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Evaluation of performance of household solar cookers

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Abstract

Household solar cookers were evaluated according to ASAE (American Society of Agricultural Engineers) Standard S580.1 — Testing and Reporting Solar Cooker Performance. Per ASAE S580.1, standardized cooking power at a temperature difference of 50°C between ambient air and cooking vessel water temperatures ($\pm 95\%$ confidence interval) was 198 (± 32) W for a parabolic-type cooker, 65 (± 12) W for a box-type cooker, and 25 (± 9) W for a panel-type cooker. ASAE S580.1 specifies standardized cooking power as a single measure of performance, and additional measures of performance, including thermal efficiency and water heating times, were evaluated. The issue of water evaporation was examined. Clarifications for ASAE S580.1 wind velocity specification are recommended. ASAE S580.1 is specified as a normative reference in the ISO (International Organization for Standardization) 19867–1:2018 standard for laboratory testing of cookstoves, and a specified deviation for average wind velocity, 1.5 m/s, is based on recommendations from this study and concurrence from other ISO working group experts.

Keywords

household solar cooker; ASAE Standard S580.1; cooking power; thermal efficiency

1. Introduction

The WHO (World Health Organization) estimates that close to four million people die prematurely every year due to diseases attributable to HAP (household air pollution) from use of solid-fuel and kerosene cookstoves (WHO, 2018). Accompanying the harmful health effects from exposure to HAP are issues including uncertainty regarding climate change impact (Archer-Nicholls et al., 2019; Huang et al., 2018; Kodros et al., 2015), unsustainable fuelwood harvesting (Bailis et al., 2015), safety (Diekman et al., 2014; GACC, 2016), economic development (García-Frapolli et al., 2010; Jeuland and Pattanayak, 2012), and gender equity (Pachauri and Rao, 2013; Shankar et al., 2014). From these issues has emerged the need for alternatives to traditional solid-fuel cooking. In the quest for low-cost,

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safe, and clean alternatives, attention has turned toward many different sources of energy, including the sun. Humans have used solar energy to prepare food and heat water for millennia. Solar cookers are currently used in conjunction with various types of cookstoves needed when solar energy is not available and with retained heat cookers: insulated containers used to reduce the loss of heat from cooking vessels removed from solar cookers or stoves. Advantages of solar cookers include zero air pollutant emissions and zero fuel use. Development of solar cooking technology is advancing in many countries (Cuce and Cuce, 2013; Harmim et al., 2014; Iessa et al., 2017; Indora and Kandpal, 2018a; Mahavar et al., 2013a; Mahavar et al., 2013b; Mbodji and Hajji, 2016; Otte, 2013, 2014; Rikoto and Garba, 2013).

An internationally-recognized method for evaluating solar cookers is ASAE (American Society of Agricultural Engineers) Standard S580.1 — Testing and Reporting Solar Cooker Performance (ASABE, 2013). This standard was initiated at the Third World Conference on Solar Cooking in Coimbatore, Tamil Nadu, India, in January 1997, and was developed with further input from the Third Latin American Congress on Solar Cookers in La Ceiba, Atlintico, Honduras in March 2001. The ASAE Solar Energy Committee SE-414 provided final development in March 2002. The standard was approved by the ASAE Structures and Environment Division Standards Committee in January 2003, reaffirmed February 2008, and was revised in August 2013. The American Society of Agricultural and Biological Engineers (ASABE) has made this standard available on the internet at no cost (ASABE, 2013).

ASAE S-580.1 has been examined by several researchers (Funk, 2000; Kundapur and Sudhir, 2009; Shaw, 2002). The standard provides a single measure of standardized cooking power, and it has been shown that results are replicable under various conditions of ambient temperature and insolation: solar energy received per unit time per unit area (Funk, 2000). Funk (2000) evaluated four box-type solar cookers, but ASAE S-580.1 is intended to “provide a single measure of thermal performance so consumers may compare different designs when selecting a solar cooker,” and the scope of the standard includes “all solar batch-process and water heating devices (solar cookers)” (ASABE, 2013). Additional measures of performance have been proposed to provide more complete characterization of the utility of cookers for potential users and those disseminating clean technologies (Fairey et al., 2002; Kundapur and Sudhir, 2009; Shaw, 2002).

