The Design and Implementation of a DC Solar Hot Plate for Rural Usage in Nigeria

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Abstract- This paper is on the design and implementation of a DC solar Hot Plate for rural dwellers in Nigeria. The need to mitigate the greenhouse effect and to reduce deforestation coupled with the increase in the cost of cooking fuels like gas, kerosene and even firewood has necessitated the consideration of alternative means through the use of solar modules for direct generation of heat (without conversion of electricity from DC to AC) using hot plate. The heating element used in this design is the Nichrome coil (element), which the required length is calculated so as to match with the rating, and ceramic material is used to design the plate's body. The hot plate is designed for 24V with the power of 800W. The cable size for termination of the plate at the solar panels is designed to withstand maximum DC current of 34A expected. Also, the expected number of solar panels to be used with the plate is calculated. With this design, the hotplate only needs the required numbers of solar panels of specified rating to be connected to it for proper functioning. It is simple, has a little or no maintenance, no moving part which make it to be cost effective and very safe to use.

Index Terms - Element, Solar, Hotplate, Module, renewable, Energy, Nichrome, Cooking

I. Introduction

The energy from the sun is so enormous that the humans usually do not harness up to 1% of its daily supply. In fact, the energy that the sun radiates daily is more than energy we need in a year [1]. Unlike fossil fuel that are in form of deposit and are gradually becoming depleted, the sun continuously emit its energy and cannot be exhausted. This is because the energy from the sun belong to the category of renewable energy. It is a green energy source which has diverse usage and abundantly available for harvest [2]. There are various means of harnessing the solar energy. It ranges from popular solar concentrators both cylindrical and concave types [3]. These concentrators are used mainly for direct heating. That is the making use of heat from the solar energy for cooking, drying and boiling of water and application of sunlight for the purpose of preservation. Also, solar energy is harvested through the use of solar modules [4]. This ensures the conversion of solar energy to electrical energy for various usage like lighting and powering of home appliances. Some of this applications may involve additional components like inverter, battery, and charge controller. One of the benefits of harnessing solar energy is the reduction or mitigation of the green house emission [5]which usually characterize the burning of coal, wood and fossil fuel which result is the depletion of the ozone layer and excess cutting of trees for fuel leading to deforestation [2]. It is therefore important to devise an effective means of harvesting solar energy as a renewable energy source for cooking purpose in especially rural areas, where their main source of fuel for cooking is fire wood, so as to reduce the emission of Carbon-di-oxide (CO_2) and methane due to incomplete combustion and to reduce the rate of deforestation and various health challenges in our local areas. This paper reveals a simple design of a solar cooker (hot plate) that converts the electric energy produced by solar panel to heat energy for convenient indoor cooking and its connection for safe use.

II. Literature Review

The renewable energy sources are gradually taking their places in energy generation across the world. Many of the developed nations are now generating as much as 20% of their needed energy through renewable energy sources. Sources such as Hydro, which have been in existence for quite some time now, have really gained ground. Whereas other sources such as Biomass are upcoming. Solar energy, all over the world, is by far in abundance to humanity [1]. It is used directly for drying clothes and food items for preservation purpose. These are some of the earliest applications of solar energy for many past generations [2]. Technological advancement has extended the usage of solar energy to electricity generation. One of the ways of achieving these is to use solar concentrators for heating of liquid like water for powering of turbine which eventually generates electricity. Another way is the use of solar modules or panels which converts solar energy to electric energy directly for diverse utilizations such as lighting of our homes, powering home appliances and cooking our meals [6].

Cooking in many rural areas involves burning of wood and the use of coal which increase greenhouse gases and generate other harmful materials [2]. The greenhouse effect in our rural communities are increasing by the day as the population is increasing, the burning of wood is increasing. This is not good for the health of our society. The greenhouse effect is easily mitigated through cooking with solar energy [7]. In this paper, a solar DC cooker (hot plate) is presented. It is a cooking plate that makes use of electrical energy derived from the solar panels. The energy conversion to heat from electrical is usually done using special wire or coil called heating element [8] [9].

