Evaluation framework for small-dimension solar cookers

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Marco de evaluación para cocinas solares de pequeña dimensión

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ABSTRACT

The present work introduces an evaluation framework for small-dimension solar cookers based on three parameters: energy efficiency, ease of use, and economic accessibility. Each parameter evaluates various quantifiable indicators, as *a*) energy efficiency: standardized cooking power, heating time, and thermal performance, *b*) ease of use: load capacity in the pot, mass in relation to collector area, orientations per hour, and *c*) economic accessibility: cost per watt generated and durability of the reflector and/or thermal accumulator. Each indicator has been assigned a maximum and minimum evaluation; data obtained from these indicators were integrated in a radial graph. The sum of the indicators constitutes the aspect to be compared, but the graph also allows us to interpret the strengths and weaknesses described above. This framework requires two or more devices, since it is a comparative tool.

RESUMEN

Este documento presenta un marco de evaluación para las cocinas solares con base en tres parámetros: eficiencia energética, facilidad de uso y accesibilidad económica. Cada parámetro evalúa diversos indicadores cuantificables: *a*) eficiencia energética: potencia de cocción estándar, tiempo de calentamiento, el rendimiento térmico; *b*) facilidad de uso: la masa en relación al área del colector, orientaciones por hora y capacidad de carga de la olla y; *c*) accesibilidad económica: el coste por vatio generado y la durabilidad del reflector y/o acumulador térmico. A cada indicador se le asigna una escala máxima y mínima de la evaluación y los datos obtenidos de estos indicadores se integran en un gráfico radial. La suma de los indicadores constituye el aspecto que debe compararse, pero el gráfico también nos permite interpretar las fortalezas y debilidades descritas. Este marco no se puede analizar una sola cocina solar, ya que es una herramienta comparativa que requiere dos o más dispositivos que deseen evaluarse.

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Solar cookers; evaluation framework; radial graph.

Palabras Clave:
Cocinas solares; marco de evaluación; gráfico radial.

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INTRODUCTION

Evaluation frameworks are methodological proposals that allow elaboration of integral, quantifiable analyses of multi-factor systems. Nowadays, there are well-founded frameworks that evaluate the sustainability of agrosystems by incorporating general attributes as quantifiable indicators. Evaluation frameworks have been a focus of interest since the 1990s for several authors. The Framework for Evaluating Sustainable Land Management (FESLM), for example, is a framework for evaluating soils consideri environmental indicators (Smyth & Dumanski, 1995). Likewise, the Evaluation Framework for Natural Resource Management Systems incorporates indicators of sustainability (MESMIS) that cover a very broad range, from environmental indicators to socio-economic indicators (Masera, Astier & López-Ridaura, 1999).

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Currently, a comparative study exists on evaluation frameworks for agro-systems (Sarandón & Flores, 2009); all these evaluation frameworks have the following characteristics: they evaluate systems on the basis of social, economic and environmental parameters or attributes that generate various quantifiable indicators, which is it allows to know the efficiency and functionality of the system. The data are integrated into radial graphs, adequate for both comparative and interpretative analyses (Brink, Hosper & Colin, 1991). Unfortunately, for energy systems that utilize renewable energy sources, ecotechnical systems and, especially, solar cookers, no such frameworks exist.

Solar cookers are thermoconverters that transform solar radiation into calorific power to cook food during varying time intervals. Today, a wide variety of solar cookers exists, and the number of models available makes it difficult to conduct comparative evaluations. Although several procedures for evaluating the thermal performance of these devices exist, even the most efficacious ones are limited to assessing cooking power, merit factors, and thermal performance. The work by Funk (2000) led to the creation of American Society of Agricultural Engineering Standard S580 (ASAE, 2003), which establishes a rigorous procedure for the thermal testing of solar cookers, based on determinations of standard cooking power.

The standard developed in 1992 by the European Research Committee on Solar Cooking (ECSCR), for example, is extensive and includes many qualitative factors, such as ease and safety of use (ECSCR, 1992). In India, the national standards uses a testing method based on research by Mullick, Kandal & Saxena (1987), which evaluates solar cookers with tools whit figures of merit.

