Cuisson solaire photovoltaique sans batteries
avec des résistances céramiques

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8ème Partie :

PRESENTATION THEORIQUE
ET PRESENTATION VIDEO

Les trois documents proposés ici proviennent du 5ème Congrès CONSOLFOOD consacré à la cuisson solaire, qui s'est déroulé à La Corogne en Espagne, du12 au 14 Juillet 2023.

Communication vidéo : présentation théorique par Prof. Antonio LECUANO NEUMANN,
disponible ICI , durée 8 mn, en Anglais

Communication video : présentation du cuiseur, par Jean BOUBOUR
disponible ICI , durée 8 mn, en Anglais

Conference Proceedings : document PDF
disponible pages suivantes ; 11 pages, en Anglais

PHOTOVOLTAIC SOLAR COOKING WITH PTC CERAMIC HEATERS WITHOUT BATTERIES

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Abstract: Due to the continuous decrease in the price of photovoltaic solar panels, it is now possible to use them to produce heat, for example, for cooking, allowing indoor kitchens. But it is still necessary to have a regulated electrical current. We propose using PTC (Positive Thermal Coefficient) ceramic resistors, whose flexibility of operation adapts well to the variations of photovoltaic electricity and avoids overheating. In some PTCs, the resistance increases sharply above ≈200°C (Curie temperature); thus, the heat production stagnates. Therefore, there cannot be any burnout or overheating. A solar cooker has been conceived using them without them. This allows a solar cooker without electronics or batteries. The regulation of the cooker consists of putting into operation the appropriate number of ceramics according to the sunshine and the power required. This is feasible with the help of a Wattmeter, which guides the user in finding the best point of heat production. Since the temperature external to the resistors and pot is always below 200°C, it is possible to thermally insulate the cooker and the cooking vessel completely with ordinary materials. Thermal insulation significantly increases the installation's energy efficiency during the heating and slows the following cooling process in retained-heat slow cooking. The paper offers the design principles, implementation, and test results. It offers information to replicate and pave the way to improve this photovoltaic solar cooker.

Keywords: photovoltaic solar cooking, PTC ceramic heaters. Sustainable development. Energy poverty.

1.- Introduction

Let's take a quick historical look at the energy needed for cooking. Since the conquest of fire, wood has been the primary energy source. For *convenience,* it was gradually replaced by coal, wood charcoal, gas, or paraffin, whose heating capacity by weight and control are much more significant. Nowadays, wood is used in remote and isolated locations out of *necessity* as modern fuels are unreachable. Because wood sometimes does not renew itself at the same rate as it is harvested, it is necessary to find a new way of cooking, sustainable and renewable. Recently, electricity has been used for cooking when available and if affordable, but grid electricity does not reach the poorest remote locations. On top of this, wood fumes are toxic indoors the home and even outside of it, responsible for many diseases and premature deaths.

And now, there is a risk that fossil fuels will no longer be able to meet our needs, or they will be banned because of atmospheric pollution. In remote and isolated communities, fossil fuels become difficult to access for the poorest part of the population. Grid electricity, mainly fossil fuel-derived energy, seems even more inaccessible.

A solution is to use the mother of all renewable energies, the sun.

For several decades, a great deal of engineering and imagination has been devoted to solar thermal cooking; for example, Luther Krueger's "Museum of Solar Cookers" in Minneapolis, USA.

Meanwhile, emerging photovoltaic technology has made great strides. The exorbitant initial costs have followed a steady downward curve, which now crosses the rising curve of other energies, reaching below 1 €/kW of peak power.

What about using photovoltaic energy for cooking? Articles appeared on the subject around 2013. Since then, the price of photovoltaic collectors has continued to fall, e. g. [1]. The result is that solar cooking using photovoltaics now seems affordable. The low efficiency of PV panels compared with thermal solar cookers is overcome as described here.

Two obstacles must be surmounted, and this is what Section 2 of this article presents. The second obstacle leads to the proposed solution. Section 3 discusses the implementation of this solution. Section 4 deals with the regulation of the cooker. And Section 5 presents the thermal performance.

2.- Two obstacles and a solution.

The first obstacle.

