CONSOLFOOD 2018 − International Conference on Advances in Solar Thermal Food Processing
Faro-Portugal, 22-24 January, 2018

PHOTOVOLTAIC SOLAR COOKING WITH THERMAL ENERGY STORAGE (TES)

Antonio Lecuona-Neumann[1] *, Daniel Victoria[1], Javier A. Perteguer[1], Ernesto García-Arés[2]

1: Grupo ITEA, Departamento de Ingeniería Térmica y de Fluidos, Universidad Carlos III de Madrid
Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain
lecuona@ing.uc3m.es, http://www.uc3m.es
2: Oficina Técnica, Universidad Carlos III de Madrid
Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain

Abstract: *Photovoltaic cooking seems viable under some circumstances.*

Solar cooking during the night seems an interesting capability as well as during cloudy intervals during the day.

Electric energy storage in batteries can cost more than the rest of the Photovoltaic (PV) cooking system, namely: panel, wiring, controller and end converter into heat. The supply of the heavy batteries to remote locations can increase their price even more. When they are abandoned after their operative life as residues it involves the risk of pollution.

Thermal energy storage can be an alternative to batteries for a lower price and complexity. Phase Change Materials (PCM) offer high energy density, viable for cooking if their melting temperature is above 100 ºC.

Erythritol is a PCM that offers advantages over some other candidates. Its thermal conductivity seems too low for a fast enough heating and cooking so that its enhancement seems a requirement.

The paper offers the result of some experiences to develop an electric utensil capable of both direct use of the PV electricity through a simple electronic controller and independent use the AC grid power when desired. Moreover, it implements a TES.

The aim is to propose some designs of utensil that can be purchased at a reasonable price and implemented after modification using local manufacturing and maintenance.

The reported results indicate that the design is viable, but still, some problems need to be solved.

Keywords: Solar, Thermal, Food processing, Photovoltaic, TES.

1. **INTRODUCTION**

The usual way of solar cooking is through the optical/thermal way [1]. Solar radiation, either directly or optically concentrated, dissipates as heat on a surface highly absorbent of the sun rays. This heat is directly or indirectly used to cook. Temperatures high enough for cooking are reached thanks to the optical concentration or/and by producing a greenhouse effect by a glass or plastic sheet covering the pot. Efficiencies based on the incident solar power $P = A_a G_T$ [2] on the aperture area A_a rarely exceed 25% [1]. Typically this heating is externally applied to the pot containing the food, thus carrying high heat losses to the ambient. Only some very large solar thermal cookers apply the heat internally. This is the case of producing steam with the solar heat and bubbling this steam inside the cooking food; but in this case, the maximum temperature cannot be higher than the steam $<$ 150 ºC.

If solar electricity would be produced, a Joule effect resistance $R = V \cdot I^{-1}$ could be located in contact with the food and both could be thermally insulated to gain the higher temperatures appropriate for fast cooking or for the desired recipe. The power produced is $P = VI = V^2 R^{-1}$, being V the voltage applied to R and I the intensity passing through the circuit.

At low scales, electricity is produced by the photovoltaic (PV) effect that with commercial technology nominally surpasses 18% of peak efficiency, and on average higher than 15% seems not real-world. This would require about 50% more aperture area exposed to the sun rays. PV panel are massively produced today so that their prices has fallen to below 0.5 € W_p, making a family size solar cooker of $A_a = 2\ \mathrm{m}^2$ yield at the peak irradiance $G_{T,p} = 1\,\mathrm{kW\ m}^{-2}$ up to a peak power $P_p = 360\ \mathrm{W}$ with a procurement cost of 180 €. Actually 310 W_p are commercially declared for 2 m^2 single panel. This seems satisfactory, but the price, for a solar cooker. With the high thermal insulation possible, heat losses to ambient can be low.

But one has to bear in mind that the electricity produced can be used for other purposes along the day. Especially interesting are charging portable LED based lights, flash lamps and also mobile phones, among others, as their charge capacity is minute compared with the theoretical production of the referred PV panel of 1.5 kWh day^{-1} as annual average in sunny regions. In contrast, heating 2 kg of water from 15 ºC up to 100 ºC consumes 0.2 kWh. Moreover, the expected life span of a PV panel is 20 to 30 years, making the electricity cost ($LCOE \sim 6\ \mathrm{c€\ kWh}^{-1}$) competitive with the grid supply, at least for remote locations. In addition to that, safety of the inhabitants is increased.