As a result, the most common evaluation protocols for solar cookers do not offer integral assessments that take into account ergonomic and economic aspects, or environmental benefits. Therefore, efforts have been made to establish more integrated evaluation systems; in some cases by suggesting the incorporation of socio-economic parameters with indicators (*i.e.*, quantifiable criteria) such as safety, ergonomics, and device quality (Fonseca, Abdala & Acosta, 2003). In their study of the evaluation of solar cookers, Kundapur & Sudhir (2009) propose consider not only thermal performance, but also parameters as stagnation capacity (Thermal accumulation), cost per watt delivered, weight and ease of use. Yahya (2013), suggests a new standard global procedure for testing solar cookers based on determining the thermal performance of parabolic concentrating solar cookers. This new standard sets limits for environmental conditions, specifies test procedures, and assesses performance in terms of cooking power. Kimambo (2007) carried out a study in Tanzania that included a bibliographic analysis; in the study, experimental testing and evaluations were made on 6 different types of solar cookers, it was intended to make a comparative tool for solar cookers. Pohekar & Ramachandran (2004), in turn, propose to formulate a policy to replace the energy used in cooking, with renewable energy, based on a multi-criteria approach. They evaluated nine cooking energy alternatives on the basis of 30 criteria that include technical, economic, environmental/social, behavioral and commercial elements. Unfortunately, these two evaluation frameworks, are attempts to elaborate more integral evaluations, lack quantitative indicators. They are qualitative, but they do not incorporate socio-economic indicators.

Solar cookers have been installed in rural areas to improve people's quality of life and mitigate the extraction of forest resources by reducing biomass combustion (González-Avilés, López-Sosa & Servín, 2013). However, implementation of these thermal solar technologies often lacks appropriate systems that allow users to employ their solar cookers continuously. In order to determine the viability of inserting a specific model of solar cooker we must understand the elements that may propitiate its implementation, a process that requires evaluating possible economic, environmental and social benefits, that is, sustainable technology. For this reason, it is of importance to elaborate integral evaluation strategies that help us understand the potential advantages of certain solar cooking systems. The following sections present an Evaluation Framework for Small-Dimension Solar Cookers (EFSDSC).

Description of the evaluation framework for small-dimension solar cookers (EFSDSC)

Due to the absence of evaluation frameworks that integrate environmental, social and economic parameters and indicators, we propose a model for small-dimension solar cookers –*i.e.*, those with less than one square meter of capture area, because they are simpler to manipulate (González-Avilés, López, Servín & González, 2014b). The goal has three parameters: *a*) energy efficiency; *b*) ease of use; and *c*) economic accessibility. Then, a series of quantifiable indicators derives from these parameters. Table 1 shows the indicators that correspond to each parameter.

Table 1.
Parameters and indicators of the EFSDSC.

Parameter	Indicator
Energy efficiency	1- Thermal performance (%)
	2- Standardized cooking power per area unit (w/m^2)
	3- Heating time (minutes)
Ease[4] of use	4- Mass of the solar cooker (kilogram)
	5- Load capacity of the pot (liters)
	6- Orientations per hour (times per hour)
Economic accessibility	7- Cost per Watt of standard cooking power ($USD)[36]
	8- Reflector durability (years)

Source: Author´s own elaboration

Table 2.
Values of the indicators of the EFSDSC.

INDICATOR[13]	MAXIMUM VALUE	MINIMUM VALUE
1- Thermal performance [%]	0.5	0
2- Standardized cooking power per area unit [w/m^2]	350	0
3- Heating time [min]	300	0
4- Mass of the solar cooker [kg]	40	0
5- Load capacity of the pot [l]	7	0
6- Orientations per hour [adimentional]	5	0
7- Cost per Watt of standard cooking power [$USD]	6[1]	0
8- Reflector durability [years]	20	0

Source: Author´s own elaboration

Parameters and indicators

In this context, the parameters are variables that can be measurable in relation to certain indicators. In simple terms, sustainable technologies are those with a behavior that falls within the limits of sustainability, or that contributes to achieve those conditions. Their interactions with society, economy, environment, and other technologies, must the smallest possible harmful impact (Amemiya, 2012). However, it is difficult to define indicators for energy systems evaluation frameworks. For solar cookers, it is not easy to identify the indicators that quantify their ease of use and environmental benefits.