To transform electricity into heat, it is customary to use nickel-chromium resistors (Ni-Cr), which can be found everywhere, e. g. electric radiators, toasters, and hair dryers. They withstand a specific power and even a little extra margin, but beyond a certain threshold, they burn out. Ni-Cr resistors, therefore, require voltage-regulated electricity to function normally. The now much-disseminated induction plate technology for cooking, which is a significant improvement, also requires an adequately regulated voltage.

The photovoltaic panel supplies electric power, primarily as an intensity I of electrons, coming from the absorption of photons, which is measured as solar irradiance W/m^2 (solar intensity G); actually, it is a collection of illuminated diodes connected in series and eventually in parallel that result in panel characteristic curves depending on the irradiance G, Figure 1. Because of that, the **operating voltage U must be selected**. The risk of resistor burnout is, therefore, permanent. A technique is necessary for ensuring a safe and efficient operation.

The second obstacle.

It is the **variable production of the photovoltaic panel**. The panel's electricity production depends on the amount of sunlight it receives. In a panel oriented to the sun, it is maximum under a clear sky at midday but decreases towards sunrise and sunset; it also decreases because of clouds and dust, either in the air or over the panel.

The characteristic line for the resistance
Let us connect with the preceding paragraph. The power P obtained is the result of matching the panel intensity I [Amperes] and the voltage U [Volts] with those of the load. The load is a resistance, which dissipates the resulting electrical power into heat; $P = I \times U$, expressed in Watts = Amperes × Volts.

The resistive load applied to a panel is characterized by R [Ohms]; according to the Ohm law, it is $U = I \times R$ [Volts], which is a straight line, depicted in Figure 1 whose steepness in the convenient U vs. I diagram is inversely proportional to the resistance R. The same Figure 1 shows three representative curves $U - I$ of the same PV panel illuminated by three values of G: $G_1, G_2,$ and G_3 although all intermediate values are possible.

When one connects a resistor R at the + and – terminal of the PV panel, the intensity across the resistance and the voltage must match the one delivered by the panel. Figure 1 shows the three crossing points, 1, 2, and 3, for three irradiances and the same R.

The characteristic curves of the PV panel

As Figure 1 shows, in a first approximation, intensity I [Amperes] delivered by the panel is proportional to the solar irradiance G (with a maximum of $\approx$1000 to 1100 Watts per square meter in the direction of the sun), which is on the plane of the panel(s) if oriented to the sun; $I \approx k \times A \times G$. k is a constant, and A is the surface area, typically around 2 m^2 for a single commercial panel. As a first approximation, for constant G, the panel intensity is almost insensitive to the voltage U for low voltages (near the short circuit, low R, delivering around 9 A for a commercial 2 m^2 panel). It falls abruptly when the voltage surpasses a definite value, reaching null Amperes when the circuit is open, $R = \infty$, as Figure 1 depicts, which is around 40 V for a commercial 2 m^2 panel. On the other hand, the resulting power $P = I \times U$ [W] increases almost linearly as U increases, up to a maximum $P_{máx}$, and for higher U it falls. Figure 1 shows the curve P for $G_2 = 500 \frac{\mathrm{W}}{\mathrm{m}^2}$. The resistor in Figure 1 has been selected for maximizing the power of irradiance, $G_2 = 500 \frac{\mathrm{W}}{\mathrm{m}^2}$. For different irradiances G, the $U - I$ combination resulting comes from the crossing of the straight line of R and the curve at the actual irradiance. The result is a fast drop in power for $G \neq G_2$ for the selected R.

A variable R is required

Thus, what determines the relation between U and I is R, as explained above, $U = I \times R$. Applying a fixed resistance R to a panel yields meager production under low solar irradiance, point 1. On the other hand, for $G_3 = 1000 \frac{\mathrm{W}}{\mathrm{m}^2}$, the power is also low, far from the maximum possible. Both points are indicated with bullets. Thus, there is a need for varying R to reach the maximum power for any G. The Maximum Power Point MPP is only reached at a specific voltage for any G, which is indicated with stars for the three values of G used. Fortunately, these optimum voltages do not mutually differ very much.