2.1 Heating Elements

There are different types of heating elements today; each one with various applications. Selecting the heating element to be used for a particular project depends on the nature of such project. There are metal heating elements which are generally consist of resistant wire and they can be used in applications such as furnaces, hairdryers, toasters, and floor heating [9]. Another type of heating elements are composite types. They can be sheathed or tubular elements making a fine coil of Nichrome-resistance heating alloy wire. There are also Positive Temperature Coefficient (PTC) heating elements using conducting PTC rubbers and they raise the resistivity exponentially with rising temperatures [10]. In general, there are properties to look for in heating element to make it suitable for usage. A good heating element should have a high tensile strength, sufficiently ductile, and with a low-temperature coefficient of resistance [11]. Other features are high melting point, relatively high resistivity and very high resistance to oxidation in open atmosphere [9]. In this paper, four popular types of materials for heating elements will be introduced and discussed briefly. They are,

1. Nichrome: The word Nichrome was coined out from two elements which are the major constituents of the alloy. Being popular for its wide applications, it can withstand heat up to a temperature of 1200^{o}C.
2. Kanthal: The element type contains majorly Iron (Fe), Chromium (Cr) and small percentage of Aluminum (Al) and also oxidizes at first usage by the reaction of atmospheric oxygen with its Aluminum constituent to form a layer that will prevent the element from further oxidation.
3. Cupronickel: From the name, it can be deduced that this heating element is made as an alloy of copper and Nickel though it has a trace of Manganese too. It finds application in low temperature heating like low wattage electric heating.
4. Platinum: Platinum as a chemical element, is a noble metal and has various applications. This element type with high resistivity is used as electric heating elements. Because of its good qualities, it is used also as resistance thermometer [8].

The Table 1 below summarizes the aforementioned heating elements [8].

Table 1: Heating Elements Properties

s/n		Heating Elements			
	Properties	Nichrome	Kanthal	Cupronickel	Platinum
1	Type	Alloy	Alloy	Alloy	Noble metal
2	Composition (Typical)	Nickel - (80%); Chromium - (20%); Iron, Manganese, Silicon - (Trace)	Iron – (72%); Chromium – (22%); Aluminum – (5.8%)	Copper – (75%); Nickel – (23%); Iron – (1%); Manganese - (1%)	Platinum
3	Resistivity	112μΩ-cm	145μΩ-cm	50μΩ-cm	10.50μΩ-cm
4	R. Temp. Coefficient	0.0004/ºC	0.000001/ºC	0.00006/ºC	0.00393/ºC
5	Melting Point	1400ºC	1500 ºC	1280 ºC	1768.3ºC
6	Specific Gravity	8.4g/cm^3	7.1g/cm^3	8.86g/cm^3	21.45g/cm^3
7	Oxidation Resistance	High	High	High	High
8	Other Properties	High Mechanical Strength, Highly Stable, corrosion resistant	Shock-proof, High tensile strength	Silvery, Corrosion Resistant	Ductile, Malleable, Tough, Stable with temperature, Rugged
9	Application	Heaters, Furnace	Heaters, Furnace	Heating elements (low temp.), Furnace	Electric Heating Element, Rheostat, Resistance thermometer

2.2 Samples of Electric Cooker

There are various electric cooker in the market. They are beautiful products. Some of them are based on induction heating method and some use one form of element or the other. Some come with single burner while others are double or even 4-in-1 cooktop. For example, master chef electrical cooker is made with cast iron heating element top with thermostat and it is double burner. Another one like Saisho Electric cooker is also double burner but with tubular heating elements [12]. Some of the cooker or hot plate are designed for compactness and durability and also have protection from corrosion. An example is Daewoo electric spiral hot plate. Whereas, most of these hot plates are designed for strength in which some are also furnished with hardened glass, with temperature adjustment and up to 2000W power delivery, they are usually power with AC supply. For a renewable energy sources like solar module power generation, converting the generated DC energy to AC before usage using these AC based appliances amount to a waste of energy due to the efficiency of the inverter that will be used during the conversion processes. A substantial energy is being lost during inverting processes within the inverter unit [13]. A better option will be to make use of the DC electrical energy generated by the solar modules directly by converting the generated electrical energy to heat energy for cooking purposes. This is the main aim of this project, and its design is based on basic electrical principles.