Therefore, we suggest an EFSDSC. It for solar cookers of small dimensions –*i.e.*, less than one square meter of catchment area, so that they can be used by people who have small kitchens. In addition, solar cookers should be efficient and easy to use (López-Sosa, González-Avilés, González & Solís, 2014).

The EFSDSC is an evaluation framework that integrates socioeconomic parameters to determine the social and economic viability of using solar cookers. Moreover, "reflector durability" indirectly evaluates the need to acquire new solar cooker within a time interval; this factor determines the quantity of technological waste generated and, therefore, the dimensions of the impact on the environment qualitatively. Also, a functioning solar cooker represents savings in the consumption, thus reduce carbon dioxide emissions (González-Avilés *et al.*, 2013).

In general, the parameters EFSDSC are social, environmental and economic, from the perspective of sustainable technology. The indicators are methodological instruments that make possible to quantify the evaluation of the three fundamental parameters. The evaluation of each indicator corresponds to established methodologies utilized to evaluate solar cookers. Each indicator generates a maximum and minimum quantitative evaluation (table 2) that goes from zero "the maximum possible value obtained in each indicator (Reported in the literature and described in the following paragraphs)".

The calculation of these indicators, and their respective maximum and minimum values, involves the following considerations:

- Thermal performance is the average yield of the solar cooking system (Kundapur & Sudhir, 2009) measured on a scale of 0 to 1; but because in reality it is practically impossible for such a system to achieve 100% of thermal performance, this scale estimates the highest possible thermal performance of solar collecting systems at approximately 50% (González-Avilés, González-Avilés & Servín, 2014a).
- Standard cooking power per unit area is calculated using ASAS580. Based on mathematical models that predict the thermal behavior of small-dimension solar cookers, the maximum cooking power for these systems is 350 watts (González-Avilés *et al.*, 2014a). The calculation of this indicator is obtained from the standard cooking power ratio and the solar collector area (equation 1).

$$i_{pc} = \frac{P_s}{A_c} \tag{1}$$

where

i_{pc} = Standard cooking power indicator [$\frac{w}{m^2}$]

P_s = Standard cooking power [w]

A_c = Collector area [m^2]

- Heating time is the minutes that it takes the pot to reach 95% of its maximum temperature (Pejack, 2003). In one day, the solar cooker can absorb a maximum of 5 h of solar radiation to cook food. As a result, the maximum heating time is 300 min.

- The mass of the solar cooker is the total mass of the system (solar cooker and pot). This indicator is measured in kilograms. A device greater than 40 kg is difficult to move, 40 kg is the maximum value.

- The load capacity is the amount of food that can be placed in the pot of cooking container, measured in liters. This evaluation framework is for solar cookers of small dimensions, so that the maximum value of charge is 7 l (Funk, 2000). This value is not per unit area, it represents the amount of food that will fit in the container of the solar cooker.

- Orientations per hour represent the number of times that the device is re-oriented. Intuitively, we consider that is impractical for a user to orient the solar cooker more than 5 times per day, so the maximum value is 5 and is dimensionless.

- Cost per watt is the ratio the total cost of the solar cooker and number of watts based on the calculation of standardized cooking power (not per unit area), equation 2. For commercial cookers like Tolokatsin solar oven (one of the most expensive until 2016), the cost per watt of cooking power generated was approximately 6 dollars (in 2017). As this cost is very high, it was taken as the maximum value for a device. This value is measured in dollars.

$$i_{\$} = \frac{C_{\$}}{P_s} \quad (2)$$

where

$i_{\$}$ = Standard cooking power indicator [$\frac{w}{\$USD}$]

P_s = Standard cooking power [w]

$C_{\$}$ = Cost of the solar cooker [$\$USD$]

- Finally, reflector durability is measured in years, in relation to the functionality of optimized reflectors, solar heaters and photovoltaic panels. Their useful lifetime is 20 years, so this is the maximum value for this indicator.