Because of these facts, many PV battery chargers and inverters incorporate an MPP Tracker (MPPT) that continuously searches for the adequate U for any G, as Fig. 1 shows with stars for the three cases considered so that maximum P is reached every time, $P_{máx}\langle G \rangle$. The variable R needed for the panel is achieved through electronics (e. g. Pulse Width Modulators PWM). In commercial devices, it is frequent that the MPPT automatically plays a dual role: optimizing the panel's production and, if applicable, also controlling the supply voltage, and very frequently, adjusting the charging process of a permanently connected battery. Avoiding battery damage requires limiting the intensity towards it, depending on the degree of charge and temperature. But also, the effective voltage applied must be slightly higher than the nominal voltage of the battery (12 V, 24 V, …) to transfer electric charge to the battery. Consequently, a charge controller is necessary to accommodate the delivery from the panel to the battery's requirements. Typically, it adapts the voltage and intensity to the battery needs, frequently losing part of the power available from the panel unless the electronics are pretty complex, i. e. using an automatic voltage converter (Buck-Boost converter). When discharging, disconnected from the PV panel, the battery offers an almost constant voltage, typically slightly below 12 or 24 V, down to the point near complete discharge when the voltage goes null. A voltage regulator must adjust the supply to 230 V AC independently of the selected panel voltage selected for supplying power to an AC grid.

Another issue is how the controller discerns to split the power from the panel(s) between charging the battery and supplying the connected load.

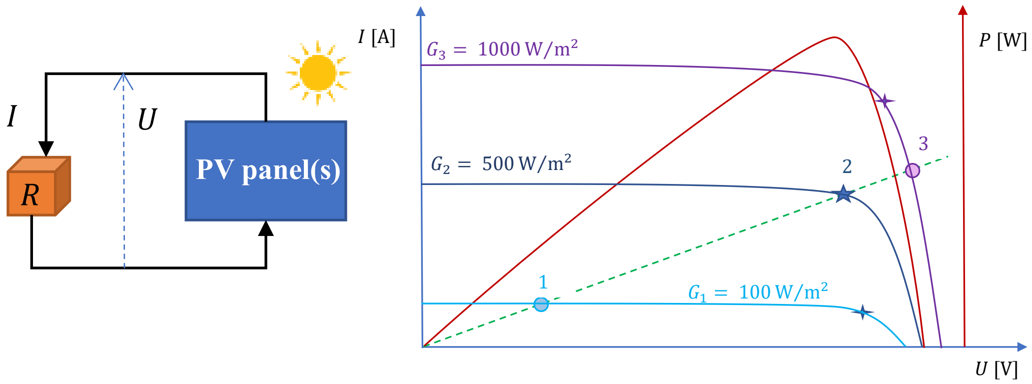


Figure 1.- Relations between voltage U and intensity I of a PV panel in good condition for three irradiances, the curve for a resistance R, and the power P delivered for only G_2 and R for MPP at G_2.

A solution, no battery

Technically, correctly interposing a battery with its regulator makes it possible to offer a complete and satisfactory system. The panel could be used near its optimum, the battery is charged according to the rules of the art, and the resistors of the cooker, of almost constant R, have a correctly regulated electric current as a result of an almost constant U. In addition, because the battery is an energy storage device, it is possible to cook off-sunshine. But this is not without its problems:

- Efficient panel/battery controllers with MPPT are expensive and typically are only available for large powers.
- The battery is expensive; although its price has decreased significantly, it is still the costliest component of a photovoltaic cooking system. It has a limited lifespan of about four years if correctly operating and much less in an extreme temperature environment or because of abuse.
- Frequent transport of batteries to remote locations is not easy.
- Finally, a battery is particularly polluting because of the metals from which it is constructed, Pb, Cd, Co, Ni, Li, etc.

On the subject of lithium batteries and according to many studies, e. g. [2], the question is, will there be enough left over for cookers in developing countries?

On the subject of rare and scarce metals, let us recall here that contrary to a current belief, there are no rare metals in photovoltaic panels [3]. The challenge is now to design a solar cooking device without a battery. Thermal Energy Storage TES can replace it.

As part of the solution, we propose the use of Positive Thermal Coefficient (PTC) ceramic resistors [4]. Like all resistors, a ceramic material produces heat when an electric current flows through it, independently of it being AC or DC. But as it heats up, its electrical resistance decreases, Figure 2. For the resistors of our interest, at ≈200 °C, the resistance is divided by around three compared to the ambient temperature, so its heating power is multiplied by three under a constant voltage. Then, beyond ≈200 °C, the resistance increases sharply, Figure 2. When it becomes remarkably high, the electric current can no longer flow, and heat production stagnates. This part is indicated with a dashed line in Figure 2.

