earth's rotation.

During Equinox, the direction of incident sunlight is perpendicular to the rotation axis as in Figure 3, and so the mirror's perpendicular would be oriented at a 45° with respect to both the rotation axis and the direction of incident sunlight. Because the direction of incoming sunlight changes by about 23.5° northward June 21 and southward in December 21, the mirror's perpendicular must be rotated by about 12° northward in June (Figure 4a), and southward in December (Figure 4b).

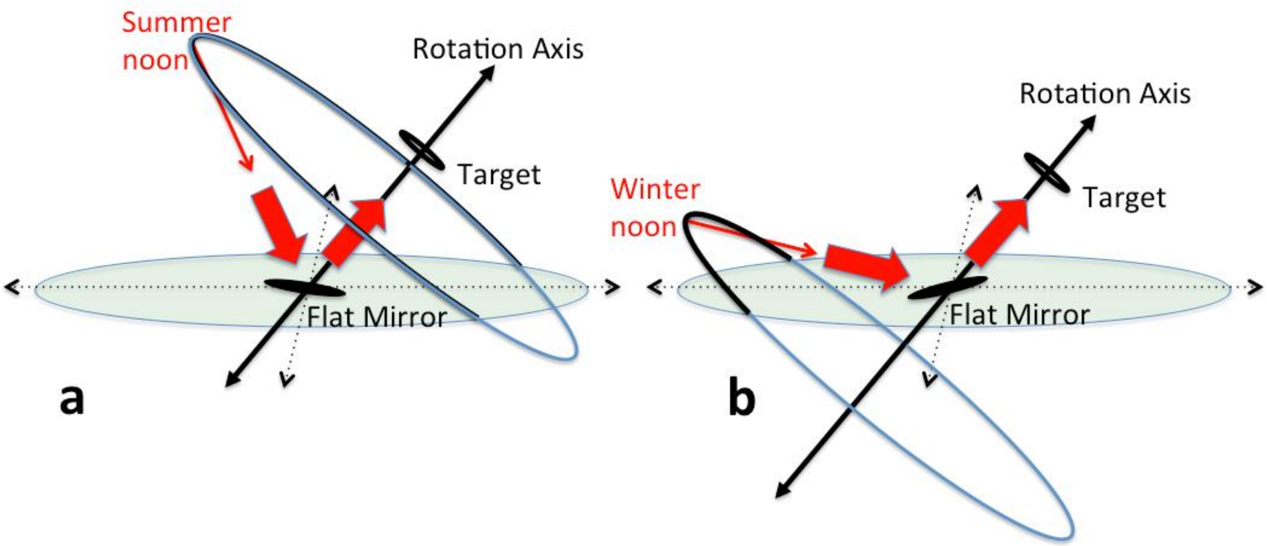

Figure 4 The upward-facing mirror in the northern hemisphere at **a)** summer solstice, and **b)** winter solstice. Note the slight change in angle of the black circular mirror between these two figures and Figure 3a), which corresponds to equinox.

While the angle between the mirror and rotation axis (declination) must be changed throughout the year to account for the seasons, the mirror still rotates daily about the same axis, simplifying daily tracking to that of a single axis.

Solar Concentration Application

A possible solar concentration application at the equator at equinox is shown in Figure 5, whereby the reflected rays from a polar tracking, flat mirror are incident upon a stationary, parabolic mirror with a central axis that is parallel to the mirror's rotation axis. Figure 6 depicts an indoor cooking facility in the tropics at equinox, where the sun is near straight overhead and the polar axis is near horizontal. An *upward* facing mirror in temperate latitudes may be more appropriate for concentrating with a Fresnel lens as in Figure 7 because rays should focus upward for cooking.