Many commercially available solar cookers have not been tested, and one of the purposes of this study is to encourage testing and reporting of results, similar to how testing has been promoted for cookstoves (Jetter et al., 2012). In this study, ASAE S580.1 was used to evaluate three types of cookers that use different approaches to capturing solar energy for cooking. In addition to the single measure of cooking power specified by ASAE S-580.1, other measures of performance were examined.

In general, solar cookers have relatively low power compared with traditional cooking methods, and food safety is important to consider, particularly regarding bacterial proliferation. When food is in the temperature range of ~4 — 60 °C, bacterial proliferation is highest, and this temperature range is sometimes called the “danger zone” (USDA, 2020). In the danger zone, bacteria can double in number in as little as 20 minutes, and food may

become inedible even if it is later heated to a temperature above the danger zone (USDA, 2020). Food is generally considered safe if removed from the danger zone in less than 2 hours, or less than 1 hour if temperatures are near or slightly above 30 °C; i.e., close to body temperature. It is commonly thought that food and water must reach boiling temperature and be held there for several minutes to kill food-borne bacteria, although most bacteria begin to die rapidly when the internal temperature of food reaches ~ 74 °C (USDA, 2020) — making this an important benchmark temperature for the pasteurization of food and water. If a solar cooker or stove is to be used safely for cooking, it should be able to heat food out of the danger zone and to a temperature of ~ 74 °C relatively quickly regardless of whether the cooking task being performed requires high power, such as boiling water or cooking a relatively large mass of food, or low power, such as slow-cooking or preparing a small mass of food. Food safety considerations are critical when deploying any low-power cooking method.

This paper is structured to provide a description of materials and methods, results from concurrent testing of three types of solar cookers, a unique evaluation of the ASAE S580.1 method, recommendations for improving test methods based on the independent data, and recommendations for future research and evaluation of solar cookers.

2. Materials and Methods

2.1 Standard testing method

Each solar cooker was tested according to ASAE S580.1. In general, this standard specifies that (1) “...test results be presented as cooking power, in Watts, normalized for ambient conditions, relative to the temperature difference between cooking vessel contents and ambient air, both as a plot and as a regression equation for no fewer than 30 total observations over three different days,” and (2) “...cooking power be presented as a single number found ... for a temperature difference of 50 °C.” Test conditions are specified for wind, ambient temperature, water temperature, insolation, and solar zenith and azimuth angles. The standard specifies that the “intercept area” be calculated for each solar cooker based on the “sum of the reflector and aperture areas,” and the amount of water placed in the pot, the cooker’s “loading,” be 7 kg of water per m² of intercept area, so that solar cookers can be objectively compared on the same basis.

2.2 Additional measures of performance

In addition to the single measure of performance specified by ASAE S-580.1, thermal efficiency is calculated as:

$$\eta_T = \frac{P_S}{I_S A_i} \times 100 \% \quad (1)$$

Where:

η_T = thermal efficiency as a function of temperature difference (%)

P_S = standardized cooking power (W), as calculated per ASAE S-580.1, Equation 4

I_S = standardized insolation (700 W/m²)

A_i = intercept area (m²)

Thermal efficiency is a function of temperature difference between cooking vessel contents and ambient air, because standardized cooking power, P_S , is a function of this temperature difference.

Additionally, times are reported for heating the ASAE S-580.1-specified water loads under the test conditions as follows: (1) time required to heat water out of the danger zone, from ~26 to 61 °C; (2) time required to heat water to temperature that kills bacteria, from ~26 to 74 °C; and (3) time to heat water from ~26 to 95 °C.