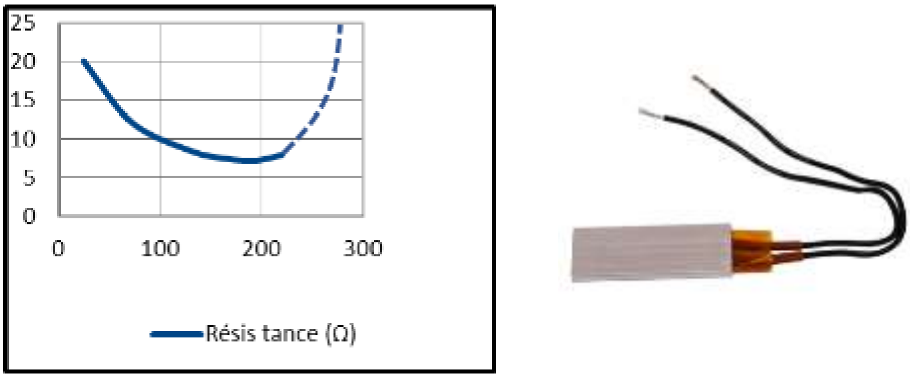


Figure 2.- Left) Example of the variation of the resistance *R* of a PTC element as a function of its temperature, obtained with the test bench herewith proposed. Right) example of a PTC heater element with a rated power of 35 to 80 W.

3.- PTC Ceramic Heaters

Although not widely known, ceramic heaters are pretty standard in everyday life. Small electric heaters, available in most household electrical goods stores and sold as auxiliary heaters, are a good example. Small and light, they are necessarily equipped with a fan that permanently drives out the heat produced by the ceramics, without which the heat production would stagnate. In cars, ceramic heaters are used to warm up the fuel and oil in winter without the risk of overheating.

Ceramic resistors can be found in DIY glue guns; the stagnation temperature corresponds to the melting heat of the glue, so there is no need for a thermostat (you don't hear a thermostat being triggered like with an iron).

The characteristics of the ceramic heating elements are interesting for our cooker:

- The heating elements do not burn out.
- The supply temperature of ≈200 °C is more than sufficient for cooking with water, such as braising, steaming, etc., except for frying in oil and grilling.
- The temperature of ≈200° is lower than the ignition temperature of cotton; it is, therefore, possible to insulate the entire cooker with cotton towels, for example. This insulation minimizes heat losses to ambient; thus, less power is needed to cook; also, insulation prolongs cooling with no power added.
- The commercial PTCs contain a ceramic wafer on which the electrical wires are soldered. A socket of Kapton® electrically insulates it pressed between two thin aluminum plates, Figure 2.

The only indication typically available from the buyer is the recommended voltage: 12, 24, 36, 48, 110, and 230 V, while a conventional resistor does not operate under a nominal voltage. In addition, the PTCs have a breakdown voltage limit not to reach. In principle, the manufacturer can indicate a maximum permissible power, which must not be exceeded. There is also a maximum temperature not to reach.

From common Chinese suppliers, usually, there is also no datasheet. The price varies from 0.40 € to 0.80 € for large quantities; it increases to around eight times higher for individual purchases.

As a main result, designing a cooker with ceramic heating elements is now possible as the Curie temperature can be as high as 250 °C. A small thermal resistance from the PTC to the pot is paramount. A layout can be as follows; several resistors are installed under a heating plate; the cooker user has two or three switches and a small Wattmeter, nowadays of such a low cost as 9 €. The user adapts the number of in-parallel resistors to the current sunshine, looking for the best operating point of the solar collector by reading the Wattmeter, or can reduce power if desired. In the case of constant sunshine, no monitoring is necessary. In case of a large increase in electrical power, the resistors are self-regulating and do not burn out.

There is the issue of starting with the PTC elements cold. Because of the high resistance, Fig. 2, they do not heat very much, especially if loading the panel with too high a resistance. Loading with a cold pot is recommended not to load until the plate has already heated itself.

The operation of the cooker can be automated, for example, using a microcontroller, e. g. of the Arduino® type. A cloudy passage could not affect the cooking process through its use, as MPPT will do the job.

The following section addresses the design of the cooker.

