Solar Household Energy, Inc.
Solar Cooking for Human Development and Environmental Relief

SHE Technical Report no. TR-09.1

A system for standard power measurements of solar cookers based on commercial off-the-shelf instruments

Paul Arveson

SHE Director of Research
Solar Household Energy, Inc.

Original: Sept. 27, 2016
Updated version: Apr. 26, 2018

Citation: Technical Report no. TR-09.1, Solar Household Energy, Inc., (Apr. 26, 2018)

Solar Household Energy (SHE) strives to unleash the potential of solar cooking to improve social, economic and environmental conditions in sun-rich areas around the world. SHE Technical Reports are intended for use within the solar cooking community, for the rapid dissemination of findings related to solar cookers. They may contain information that is based on limited data, and/or conclusions and recommendations that are solely the opinions of the author, not of the organization. Please contact the author for further correspondence.

A system for standard power measurements of solar cookers based on commercial off-the-shelf instruments

Executive Summary

Billions of people still depend on food cooked over an open fire. This ancient practice has many serious health and environmental consequences, It is estimated that 3.5 million deaths annually are caused by respiratory diseases of women and children exposed to cooking smoke. Currently an ISO standard is being developed to define protocols for measuring the performance of improved cookstoves of all types. This includes solar cookers, which have no emissions, use no fuels, and can reduce fuel costs for low-income people and refugees. In the US, there is an existing standard for solar cooker power (American Society of Agricultural and Biological Engineers ASAE S.580.1).

This report documents instrumentation requirements, selected products and preliminary measurements made in compliance with this standard. Heating tests of several solar cookers were conducted to establish repeatability of temperature measurements. Sources of variation were identified and mitigation strategies were developed. This experience will be useful in continuing work aimed at implementing the protocol in the ISO standard and for constructing automated systems for solar cooker testing.

Background
ISO is the International Organization for Standards, based in Geneva. ISO manages the development of international standards for all types of products, services, processes and methods used by industry all over the world. These standards in many cases supersede national standards and replace them.

The purpose of the ISO-19867/8/9 standards for "Clean Cookstoves and Clean Cooking Solutions" [1] is to define a set of measurement protocols for consistent tests on cooking power, efficiency, emissions, durability, safety and user acceptance of all types of household-scale devices used for cooking food or heating water. The standard is not focused on product designs, materials etc. but on how cookstoves are to be tested.

There are several audiences for whom the standard is being written. One is national regulators. Another is technicians in testing labs and the field. (Some people advocated that the standard should be simple enough to be understood by end users, i.e. the general public. This is clearly not the case. It is a technical standard.)

The draft ISO standard includes a protocol for solar cooker power measurements, ASAE S.580.1. Having such a standard achieves many desirable goals:

- It raises the quality and performance of solar cookers by establishing a level playing field for everyone to define performance in the same way.
- It raises the credibility of solar cooking as a viable option to complement other types of cookstoves in locations where the climate is suitable.
- It encourages the manufacturing and distribution of solar cookstoves and thus unleash the many benefits of this technology to the world.

ISO standards are subject to period reviews, and it is possible that additional solar cooker protocols could be added to the standard in the future. The ISO teaches the concept of "consensus", in which the majority of experts agrees to tolerate a proposal, even though they may have some reservations about it, in order to allow the whole document to proceed the status of a Draft International Standard [2]. This flexibility allows additions and revisions to be made as experience is gained.

Selection of a Solar Cooker Test Protocol

Several countries already have developed national standards for measuring the performance (*i.e.* power and efficiency) of solar cookers. But selection of a protocol for the ISO standard was not approached merely as an arbitrary choice among existing protocols. We could not assume at the outset that there even *are* any protocols that are suitable. Rather, we took a top-down approach by defining several criteria that a well-specified protocol should meet. These include the following:

- The protocol should conform to the ISO definitions used for other types of cookstoves to the extent possible. We do not want solar cookers to appear to be "outliers", excluded from the rest of the cookstove types. (That proposal was floated frequently during the standard development discussions and we have had to push back on it).

- The protocol should measure cooking power in watts delivered to the food.
- The protocol should avoid measurements near boiling, because the increased vapor pressure leads to non-repeatable results.
- The protocol(s) should accommodate a wide range of types and sizes of solar cookers.
- The protocol should provide repeatable results within some specified margin of error.
- The protocol should provide reproducible results at any location in the world.
- The protocol should be relatively easy to learn, easy to use and productive.
- The protocol should be supported by low-cost instrumentation.
- The protocol should be possible to automate to a great extent.

Several protocols were reviewed against these criteria (although there is no claim that all existing protocols were examined, because we do not have access to all of them). One protocol that appeared to be suitable is the US standard, ASAE (American Society of Agricultural and Biological Engineers) S580.1 [3], which was developed by Dr. Paul Funk [4]. Tests performed using this standard were reported at the Clean Cooking Forum 2015 in Ghana by Jim Jetter, who operates the cookstove testing laboratory of the US Environmental Protection Agency [5]. Based on their decision, this protocol has been included in the Committee Draft of the ISO standard.