2.2 Relevant principles

1. **Heat Energy**

Heat is a form of energy. In these case it is the end quantity to be generated through the use of solar panels. The output of the solar panel is electrical and it is usually expressed as follows

$$E = IVT = I^2RT \quad (1)$$

Where E is the electrical energy, I is the current in the element, V is the voltage across the element, R is the resistance of the element and T is the time. This is then converted to heat energy through the connection of element across its ends [11] [14].

2. Ohm's law

The current flowing in a metallic conductor is directly proportional to the voltage applied across its ends provided that temperature and other physical parameters are kept constant [14].

$$V = IR \tag{2}$$

Where *V* is the voltage, *I* is the current and R is the resistance of the coil. See the Figure 1 below.

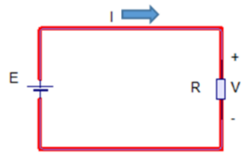

Figure 1: Ohm's Law

3. Kirchhoff law

There are *Kirchhoff Current and Voltage laws* and they are stated as follow [14].

Kirchhoff current law also known as KCL states that the algebraic sum of current at a node is zero. In other words, the sum of all the current components entering a node in a circuit is equal to the sum of all the current components going out of the same node.

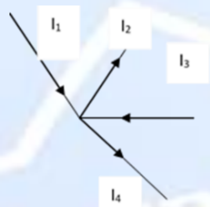

Figure 2: Illustration of KCL

$$I1 - I2 + I3 - I4 = 0 \tag{3}$$

Kirchhoff Voltage Law also known as KVL states that the algebraic sum of voltages in a loop is zero. This means that the sum of all the voltage sources in a loop is equal to the sum of all the potential drops in the same loop [15].

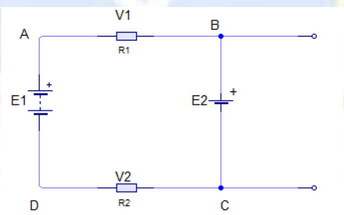

Figure 3: KVL illustration

$$V_{AB} + V_{BC} + V_{CD} + V_{DA} = 0 \tag{4}$$

$$E1 - E2 = V1 + V2$$

III. The Design

The design of this hot plate is based on the conversion of energy as shown below in Figure 4.

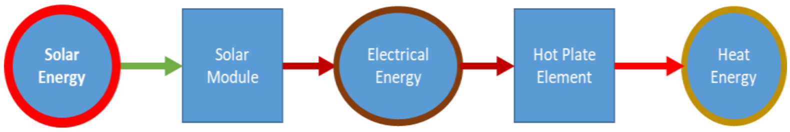

Figure 4: Energy Conversion Block Diagram

For effectiveness of the solar cooker (hot plate) the design is necessary for proper rating of the product. The stove is designed using electrical Resistive element called Nichrome. This coil is used in AC based electrical cooker and other heat generating products. Nichrome at red-hot temperatures, formed a layer of chromium oxide at its outer side and this makes it stable thermodynamically, therefore resisting further oxidation. The Nichrome coil used has specifications as shown Table 2 below.

Table 2: Properties of Nichrome Heating Element

	Features	**Specification**
1	color	Silver-grey
2	Corrosion	Resistant
3	Oxidation	Resistant
4	Stability	Highly stable
3	Melting Point	1400°C
4	Resistivity	112 μΩ–cm
5	Strength	high mechanical and creep strength
6	Alloy	Nickel and Chromium majorly

3.1 Coil Design

For the purpose of the design, a market survey was conducted to source for the coil to be used in the project. A typical coil of Nichrome found is 1500W and its length is 28.6cm. This is the maximum power the coil can withstand without burning out. In this design, for robustness, it is being assumed to be 1000W and most time, it is being used on 1000W ac hotplate. This 1000W hot plate is usually powered by ac Voltage of 220V rms in our various homes. With this coil at full ac voltage, the coil on the plate become red hot which make it possible for people to use it to cook all manner of sizable dishes at home. In order to achieve the same effectiveness while powering with a dc source, the coil voltage must be matched in such a way that the current passing through the coil using ac source is equal to the one passing through the coil when connected to a dc source. It should be noted that the RMS Voltage is the equivalent value of dc Voltage in a circuit. Thus, the DC hot plate will be calculated from these values. It should also be emphasized that the length of the coil before stretching it is 28.6cm as mentioned above and it can conveniently be used for 1000W hot plate. Therefore, the following calculation can be true for the 800W dc hot plate.

