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A simplified method for determining standard power of solar cookers using low-cost instruments

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A simplified method for determining standard power of solar cookers using low-cost instruments

Paul Arveson

Abstract: *This report describes a method for measuring standard solar cooker power with low-cost commercial instruments. A previous Technical Report, TR-17 [1] concluded that a low-cost lux meter can be used in place of a pyranometer for measuring solar irradiance. This report incorporates a lux meter into a complete package of common instruments for measuring power in accordance with international standards, provided proper calibrations and procedures are followed.*

The American Society of Agricultural and Biological Engineers (ASABE) S.580.1 standard [2] and the International Standards Organization (ISO) 19867-1 standard [3] for solar cooker power measurements require the measurement of direct normal irradiance (DNI) of solar radiation, as well as temperature and wind speed measurements. Previously, in Technical Report TR-09.1 (2018) [4], we described a system that was assembled using commercial off-the-shelf instruments to collect the required data [4]. However, the cost of this instrumentation is about $1000 US. We were asked if low-cost instruments could be used as a reasonable substitute for solar cooker performance tests.

In previous Technical Report TR-17 [1], we reported the feasibility for using a low-cost instrument for measuring irradiance. These findings are combined here with recommendations for use of low-cost thermometers and a manual procedure for conducting a full standard power measurement of a solar cooker. It is hoped that this information will enable standardized power measurements of solar cookers to be easier and more affordable in sunny locations around the world.

Irradiance measurements

The standards require the measurement of direct normal irradiance (DNI) of solar radiation. They use a pyranometer, which is calibrated to measure total solar radiation, or irradiance, in units of Watts/m^2. Commercial pyranometers are scientific instruments and cost $200 or more.

A lux meter is an instrument for measuring illuminance from the sun or other light sources. Lux meters are calibrated to measure visible light as seen by the human eye, which is called illuminance. Units are lux, which are equivalent to lumens/m^2. Several low-cost (under $40 US) lux meters are available from Amazon. They are powered by one 9V battery. They are made in China, and sold under brand names Dr. Meter, MoonCity, LONN, FHX, TOOGOO, RZ, etc. but they are all have the same model number, LX1330B (Figure 2). They have a range up to 200,000 lux. It is important to have this high range in order to measure full sunlight illuminance. It is also necessary to have an instrument that has a sensor separated from the meter by a cable.

Figure 1. The LX1330B lux meter.

All lux meters and most pyranometers use a silicon photodiode sensor, which has a peak spectral sensitivity in the near infrared at about 950 nanometers. The lux meter has a blue filter which adjusts the spectral response of the sensor closer to that of the human eye. In use, the lux meter is aimed by hand toward the Sun and the maximum reading is recorded.

The ratio of the lux meter readings to pyranometer readings, that is, illuminance / irradiance (in units of lumens/W) is called luminous efficacy [5]. Substitution of a lux meter would be feasible if the ratio of readings between the two instruments (the luminous efficacy) is constant across a wide range of sun and sky conditions. Then the readings from the lux meter could be multiplied by this constant to estimate values of solar irradiance that would be measured by a pyranometer.

We collected a data set of 79 pairs of samples from all the experimental data recorded in the summer of 2016 [6]. We plotted these data (ratio vs. sample number) to see if there was a reasonably flat ratio (luminous efficacy) across all the data.
The plot in Figure 3 (copied below from reference [1]) clearly shows such a constant ratio (luminous efficacy) in most of the data, with a median value of 123 (luminance in lux / irradiance in Watts/m^2). There were a few "outlier" points from measurements that were taken very late in the day, or due to variations in measurement times between the two instruments on partly cloudy days, when radiation was rapidly changing.