In order to establish any solar cooker standard, the following steps will need to be taken in order to set its parameters appropriately and assess its practicality and suitability:
1. Define instrumentation requirements and construct system needed to perform the protocol.
2. Conduct several heating tests of solar cooker models to establish repeatability of temperature measurements and to determine causes of variability in data.
3. Conduct multiple tests in different locations in accordance with the protocol, to determine if it yields reproducible measurements of power.
4. Determine if any revisions to the proposed protocol are needed to make it more complete, easier to use and/or more practical in an international standard.

The remainder of this report documents the first item in the list: the current status of instrumentation that has been assembled to conduct measurements in accordance with the ASAE S.580.1 standard. The second item, the establishment of repeatability of measurements, is addressed in another article [6].

Measurement Requirements in the ASAE S.580.1 Protocol

For any cookstove, the most important parameter to determine is its heating power, which relates to its ability to cook food. A secondary performance measure is its thermal efficiency. In the case of solar cookers, the energy source (the sun) is free, but efficiency is based on the size of the reflector used to capture solar energy. High efficiency means the reflector area can be kept to a minimum. This reduces material use, shipping and storage requirements.

The ASAE S.580.1 standard provides a specific protocol for determining the heating power of a solar cooker. Efficiency is easy to derive from the data collected in this protocol. The standard requires the following physical measurements to be collected as a function of time:

1. Solar irradiance
2. Wind speed near the location of the cooker
3. Ambient temperature
4. Internal temperature in the cooking vessel

1. Solar irradiance measurement requirements

The requirement is to measure solar radiation that is incident on a solar cooker's intercept area. Solar irradiance refers to the power flux received from the sun, measured in Watts per square meter.

There are several types of solar irradiance data. For many solar energy applications (such as photovoltaic panel installations), the prescribed measurement is Global Horizontal Irradiance (GHI), which is equivalent to the power on a 1 square meter horizontal surface. "Global" refers to the inclusion of both direct and diffuse radiation scattered from the entire sky. However, for most solar cooker designs, GHI is not the appropriate measurement, because solar cooker reflectors can only concentrate the direct radiation, not the diffuse radiation. Therefore, an alternative quantity is often defined that includes only the direct component. A further modification is needed, because direct radiation must be measured in the direction of the sun, not in a horizontal direction. This is called Direct Normal Irradiance (DNI).

Typically, DNI is measured with a pyrheliometer. This is a complex instrument that includes a motorized sun tracker, a telescope to maintain a 5-degree wide view centered on the sun, and a thermopile sensor that must be carefully temperature-controlled and shielded. Interpretation of the data, as discussed by Gueymard [7], indicates the technical complexities involved in these measurements. In addition, pyrheliometers are very expensive instruments.

The ASAE S.580.1 standard calls for another instrument, a pyranometer. A pyranometer is a much simpler, low-cost instrument that uses a light sensor with a cosine directivity response. Typically these are used to measure GHI. However, the standard prescribes their use to measure Tilted Normal Irradiance (TNI), by tilting the sensor to point toward the sun. The resulting data is a “hybrid”: the instrument is pointed directly toward the sun direction, but it uses a sensor with a wide-angle cosine response. This requirement in the standard is a brilliant idea. It is more appropriate than GHI, because it is aimed toward the incident radiation, as a solar cooker would do. But it has a wide acceptance angle, as is typical for box and panel-type solar cookers. Therefore, this design is more likely to represent the actual radiation that is collected in these types of solar cookers. For parabolic cookers with a narrow acceptance angle, there will be a small deviation from TNI if there are clouds in the vicinity of the sun.

(In this regard project planners should be reminded that maps of solar radiation or insolation for solar cooker purposes should use DNI data, not GHI. DNI data are appropriate for *concentrating* solar energy, either for power plants or solar cookers [8].)

<u>Instrumentation:</u>
Low-cost silicon diode pyranometers are available from many suppliers that provide stable and reliable output. They are self-powered, but the maximum output is only about 200 mV, so it may be desirable to amplify the signal. Such devices are available at a slightly increased cost.

For redundancy, one pyranometer should be used for tilted irradiance measurements, and another will be included for conventional GHI (horizontal) measurements.

Pyranometers should be calibrated periodically against a secondary standard. The procedures for doing this are specified in standards such as ISO-9901 [9].

2. Wind speed measurement requirement

The ASAE S.580.1 standard requires that solar power measurements be discarded if a 10-minute average of wind speed exceeds 2.5 meters per second. The concern is that high wind speeds may increase the heat loss from the solar cooker and reduce its heating power. By eliminating readings during periods of high wind, this concern is eliminated.

