

Development and Implementation of a Performance Evaluation Process (PEP) for Solar Thermal Cooking Devices

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Abstract

Solar Cookers International staff designed and built portable test stations for a performance evaluation process (PEP) for solar thermal cookers in response to a specific need expressed by the solar cooking sector that an independent, neutral agency develop a testing process for solar thermal cooking devices. The PEP test stations are based on commercially available components, including thermocouples, an anemometer, a pyranometer and Arduino hardware. The test station control software was designed to automate the American Society of Agricultural and Biological Engineers (ASAE) S580.1 protocol for Testing and Reporting Solar Cooker Performance; it measures temperature changes in an amount of water proportional to the intercept area of a solar cooker, while monitoring wind speed and solar insolation, for normalizing results. With its development and implementation of its PEP solar cooker testing program, Solar Cookers International has built the capacity for testing solar cookers according to internationally agreed upon standards. PEP measurements produce the standardized cooking power performance specifications of solar cookers, and those specifications can guide customers and investors in making informed decisions.

Keywords: Testing standards, Solar cookers, Sustainable development, Solar thermal cooking, Tier 4 cookstoves

1. Introduction

According to the World Health Organization, for the approximately three billion people cooking food by using biomass fuel such as firewood, charcoal or animal dung, smoke particulates from cooking indoors is linked to some 4.3 million premature deaths annually worldwide (World Health Organization, 2016). It also is having negative impacts on the health of people, mostly women and children, regularly exposed to high levels of indoor air pollution. Solar thermal cookstoves that convert solar energy directly into heat energy are viable options for clean sustainable cooking that are beneficial for all, including the most vulnerable populations.

Solar cooking devices harness free, solar energy with no-emissions, clean sustainable cooking. Solar cookers collect solar energy with reflectors, absorb solar energy with black surfaces to transform solar energy to heat energy, and retain heat using insulation. People can generally obtain a solar cooker by purchasing a commercial product, by building one using an open-source design, or by innovating and implementing a new design. Prices for commercial solar cookers range from tens to hundreds of US dollars.

Types of solar cookers include the reflective-panel, box oven, parabolic reflector, evacuated tubes, Fresnel lenses and Fresnel mirrors. Institutional solar cooking systems are another type of solar cooker. These systems can be mounted on rooftops to concentrate solar energy, heat water, and create steam, or heat a thermic fluid, such as oil, that is transferred to a kitchen inside the building. In India, for example, there are institutional solar cooking systems that power mega kitchens that can cook tens of thousands of meals per day (Eswara & Ramakrishnarao, 2013).

Solar cooking has numerous benefits that can transform lives, particularly for women and girls in developing regions who are disproportionately exposed and impacted by harmful aspects associated with acquiring and using combustible cooking fuels such as firewood and charcoal. Solar cookers are suitable for nutritious meals, like legumes and pulses that are otherwise fuel-intensive to cook. Furthermore, with solar cooking, less time is spent scavenging for firewood, freeing up time for education and micro-enterprises; indoor air quality improves; deforestation is reduced; and family budgets for cooking fuel can be reduced (Bigelow, Fox, & Hughes, 2020). Solar cookers can pasteurize water, killing water-borne microbes (bacteria and viruses)

(Ciochetti & Metcalf, 1984). Solar dryers heat their contents using solar thermal methods to dehydrate and preserve food, which adds post-harvest value and increases food security (Eswara & Ramakrishnarao, 2013).

Solar cooking can make a positive impact on all 17 United Nations Sustainable Development Goals (SDGs) (United Nations, 2022); hence, solar cooking's potential for social, economic, and environmental solutions suggests it for bold and transformative steps which are urgently needed to shift the world to a sustainable and resilient path for environmental and human preservation.

Solar Cookers International (SCI) is a non-profit organization whose mission is to improve human and environmental health by supporting the expansion of effective carbon-free solar cooking in world regions of greatest need. SCI leads through advocacy, research, and strengthening the capacity of the global solar cooking movement. SCI is a convener that connects 500+ collaborators in 135 countries and hosts the Solar Cooking Wiki that has over 1,700 pages of information about solar cooking, including open-source design plans (Solar Cookers International, 2022).

SCI is an independent and brand-agnostic international agency. Because of its objective leadership status and expertise, SCI was well-positioned to respond to the solar cooking sector's request for an independent organization to develop a platform for evaluating solar cookers according to existing testing standards. The outcome is SCI's development and implementation of the Performance Evaluation Process (PEP) for testing the thermal performance of solar cookers. PEP implementation is poised to boost the solar cooking sector and enhance the impact from use of solar cookers. More specifically, PEP is benefiting the solar cooking sector by assisting customers in selecting solar cookers; building credibility and verification for the solar cooking sector; encouraging manufacturers to develop superior products; and guiding project managers in selecting appropriate solar cookers for their projects.

In developing the PEP, SCI has established a standard testing platform for measuring the thermal performance of no-emissions solar cookers. SCI is included on the list of Regional Testing and Knowledge Centers (RTKCs) posted by the Clean Cooking Alliance (Clean Cooking Alliance, 2022). In addition to SCI's testing locations in California, USA and New York, USA, SCI has provided instrumentation and training to two other RTKCs (Center for Rural Technology, Lalitpur, Nepal; and University of Nairobi, Nairobi, Kenya), which now have the capacity for PEP testing of solar cookers in their respective regions.