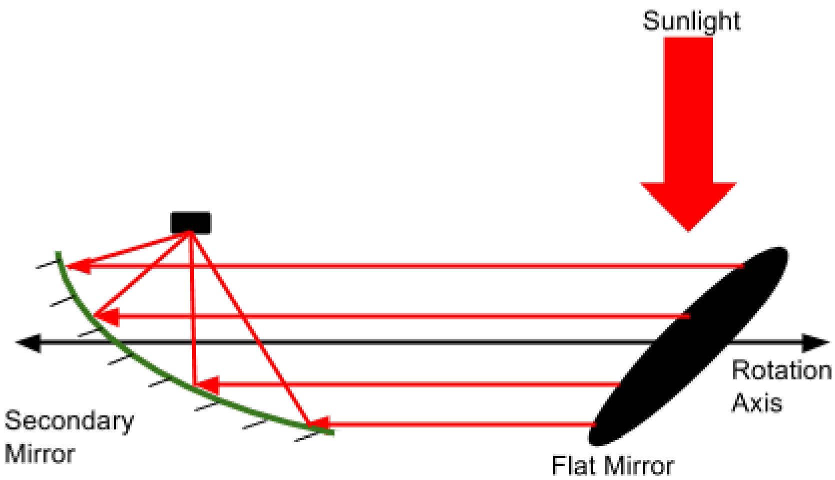

Figure 5 Parabolic mirror concentrator. The light reflected to the left from the rotating flat mirror is incident upon a stationary parabolic mirror (green) with a central axis that is parallel to, but displaced upwards from the rotation axis of the flat mirror in order to place the focus away from the rotation axis. This concentrator is configured for noon during equinox at the equator.

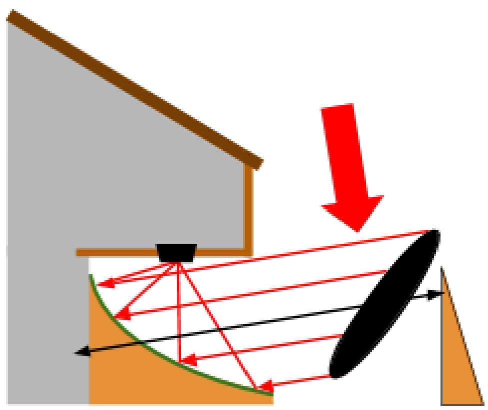

Figure 6 Tropical indoor solar concentrated cookstove at about 10° Latitude. This geometry allows the focused light to be upward and the cooking facility to be indoors and sheltered.

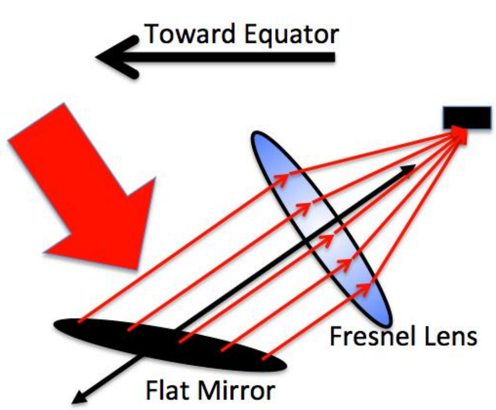

Figure 7 Fresnel lens concentrator. The light reflected upward from the rotating flat mirror is incident upon a stationary Fresnel lens (blue) oriented perpendicular to and centered on the rotation axis. The axis is tilted at 35° (Cal Poly's Latitude) with respect to the horizon, and the black arrow indicates the direction of the equator.

Another application for redirecting sunlight for buildings could have the target itself be a flat mirror that simply reflects the sunlight to the desired location, such as in a north-facing window as shown in Figure 8. Similarly, if the pot in Figure 6 were removed, the focused light would enter the living space and defocus, providing heat and light to the room.

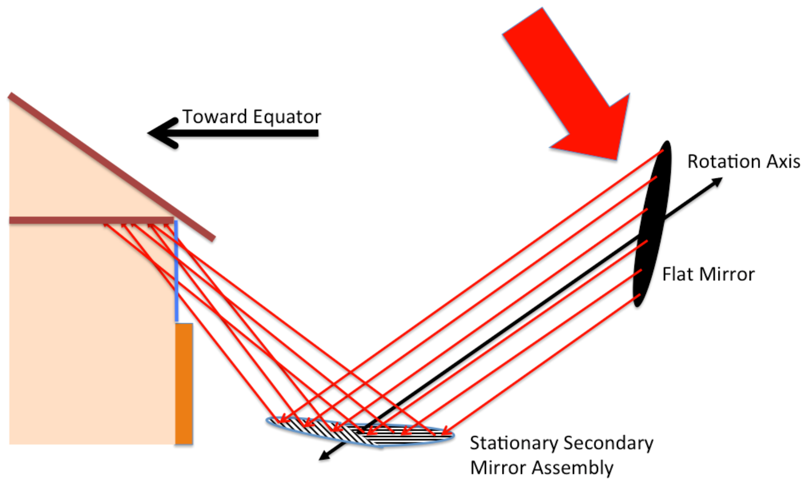

Figure 8 An inexpensive heliostat. The redirected sunlight is incident on flat mirrors, reflecting heat and light through a window that would otherwise not receive sunlight.