<u>Instrumentation:</u>
An anemometer is used to measure wind speed, and in this case the anemometer must be located near the solar cookers being tested. (This measurement is different from the conventional wind speed measurements at 10 m altitude for weather purposes). There are several types of wind speed measuring devices, including cup-type anemometers with a rotating magnet, a reed switch, or a light chopper. Other devices use a heated wire or acoustical sensors. The standard requires only indication of a threshold, so a simple, low-cost cup-type anemometer is sufficient. However, the rotating-magnet type

may use a field coil that requires an external power supply; others are self-powered. This may be a consideration if portability is required.

3. Ambient temperature measurement requirement

Power calculations in the standard are based on the difference between internal vessel temperature and the ambient temperature of the air temperature in the vicinity of the solar cookers being tested.

Instrumentation:

A calibrated thermometer or temperature sensor in a shaded enclosure can suffice for measurements of the ambient temperature. In order to provide a valid ambient temperature, the instrument must be shaded from direct sunlight, but allowed to have direct contact with the air. Also, it should be suspended above the ground at the level of the devices being tested. It is convenient to house the thermometer (and other instrumentation) in a “Stevenson box”, which is traditionally used for air temperature measurements by meteorologists.

4. Internal cooking vessel measurement requirements

The internal temperature of the load in the cooking vessel must be measured at intervals not to exceed 10 minutes.

Although it is not a stated requirement, it is assumed that all solar cooker measurements will be made on at least two copies of the test item at the same time. This will provide a check on the repeatability of the measurements and the item under the same solar conditions.

Instrumentation:

The ASAE S.580.1 standard specifically calls for a thermocouple to be placed at the center of the cooking vessel 10mm above the bottom. Because they will be immersed in water, it is preferable to use sealed sensors. Thermocouples are small, so their wire leads are also small. This is important because it has been found that gaps in the cooking vessel lid are a major cause of heat loss. If this is a concern, it may be necessary to place wires through a sealed hole in the cooking vessel.

The thermocouples must be supported under the water but not in contact with the walls of the cooking vessel. Maintaining the thermocouples at the correct position in a pot of water can be difficult. Tape cannot be used, because of the wet and high temperature environment. Weights would affect the data. Wire supports may be used; if so they should be made of stainless steel. However, if thermocouple wires are sufficiently stiff, they may serve as adequate supports. The use of two thermocouples in the same vessel will allow a check on their repeatability.

Other Instrumentation requirements

Data loggers:
To collect the data from the various sensors, programmable digital data loggers are required. The data loggers must have sufficient voltage range to accommodate the sensor signals. Also, they must have resolutions somewhat smaller than the measurement requirements, so that they do not contribute resolution errors to the data. (A full error analysis of the assembled instrumentation is to be developed).

A minimum of five channels of data need to be logged; this implies that two internal temperatures will be measured from two test items simultaneously. Additional channels would be desirable for redundancy checks.

Measurement platform:
Panel and box-type solar cookers should be mounted on a platform that will allow the user to adjust the tilt angle of the base. This is necessary to allow the system to maintain similar sun angles depending on the latitude of the test location. Also, each cooker reflector must be allowed to rotate at specified intervals to track the sun. For typical box or panel cookers, the cooker is turned once per hour; however, the manufacturer may specify a different interval and angle.

These requirements lead to a platform that has three parts: a) the base on which the whole platform is supported; b) the tilt platform with a tilt angle indicator; c) the rotating platform, on which the test item is placed; this platform has a horizontal angle indicator.

The pyranometer that measures Tilted Normal Irradiance (TNI) is mounted on an arm on the rotating platform and set at a vertical angle as specified by the manufacturer (i.e. the angle of maximum efficiency of the reflector). All exposed parts of the upper platform and arm are painted black to minimize unwanted reflections.

Supporting instruments and tools:
In addition to the technical instrumentation requirements, there are several supporting items that will be needed for solar cooker power measurements.
a) A quality camera is essential for documenting all experimental setups.
b) A variety of cooking vessels should be on hand.
c) Vessels must be painted black using a truly good quality black spray paint and primer. Not all "black paint" is the same; some is blacker than others. Also, it is important to ensure that the paint can handle high temperatures.
c) An assortment of clips and clamps will be helpful in adjusting reflectors.
d) A digital kitchen scale capable of weighing up to 5 kg should be available.

e) Jugs of distilled water will be needed to provide the standard load for testing. Distilled water is recommended, because it can be reused and will not leave residues on vessels in which the water was boiled.
f) 1-liter measuring pitchers, cylinders, and funnels will be needed to handle the distilled water. Use good quality products made of polypropylene.