Thus a big step can be produced to families located in remote and even isolated locations, switching from burning wood for cooking and oil for lighting to a fully electrified sustainable home. This is only ideal, as the solar electricity would not be available every day, but the big step would be certainly real. Establishment of a family or community small electricity (smart) grid now is open, even an ulterior larger one could be easily implemented. Hydro, wind or biomass based electricity becomes possible as a renewable energy backup. Actually some initiatives reckons the high value of PV for lighting and telecommunication, but as is frequent, ignores solar cooking because of the higher power required. Such are M COPA [3] and Pay-As-You-Go [4].

An additional advantage of PV cooking can be claimed. This is cooking indoors, avoiding sun exposure, bad weather pains, food contamination by dust or animal intrusion and even health risks in high altitude locations. Intimacy is also gained. The daily effort of collecting the thermal solar cooker after its use outdoors disappears and indoor space for its stowage is not necessary.

The capability of cooking when solar is not available is greatly appreciated, typically dinner and following day breakfast. The use of batteries for storing electricity is common in PV, but their price is high, probably doubling the other parts total cost. The most common lead/sulphur type is contaminating, very heavy and their life is short. Moreover its discharge capacity is much less than the nominal capacity. The avoidance of batteries seems of high interest.

Maximum solar collection is produced by a two-axis motorized solar tracking. This seems impractical for the intended application. Only some manual seasonal elevation adjustment seems reasonable to compensate solar declination. The panel should be oriented toward the equator with local latitude tilting.

This paper proposes an innovative PV cooker. It is based on a DC circuit, not requiring batteries for operating. Instead a Phase Change Material (PCM) Thermal Energy Storage (TES) is proposed. This requires a specific control circuit for the PV panel, whose development results are described. The reason for that is that commercial PV controller are based on a battery charger, thus requiring to be connected to a battery bank.

2. PV SOLAR COOKING PROPOSAL

A single panel fixed to the roof feeds a proprietary circuit controller to adapt the operating curves of the PV panel under varying sun radiance to a fixed resistance added to an electronic commercial cooking pot modified to suit this new application, but not renouncing to its original purpose. The maximum PV power is applied. Part load capability should be an ulterior development, as well as external electric charging, as Figure 1 depicts. As an option the inner container can incorporate a PCM-TES. If the thermal insulation of the electrical pot is not enough, after cooking process A, the food can be moved to a highly insulating device, process B, similar to a “hay basket” heat retention device [1], Figure 1, either with the PCM-TES or without it.

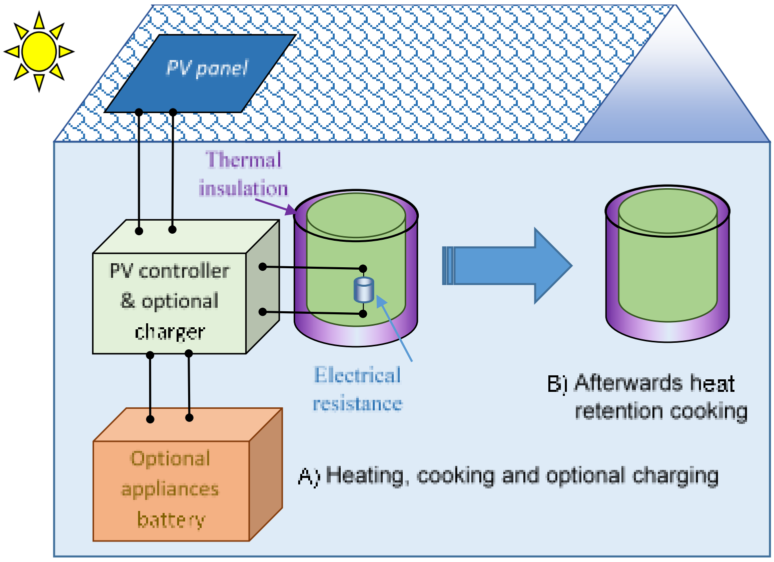

Figure 1. General layout of the proposed PV cooker. PCM-TES not explicated.