3.- Ceramic resistors and the cooker

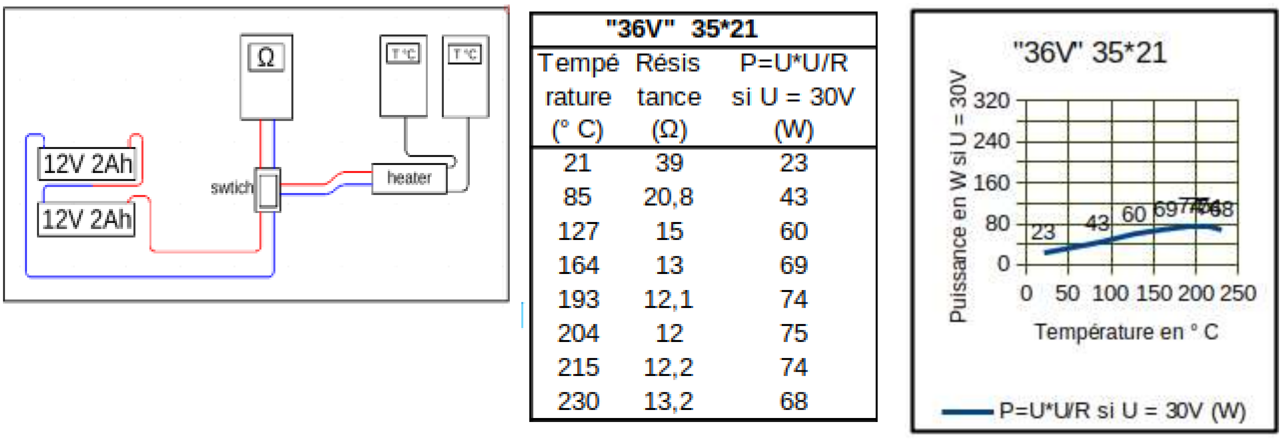
Almost all of the choices made below are not imperative, just the result of the research; many variants are available to the designer.

A first choice concerns the operating voltage of the installation. For reasons of user safety, exceeding a voltage of 40 V is not recommended, i. e. using a panel producing a voltage of ≈40 V in open-circuit, and therefore approximately 22 to 32 V in the usual operation.

Commercial resistors stamped as for 36 volts, of standard dimensions 35 x 21 x 5 mm, have been used successfully; 48 volts PTCs would also be suitable. Resistors stamped 24 volts were not used, as they have too low R.

The PTC test bench

Given the limited information provided by the manufacturer or seller, and also because of wide tolerances, it is essential to test the ceramics on a test bench, such as the one proposed here, Figure 3.



"36V" 35*21

Température (° C)	Résistance (Ω)	P=U*U/R si U = 30V (W)
21	39	23
85	20,8	43
127	15	60
164	13	69
193	12,1	74
204	12	75
215	12,2	74
230	13,2	68

Figure 3.- Left) A simple test bench for PTCs. Center) A sample of results. Right) calculated power.

The resistor is held between two pieces of wood and instrumented by one or two wire thermocouples; type T or K are suitable and widely available in a ready-to-use configuration. A laboratory bench power supply of variable voltage up to 24 V DC is suitable; instead, two 12 Volt / 2 Ah batteries are suitable too, or a 24 V AC plug should also be suitable, with an autotransformer if reasonable control is desired. In the center of the circuit, there is a three-position switch, Figure 3. The operator powers the resistor while observing the temperatures, flipping the switch, and reading the Ohm value after the off-line temperature measurement somewhat stabilizes. Seven or eight measurements, spaced about 30 °C apart, are sufficient. Measurements for higher than the Curie temperature are difficult with this test bench unless extra power is available and/or extra thermal insulation is added.

A measurement example

The Figure 3 Center) offers the first two columns of some measurements. The third column shows the calculated power of the resistance, for an assumed voltage of 30 V, according to the formula $P = U^2/ R$.

The graph on the Right) shows the power values. The operating temperature of the heating plate is estimated at 150 °C, as there is a temperature drop from the PTC to the hot plate, and there are heat losses. It varies according to the temperature of the cooking vessel, depending on whether it is being heated or maintained hot. The corresponding power is noted graphically, 65 W.

The arrangement of the resistors under the hotplate is carried out according to these elements.