2. Theoretical framework

There are multiple ways to evaluate a solar cooker, such as these existing approaches for evaluating the thermal performance of solar cookers: 1) ASAE S580.1 Testing and Reporting Solar Cooker Performance (American Society of Agricultural and Biological Engineers, 2013); 2) the Indian Standard: Solar Cooker - Box Type - Specification (Bureau of Indian Standards, 2000); and 3) the Focusing Solar Cooker (Ministry of Agriculture of the People's Republic of China, 2003). After reviewing those approaches, SCI chose to base its testing platform on the ASAE S580.1 protocol. The ASAE S580.1 protocol was initiated in January 1997; has received further evaluation (Funk, 2000) (Ebersviller & Jetter, 2020); and is specified by the International Organization for Standardization (ISO) as a normative reference for measuring standardized cooking power for solar cookers in the ISO 19867-1:2018 standard for laboratory testing of cookstoves (International Organization for Standardization, 2018) and in the ISO 19869:2019 standard for field testing of cookstoves (International Organization for Standardization, 2019). Furthermore, the solar cooking sector agreed that ASAE S580.1 was the most suitable protocol for evaluating solar cookers (6th SCI World Conference, January 2017), and it has recognition at the Clean Cooking Alliance. SCI's PEP automates the ASAE S580.1 protocol to determine a performance metric according to the ISO standards mentioned above. Those ISO standards include protocols for durability and safety metrics that apply to solar cookers.

The ASAE S580.1 protocol for evaluating solar cookers provides a single measure of performance: the standardized cooking power, $P_{s(50)}$, expressed in watts. This value for standardized cooking power is evaluated when the cooking temperature is 50 °C above ambient temperature, at a temperature relevant to the onset of cooking. Standardized cooking power is derived from measurements of temperature change in an amount of water proportional to a cooker's intercept area (7000 g/m²); hence, it is a measure of the uptake of power in water that is within a cooking vessel and can be interpreted as a heating rate for a given quantity of water. Standardized cooking power results are normalized using incident solar radiation, allowing comparable results

independent of testing date and location. The testing protocol includes constraints on ambient temperature and wind speed values to limit heat loss due to those factors.

SCI added several refinements in applying the ASAE protocol to improve solar cooker evaluations. These steps are described further in the methodology section below and include using an automated data acquisition platform, on-board and post-processing routines, Global Positioning System (GPS), horizontal pyranometer positioning with trigonometric evaluation of irradiance values, a trigonometric correction of the solar cooker intercept area, default cookware, feed-through thermocouples and a thermocouple calibration routine, and emphasis on using a level surface while testing.

To summarize the ASAE S580.1 protocol, it first calculates the cooking power for a solar cooker during successive 10-minute intervals using equation 1 (eq. 1), where, for each i^{th} 10-minute interval, P_i is the cooking power (W); T_1 is the initial temperature ($^{\circ}\text{C}$); T_2 is the final water temperature ($^{\circ}\text{C}$); M is water mass (kg); and C_v is heat capacity of water (4186 J/[kg $^{\circ}\text{C}$]).

$$P_i = \frac{(T_2 - T_1)MC_v}{600\text{ s}} \quad (\text{eq. 1})$$

Adjusted cooking power, P_s , for each 10-minute interval is corrected and normalized to a standard insolation of 700 W/m² by multiplying cooking power P_i by 700 and dividing by the interval average insolation I_i , as shown in equation 2 (eq. 2). The term insolation is used interchangeably with irradiance in this article.

$$P_s = P_i \left(\frac{700\text{ W/m}^2}{I_i} \right) \quad (\text{eq. 2})$$

Adjusted cooking power values are then graphed with respect to temperature difference between the water and the ambient air – a minimum of 30 adjusted cooking power values (observations) are required. Standardized cooking power, $P_{s(50)}$ (W), the single measure of performance for a solar cooker, is determined where a linear regression fit to adjusted cooking power values crosses the temperature-difference value of 50 $^{\circ}\text{C}$. This method for determining standardized cooking power is explained further below (Findings and discussion), and shown in Fig. 6.

3. Methodology

With the ASAE S580.1 available as an internationally-agreed-upon standard for testing solar cookers, a corresponding need was for standard instrumentation with consistent components for automating the protocol. A standard test platform with consistency in instrumentation and post-processing routines can provide uniformity in data acquisition. SCI therefore developed a common test platform to facilitate consistent data collection and analysis. SCI self-imposed the following design requirements when developing PEP test stations: the instrumentation should be robust and relatively inexpensive. SCI met these requirements. The PEP test station is robust: it is portable (fits inside carry-on luggage), easy to set up, powered at the test site, and able to withstand most test environments. The PEP test station is relatively inexpensive; its design includes Arduino electronics and requires minimal software programming skills. SCI has designed and created such PEP test stations that: 1) automate the ASAE S580.1 protocol for evaluating solar cookers, and 2) satisfy all the design requirements.