3.1. PV operating curves and controller

Figure 2 depicts the typical voltage-intensity $V-I$ and the corresponding voltage-power $V-P$ curves of a silicon PV panel under different solar irradiations. Intersections with a fixed load resistance R [Ohms] directly attached are indicated with round points, as well as the Maximum

Power Point (MPP) combination, $\max(I \cdot V)$, with stars. This corresponds to the tangent hyperbola $I \cdot V = \text{const.}$ The selected value of R in this particular case makes that the star and circle coincides at an irradiance of 1.0 kW m^{-2}. As one can notice, even in the present case, where R matches the MPP at maximum expected irradiance at noon, during lower irradiations the power obtained diminishes drastically (round points). A higher resistance would increase the extraction of electrical power, but this would require a high power switch, expensive and probably dangerous. The $V-P$ curves show the Maximum Power Point Tracking (MPPT) line, joining the stars that define the maximum power deliverable at all irradiances. As one can notice, the appropriate $V = \text{const.}$ line approaches the MPPT line fairly well. This raises the idea of conceiving an electronic circuit that instead of incorporating an MPPT algorithm using a microprocessor (as it is commercially available), simply controls a PV panel adjustable input V by modulating the duty cycle of a pulsed solid state circuit, named pulse width modulation PWM circuit. This way the PV panel is periodically connected and disconnected from the load R, using a MOSFET solid-state relay, so that the RMS value of the input V is constant. This can be performed with a simple circuit. With an ideal circuit the vertical of constant voltage V would be described when the radiance varies.

A circuit has been developed keeping in mind to minimize the cost and the possibility of being manufactured, repaired and maintained in low technology locations, actually on-site. For that, a single side printed circuit board (PCB) is necessary. The price to pay is some power loss in the circuit. Figure 3 depicts the circuit. Test already performed indicate that for irradiances above around 600-700 W m^{-2} the present control circuit is not necessary, indicating a way of improvement.

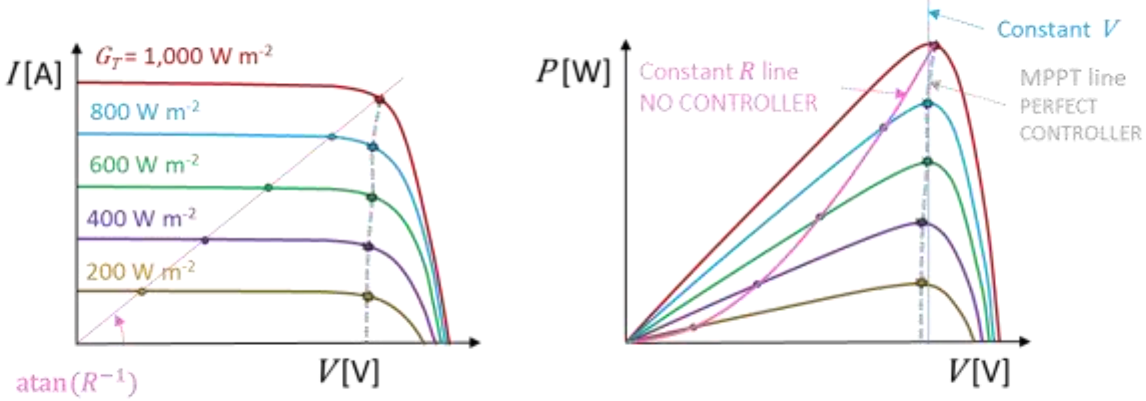

Figure 2. Curves of a PV and a MPP matched resistance R. (left): panel $V-I$ vurves at several irradiances. (right): corresponding panel $V-P$ curves showing the MPPT line (grey dashed line) and the approximating $V = \text{const.}$ line (vertical thin continuous line).

3.2. Cooking utensil and PCM-TES

A locally manufactured utensil formed by a pot with the embedded single resistance R could serve as an embodiment of the concept. In the present research an alternative option has been chosen, based on a commercial electronic pressure pot similar to a rice cooker, manufactured in China. It consumes up to 900 W @ 230 V AC, with an on-the-shelf cost of around 30 €. As Figure 4 depicts its baseplate has been mechanized for incorporating a plane DC resistance for 24 V nominal PV power. This way future operation using AC grid is maintained. Figure 4 shows its construction and modifications implemented. Moreover, the removable inner pot has been separated in two parts by an aluminum sheet:

I. The lower part forms a vessel or tank containing 3.0 kg of a PCM that is a sugar polyol, erythritol, industrially used as a low-cost calorie-free sweetener [5]. This substance show a phase change at 118 ºC involving 340 kJ/kg heat, an amount similar to ice melting/solidification. It is edible and of low cost. Aluminum tubes are incorporated to the PCM to enhance heat conductivity. All the test performed have not shown appreciable supercooling effect. This way the heat coming from the bottom located resistance directly heats the PCM storage, Figure 4.