Ray-Tracing Results

In order to establish the necessary tolerances for a concentrator such as in Figure 6, a Matlab-based ray-tracing program simulates sunlight for time of day and time of year as well as for various types of imperfections. The results help define the tolerances on the surface of the secondary reflector and the alignment of the two reflectors necessary for adequate performance.

The primary reflector was assumed to not have significant deformation since it is a flat surface, which leaves the secondary mirror surface and alignment as the only source of imperfections. Because the flat primary mirror is inexpensive, we make the primary mirror big enough for the secondary mirror to always be fully illuminated. The code simulates a circular sun of uniform intensity subtending an angle of 0.533º.

For the purpose of the simulation, the secondary mirror accepts light of a circular cross section of 1 meter radius, giving the reflector an effective area of 3.14 m^2 and a power of 3.14 kW assuming solar flux of 1 kW/m^2. We neglect reflective losses although they may be significant. The two mirrors are placed approximately two meters apart and a target area (cooking surface) is a 10 cm radius circle. With a perfectly shaped reflector the sun subtending angle results in a 2 cm diameter focus corresponding to a concentration greater than 5,000 suns. Figure 9 shows a visual representation of the tray tracing of this reflector with an imperfect surface during midday of equinox at the equator.

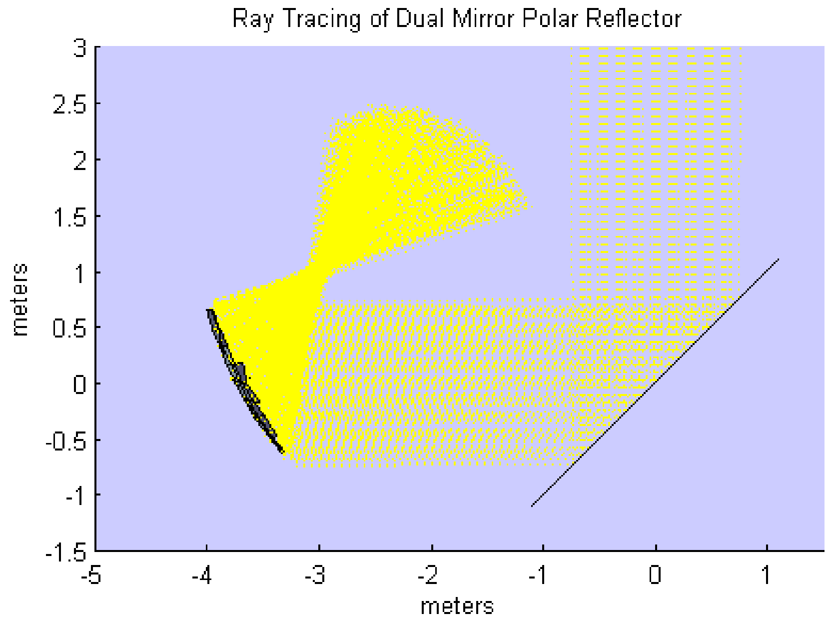

Figure 9 Visual representation of an imperfectly manufactured polar tracking dual axis reflector focusing light from a real sun. The secondary mirror is configured with the highest tolerances (poorest quality) that allow for an efficiency, ignoring reflective losses, above 90% of ±2º and ±4 cm surface roughness.

We introduce three types of imperfections into the system and evaluate the quality of the focus based on the percentage of light that hits a 10 cm radius target (efficiency) and the average sunlight intensity in a 1 cm radius target inside of the 10 cm target.

The first imperfection is a misalignment between the axis of the secondary mirror and the axis of the light reflected off the primary mirror. This imperfection is important because it can represent both an error in assembling the reflector or the error that arises in improperly adjusting the primary reflector seasonally. The blue data set in Figure 10 shows the degradation of the focus as the axes become misaligned by up to 5 degrees. The percentage of light focused degrades very quickly after 2º because the focal point moves outside the target area. By noticing that the light is pointed outside of the target area the misalignment can be diagnosed and corrected by bending the rotation axis slightly, so this imperfection is not a major area of concern.

We also simulated surface roughness with localized angular and displacement deformations on the secondary reflector surface. For example, an outward bump in the reflective surface of the dish has a displacement from the surface and parts which are at angles different than the ideal dish surface. Computationally this was simulated by adding a random, uniformly distributed angle between ±x degrees and/or displacements between ±x centimeters to the perfect shape of the secondary reflector for each ray upon reflection. This represents inaccuracies on the surface due to shaping the of the secondary reflector. Deformation in angles have a significant impact on the focus, though the reflector will still focus about 80% of the light with concentrations of over 1000 suns with angular deformations between ±3º. Conversely, deformation in surface displacement has negligible effect on the focus even at ±5 cm.