2.3 Equipment

All environmental variables were monitored continuously and recorded as five-second averages by a data acquisition system connected to a computer. Temperatures were measured with Type K thermocouples, water mass was measured with an electronic balance, insolation was measured with a Model LI-200 pyranometer (LI-COR Biosciences, Lincoln, NE, USA), and two-dimensional wind speed was measured with a Model 81000 Ultrasonic Anemometer (R.M. Young Company, Traverse City MI, USA) collocated with the cookers, as shown in Fig. 1. The pyranometer was mounted on the frame of the parabolic cooker so that it faced the sun with the same angle of incidence as the cookers tested. Thermocouples and the electronic balance were calibrated before and after testing by the USEPA (United States Environmental Protection Agency) Metrology Laboratory in Research Triangle Park, NC, USA. The pyranometer and the anemometer were calibrated before and after testing by the manufacturers.

2.4 Solar cookers tested

The HotPot (Solar Household Energy, Inc., Washington, DC, USA) is a panel-type solar cooker consisting of a multi-paneled, collapsible aluminum reflector and a black pot that fits inside a glass enclosure and lid. The manufacturer refers to the glass enclosure as a second pot, see Fig. 1c. This solar cooker is intended for slow cooking (HotPot, 2020). The manufacturer produces the cooker for distribution in the U.S. and Mexico, as well as sales to other countries, via Solar Household Energy, Inc. (SHE, 2020). The intercept area of the cooker was 0.2869 m², and the ASAE S-580.1-specified loading based on this intercept area was 2008 g of water. The manufacturer-supplied pot held this amount of water when nearly full.

The Global Sun Oven (Sun Ovens International, Inc., Elburn, IL, USA) is a box-type cooker with a transparent glass door located between four collapsible reflector panels, see Fig. 1d. Gasketing material is located between the body of the oven and the door, and a latch holds the door shut. The manufacturer recommends the cooker for foods to be “boiled, steamed, roasted or baked” (SOI, 2020). Sun Ovens International reports they have capability to place assembly facilities in-country (SOI, 2020). The intercept area of the Global Sun Oven is 0.5247 m², and the ASAE S-580.1-specified loading was 3673 g of water. There was no pot supplied with the Sun Oven, and the largest pot that would fit inside the Sun Oven with the

door closed held approximately 3200 g of water, so the cooker was tested with this amount of water. ASAE S-580.1 provides no specific guidance regarding this issue, but regarding solar tracking, ASAE S-580.1 specifies that “Testing should be representative of local conditions, i.e.; how the typical consumer is expected to use the cooker.”

The Sun Chef Cooker (Sun Chef Cookers, Waddell, AZ) is a parabolic-reflector-type cooker with a multifaceted aluminum reflection surface anchored to a round aluminum hoop, see Fig. 1d. The assembled reflector is not designed to be collapsible and is mounted on a frame that allows it to be tilted and rotated about the axis of the frame’s aluminum tripod legs to facilitate positioning. The manufacturer/distributor recommends the cooker for baking, frying, and grilling. Originally, the cooker and the manufacturer had the name, “Sun Power Cooker” (SCIA, 2018). The Sun Chef Cooker had the largest intercept area, 0.8659 m^2 , and the ASAE S-580.1-specified loading was 6061 g of water. The Sun Chef Cooker did not come supplied with a pot from the manufacturer, so a 7-liter stainless steel pot was used with the specified loading, see Fig. 1.

2.5 Experimental design

The tests were conducted at the USEPA’s facilities in Research Triangle Park, NC, USA. The cookers were tested outside a building in a wind-sheltered bay area with no overhead obstruction and clear line-of-sight to the sun throughout the course of the tests. The facility is located at $35^\circ 52' 53.7''$ N latitude (USNO, 2019). All test replicates were performed within a 7-day time period during June 27–28 and July 3, 2012 to minimize variation in solar radiation intensity. Per ASAE S-580.1, all tests were performed during the 4-hour time period surrounding solar noon, $\sim 13:19$ EDT at the time the tests were performed (Solar-Noon, 2018). The average solar azimuth angles relative to global position, averaged across all tests, were $108.3 \pm 0.2^\circ$ east of north at the initiation of cooker insolation and $254.6 \pm 0.6^\circ$ at the end of insolation. The three cookers were tested simultaneously and were concurrently attended, approximately every 15 minutes, to adjust their positions relative to the sun. All cookers were tested with lids kept closed on pots, and the water in each cooker was changed when it reached 5°C below boiling temperature, 95°C , per ASAE S-580.1.