3.1. Hardware

After considering the cost advantages from a do-it-yourself approach, each PEP test station (see Figure 1) was built using commercially available components with a total parts cost of less than 1,000 USD. Test station hardware includes an Arduino Mega open-source electronics platform, GPS, liquid crystal display, three type K thermocouples with controllers, an anemometer (Adafruit, New York, New York, USA), and an SP-215 amplified pyranometer (Apogee Instruments, Inc., Logan, Utah, USA). Electronics are housed in a weather-resistant enclosure and data are stored on a removable SD card; see Figure 2. The pyranometer mounts to a horizontal, bubble-leveled plane, as suggested by the manufacturer; the PEP test station is in the same proximity as the solar cooker(s) being tested, and testing sites are clear of nearby objects that could create shadows and/or reflections. While this positioning differs from the sun-angle alignment suggested in the ASAE protocol, software based trigonometric corrections to SCI solar irradiance measurements give accurate results within instrument tolerance, for solar irradiance incident on solar cookers being tested. The ASAE protocol

allows changes in approach, such as this, if they are notated in the results report. The system is expandable and can accommodate up to eight thermocouples and Bluetooth connectivity.

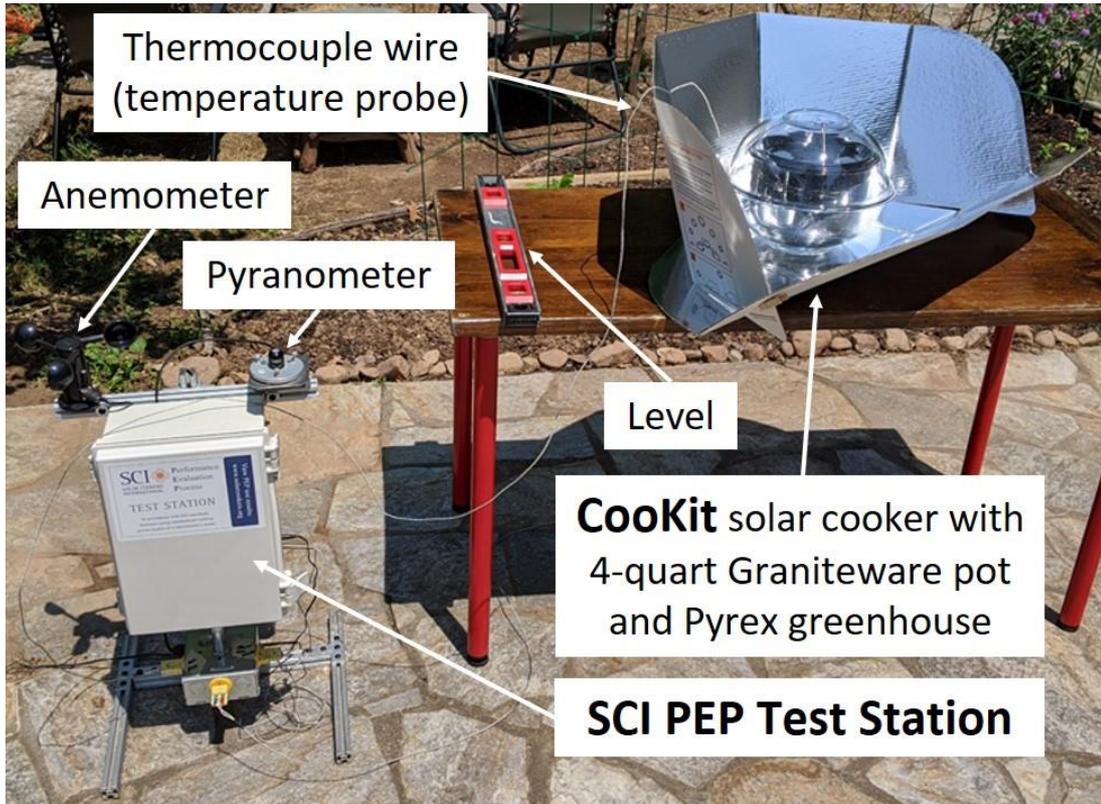


Fig. 1: Picture from 2 July 2020 of an SCI PEP test station while evaluating the thermal performance of an SCI CookKit, a reflective-panel cooker, using Pyrex bowls as a greenhouse.