28.6cm of coil has 1000W (this assumption has taken care of the loss that could happen during the course of using the hot plate since the coil has been de-rated)

1cm of coil has $\frac{1000W}{28.6} = 35W$

To achieve 800W, the length of the coil will be

$$\frac{800}{35} = 22.86cm$$

The plate is designed to have five (5) grooves of equal length (Note that the number of the grooves can be increased or decreased; it all depends on the choice of design); this means that the coil is divided into five.

The termination of these coils are done at the reverse side of the plate. This will require additional length of coil which will be straightened out. Therefore, 4mm (0.4cm) is added to each coil. This brings the length of each coil to

$$22.86 + 0.4 \times 5 = 24.86cm$$

This length of coil is cut into five equal parts to give the length in each groove.

$$\frac{24.86}{5} = 4.97cm$$

The length of each groove should not be less than twice the length of the coil (4.97cm). This is because the coil has to be stretched out to at least twice its length before powering it.

The prototype was made with brick material (sand, cement mixed with water) for demonstration purpose. It was molded to have three short stands and its top is circular while the grooves are in fish hook shape. This is so designed to give even heat energy distribution. The grooves are also provided with holes that link it to the reverse side of the pot for the element termination.

2.2 Cable Design

Another area of design is the minimum recommended thickness of the copper cable to be used for connection of the hot plate to the solar panel.

From the Ohm's law

$$V = IR \tag{2}$$

But the resistance of a wire is directly proportional to its length and inversely proportional to its cross-sectional area, mathematically

$$R = \rho \frac{l}{A} \tag{5}$$

Where R is the resistance of the Wire, l is the length and A is the cross-sectional area of the wire. ρ is the resistivity of the wire [14] [16].

Rearranging the formula, we have

$$A = \rho \frac{l}{R} \tag{6}$$

Substituting equation 5 into equation 6 in order to eliminate R

$$A = \rho \frac{l}{V/I} \tag{7}$$

$$A = \rho \frac{lI}{V} \tag{8}$$

Where I is the maximum current expected to flow in the wire during the usage of the hot plate and V is the allowable voltage drop between the solar panels and the hotplate.

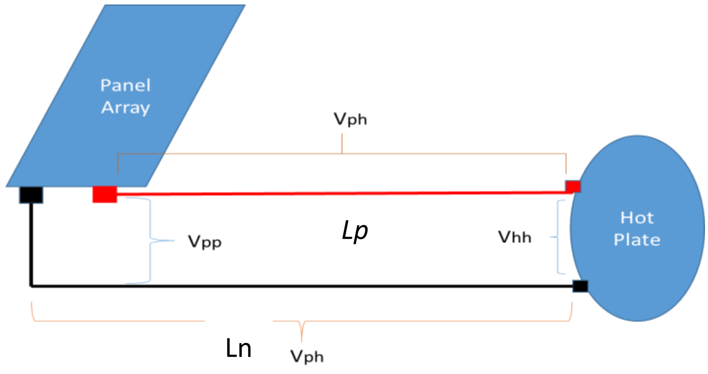

Figure 5. Cable consideration Diagram

In the figure 5 above, the solar array generates electricity which is used to power the hot plate. It can be deduced using KVL that

$$Vpp = Vph + Vhh + Vph \quad (9)$$

Assuming that Lp is equal to Ln, which is usually the case. Where Lp is the length of the positive cable and Ln is the length of the negative cable. Then,

$$l = Lp + Ln = 2Lp \quad (10)$$

$$Vpp = 2Vph + Vhh \quad (11)$$

Where Vpp is the panel voltage, Vph is the voltage drop across the cable and Vhh is the voltage across the hot plate. Figure 6 below is the electrical circuit.