3. Results

Standardized cooking power versus temperature difference for the three solar cookers is shown in Fig. 2, per ASAE S-580.1, with regression equations and r^2 values shown for each solar cooker. Values of r^2 for all cookers were greater than the lower limit specified by ASAE S-580.1: $r^2 \geq 0.75$. Results for standardized cooking power at a temperature difference of 50°C , per ASAE S-580.1, are given in Table 1, and $\pm 95\%$ CI (confidence interval) values are also given, although reporting CI values is not required by ASAE S-580.1. Additional measures of performance, as described above, are given in Table 2. Although not required by ASAE S-580.1, representative thermal profiles for load temperatures, ambient temperature, and insolation for concurrent tests of the three solar cookers are shown in Fig. 3.

4. Discussion

4.1 Cooking power

As shown in Fig. 2, cooking power decreased with increasing temperature difference, and cooking power increased with larger intercept areas for each solar cooker. Similarly, Funk (2000) evaluated solar cookers using ASAE S-580.1 and found that the y-intercept of the regression line, called the “initial cooking power,” increased with larger intercept areas, but this trend was not consistent for all solar cookers evaluated in this study. While the parabolic cooker had both the largest intercept area and the largest initial cooking power, the initial cooking powers of the box-type and panel-type cookers were almost identical, despite the nearly twice-larger intercept area of the box-type cooker. These data suggest that initial cooking power does not always correlate with intercept area.

Funk (2000) also noted that the slope of the regression line can be used to qualitatively evaluate the effectiveness of cooker insulation and potential for radiative heat loss, called the “heat loss coefficient.” The cookers tested here followed the trend noted by Funk. The parabolic cooker had no insulation at all and had the greatest regression line slope, -2.68 , see Fig. 2. The glass body of the panel cooker provided some insulation, and the slope, -1.62 , was less, while the box cooker appears to insulate most effectively with the smallest slope, -0.86 . In general, less slope is desirable, as it indicates that cooking power drops off less with increasing temperature difference. These data show that heat losses tend to increase as temperature differences increase. As cooking power decreases, a solar cooker can effectively heat a smaller load.

Though cooking power varies with insolation, the standardized cooking power measured for these household solar cookers is low compared with cooking power for typical fueled cookstoves. Maximum standardized cooking power shown in Fig. 2 is approximately 100–300 W, but maximum cooking power for typical cookstoves is approximately 800–1,500 W (Jetter et al., 2012).

4.2 Thermal efficiency

In addition to cooking power, thermal efficiency may be a useful metric, see Table 2. Although solar energy is free of cost, materials used to construct solar cookers are not free, and a solar cooker with greater thermal efficiency will provide greater cooking power for a given intercept area. Improving thermal efficiency for solar cookers will not reduce operating cost but may reduce initial cost per watt of cooking power. Of the three solar cookers tested, the parabolic type had the greatest thermal efficiency at both 10 and 50 °C temperature differences. The box-type cooker had the lowest thermal efficiency at a 10 °C temperature difference but maintained a greater thermal efficiency at a 50 °C temperature difference, compared with the panel-type cooker.

4.3 Water heating time

The time required to heat water to specific temperatures, as shown in Table 2, depends on conditions including insolation, water loading, and ambient temperature. Average insolation $\pm$ SD (standard deviation) during testing was $948 \pm 15 \text{ W/m}^2$, compared with 700 W/m^2 , as

specified in ASAE S-580.1 for calculating standardized cooking power. Water loading was different for each solar cooker based on intercept area, as reported in the Section 2.4. Average ambient temperature $\pm$ SD during testing was 31.0 ± 2.0 °C. The times reported in Table 2 may be compared between the three solar cookers, because the cookers were tested concurrently, but it is important to note that the times are not comparable for cookers tested under different conditions. It was not possible to test the box-type cooker with the full loading specified in ASAE S-580.1, because of the limited space inside the cooker, as discussed in Section 2.4, and the 13 percent lower loading would slightly decrease the time required to heat water to specific temperatures, but the lower loading likely would have little effect on the standardized cooking power.