The arrangement of the resistors:

For a 300 W peak panel, six identical ceramic resistors nominally declared for 36 V, with a calculated power of 65 W at 150 °C, were installed. They were arranged into three groups:

- A group of 3 resistors in parallel.
- A group of 2 resistors in parallel, actually a double-size PTC.
- A group of 1 resistor.

The user has three switches on this proposed cooker, allowing him to parallel set the power on 7 levels, including null. Thus, there is no electronic control at all.

Construction of the cooker

Below, in Figure 4, there is a one-piece cooker made from plywood, which an artisan can build. It is also possible to have the control unit separate from the heating element to facilitate cleaning and hygiene or to enclose it in a waterproof container. The heating plate is cut out of 5 mm sheet metal; aluminum is preferred. The insulation, which surrounds the heating block and the cooking vessel, is shown.

4.- The power control of the cooker

The role of approaching the MPP

At first sight, the regulation of the cooker consists of searching for the MPP with a couple of values (U, I); fortunately, U for maximum P does not vary very much when G is varied, Figure 1. MPP is achieved by putting the appropriate number of ceramics into operation, among the six ones installed under the cooker's heating plate. For that, the characteristic curve of the commercial PV panel(s) is consulted. If only a graph of intensity versus voltage for different Gs is provided, the power curves $P\langle U\rangle$ must be drawn and the maxima discovered so that the minimum PTC resistances (just indicative of the working point) are determined by calculation as $R_{mín} = U^2_{P_{máx}}/P_{máx}$. Alternatively, it is near the knee in the intensity versus voltage $I\langle U\rangle$ curve and $P_{máx} = U_{knee} \times I_{knee}$ so that it becomes $R_{mín} = U_{knee}/I_{knee}$.

The power of these ceramics installed varies according to their temperature, which varies with the temperature of the contents of the cooking vessel, but not so much according to their self-regulating nature. The temperature of the contents rises during the heating period and stagnates (steady-state) during the cooking process when input power equals the heat losses to the ambient, in addition to producing steam.

Manual control and automatic control

In the case of the manual regulation studied here, the user has six adjustment levels. The user makes a choice that can be verified with a Wattmeter. When the day is clear and sunny, the user can go about his cooking duties without worrying about the cooker.

An additional automatic control has been developed with a small microcontroller, for example, an Arduino®. The rudimentary algorithm is of the "Perturb and Observe" type. Two sensors for voltage and current transmit the information to the microcontroller. It calculates the instantaneous power. It then slightly modifies the number of ceramic resistors in operation, checks the effect on the instantaneous power, and confirms or denies the previous modification, repeating the process.

The automatic control tested had 13 levels, which is more precise than the manual control. A time delay is necessary to allow for the stabilization of temperatures.

In the event of a malfunction, there can be no damage. If the resistors are overloaded, the ceramic material plays its regulating role. If the resistors are underpowered, the cooking process continues like a "Norwegian pot", "heat bag", or residual heat cooking at low-temperature.

5.- Results obtained

Some examples of cooking.

They were carried out with a panel of 1.66 m², peak power 280 W MPP. Placed on Brittany, France, oriented to the South, and with an inclination angle of 50 degrees. No Sun tracking. Tested during summer on clear and sunny days at noon hours, Figure 4.

Figure 4.- Left) The developed prototype is shown under testing. The pot is insulated with cotton tissues [5].

Three examples and recipes:

- Plain rice: rice 300 g, water 500 g. Total cooking time: 55 min.
- Cooked vegetables: Onions 250 g, tomatoes 800 g. Total cooking time: 1 h 30 min
- Chicken casserole: 3 chicken thighs 680 g, onions 145 g, fennel 175 g, courgettes 270 g, red pepper 225 g, green pepper 215 g, crushed tomatoes 200 g. It is cooked in a Lagostina® pressure cooker of 3.5 liters capacity. The temperature reaches 110 °C after 1 hour, then cooked for 15 minutes.
- Chicken Basquaise: 4 chicken legs with drumstick and onions, to be browned. Addition of 200 g of tomatoes and 200 g of peppers. Heat up to 100 °C after 35 minutes; then cook from 100 to 115 °C for 20 minutes. Cooked in a Lagostina® pressure cooker of 3.5 liters capacity. Continuous irradiance measured on the plane of the panel $G = 930\ \mathrm{W/m^2}$, constant power of the cooker 220 W.