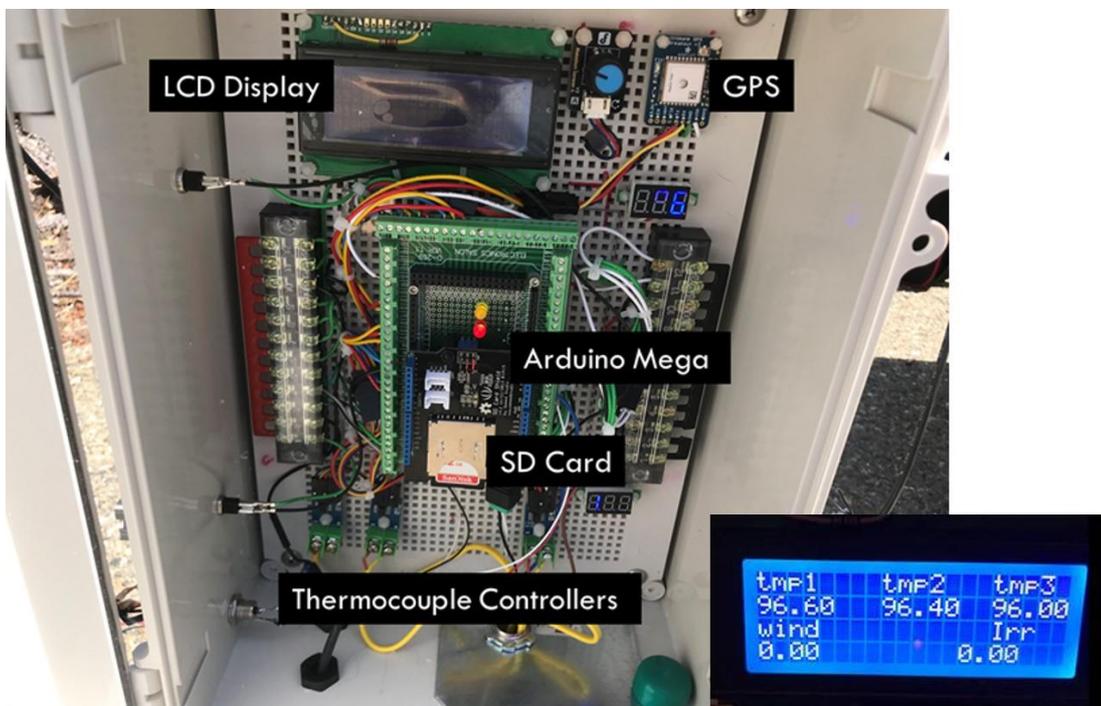


Fig. 2. Picture showing the electronics layout for an SCI PEP test station with a close-up of the LCD display (lower right corner).

3.2. Software

Control software for the PEP test stations was written in-house using C++. The software accepts user input listed in a config.txt file with parameters, such as duration of evaluation, duration of observation intervals, average sun elevation during the test, and water load values. Data is stored on an SD Card as a space delimited text file. This approach automates data acquisition from all sensors. Raw data is post processed by an external program written in C++, including bounded Adjusted Cooking Power calculations according to the ASAE S580.1 protocol. It also applies a 2-point calibration correction to the thermocouple sensor channels to ensure accurate temperature readings. After a solar cooker evaluation, the user can open the resulting data and post-processed files into Microsoft Excel, for example, to inspect the data and prepare graphs for a PEP results report.

3.3. Testing

SCI's PEP requires several set-up steps. First, since the water load for a PEP test is proportional to the intercept area of a solar cooker, one needs to determine that area prior to the test. If the maximum intercept area and the elevation angle for the solar cooker are known, one can apply a trigonometric correction with respect to the sun elevation angle to determine the effective intercept area of the solar cooker for a specific test date and location. When those values are unknown, one can use a photographic approach to calculate the applicable aperture area of a solar cooker for a specific sun elevation angle (Müller, 2022). This approach can also be used to determine the maximum intercept area. After determining the solar cooker elevation angle using the relationship, $\text{elevation angle} = \arcsin(\text{footprint} / \text{hypotenuse})$, photograph the solar cooker from a reasonable distance (about 5 meters; to minimize spatial distortions) along a line parallel to the solar cooker elevation angle, as shown in Figure 3. Then, load the picture into a computer program for Binary Large Object (BLOB) analysis or into a computer application, such as Microsoft PowerPoint, where one can superimpose and tile geometric shapes (with areas scaled according to size of cooker) over the entire intercept area and sum the areas of those shapes to obtain the maximum intercept area.

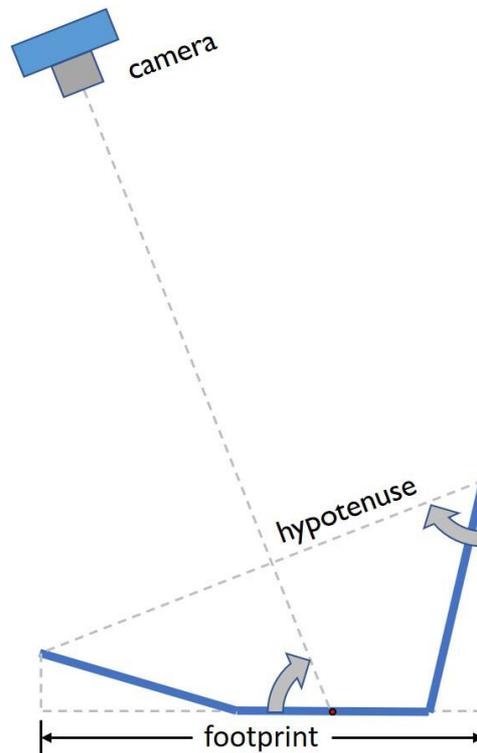


Fig. 3. Schematic of a solar cooker side view, in blue, and reference lines, in gray, for determining the solar cooker elevation angle (gray arrows).