With the intention of having a homogeneous scale for all values of the indicators, data are normalized to have values from 0 to 10. The values of the indicators range from 0 to 10, where 0 is the minimum value and 10 is the maximum value, except for the "Cost per watt" and “the mass of the solar cooker” indicators, where 0 is the maximum value and 10 is the minimum value. 2 That is, if the solar cooker have a high cost, the indicator will have a low value, and a low cost solar cooker has a higher value. Something similar happens with the mass of the solar cooker; a heavier system has small values and a light system, high values. The results were integrated in a radial-type graph to interpret the strengths and weaknesses of each solar cooking system evaluated.

RESULTS AND DISCUSSION

The EFSDSC is an instrument proposed for evaluating solar cookers from a comparative perspective; thus, it cannot be used to assess individual models of such solar devices. However, the results of comparative analyses of two or more solar cooking systems can serve to demonstrate which device the best, or most favorable, energy, ergonomic, and economic features.

The first step of the comparative tool consists in conducting the evaluation of each indicator for each device. In this study, we analyzed the following three systems: (1) the Tolokatsin solar oven (Rincón & Osorio, 1999), a multi-component system of parabolic concentrators; (2) the HOT-POT solar cooking system, a commercial apparatus with an extensive chain of industrial production; and, (3) the Rural Solar Cooker (RSC) (López-Sosa & González, 2013), which is equipped with three dimension parabolic concentrators and has been implemented for use in various communities in the state of Michoacán, Mexico. These systems were selected based on the cost and size of the solar cooker. That is, high, intermediate and low cost; and small, large and medium size. Figure 1 shows the three models.

Direct data obtained in relation to the indicators are shown in table 3, while table 4 presents the values for each indicator after conversion to the EFSDSC evaluation scale (0 to 10).

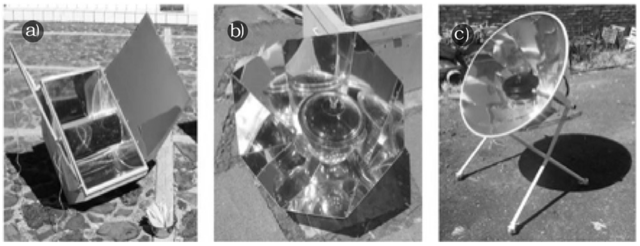

Figure 1. a) *Tolokatsin* solar oven, b) *HOT-POT* Solar Cooker, c) Rural Solar Cooker (RSC).
Source: Author´s own elaboration.

Table 3.
Real values of the EFSDSC indicators.

INDICATOR	TOLOKATZIN	HOT-POT	RSC
1- Thermal performance (%)	0.252	0.297	0.275
2- Standardized cooking power per area unit (W/m^2)	113.3	138.0	203.1
3- Heating time (Minutes)	122.5	95.00	120.0
4- Mass of the solar cooker (Kilograms)	20.00	5.000	18.00
5- Load capacity of the pot (Liters)	6.000	5.000	6.000
6- Orientations per hour	1.000	1.000	1.000
7- Cost per Watt of standard cooking power ($USD)[37]	6.00	2.74	1.195
8- Reflector durability (years)	20.00	20.00	20.00

Source: Author´s own elaboration

Table 4.
Values for indicators after conversion to the EFSC scale.

INDICATOR	TOLOKATSIN	HOT-POT	RSC
1- Thermal performance	5.04	5.94	5.50
2- Standardized cooking power per area unit	3.24	3.94	5.80
3- Heating time	5.92	6.83	6.00
4- Mass of the solar cooker	5.00	8.75	5.50
5- Load capacity in the pot	8.57	7.14	8.57
6- Orientations per hour	8.00	8.00	8.00
7- Cost per Watt of standard cooking power	0.00	5.43	8.00
8- Reflector durability	10.0	10.0	10.0

Source: Author´s own elaboration

Table 5.
Values reflecting the sum of all indicators.