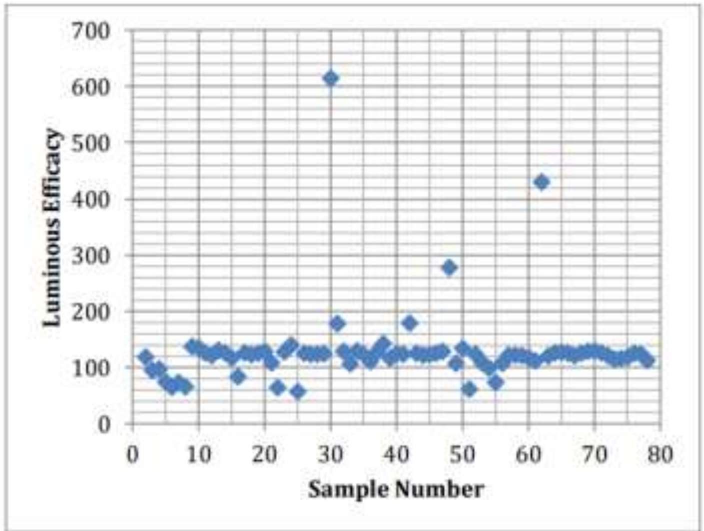

Figure 3. Direct luminous efficacy ratios in 79 pairs of measurements

Perez *et al*. [7] shows values of direct luminous efficacy of about 110. The reason for the difference from our data may have to do with the fact that the lux meter measures some irradiance beyond the very narrow 0.5-degree direct beam from the Sun. Also, it may have to do with the spectral response of the silicon photodiode in the lux meter and how it was calibrated. Hence it is recommended that individual lux meters should be calibrated in sunlight against a properly calibrated pyranometer before being used in the field. Provided such a calibration is done, we conclude that it is feasible to follow the ASABE S.580.1 protocol using a low-cost lux meter for solar DNI measurements.

Temperature measurements

The other essential measurement that is required for solar cooker power testing is the temperature inside the cooking pot. In the instrumentation described in ref. [4], small thermocouples are used. They are small enough to fit through the steam vent holes on many cooking pot lids. Low-cost substitutes are Taylor Digital Probe kitchen thermometers. They have a probe with a diameter of 4mm and a silicone cable of 2mm

thickness that is 1.2 m long. They use 2 AAA batteries for power. These devices are mass-produced in large quantities and are widely available at low cost. They measure temperatures from 0 - 200˚C. (Another thermometer is needed to measure ambient air temperature. To save time and increase reliability, it is suggested that two solar cookers of the same type should be tested at the same time. (But this would require a third thermometer to be purchased.)

The accuracy of each thermometer should be checked before being used for standard tests. Two calibration points can be tested: the freezing point and boiling point of water. To check the freezing point, stir a mix of ice and water in a cup and record the temperature reading; it should be very near 0˚C. Then bring some water to a full boil in a pot and record the reading; it should be near 100˚C (with a correction for altitude if necessary). Any bias or offset from these values can be used to determine a calibration adjustment, if needed. (A sample we tested showed accuracy within 1˚ C.)

It will likely be necessary to drill a hole in the side of a test pot for the thermometer probe, so that it does not pass over the lid of the pots. A stiff wire coil may be wrapped around the probe tip to ensure that the probe does not make contact with the walls of the pot. Metal tape may be used to ensure that the probe is submerged.

Wind speed restriction

The protocol [2] specifies that tests can only be conducted when the wind speed is less than 2.5 m/s. However, *the actual value of the wind speed is not needed*; it is only a threshold. If wind at the test location is noticeably windy, this may preclude measurements, or the tests should be conducted in a location that is shaded from the wind. A suspended cloth or flag may be sufficient to indicate this, so that an anemometer is not an explicit requirement of the protocol. This will reduce the cost and complexity of the procedure.

Complete instrument requirements

- Lux meter LX1330B, about $35 US
- Probe thermometers, such as Taylor Slow Cooker Digital Probe Thermometer Model 1470N, about $20 US each (2 or more required)
- Stopwatch or kitchen timer, under $10 US (or a free smart phone app could be used instead)
- Batteries for above (one 9V and three 1.5 V AAA batteries), about $6
- 1-liter measuring cup, a white sheet, and other common items
- A laptop computer running Microsoft Excel (not included in the costs)

So the low-cost instruments would cost under $80 US. Thus, the cost of instrumentation is reduced by a factor of more than ten compared to the instrumentation described previously [4]. (It is assumed that the laptop computer is also available.)

Standard power measurement using Excel

A power calculation using Excel [8] has been prepared based on the standard developed by Dr. Paul Funk as ASAE S.580.1, and which was incorporated into the ISO 19867-1 international standard. This calculation is nearly as accurate as a full software program such as the Python program [9], which was used previously to calculate cooking power. The new procedure requires a laptop running Microsoft Excel (or LibreOffice Calc) for performing calculations and plotting graphs.

The Excel file has two sheets: the Load calculation sheet and the Power calculation sheet. An example of a filled-in report is also provided in reference [8].