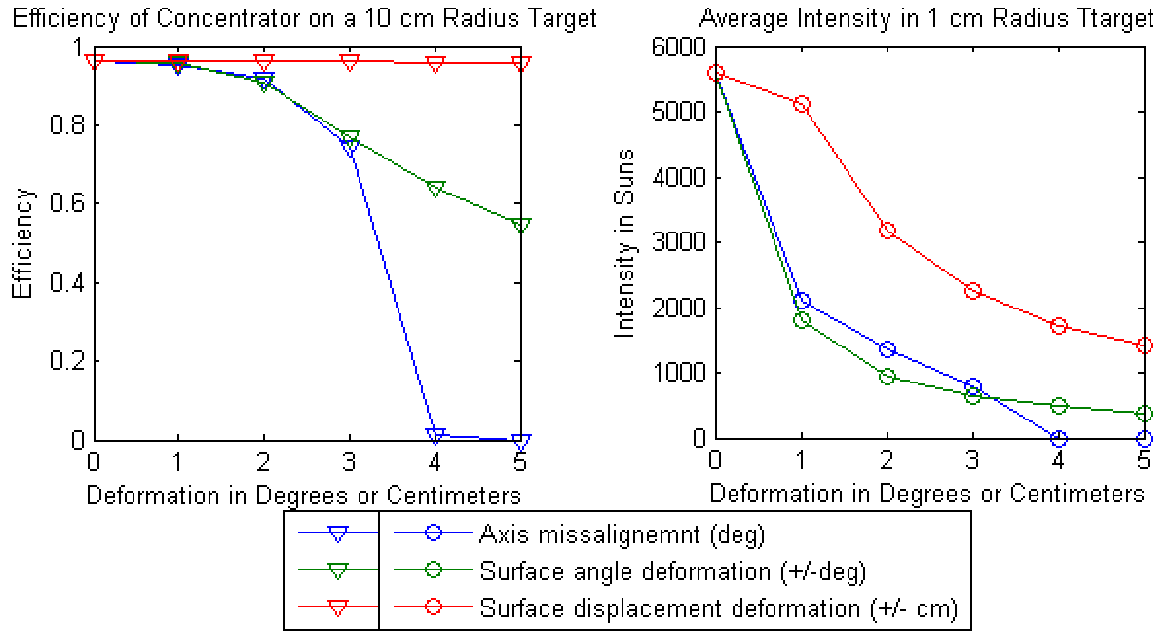

Figure 10 Degradation of focus for given manufacturing tolerances in percent of light falling on a 10 cm radius target (left) and average intensity of radiation on a 1 cm radius target (right).

It may be instrumental to observe the effect of the superposition of the imperfections. The blue data in Figure 11 show a reflector with both angle and displacement deformations, as would be expected from a hand shaped secondary reflector, with perfectly aligned axes. We see that 90% of the light is focused with tolerances of ±2º and ±2 cm, while over 75% is focused with tolerances of ±3º *and* ±3 cm, both with solar intensities of over 500 suns. The green data in Figure 11 show a combination of all types of imperfection showing a quick degradation in the focus mostly due to the axis misalignment. The axis misalignment must have a tolerance of ±1º to focus more than 90% of the light.