Under the test conditions, the time to heat water out of the danger zone for the three solar cookers, as shown in Table 2, was less than the 2-hour limit recommended by the USDA (U.S. Department of Agriculture), but heating times could be different under other conditions. It is recommended that the temperature of food or water be monitored to ensure that bacterial proliferation is not a problem—especially when cooking under low-power conditions. Among the three solar cookers, the parabolic type had the fastest times to heat water and was also loaded with the largest amount of water. The time to heat a given volume of water to near the boiling point is a nonlinear function of cooking power due to evaporation (Jetter et al., 2012).

Mahavar et al. (2015) defined required times for heating or cooking in two steps. In Step 1, a load should attain 80 °C within two hours for food grains to be properly cooked (Mahavar et al., 2015). The Step 1 requirement was met by the parabolic- and panel-type cookers but not by the box-type cooker, as shown in Fig. 3. In Step 2, the load should increase in temperature from 80 to 90 °C within 30 minutes for softening of foods. The Step 2 requirement was met by the parabolic- and box-type cookers but not by the panel-type cooker. Step requirements may be met by box- and panel-type cookers if loadings are smaller than specified by ASAE S-580–1. The Step 2 requirement was easily met by the parabolic-type cooker because of higher cooking power at all temperature differences, even though the heat-loss coefficient indicated by the slope of the regression line was greater, as shown in Fig. 2.

4.4 Water evaporation

As the temperature of the water approaches the final temperature, 95 °C, during testing, water evaporates as steam, but the energy of vaporization is not accounted for in the calculation of cooking power per ASAE S-580.1. The average $\pm$ SD values for the mass of water evaporated were 138 ± 11 , 38 ± 1 , and 101 ± 10 g for the panel-, box-, and parabolic-types, respectively. The box-type cooker had the least water evaporation, because water vapor was trapped inside the box with the tightly sealed glass door. Condensed water vapor was observed on the inside of the glass during testing and likely caused degradation of performance. The panel-type cooker had the most water evaporation, because it had relatively low cooking power, and steam was produced over a long period as the water temperature slowly approached 95 °C. For any solar cooker with an unpressurized cooking

vessel, evaporation will occur as the water temperature approaches the boiling point. In actual use, evaporation may or may not be desirable, depending on the cooking process.

Cooking energy used for heating water is included in the calculation of cooking power per ASAE S-580.1 and is calculated as:

$$E_h = (T_2 - T_1)MC_v \quad (2)$$

Where:

E_h = cooking energy for heating water (kJ)

T_2 = final water temperature (°C)

T_1 = initial water temperature (°C)

M = water mass (g)

C_v = heat capacity of water ($4.186 \cdot 10^{-3}$ kJ / [g•°C])

Cooking energy used for evaporating water is not included in the calculation of cooking power per ASAE S-580.1 and is calculated as:

$$E_e = M_e h_{H_2O} \quad (3)$$

Where:

E_e = cooking energy for evaporating water (kJ)

M_e = evaporated water mass (g)

h_{H_2O} = specific enthalpy of vaporization of water (2.260 kJ/g)

Values for cooking energy used for heating and evaporating water for the three solar cookers are given in Table 3. The energy used to evaporate water is less than the energy used to heat water, but nevertheless represents unaccounted energy in the calculation of cooking power per ASAE S-580.1. The fraction of cooking energy used to evaporate water compared to that used to heat water is the highest for the panel-type cooker due to the relatively small mass of water heated and the large mass of water evaporated. ASAE S-580.1 specifies the calculation of cooking power for each 10-minute interval, as indicated by each data point in Fig. 2. At low water temperature, a negligible amount of water is evaporated, and the calculation of cooking power per ASAE S-580.1 is accurate, but at high water temperature, steam is produced, and the calculation of cooking power becomes less accurate. The data points on the right side of Fig. 2 are negatively biased due to the unaccounted energy of vaporization. The bias could be eliminated by ending the test when the water temperature reaches a lower temperature before steam is produced, such as 20 °C below the boiling point, but then the regression line may need to be extrapolated to the 50 °C temperature difference specified in