Products Selected for the Prototype Standard Measurement System

1. 4-channel 16-bit analog data logger, UX120-006M, Onset Computer Co.
2. 4 signal cables, 2.5mm stereo mini plugs, 10 ft., Video Products Inc.
3. 4-channel thermocouple data logger, UX120-014M, Onset Computer Co.
4. Type T thermocouple sensors, pack of 5, STC-TT,T,24-72, Omega Engineering Inc.
5. 4 Miniature thermocouple connectors, SMPW-CC-T-M, Omega Engineering Inc.
6. Pyranometer, Institute for Earth Science Research and Education, www.instesre.org
7. Pyranometer, Apogee SP-212 (amplified).
8. Anemometer, Item 1733, Adafruit, Inc. www.adafruit.com
9. 15W PV Solar Panel module 12V, Acropower Inc.
10. Solar Panel Charge Controller 12V, JVR Inc.
11. 12V lead-acid storage battery, Micro Center Inc.

Total cost of instruments: $956.40
(This list does not include assorted cables, enclosures, batteries and other items used in the assembly of apparatus.)

This is a first-generation system based on off-the-shelf commercial instruments. Alan Bigelow of Solar Cookers International has developed a low-cost open-source testing system using an Arduino microprocessor. Martin Steinson at the National Center for Atmospheric Research in Colorado is developing a low-cost weather station using 3D-printed components and low-cost Raspberry Pi computers. These will lead to a system that is much smaller and lower in cost than previous weather instrumentation [10].

The Assembled Measurement System

Figure 1 shows the prototype system used in the summer of 2016 for solar cooker tests.

Notice that there are two solar cookers under test. A minimum of two items are measured at one time in order to verify repeatability of the data. The system can actually measure up to four cookers at one time, which can increase productivity of operations. (The test platforms were not constructed at the time of this photo.)

The white “Stevenson box” has a pyranometer and the anemometer attached to the top, and it contains the electronics package. A small solar PV panel is also deployed to provide power to the anemometer and powered pyranometer.

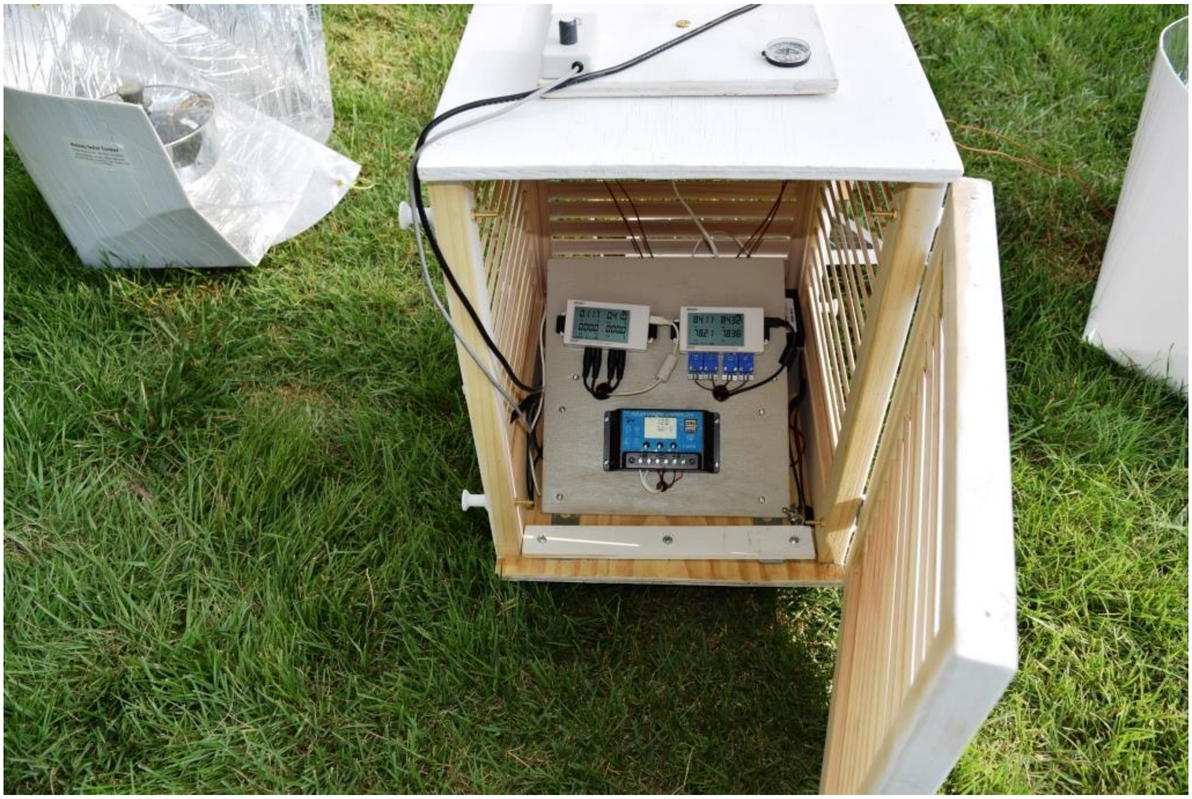


Figure 2 shows the instruments in the interior of the Stevenson box. It contains the two Onset data loggers and a controller for the PV panel. There is a 12V lead-acid storage battery behind the panel.