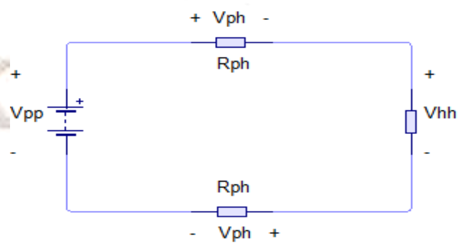

Figure 6. Cable Consideration circuit diagram

In the above diagram, Rph is the lump resistance of the cable use in connecting the hot plate to the solar panel.

$$R = Rph + Rph = 2Rph \quad (12)$$

Therefore, from equation 2,

$$V = 2IRph \quad (13)$$

Let's assume that 1Volt is allowed to drop between the panel and the plate along the copper cable, then

$$V = 1\,Volt$$

Since the power of the hotplate is 800W and it is to be operated on the minimum Voltage (Vmin) of 24V, the maximum expected current is

$$I = \frac{P}{Vmin} \quad (14)$$

Where P is the power rating of the hotplate.

$$I = \frac{800}{24}$$

$$I = 33.33A$$

This is the current that the wire should be able to handle conveniently.

For a bungalow, the length of the cable needed should be less than 10 meters. Let's assume

$$Lp = 10m$$

Then

$$l = 2Lp = 2 \times 10m = 20m$$

The resistivity of copper is given as [17]

$$\rho = 1.7 \times 10^{-8}\Omega m$$

$$A = \rho \frac{lI}{V} \quad (8)$$

$$A = 1.7 \times 10^{-8}\Omega m \times \frac{20m \times 33.33A}{1V}$$

$$A = 1133.22 \times 10^{-8} m^2$$

$$A = 1133.22 \times 10^{-2} mm^2$$

$$A = 11.33 mm^2$$

3.3 Panel Specification

With negligible loss in the circuit breaker, the expected loss along the cable is calculated as follows.

The voltage drop across the cable (both positive and negative) is given as:

$$V = 2IRph \quad (13)$$

The maximum current expected to pass through the cable is

$$I = 33.33\text{A}$$

$$Ploss = VI = 1 \times 33.33 \quad (15)$$

$$Ploss = 33.33\text{W}$$

Therefore, the maximum power expected from the panel is

$$Ppanel = Ploss + Ph \quad (16)$$

Where P_{panel} is the watt peak of the solar panel array required, P_{loss} is the power loss in the cable and P_h is the rated power of the hot plate.

For P_h of 800W and P_{loss} of 33.33W as calculated above,

$$Ppanel = 33.33 + 800 = 833.33Wp$$

Assuming a panel of $P1 = 220Wp$,

Number of panel needed Np is

$$Np = \frac{Ppanel}{P1} \quad (17)$$

$$Np = \frac{833.33}{220} = 3.79$$

$$Np \approx 4\ panels$$

For panel of 30V, the four panels will be connected in parallel as shown in figure 10.

3.4 Body Design

The body specification of the plate varies depending on the choice. For the prototype being considered here, it has a radius of 12cm and a height of 6cm. Each of the five grooves are about 12cm in length. See Figure 7. The element to be placed in each groove is 4.97cm. This includes 0.4cm to be straightened out for termination purpose. The remaining is stretched out to cover the length of the groove.

There is also need for the proper termination of the element. This is necessary to ensure minimum loss at the terminals during operation (usage). This is achieved by copper screw and nut for the terminals. It is also put into consideration the amperage of the current that will be passing through the terminals, which the terminals must be able to handle it.

To achieve the red hot and efficient operation, the solar panels that will power the hot plate must be sufficient in term of wattage.

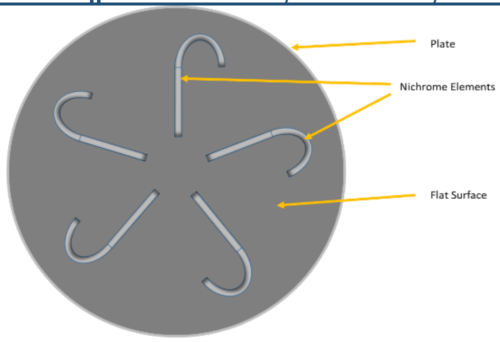

Figure 7: Element Arrangement on Plate

IV. Implementation and Operation

4.1 Arrangement of elements

The elements are arranged radially on top of the plate. Each element forms the shape close to that of fish hook as shown in Figure 7. One end of each element is assigned positive and the other end is taking as negative. Since 5 coils are used on the plate the angle from the center between two elements is 72^0. This ensures that the coils are evenly spaced for even heat distribution.