PEP results apply to an entire solar cooking system, which is the solar cooker and the cookware or cooking pot. Since cookware and cookware material can impact PEP results, it is important to use the same type of

cookware consistently throughout a PEP test of a solar cooker. When conducting PEP tests, SCI prefers to use cookware provided by a solar cooker manufacturer; however, while some manufacturers include cookware with their solar cookers, others do not. SCI chose Graniteware as default cookware for PEP for solar cookers that do not include cookware. Graniteware is commonly available worldwide and often used for solar cooking. SCI testing centers in California, USA and New York, USA both have a set of Graniteware pots and select a best match of pot size to the amount of water needed for the PEP. In its PEP results reports, SCI specifies what cookware was used during each test.

The SCI testing centers favor using a feed-through thermocouple probe mounted to a hole drilled near the center of a cookware lid to reduce thermal leakage during a test. Further steps required for a PEP test are to load 7000 grams of water per square meter intercept area. One should use a scale to weigh the water load to the nearest gram. Also, the PEP test operator should use a leveling device to ensure a level surface for the test and use a consistent tracking time interval, such as 20 minutes.

4. Findings and discussion

Numerous tests across different types of solar cookers conducted since 2017 using the SCI PEP test stations at SCI testing centers in California, USA and in New York, USA indicated that results are repeatable with close correlation between the two locations, thus validating the test platform prior to SCI officially launching its PEP testing program for solar cookers.

Presented here are PEP results acquired at the SCI testing location in New York, USA during 26 May, 8 June, and 2 July 2020 for the following solar cooking system: CooKit reflective-panel solar cooker with a 4-quart Graniteware cooking vessel placed in a Pyrex greenhouse. The PEP test station recorded temperatures, solar irradiance, wind speed and GPS location to a space delimited file on an SD card for later post-processing. Graphical versions of data acquired by the SCI PEP test station include temperature profiles shown in Figure 4 and irradiance and wind speed profiles shown in Figure 5. Adjusted cooking power values are shown in Figure 6 along with the standardized cooking power.

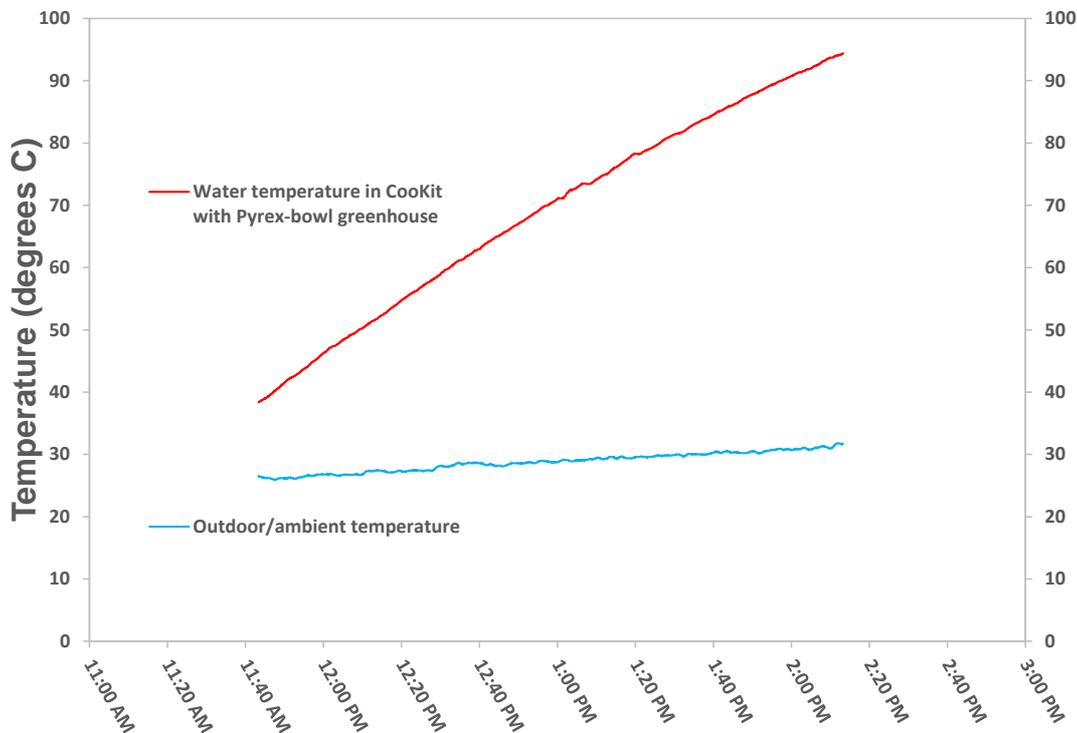


Fig. 4. Temperature profile of 3.256 liters of water (in red) and ambient air (in blue) recorded by an SCI PEP test station on 2 July 2020 while monitoring a CooKit reflective-panel solar cooker with a 4-quart Graniteware cooking vessel placed in a Pyrex greenhouse.