Load calculation

The "Load" spreadsheet can be used to determine the load mass required for a standard test. As input, it uses the date of the test, the latitude and longitude of the test location, and two measurements of the device under test: the maximum possible intercept area of the reflector, and the zenith angle at which the maximum possible intercept area is viewed.

According to the standard, the load mass must be 7 kg per square meter of reflector intercept area.” The intercept area is “the sum of the reflector and aperture areas projected onto the plane perpendicular to direct beam radiation. Use the average beam radiation angle as calculated for the entire test period."

In the Excel calculation, the average beam radiation angle during the test will be estimated based on user-provided latitude, using the average of the Sun angle at 10am and solar noon. Such an average is necessary in order to define the load for a test as recommended by the standard.

The intercept area for a simple shape, such as a round or square reflector, can be calculated easily. However, for more complex reflector shapes, it will be necessary to use image processing software to measure the area inside the perimeter. A report describing this procedure was documented in TR-10 [10]. The actual intercept area on a particular day and time depends on the Sun’s elevation angle and on the orientation of the solar cooker. For concentrating-type solar cookers such as parabolics which must be frequently reoriented to track the sun very closely, the maximum possible intercept area is used to calculate load. For certain box and panel-type cookers that cannot be oriented in every direction to track the sun closely, the intercept area at the average beam radiation angle must be calculated before testing to determine the load. This is illustrated in Figure 3 for an example panel cooker (Haines Solar Cooker model 2).

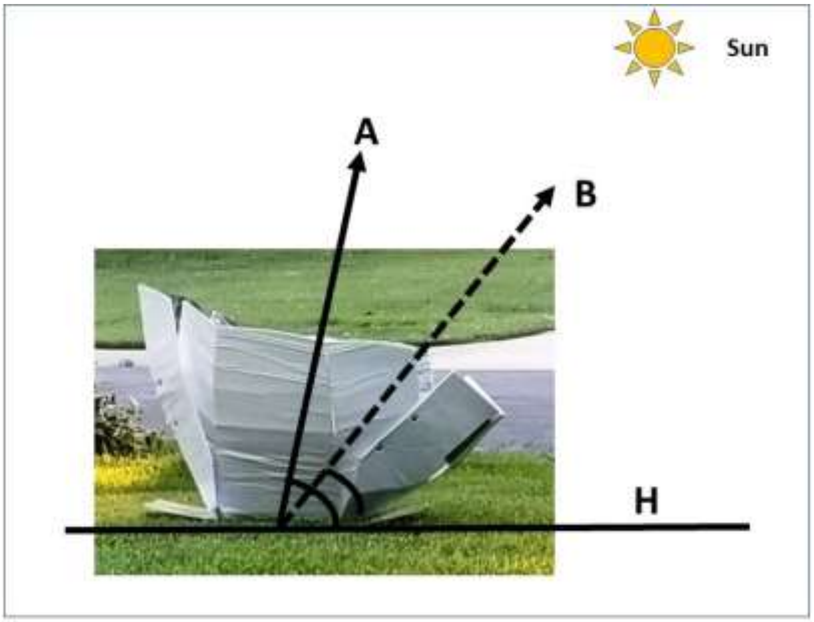

Figure 3. Angles of importance for a typical solar cooker reflector.

In this illustration, the base of the panel cooker is on the horizontal line H. The angle that yields the maximum reflector area is angle AH. But the angle to the Sun at a particular time is its elevation angle BH. The intercept area for the average Sun angle on the day of the test can be calculated as the maximum possible intercept area times the cosine of the difference between these two angles.

The maximum intercept area of the cooker and the angle (AH) for reaching this maximum angle are two parameters that characterize the device itself. It is necessary to know these parameters before one can carry out standard power testing, because they determine the mass of the load for the test. (Note that the angle of maximum reflector intercept area is not necessarily the same as the angle of maximum power for the cooker. A report describing a procedure for measuring the directivity of a solar cooker was provided in TR-27a [11].)

The "Load" sheet calculates the standard load to be used with a particular model of solar cooker on a particular day and location. The water load volume must be determined prior to making standard measurements.

Power calculation

The Excel Power spreadsheet calculates the standard power in Watts. It uses the measured lux data to infer the DNI irradiance values, based on the luminous efficacy factor as determined for the LX-3340 lux meter, which was 123 Lux per Watt for the instrument that was evaluated [1]. (Of course, this value could vary somewhat for different instruments, so it should be checked). The spreadsheet also uses the temperature measurements collected during each 10-minute interval using the procedure described above.