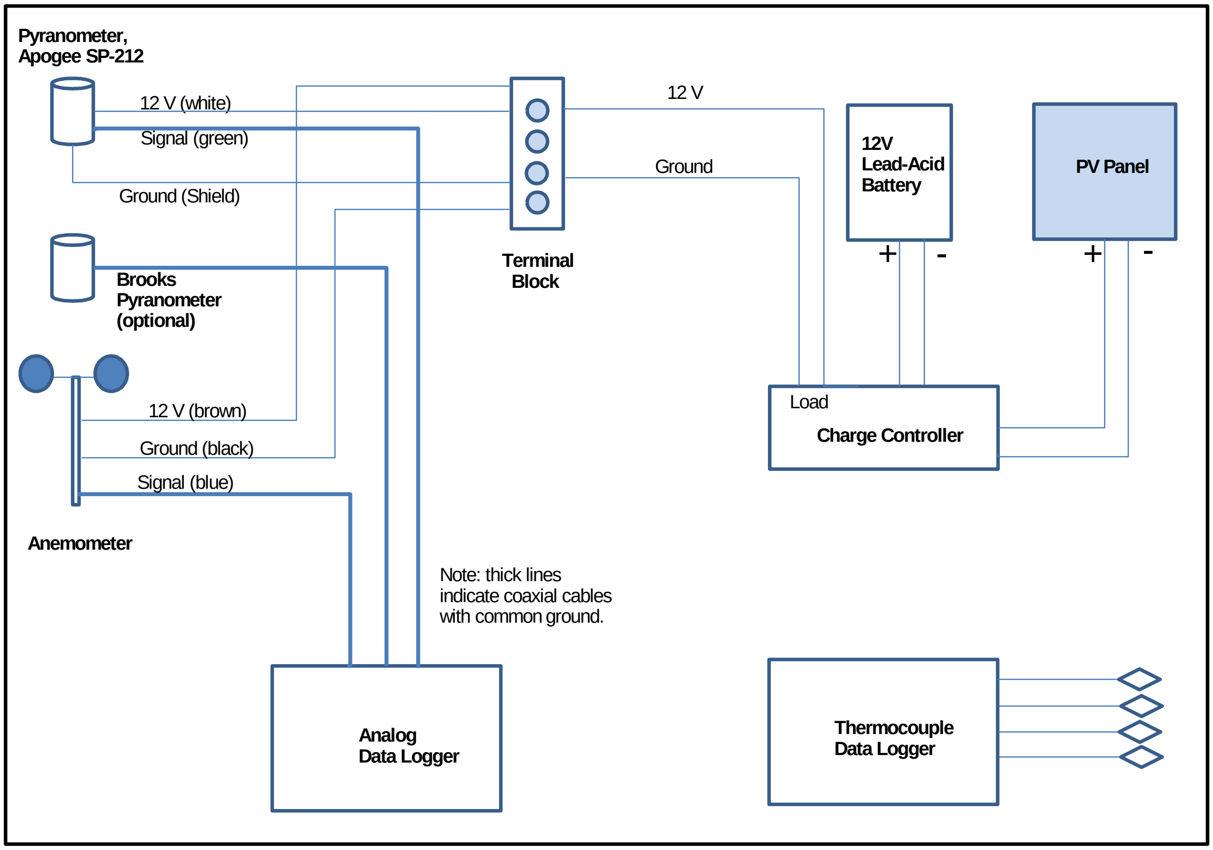
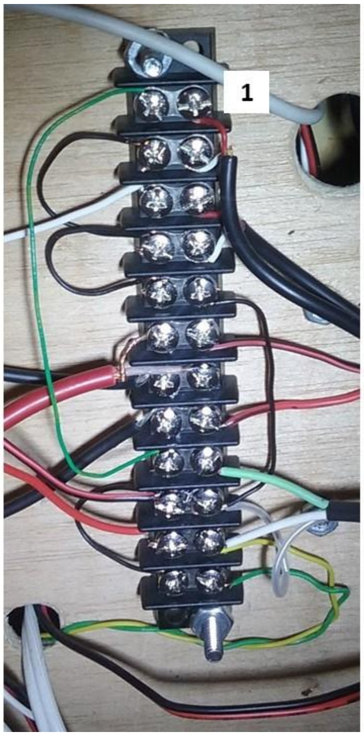


Figure 3 above shows a circuit diagram of the entire system. Both the amplified pyranometer and the anemometer require 12V dc power, which adds to the complexity of the instrumentation. If a self-powered pyranometer and anemometer were used, the system could be much simpler. The data loggers are powered by internal AA batteries.

The analog data logger requires 2.5mm mini plugs for input connections. These were purchased from Video Products, Inc. Their cables contain two signal wires, red and yellow, and a ground shield. For this application, the yellow wire is not used.