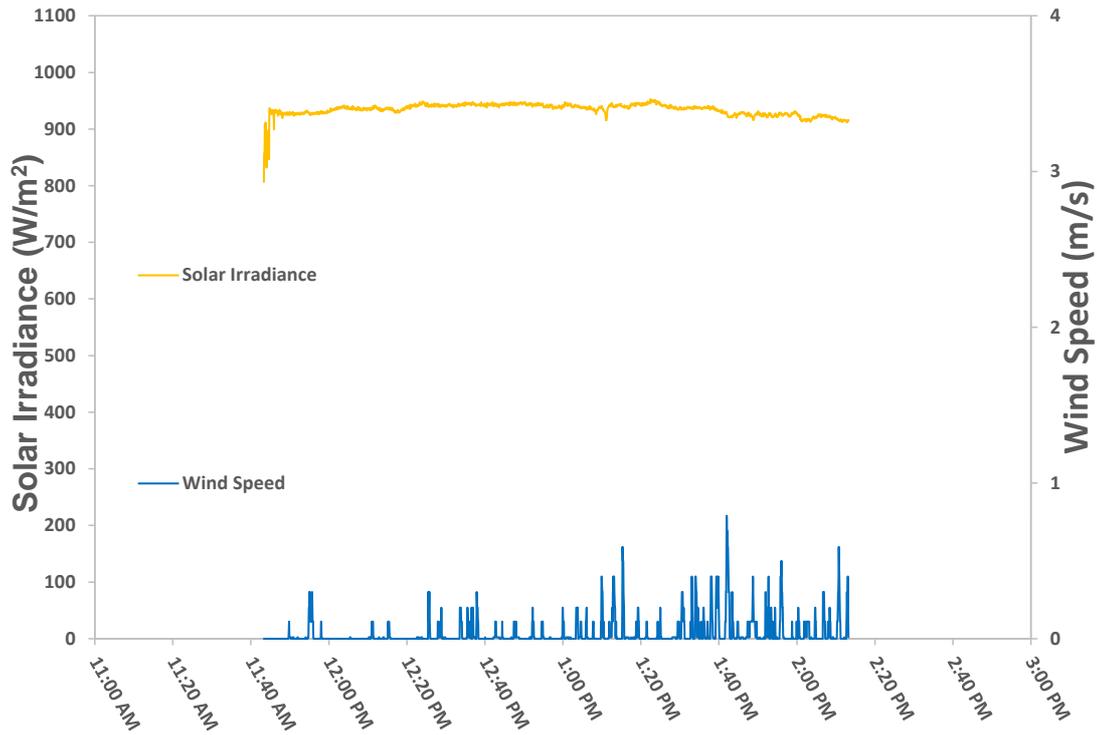


Fig. 5. Solar irradiance and wind speed recorded by an SCI PEP test station on 2 July 2020.

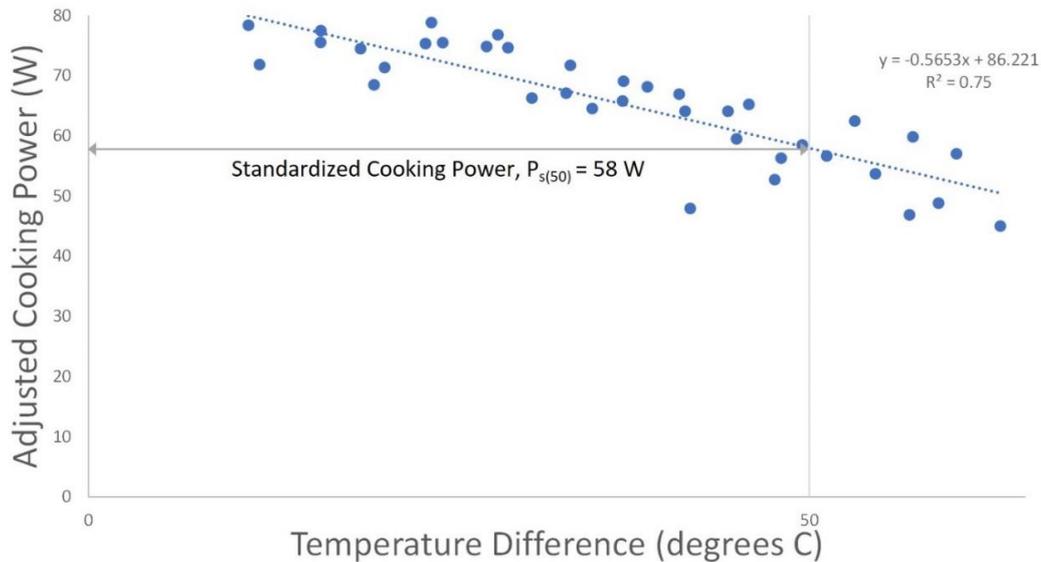


Fig. 6. Adjusted cooking power recorded by an SCI PEP test station during 26 May, 8 June, and 2 July 2020. These results from three non-consecutive days of testing produced 37 observations (exceeding the 30 observations required by the ASAE protocol) and demonstrate reproducibility and that the standardized cooking power of a CooKit with a Pyrex greenhouse is 58 watts.