4.2 Electrical connections

The connection is done as shown below. All the positive terminals are connected together and all the negative terminal are connected together as shown in figure 8.

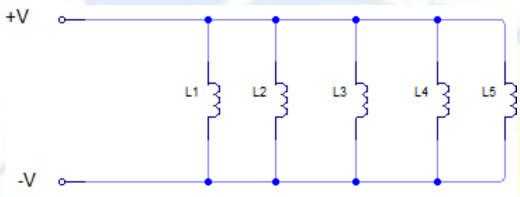

Figure 8: Circuit Diagram of the element

The expected current to be drawn by all the elements is taking into consideration so that the copper wire is not heated up thereby consuming substantial amount of energy generated by the solar modules. The termination of the copper wire is done on the body of the hotplate with the help of two copper pins of diameter 3mm protruding from the body of the hot plate. The ends of the two copper terminals are provided with high quality copper connectors for easy termination with the solar panels. The connection at the reverse side is as shown in figure 9 below. It should be observed that the shorter copper terminal is taking as positive. This is done to reduce the heat loss along the copper wire.

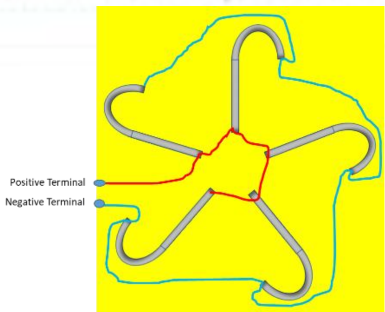

Figure 9: Reverse Side Wiring Diagram

4.3 Operation

The full wiring diagram is as shown in figure 10. During the day when the sun impinges on the solar panel array, the solar energy is converted to electrical energy. the amount of energy to be realized per unit time depend on several factors such as the solar irradiance, solar panel efficiency, incident angle of solar energy impinging on the panel, the overall wattage of the panel arrays, the cleanliness of the panel surfaces and the quality, length and size of the cable being used. The cable, both positive and negative terminals from the solar panel array is connected to a circuit breaker. This breaker performs dual purpose of protection in case of any short circuit and also regular isolation when the hot plate is not in use. The output of the breaker is then terminated on the hot plate as shown in the figure 10.

The arrangement and the wiring connection of the panel array can be parallel or series/parallel depending on the voltage rating of the panels to be used. For solar panel of rated voltage of 30V to 36V, all the panels are connected together in parallel as shown in the figure. But for 18V voltage specification, the panels are connected in series parallel form as depicted in the diagram of figure 11,