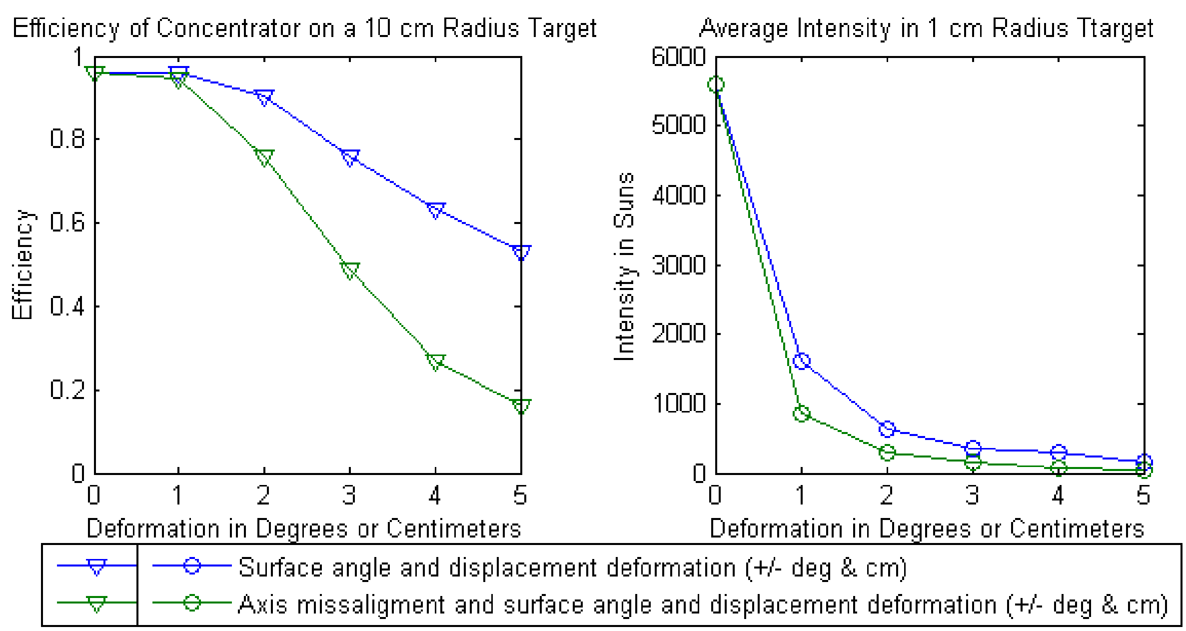

Figure 11 Degradation of focus for given a combination of manufacturing tolerances in percent of light focused

Ray-tracing results for the proposed 3.14 kW solar cooking facility identify tolerances for a design where 90% of the incident sunlight reaches a 10 cm radius circle, corresponding to a concentration of about 1000 suns. Inclusion of 90% reflectivity coefficient for both reflectors reduces the power concentrated to 2.3 kW. To achieve this level of concentration the misalignment between the axes must be no more than 2º regardless of other imperfections. Additionally the manufacturing tolerances of the secondary mirror must be less than what is shown in Figure 9: ±2º and ±4 cm.

Accessibility to Concentrated Solar in Developing Countries

Like Scheffler, our goal is not to minimize the cost of a technology for sale, but to bring to people the means of technology production itself. Thus, barriers to acquire a technology should be thought of in terms of complexity, or level of expertise needed to construct and maintain a technology, as well as cost and availability of materials. Driving down costs through optimized, centralized production does not bring the same value to developing countries as it does to industrialized nations. Human labor is readily available in developing areas, so saving time with economies of scale is not as important.[4] Additionally, producing something by hand employs and empowers locals to be self-sufficient. However, it requires that they be appropriately prepared for the task's level of complexity.

Cooking for the poor in developing countries is usually done by burning wood or some other biomass inside often poorly ventilated kitchens. The resulting indoor air pollution claims more children's lives than malaria.[5] Where fuel is scarce, families struggle to obtain fuel with results that may include deforestation, long difficult trips, and exposure to violence. Solar cooking provides an inexpensive, safe alternative that is free of emissions and other environmental degradation, but solar cooking technologies are often not adopted because they are not convenient or powerful enough. Our new design offers convenience and effectiveness similar to natural gas or electricity.

This new design doesn't rely on scarce or expensive materials, and can be adapted to most sunny environments. Only the tracking automation requires machinery, which could be as simple as a clock or a closed-loop circuit comparing signals from (for instance) two photodiodes and small electric motor. The secondary mirror can be shaped in the earth or formed out of any readily available material that can hold its shape, some possible examples are show in Figure 12. Reflectivity can be provided by aluminized mylar (ubiquitously available from discarded snack bags), aluminum foil, or by tiled broken mirror pieces.

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[4] E. F. Schumacher, Small Is Beautiful: A Study of Economics As If People Mattered, Blond and Briggs, 1973

[5] Ezzati M, Kammen DM (November 2002). "The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs". *Environ Health Perspect.* **110** (11): 1057–68

Figure 12 Three possible construction techniques for the secondary parabolic mirror: (left) curved wood slats, (center) concrete latex and burlap composite, and (right) fiberglass.

Conclusion

Sunlight can be reflected to a stationary point during the day with a heliostat rotating on a single axis, polar mount. The reflected light can then be concentrated or otherwise processed at a stationary position, reducing complexity. In developing countries and for residential uses everywhere, seasonal declination needs only to be adjusted occasionally by hand. The ease of construction and maintenance may allow communities everywhere to construct their own solar concentration facilities.

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