The linear regression fit to the adjusted cooking power values results in a linear equation that can be evaluated for any temperature difference. In the example shown in Figure 6, the regression line equation $y = -0.5653x + 86.221$. When the regression line for this example is evaluated for x at a temperature difference of 50 degrees C, the resulting standardized cooking power is 58 W, which is the uptake of power into the medium being heated (water). The fundamental definition of power can be expressed as energy per time, and since heat is a form of energy (thermal energy), the standardized cooking power can be interpreted simply as a heating rate for the specified amount of water used during the test, when the temperature difference is 50 degrees C.

SCI PEP results for which manufacturers have given written permission for SCI to publish on the SCI website are summarized alphabetically by solar cooker name in Table 1 (Solar Cookers International, 2022). The PEP results presented here were current at the time of submitting this manuscript (October 2021). Manufacturers may improve products or develop new products, and arrange for follow-up PEP tests with SCI. Additionally, other manufacturers may agree to PEP testing at any time. Updated and most current PEP results are available on the SCI webpage for PEP results (Solar Cookers International, 2022).

Table 1: Summary of SCI PEP results for solar cookers

Solar Cooker Name	Manufacturer	Solar Cooker Type	Standardized Cooking Power (watts)
CooKit with oven bag greenhouse	CooKit	Reflective panel	46
CooKit with Pyrex bowl greenhouse	CooKit	Reflective panel	58
Fornelia Mini	Fornelia	Evacuated tube	93
Glenergy Solar Cooker	Glenergy	Evacuated tube	85
GoSun Sizzle	GoSun	Evacuated tube	99
Haines 1	Haines Solar Cookers	Reflective panel	41
Haines 2.0	Haines Solar Cookers	Reflective panel	82
StarFlower	Solar Chef International	Box oven	117
SunFocus	Sun BD Corporation	Box oven	52
SurviveIt2	SurviveIt2 LLC	Evacuated tube	24
UGLI	Sun BD Corporation	Box oven	61

In obtaining the standardized cooking power, the regression line also provides two additional aspects of the solar cooker: 1) the heat loss coefficient (the slope), and the initial cooking power (the y-intercept). These values suggest the insulation quality and there is potential for correlating these values with different types of solar cookers (Funk, 2000) (Ebersviller & Jetter, 2020). These values are provided in all SCI PEP reports via the regression equation, which can also provide guidance for solar cooker designers and manufacturers to meet their goals.

In addition to measuring standardized cooking power (in watts), PEP results suggest design-based aspects that can improve performance: 1) use a larger collector for gathering more incident solar energy – there is a general trend that standardized cooking power scales with intercept area, and 2) give attention to cookware and greenhouse material, as they are a part of the entire solar cooking system being PEP tested. Regarding greenhouse material, for instance, it may be desirable to use a clamshell of two 4-quart Pyrex bowls instead of a plastic bag as a greenhouse for reflective-panel solar cookers such as the CooKit. The transmission spectrum for Pyrex (Präzisions Glas & Optik, 2022) shows that it has high transmission for visible light - it lets sunlight in - and poor transmission for infrared light emitted from a hot black-body irradiator - it blocks heat radiation from a cooking pot from escaping (File:BlackbodySpectrum loglog 150dpi en.png, 2022). While transparent plastic bags can also have optical spectra favorable for solar cooking, surface topology and material overlap for plastic-bag greenhouses can reduce incident sunlight transmission. Furthermore, designers should evaluate aspects about materials regarding sustainability, durability, expected lifetime, insulation quality, ease of use and transport, cost, and availability. For example, plastic bags are banned in some countries. PEP results can also help inform consumers and users to choose design characteristics suitable for the types of food and the desired cooking times that they would like.