1 - pyranometer signal (green)
2 - pyranometer ground
3 - anemometer signal (white, spliced to blue wire)
4 - anemometer ground
5 - ground
6 - battery negative and - terminal from charge controller
7 - switch and battery +
8 - switch and battery + terminal from charge controller
9 - pyranometer signal (green)
10 - anemometer ground and pyranometer shield
11 - pyranometer and anemometer power, load positive from charge controller
12 - ground, charge controller load negative

All of the internal connections are made via a barrier terminal block as shown in Figure 4 above. The color codes for each of the wires is as shown.

For testing panel and box solar cookers, the reflectors are rotated periodically by hand to track the sun. This represents the expected operation by cooks in the field. Work has begun on an automated system that will rotate the cookers at a specified angle and interval. This will increase productivity of the system.

Measurement Accuracy and Precision Requirements

An analysis of the power calculation in the ASAE S.580.1 standard shows that the accuracy of the final power measurement is directly dependent on the accuracies of the solar irradiance measurements and the temperature measurements. Hence the instruments making these measurements must have deviations in accuracy and precision that are smaller than those expected due to random variations in the solar cooker tests.

Solar irradiance measurements

<u>Accuracy</u>: Pyranometers are calibrated by comparison to readings of another pyranometer that has been calibrated relative to a secondary standard. The primary standards are kept at a laboratory in Davos, Switzerland. The products purchased have been calibrated by the manufacturer using a standard that is traceable to this primary standard. The accuracy of the Apogee SP-212 pyranometer is quoted as +/- 5%.

The pyranometers used in this system use silicon photodiode sensors, which are quite stable over time, with variations of less than 2% per year. However, they should be recalibrated every few years. The data logger has four channels; one is for the anemometer and the other three are available for pyranometers. In the prototype, two different pyranometers are used, so that relative differences between them can be measured at any time to verify stability.

Precision:

A self-powered photodiode pyranometer has an output of about 0.2 Volts for a solar irradiance of 1000 W/m^2. This is a fairly weak signal. The Onset 4-channel data logger has a resolution of 16 bits and a full-scale input of 2.5 V. This means that 1 bit = 0.038 mV. For a change in irradiance of 1 W/m^2, the pyranometer will change by 0.2 mV, so the data logger will read 0.2/.038 = 5 bits. So the self-powered pyranometer will be able to provide a resolution as small as 0.2 W/m^2.

The tilted pyranometer must be mounted on the test item platform, which is some distance from the data logger. In some cases, electromagnetic interference was observed with the weak signal, so it was decided to use an amplified pyranometer for this application. The Apogee SP-212 amplified pyranometer has a 2.5 V full scale output, which adds about 3 bits of resolution to the measurements. In any case, the precision of the digital data is much better than the accuracy specification of the sensors.

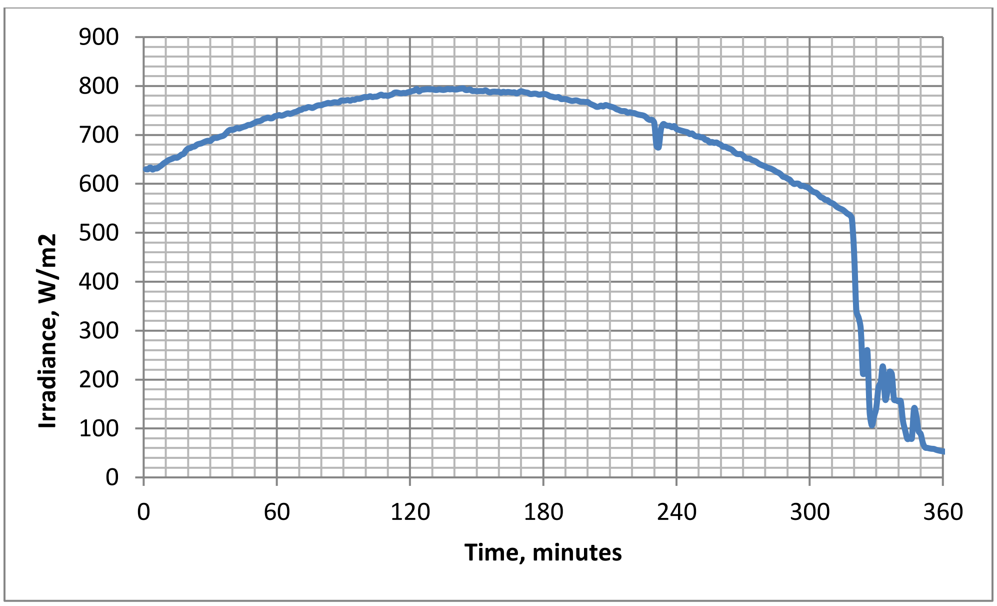


Figure 5 above shows typical data from the pyranometer that was measuring global horizontal irradiance on a clear day (9/23/2016). The drops in the signal represent times when shadows or clouds blocked sunlight. The calibration of this anemometer was obtained from the manufacturer, in comparison to a secondary standard.