- Coral lentils dahl: browned onions 210 g, tomatoes 400 g, lentils 300 g, coconut milk 400 ml, stock 1/4 liters. Heating up to 100 °C after 3/4 hour. $G = 900$ to $960\ \mathrm{W/m^2}$, almost constant power of the cooker at 220 W. Then, cooking as a Norwegian pot for half an hour without any power supply; during this half hour, the temperature dropped from 100 °C to 90 °C with the insulation shown in Figure 4.

A method of measuring the performance of the panel plus cooker combination

The time taken to bring 1 liter of water to boil can be measured; this is already a good indication of this cooker prototype's performance. However, one may wish to be more precise in performing thermal calculations, in which case the notion of boiling could not be precise enough. The proposed methodology is to measure the starting temperature, then measure the time needed to reach the water temperature of 97 °C inside the pot, just before boiling at sea level. In an experiment with a starting temperature of 25 °C, it reached 97 °C in 40 minutes. The specific heat of the water is $4.18\ \mathrm{J/(g\ °C)}$. The amount of energy is (97-25) °C ×$4.18\ \mathrm{J/(g\ °C)}$ ×1,000 g= 301 kJ. Duration of the operation: 40 min×60 s/min = 2,400 s. The average net power of the cooker is 301,000 J/2,400 s ≈ 125 W. As the average electrical power of the cooker has been measured as 220 W, this implies an average electricity-to-heat efficiency of 57%. The average sun-to-electricity PV efficiency is ≈ 20%, with a resulting overall efficiency of ≈15%.

6.- Some additional notes

Heat storage

In the case of a cooker without a battery, a substitute would be the storage of thermal energy for a few hours, for example, with a phase change material, such as erythritol [6], [7], [8], [9], and [10] among others. This, with good insulation, makes it possible to heat the breakfast the following day or to prepare hot sanitary water for a baby just with the residual heat. It should also be noted that the ceramic cooker can operate perfectly well on a previously charged battery.

Lighting and telephony

Without a battery, these devices can be recharged with a DC/DC USB converter worth only a few euros. When connected to the panel, it charges mobiles and lanterns via a small solar-integrated "USB Power Bank".

Quality of the switches

The quality of the switches, known as "rocker switches", is crucial. In the present case, the voltage is low, but the current is high, and DC. After closing the switch, the inner contact blades will heat up if they are loosely in contact with each other. This is a lost energy for cooking and is also a risk of an accident if overheating. Manufacturers of suitable quality switches state a maximum contact resistance of 50 milliohms in their data sheets. Do not hesitate to check this value with an ohmmeter after delivery. Last but not least, a peculiarity of direct current DC is that it causes arcing when the switch is opened, resulting in abnormal wear of the contacts. Reducing arcing with additional electronic elements is possible.

A small and bizarre phenomenon

Let's say a cooker is in operation. When removing the cooking vessel, the hot plate rises in temperature to the point of stagnation, then the Wattmeter indicates almost no power, even though it is sunny, but there is no malfunction. Putting a container back on the plate filled with cold water brings power back.

7.- Conclusions

The paper offers the possibility of constructing a PV-based solar cooker with no battery and no electronics, thus, suitable for sustainable developments for energy-vulnerable communities.

It can be manufactured on-site in many locations.

The paper offers the basics and practicalities particularized to a small power prototype, which has been tested for thermal performance and under real cooking. Escalation to higher powers is straightforward with the information offered.

Information on the construction and use of a cooker with ceramic heaters can be found at photovoltaic-solar-cooking.org. The contents are free of rights. From this basic model, a multitude of different cookers can be designed.

In this heating device, instead of adapting the electricity to the resistors, the resistors adapt to the available one. There is only not to exceed the limits of the device: maximum power, maximum temperature, and maximum voltage. The proposed design offers a high simplicity and a low cost.

8.- Acknowledgments

Jean Boubour founded photovoltaic-solar-cooking.org, which gathers some retired people in the industry informally in Brest (Brittany), France. Their help is deeply recognized. This activity progresses without any economic aim on devices of electro-solar cooking and incidentally for producing sanitary hot water. The prototype described here was constructed within this group by Mr. Jean Boubour. It is now under testing, mathematical modeling, and additional development at UC3M.

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