II. The upper part of the inner pot is reserved for indirect cooking, either using solar heat simultaneously to PCM charging or using just the TES-PCM off line after it was charged during the day. In any case, an empty inner pot can be used for direct cooking.

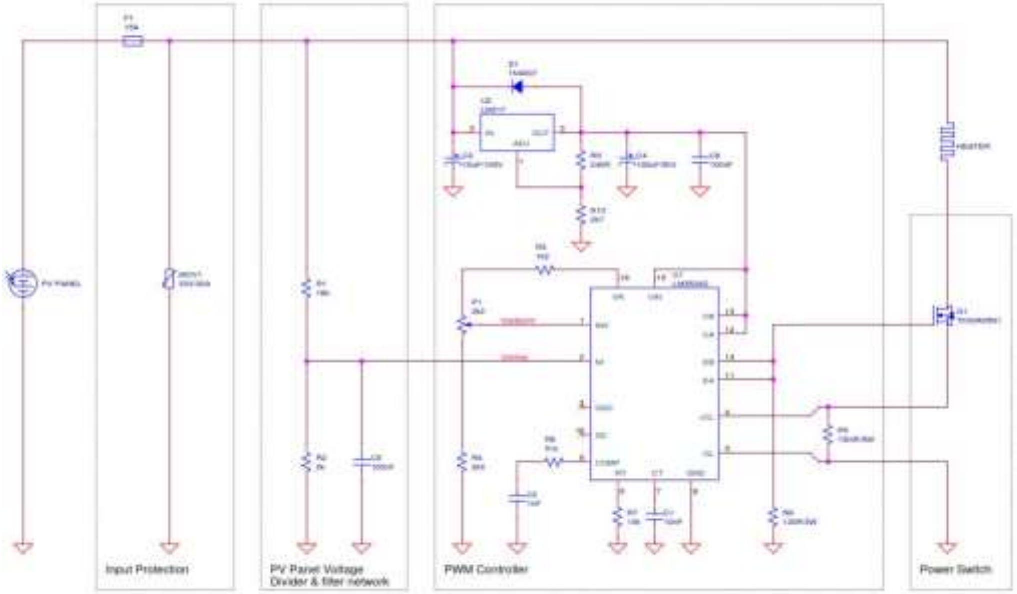

Figure 3. Circuit for operating without batteries. An internal voltage regulator serves as a reference.