ASAE S-580.1. The bias could be eliminated by including the energy used for evaporating water in the calculation of cooking power for each 10-minute interval, but this would entail weighing the water at the beginning and end of each interval. It would disrupt the test to remove the cooking vessel every ten minutes, but the mass could be obtained if the entire solar cooker and cooking vessel were placed on a weighing scale, although wind could cause the weight measurement to fluctuate. The bias could also be eliminated by using a pressurized cooking vessel that would stop evaporation if removed at 5 °C below the local boiling point, as specified in ASAE S-580.1, but this would be inconsistent with how solar cookers are typically used. An experimental study is recommended to determine the best approach to eliminating the bias.

4.5 Attending frequency

Although solar cookers can be used practically at lower attending frequency, concentrating type cookers, such as the parabolic type, perform best if repositioned to face the sun approximately every 15 minutes, as recommended by the manufacturer. During testing, the three solar cookers were attended approximately every 15 minutes. The panel-type and box-type cookers may require less frequent attending, but performance was not tested with less frequent repositioning. Additional tests could be conducted at various attending intervals to evaluate the sensitivity of performance to repositioning, but this would add complexity and cost to the test protocol.

4.6 Wind conditions

Although solar cookers can be used practically at higher wind speeds, cookers tend to perform best at low wind speed, and ASAE S-580.1 specifies relatively low wind speed for consistency. ASAE S-580.1 specifies in Clause 5.1: “Average Wind. Tests shall be conducted when the average wind during the duration of the test is less than 1.0 m/s,” but this condition was difficult to meet in the test location. Testing was conducted as specified in ASAE S-580.1 on days with relatively low wind velocity for the local area and in a wind-shielded area, next to a tall building. Buildings and other shields may reduce wind speed in the testing area, but eddy currents can form around these barriers. ASAE S-580.1 also specifies that tests be conducted between 10:00 and 14:00 solar time, and mid-day solar radiation generally causes thermal air currents and instability in the atmosphere resulting in variable and relatively high wind speeds. The average wind speed $\pm$ SD over the course of testing was 1.1 ± 0.1 m/s, exceeding the 1.0 m/s limit. ASAE S-580.1 specifies that the wind speed be recorded at least every 10 minutes, but the data acquisition system used in this study recorded wind speed every 5 seconds. The sonic anemometer used to measure wind was very sensitive and measured instantaneous velocity. ASAE S-580.1 does not specify whether wind speed measurements are instantaneous or averaged over a certain period.

ASAE S-580.1 also specifies: “Maximum Wind. Should the wind exceed 2.5 m/s for more than ten minutes the test data shall be discarded.” During the testing, wind never exceeded 2.5 m/s for more than ten minutes on a sustained basis. Instantaneous wind velocities frequently exceeded 2.5 m/s, but wind speed never exceeded 2.5 m/s when averaged over a 3-minute period.

Following are recommendations for the next revision of ASAE S-580.1: (1) reconsider the average wind speed limit based on an experimental study, (2) consider adding accuracy requirements for measurement of wind speed, (3) consider requiring wind speed measurements more frequently than every 10 minutes, (4) specify the averaging time period for wind speed, and (5) clarify whether "...test data shall be discarded" refers to the data for the 10-minute periods with wind exceeding 2.5 m/s or to the data for the entire test.

The ISO (International Organization for Standardization) 19867–1:2018 standard for laboratory testing of cookstoves (ISO, 2018) specifies ASAE S580.1 as a normative reference for measuring standardized cooking power for solar cookers. ISO 19867–1:2018 specifies a deviation from ASAE S580.1 for average wind velocity of 1.5 m/s for the duration of the test based on recommendations from this study, concurrence from other ISO Technical Committee 285 working group experts, and approval through the ISO standard development process.