Wind speed measurements

An anemometer is mounted on the top of the Stevenson box for recording wind speed during the measurements. The ASAE S.580.1 standard requires wind speed to be lower than 2.5 m/s during any 10-minute interval and average less than 1 m/s for the duration of the test. The calibration of the wind speed was obtained from the manufacturer and verified by tests with a large fan. For the anemometer used here, the calibration was found to be 21.17, and the offset was approximately 0.4 volt.

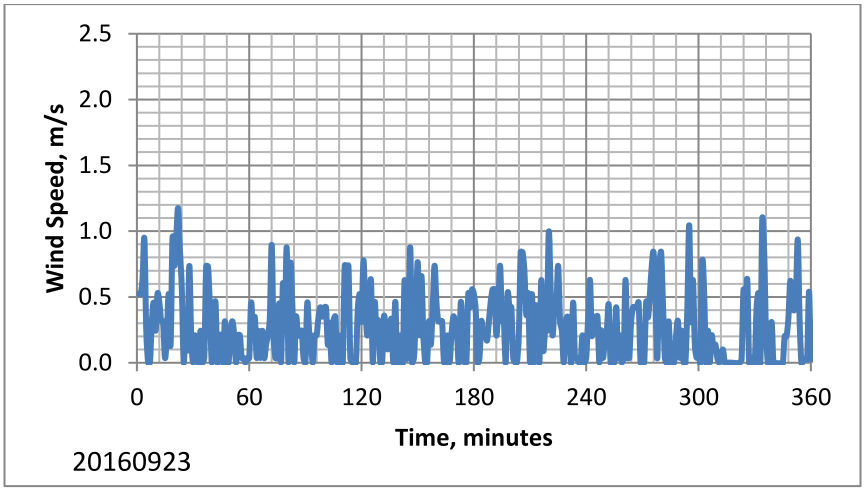


Figure 6 shows a sample of the raw data from the anemometer obtained on 9/23/2016. For standards purposes, these data should be averaged over 10 minutes, but it is evident from these data that the standard criteria were not exceeded during this test.

Temperature measurements

Accuracy: The accuracy of temperature measurements was evaluated at two points: in an ice bath at 0 degrees C, and at the local boiling point of water, near 100 degrees C. All four Omega thermocouples showed accuracy within +/- 0.5 degree C. in both cases.

Precision: The Onset 4-channel thermocouple data logger reports temperature measurements with a resolution of 0.01 deg. C. This is much smaller than the variations in accuracy of the thermocouples as measured experimentally, and thus the data logger is quite satisfactory for these measurements. (The ambient temperature is measured using the thermistor reference located inside the data logger). See the figures below showing variations in all four thermocouple channels over about an hour.

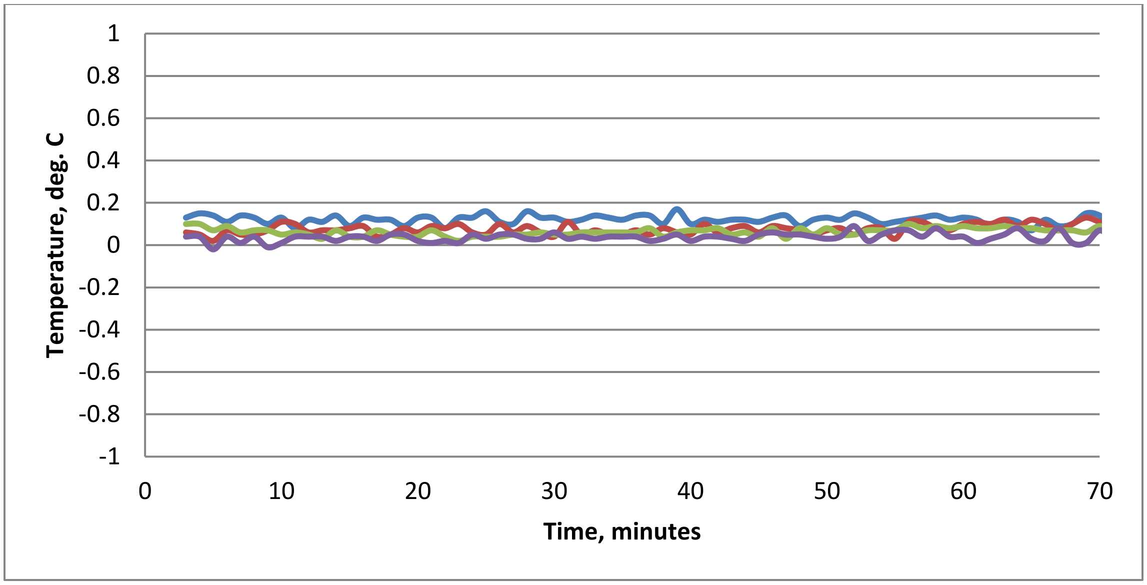


Figure 7. Comparison of readings from four thermocouples in ice bath at 0 deg. C.