The standard requires the DNI irradiance values to be normalized or “adjusted’ to 700 W/m^2 by dividing 700 by the measured values from each interval *i*:

$$Ps_i = P_i \frac{700}{I_i}$$

where $I_i = L_i/123$ where
L_i = solar irradiance (Lux).
Ps_i = standardized cooking power (W)
P_i = interval cooking power (W),
I_i = interval average solar insolation (W/m2)

Thus the standard power Ps_i

$$Ps_i = \frac{(T2_i - T1_i)M\ Cv}{600} . \frac{700 * 123}{L_i}$$

where *T1* and *T2* are load temperatures at two successive 10-minute intervals; *M* is the load mass in kg, and *Cv* is the heat capacity of the water load. The standard power in each interval reduces to

$$Ps_i = 143.5\ \frac{(T2_i\ -\ T1_i\ )\ M\ Cv}{L_i}$$

A table on the sheet is used to calculate the adjusted power in each 10-minute interval. These power values are plotted *vs.* the temperatures above ambient. A linear regression on this plot gives the slope and intercept values of the regression line. The standard specifies selecting the value at 50˚C. This is the standard cooking power.

Measurement procedure

The standard protocol requires measurements of direct normal irradiance and cooker pot temperatures every ten minutes. Without data loggers, it will be necessary for the irradiance and temperature measurements to be recorded manually. This might be hot, repetitive work, and subject to more errors than by using automated instruments. It is therefore recommended to use ***two technicians*** for recording readings.

The ”Load” Excel sheet requires the user to enter the following information:

- Latitude of the test location
- Date of test
- Planned start time, stated as minutes before local solar noon
- Maximum intercept area of the solar cooker

- Solar cooker elevation angle for maximum intercept area relative to the horizontal

The solar cooker parameters should be measured in advance of the test time or obtained from the manufacturer. When these values are entered, the prescribed water load to be used in this particular test is calculated.

The procedure (following the ASAE test protocol in ref. [2]) requires these steps:
1. Prepare cooking pot(s), with holes drilled in the side if necessary, and load with an amount of water as prescribed in the protocol. Place a probe thermometer in each pot and ensure that the probe tip is submerged and does not contact the sides of the pot. Place the other thermometer in a location off the ground and in the shade near the test item.
2. The measurements are to be performed only at times when the wind speed is light (less than 2.5 m/s) and the sky is clear.
3. Prepare to start the measurements at exactly 10 am if possible. Set the test items to be pointed toward the Sun, but keep them shaded with a white cloth until the test begins.
4. Technician A sets the stop watch or timer for a 10 minute alarm.
5. After 10 minutes, technician A resets the timer, and technician B reads aloud the thermometer values, then reads the lux meter. To get the maximum reading, the meter's sensor must be pointed toward the Sun and slowly tilted up and down, right and left.
6. Technician A writes down the readings on a printed **prepared form** as shown on the next page. This cycle continues until the temperature in the pot reaches 95˚C, or until the time goes 2 hours past solar noon. The cooker may be turned toward the sun direction as required by the manufacturer.
7. When finished, copy the values from the prepared form onto the Excel Power sheet. Use the data from the pot temperature, ambient temperature and luxmeter to calculate the standard power

The ASAE protocol requires tests of a particular item to be repeated three times and averaged in order to provide a reliable value for the standard cooking power.

A video has been prepared that illustrates the testing procedure [12]. This video used the higher-cost instruments, but much of the procedure is similar to the above and this video adds some tips that may prove helpful to users.

Experience with this simplified method may lead to improvements, and users are encouraged to provide any feedback on their experience to the Director of Research at Solar Household Energy, Inc.

Solar Cooker Standard Power Measurement Form

Technicians: ____

Date: ______________________ Location: __________________________________

Latitude: ____________________ Altitude, m. ___________ Photos taken? _________

Product description	
Mass of load	

Start time: ___________ Data at each 10 minute interval:

Time Interval (minutes)	**Illuminance (Lux)**	**Amb. Temp. ˚C**	**Pot Temp. ˚C**	**Notes**
0				
10				
20				
30				
40				
50				
60				
70				
80				
90				
100				
110				
120				
130				
140				
150				
160				
170				
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200				
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220				
230				
240				

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