TOLOKATSIN	HOT-POT	RSC
45.77	56.03	57.37

Source: Author´s own elaboration

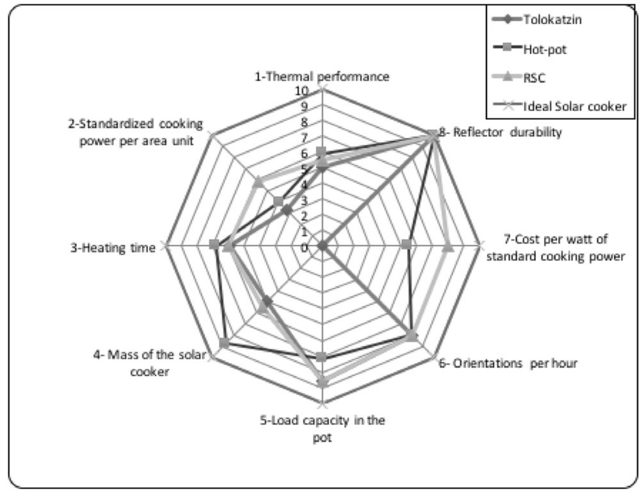

Figure 2. EFSDSC applied to 3 solar cookers
Source: Author´s own elaboration.

Figure 2 shows the final stepof the EFSDSC with the radial graph that integrates the results of the comparative analysis of the three solar cookers: RSC, HOT-POT and Tolokatsin. A spreadsheet can be used to elaborate comparative graphs like this one for of solar cookers that one wishes to compare.

Data from the EFSDSC scale, together with the results of the evaluation, must present the quantities to two decimal. The analysis of the EFSDSC scale for the three solar cookers evaluated is shown in table 5, where it is clear that RSC is the device with the best characteristics. In addition to the sum of indicators, it is possible to conclude qualitatively that RSC is more energy and economic efficient. That is, if an efficient and economical system is desired, RSC has these characteristics, and in score of evaluation framework is better than other solar cookers analyzed.

EFSDSC is a comparative tool for solar cookers of small dimensions. It seems that if the efficiency of the solar cookers increases, all the charges also increases, but it does not. EFSDSC limits charges when the cost of the solar cooker is high because the normalized value of the indicator from 0 to 10 is low. On the other hand, if the solar cooker has a large pot to cook food, the value of the indicator is high. This contributes to the economic parameter.

If the pot is large, it is possible that the device is large because it must have a large collector area to cook more food. But that does not always happen. There are solar cookers with small area and large pot. So EFSDSC represents a useful tool for all types of small solar cookers.

Therefore, the sum of the indicators is comparative value of solar cookers, because it suggests the highest values in the economic (low cost), environmental (efficiency) and social (Ease of use) parameters. These parameters are required for people and have been documented in the literature (González-Avilés, López-Sosa, Servín-Campuzano & González-Pérez, 2017).

When the sum of the values of the indicators is small, the higher parameters determine which solar cooker is best, according to the parameters considered most important for the user.

EFSDSC is a quantitative and qualitative tool that can be useful to evaluate solar cookers and to know the strengths of these systems to implement in the urban or rural areas (González-Avilés *et al.*, 2017; González-Avilés *et al.*, 2014b)

CONCLUSIONS

EFSDSC is proposed as an evaluation framework for solar cookers that incorporates social, economic and environmental parameters. Based on the assessment of a series of indicators, a data table was elaborated that makes possible to compare two or more solar cookers. On the basis of this proposal, the following conclusions can be reached:

- EFSDSC incorporates evaluations of the thermal performance, cost-benefits, ease of use, and durability of the solar cookers assessed.
- EFSDSC is a simple, integral medium for evaluating solar cookers that is applicable to small-dimension devices (*i.e.*, less than one square meter of capture area).
- EFSDSC has detected improvements that include: the reduced consumption of energy resources as firewood and gas, and reduced carbon dioxide emissions; two key indicators for assessing the parameter of environmental impact.

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