4.7 Additional Considerations

Many suggestions are found, in both peer-reviewed and other literature, for additional metrics that could be used to evaluate solar cookers (Andreatta, 2014; Fairey et al., 2002; Fehr et al., 1977; Kundapur and Sudhir, 2009; Shaw, 2002). Factors such as safety, ergonomics, cost-per-benefit, mass-per-Watt, and durability have been proposed for further evaluation, although some of these characteristics may be challenging to quantify in a meaningful way (Otte, 2009; Shaw, 2002).

Durability is likely to be important as reflective surfaces can become scratched, dented, or broken. Cookers could be stress-tested under windy conditions. While testing with natural winds is not likely to be practical or repeatable, more-repeatable testing might be achieved by using a fan or blower. Cooker performance in terms of cooking power and thermal efficiency could be evaluated under various wind conditions in addition to the relatively low wind speed specified by ASAE S-580.1. Additional tests with controlled wind velocities would add complexity to the test protocol but could provide useful information on the ability of cookers to perform under wind conditions likely to be encountered in the field. Testing the time needed for cooker contents to reach several temperatures of interest as was done here may be useful for devices used to pasteurize water or slow-cook food (Andreatta, 2014; Bergler et al., 1999; Bigoni et al., 2014), but these times are not comparable for tests under different conditions. Additional tests could characterize performance at low zenith angles that occur when a cooker is used just after sunrise or before sunset (Kundapur and Sudhir, 2009; Shaw, 2002). Additional testing could relate cooking power and efficiency to the frequency of tending; e.g., how often the cooker needs to be reoriented relative to the sun's position.

Evaluation of many variables would involve trade-offs between the benefits of additional information and the time/cost of testing. In addition, evaluation of some variables may be appropriate only for certain cooker types. For example, evaluation of performance at low zenith angles may be appropriate for parabolic-type cookers but not for some other types of cookers. In addition to the typical household-sized cookers included in this study, community- and institutional-scale solar cookers are also in place (Indora and Kandpal,

2018b; SCIB, 2018). Large-scale cookers may be evaluated using similar methods, but more research is needed to establish applicability of these methods. Integrated cooking systems may include a solar cooker used when solar energy is available, a retained heat cooker used to extend cooking time, and a cookstove used when solar energy is not available. Evaluation of integrated systems would also require additional methods.

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Fig. 1. Solar cookers collocated with a) pyranometer and b) sonic anemometer. Solar cookers were c) panel-type, d) box-type, and e) parabolic-type.

Fig. 2.
Standardized cooking power versus temperature difference

Fig. 3.
Temperatures and insolation versus time

Table 1.

Standardized cooking power for a temperature difference of 50 °C ($P_{S, 50}$) per ASAE S-580.1

Cooker	$P_{S, 50} \pm 95\% \text{ CI (W)}$
Panel type	25 ± 9
Box type	65 ± 12
Parabolic type	198 ± 32

Table 2:

Additional measures of performance

Measure of performance	Units	Panel-type	Box-type	Parabolic-Type
Thermal efficiency at 10 °C temperature difference, η_{10}	%	45	27	50
Thermal efficiency at 50 °C temperature difference, η_{50}	%	13	18	33
Time to heat water out of the danger zone, from ~26 to 61 °C	min	40	72	35
Time to heat water to temperature that kills bacteria, from ~26 to 74 °C	min	59	100	49
Time to heat water from ~26 to 95 °C	min	229	195	97

Table 3:

Mass of water and cooking energy for water heating and evaporation.

Parameter	Units	Panel-type	Box-type	Parabolic-Type
Mass of water heated	g	2008	3200	6061
Mass of water evaporated	g	138	38	101
Cooking energy used to heat water	kJ	580	924	1751
Cooking energy used to evaporate water	kJ	312	86	228