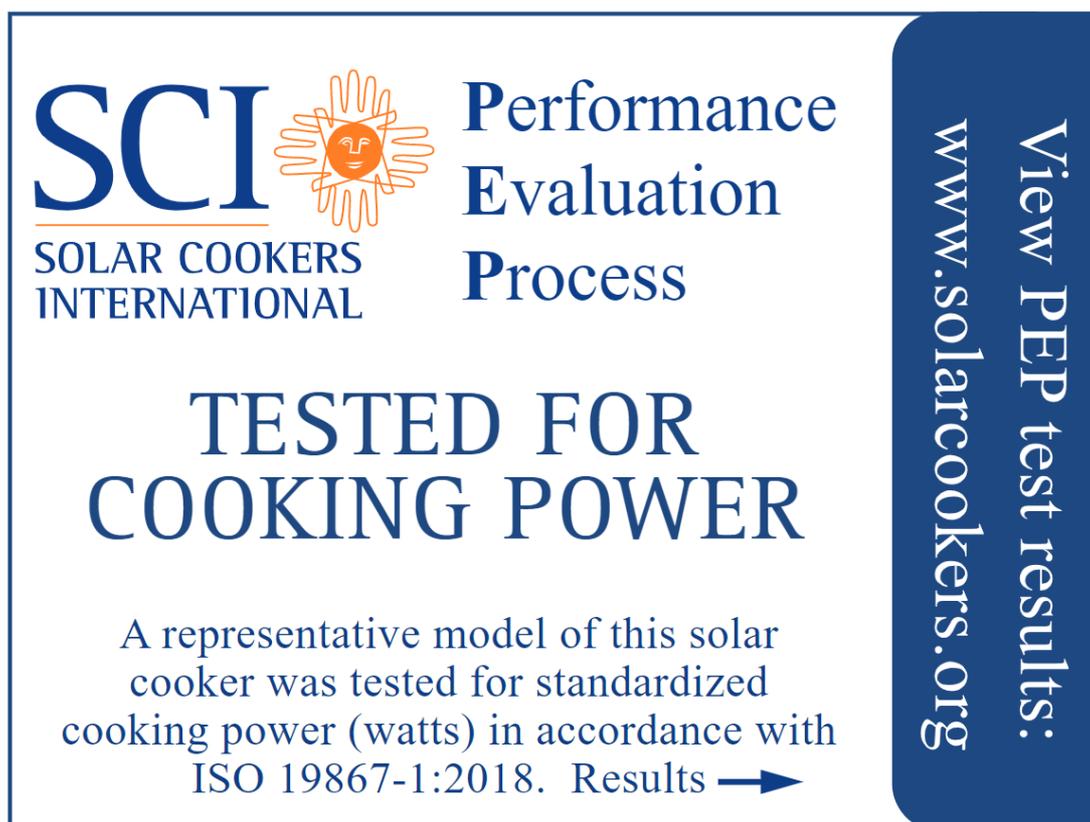


Fig. 7. The SCI PEP tested label, which solar cooker manufacturers can associate with their PEP-tested products and gain recognition for having product tested by an independent organization and according to ISO standards.

SCI generated its first official PEP results reports during 2019 and SCI's testing program has been gathering momentum along several fronts: with manufacturers, with national policymakers and with solar cooks. The steps for completing a PEP testing cycle involve: 1) manufacturer arranges for PEP testing by SCI with a signed agreement; 2) SCI conducts PEP testing of a like-new model of the manufacturer's solar cooker at one of SCI's testing locations; 3) SCI prepares a PEP results report and sends it to the manufacturer; 4) pending manufacturer approval of the PEP results report, manufacturer signs an agreement with SCI for SCI to publish their PEP results; and 5) SCI publishes the PEP results and manufacturer gains use of SCI's PEP tested label, shown in Figure 7. Furthermore, SCI showcases PEP-tested solar cookers as part of its advocacy efforts for example, at the United Nations, which dovetails with SCI's efforts in strengthening the capacity for solar cooking worldwide.

5. Conclusion

SCI has developed, built and implemented four PEP test stations for acquiring data to measure the thermal performance of solar cookers according to ISO standards at SCI testing centers in California, USA, in New York, USA, in Lalitpur, Nepal, and in Nairobi, Kenya. SCI developed several refinements in applying the ASAE S580.1 protocol, including using an automated data acquisition platform, on-board and post-processing routines, GPS, horizontal pyranometer positioning with trigonometric evaluation of irradiance values, a trigonometric correction of the solar cooker intercept area, default cookware, feed-through thermocouples and a thermocouple calibration routine, and emphasis on using a level surface while testing. SCI posts PEP results and reports on its website following approval and permission by respective solar cooker manufacturers.

Manufacturers are encouraged to have their solar cookers PEP tested by SCI. PEP results can have a role in design optimization and product improvements. SCI also suggests that manufacturers post PEP results in terms of the standardized cooking power (in watts) as performance specifications for their products. Standardized cooking power values can help consumers, project leaders and national policy makers decide which solar cookers to invest in. SCI also encourages individuals, organizations and governments to invest in solar cooking,

which can increase cooking-energy independence and food security. Investment in solar cooking can also help with climate change mitigation and adaptation, and it can be particularly beneficial with overcoming social stressors linked with global pandemics and internal displacement.

SCI hosts a global evidence base for solar cookers that can be viewed as a map of the worldwide distribution of solar cookers (Solar Cookers International, 2022). The map is interactive, where a user can obtain details such as number of cookers, implementing organization, and location. SCI encourages the solar cooking sector to post its distribution data – quantity, type, and approximate location – to further this evidence base. SCI shares this evidence with policy makers and the public to demonstrate the advantages of solar cooking. This information has also informed the creation of SCI's Economic Impact Summaries, a country-by-country analysis of the estimated to-date and potential environmental, health, and economic benefits of solar cooking on SCI's website (Solar Cookers International, 2022).

PEP results have potential to add another dimension to this evidence base, which is to produce a global distribution of installed solar cooking capacity (in watts) per nation. A map view of the installed solar cooker capacity could inspire more innovation and competition among nations to increase their solar cooking capacity.

Furthermore, PEP results increase the accountability and the credibility of the solar cooking sector. Solar cooking is an innovative, inclusive, and cross-cutting solution that helps to achieve all 17 United Nations SDGs. It is an affordable, accessible, clean and sustainable cooking solution for reducing CO₂ and black carbon emissions; hence, solar cooking is a readily available approach that national leaders can include in their plans to reduce emissions, such as their Nationally Determined Contributions (NDCs), which are part of the Paris Agreement within the United Nations Framework Convention on Climate Change. In the context of global efforts, such as those at the United Nations level, PEP results for solar cooker performance specifications can help unlock funding pathways for large-scale solar cooking opportunities that can enhance the economic impact from solar cooking at the national level (Solar Cookers International, 2022).

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