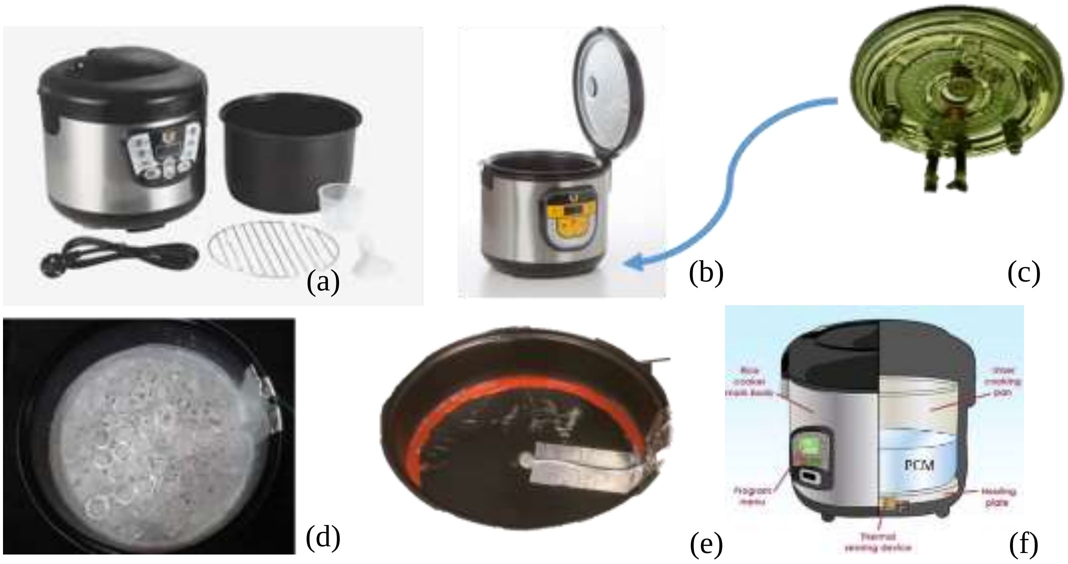

Figure 4. (a) Original electronic pot set showing the removable inner pot of the utensil. (b) Open utensil showing the pressure cooking valve and the thick insulating walls. (c) Modified baseplate showing the inner flat DC resistance for PV. (d) Erythritol powder filling the lower part of the inner pot and showing the aluminum tubes. (e) Top of the inner pot PCM-TES tank leaving space for cooking; it shows the top monitoring thermocouple. (f) diagram of the design layout.

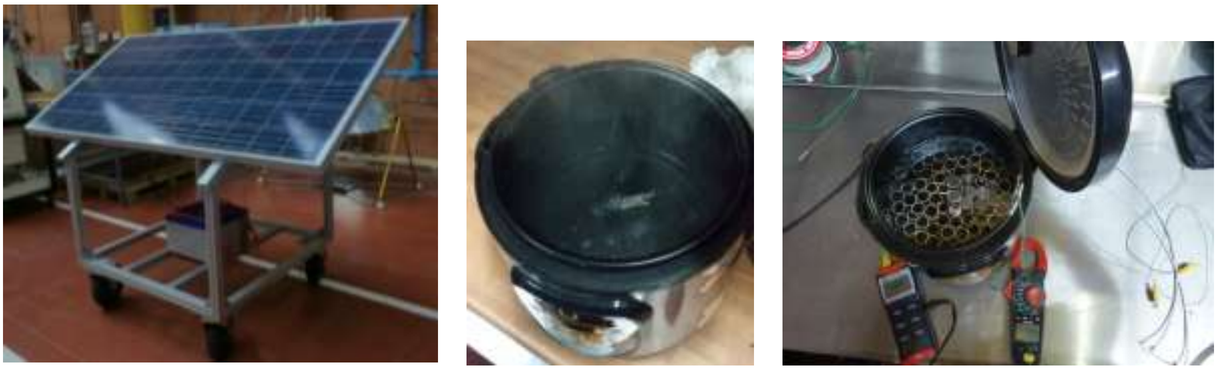
(a) (b) (c)

Figure 5. (a) Test rig. (b) boiling test without PCM. (c) PCM melting test with the TES vessel open.

4. RESULTS

The test have been performed following well documented practices to determine basic performances of the cooker, such as described in [1]. Here only some of them are described.

For the experimental determination of the capacity of retaining heat by the electronic pot thermal insulation, a no load (water empty to avoid evaporation losses) cooling test has been performed. Figure 6 shows an initial cooling down to the phase change temperature, when temperature stabilizes, during 5.8 h. This period reduces to 4.0 h when the inner pot is loaded with water. After that, cooling continues thanks to sensible cooling, reaching the 70 ºC line indicated after 9.3 h, Figure 6. It indicates that dinner cooking is possible using the bare PCM-TES device, but not overnight breakfast cooking, although food heating and sanitary hot water preparation is possible the following morning. If the charged pot is moved to a "hay" basket the constant temperature period increases up to 14 h, enabling the following day breakfast cooking.