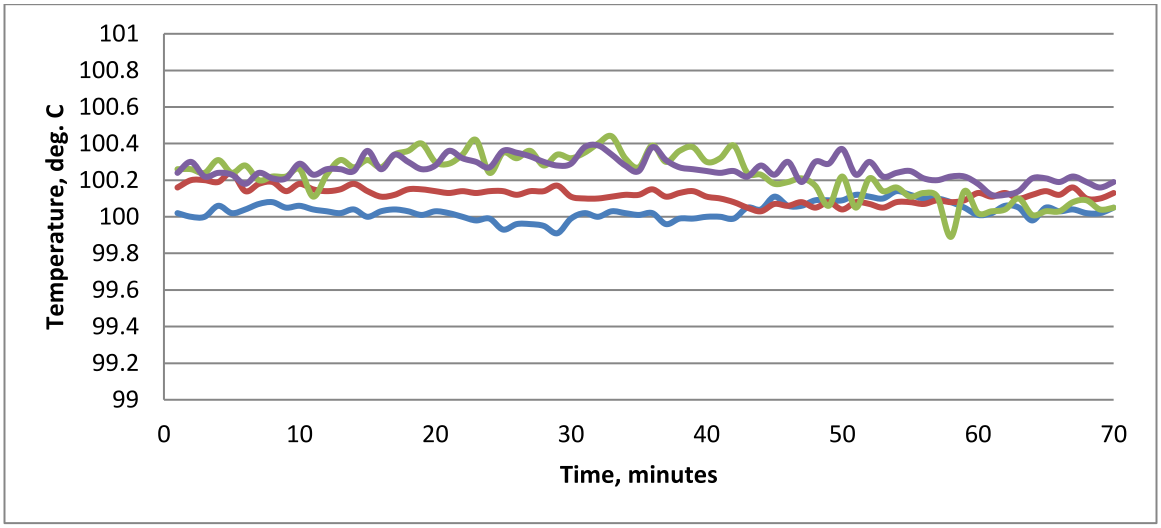


Figure 8. Comparison of readings from four thermocouples in boiling water, 9/23/2016.

Conclusions

A prototype instrument package for solar cooker power measurements has been constructed. The design is agnostic with respect to the specific details of the performance testing protocol, but the prototype was used during the summer of 2016 to collect data in accordance with the ASAE S.580.1 protocol. In another report, the compilation of heating data and power calculations is described. Increased experience with this system will allow users to determine its repeatability and reproducibility, so potential users, especially those at Regional Testing and Knowledge Centers [11] are encouraged to replicate this system for local testing purposes, and to exchange data with the author.

Instructions for conducting solar cooker power measurements with this instrumentation are described in another technical note in this series (TR-16.1) [12].

Acknowledgements

The idea of developing a set of instruments for testing solar cookers was inspired by a conversation with Dean Still of Aprovecho, a major US testing center for combustion cookstoves. Financial support for instrument purchases was provided by Solar Household Energy, Inc.

References

1. ISO-19867-1, "Clean cookstoves and clean cooking solutions, Part 1", http://www.iso.org/iso/catalogue_detail.htm?csnumber=66519

2. "Engaging stakeholders and building consensus", ISO Guidance to National Standards Bodies, ISO, Dec. 2010.

3. "Testing and Reporting Solar Cooker Performance", American Society of Agricultural and Biological Engineers, ASAE S.580.1, Nov. 2013. http://www.ASAE.org/media/200979/s580.1.pdf

4. P. A. Funk, "Evaluating the international standard procedure for testing solar cookers and reporting performance", *Solar Energy* 68(1):1-7.

5. J. Jetter, "Solar cooker power test results", a presentation at the Clean Cookstove Forum, Ghana, Nov. 10, 2015.

6. P. Arveson, "Towards an International Standard for Measuring Solar Cooker Performance*", J. Wash. Acad. Sci.* **102**, 3 (Fall 2016).

7. Gueymard, C. A., "From global horizontal to global tilted irradiance: how accurate are solar energy engineering predictions in practice?", Solar 2008 Conference, American Solar Energy Society

8. Free solar maps, http://solargis.com/products/maps-and-gis-data/free/download/

9. ISO/TR 9901:1990, "Solar energy – Field pyranometers – Recommended practice for use"; ISO 9847:1992, "Solar energy – Calibration of field pyranometers by comparison to a reference pyranometer"

10. D. Hosasnsky, "3D-Printed weather stations fill gaps in developing world", AtmosNews, University Corporation for Atmospheric Research (UCAR), June 2, 2016, https://www2.ucar.edu/atmosnews/news/21287/3d-printed-weather-stations-fill-gaps-in-developing-world

11. "Connect with Testing Centers", Global Alliance for Clean Cookstoves, http://cleancookstoves.org/technology-and-fuels/testing/centers.html

12. P. Arveson, "Instructions for conducting a solar cooker power measurement using data loggers", Technical Report no. TR-16.1, Solar Household Energy, Inc. (Sept. 2017).