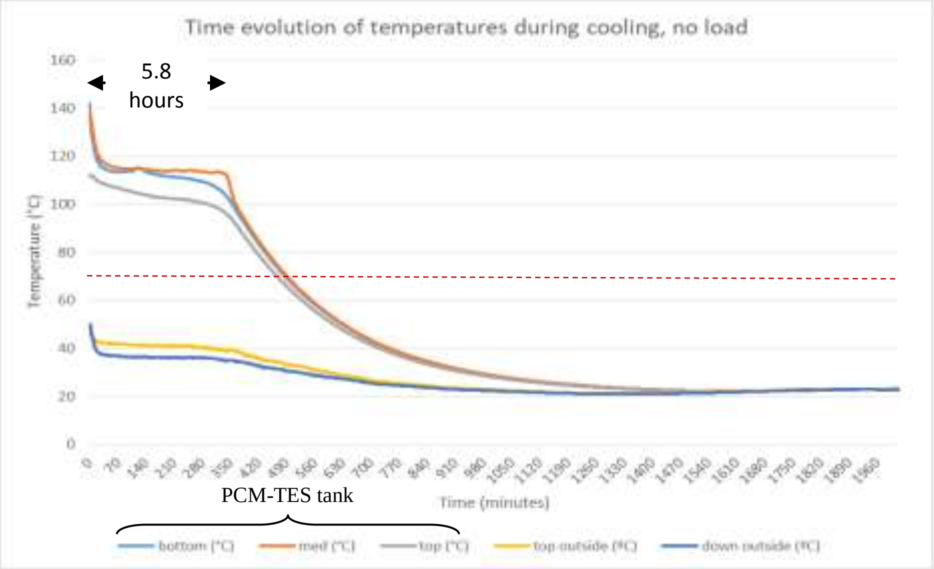

Figure 6. No load cooling test of the electronic pot with the PCM-TES incorporated.

Figure 7 shows the dynamic capability of the electronic pot, not loaded and with the PCM-TES fully charged, to heat successive loads of cold water, with intermediate un-loadings. It shows that 74 ºC are reached in the three first loads after 25 minutes each. The fourth load does not reach this temperature, barely surpassing 60 ºC.

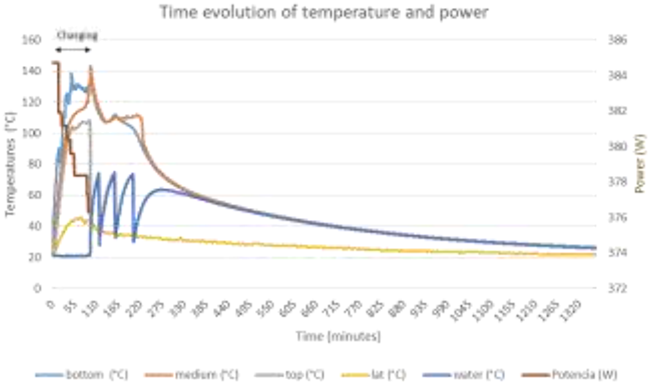

Figure 7. Charging the electronic pot incorporating the PCM-TES and afterwards loading four consecutive times with 2 kg of ambient temperature water to be heated.

5. CONCLUSIONS

- A new type of solar cooker has been developed. It uses a family owned single PV panel and no batteries for storage. Instead a PCM-TES storage serves for cooking when the sun is not shading. An edible, low cost PCM, erythritol has been tested successfully filling a moveable kitchen utensil.
- A composite material has been developed for enhancing the heat transfer inside the PCM. For that, short pieces of aluminum tubes have been tested. For a lower cost steel can be used.
- A proprietary PV control basic circuit has been developed showing also that simple electronics can be appropriate for supporting the PV cooker and at the same time propel a local technological development. This circuit can be refined to implement a better control and incorporating auxiliary services, such as incorporating a USB charging port.
- Results indicate a promising concept. Still practical testing is needed before a pilot deployment.

ACKNOWLEDGEMENTS

The help of several students at Universidad Carlos III de Madrid is acknowledged when they have developed their end-of-studies thesis under the supervision of Prof. Antonio Lecuona-Neumann.
The help of the AECID CYTED AESCA project [6] is acknowledged for partial funding diffusion.

REFERENCES

[1] Lecuona-Neumann A, Cocinas solares. Fundamentos y aplicaciones. Herramientas de lucha contra la pobreza energética. Barcelona: Marcombo, 2017.
[2] Duffie JA, y Beckman WA. Solar Engineering of Thermal Processes. Hoboken, New Jersey: John Wiley & Sons, 1991.
[3] http://www.m-kopa.com/products/ accessed 2018/01/07.
[4] http://www.wri.org/blog/2017/02/pay-you-go-solar-could-electrify-rural-africa accessed 2018/01/07.
[5] Lecuona, A., J. I. Nogueira, R. Ventas, M. C. Rodríguez-Hidalgo, and M. Legrand. Solar cooker of the portable parabolic type incorporating heat storage based on PCM. Applied Energy 111 (2003): 1136–1146.
[6] CYTED Project "ALMACENAMIENTO DE ENERGÍA SOLAR PARA COMUNIDADES AISLADAS" Coordinator: Juan José Milón, UTP, Arequipa, Perú. http://www.cyted.org/?q=es/detalle_proyecto&un=933 and https://www.facebook.com/cytedAESCA/ accessed 2018/01/06.