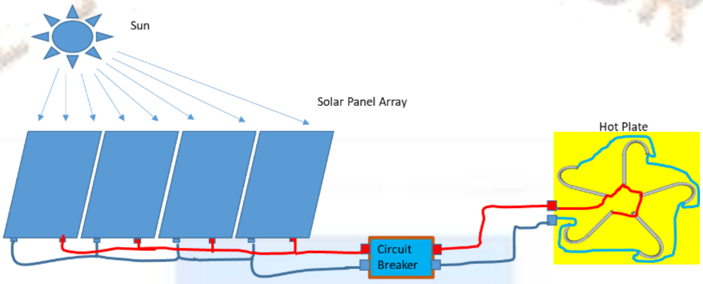

Figure 10: The complete wiring diagram

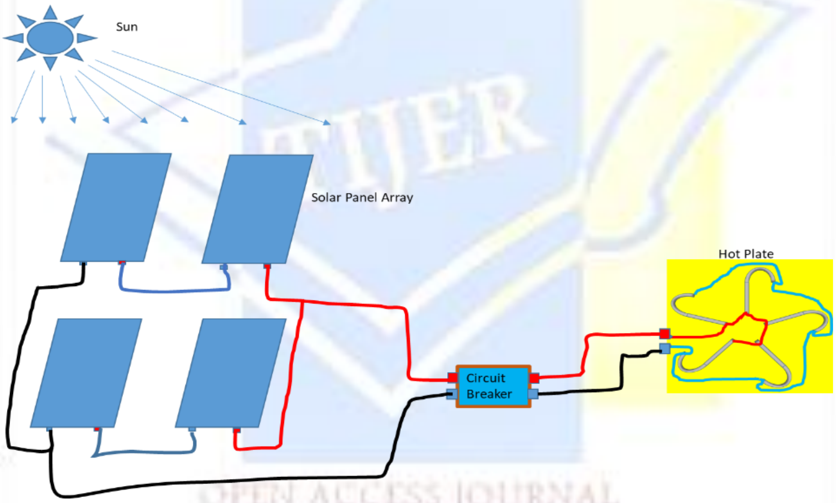

Figure 11: Series Parallel Solar Panels Arrangement

4.4 Merits of the Hot Plate

The higher the irradiance, the hotter the hot plate becomes. Since there will be negligible voltage drop across the connecting cable, most of the electrical power from the solar panel array is transferred to the coil of the hot plate. The arrangement therefore is very efficient, simple and convenient to use within individual homes both in the cities and among the rural dwellers. The hotplate can easily be adapted to existing stand-alone photovoltaic system. It is less risky, since it operate at low DC voltage. The plate is portable and thus can be disconnected and taken to any remote places like farm, picnic and camping program for usage. It is very rugged and have very low failure rate because of its simple design. It is also affordable and does not require special training or education except for few safety precautions.

5 Conclusion

The solar Energy is in abundance upon the earth and this can be harnessed for the good of the teeming populace. The challenge is the conversion of the solar energy to suit our daily activities and also give room for convenience. The solar hot plate has been designed to provide solution to these challenges. The simple direct conversion has made it possible to reduce wastage of energy that is usually experienced due to conversion efficiency (like dc to ac conversion using inverter). The design can be well utilized if deployed to the rural areas where their only or main source for cooking purpose is firewood. This will reduce deforestation in our rural areas and also contribute to the mitigation of greenhouse gases.

References

[1] The NEED Project, "Energy from the Sun," The NEED Project, Manassas, 2018.

[2] A. V. Herzog, T. E. Lipman and D. M. Kammen, "Renewable Energy Sources," Energy and Resource Group, Rerkeley.

[3] SinoVoltaics Group Limited, "Solar Concentrators: What are the different Technologies," 28 September 2023. [Online]. Available: https://sinovoltaics.com.

[4] B. Adithya, D. Ritesh, H. Rajini, B. Manish and B. Pavan, "Design of a Standalone PV System for the All-Weather Condition: A Practical Approach," in *AIP Conference Proceedings 4261*, Bangalor, 2022.

[5] I. Atmane, N. E. Moussaoui, K. Kassmi, O. Deblecker and N. Bachiri, "Development of Innovative Cooker (Hot Plate) with Photovoltaic Solar Energy," *Journal of Energy Storage*, vol. XXXVI, April 2021.

[6] V. A. Ani, "Design of a stand-alone Photovoltaic Model for home lightings and clean environment," *Frontiers in Energy Research*, vol. III, pp. 1-12, 11 January 2016.

[7] K. Sopian, A. Elbreki, M. Ruslan, A. NajahAl-Shamani, B. Elhub, A. M. Abed, H. Hasan and M. M. S. Dezfouli, "A stand-alone Photovoltaic System Design and Sizing: a Greenhouse Application in Sabha City: Case study in Libya," in *Engineering Science And Technology International Conference*, Padang Indonesia, 2017.

[8] Electrical4U, "Heating Element Materials: Types, Properties and Applications," 19 June 2023. [Online]. Available: http://www.electrical4u.com. [Accessed 15 September 2023].

[9] A. Nidek, "Heating Element," 28 September 2023. [Online]. Available: http://farnam-custom.com.

[10] Sisler Companies, "PTC Heating Elements: What You Need to know," 21 July 2022. [Online]. Available: https://www.sislercompanies.com.

[11] Heating Element Alloys, "Materials Used for Heating Elements," 1 October 2023. [Online]. Available: https://www.heating-element-alloy.com. [Accessed 12 October 2023].

[12] JUMIA, "Saisho Electric Cookers," 1 October 2023. [Online]. Available: https://www.jumia.com.ng. [Accessed 12 October 2023].

[13] G. Arora, N. Aggarwal, D. Sen and P. Singh, "Design of Solar Power Inverter," *International Advanced Research Journal in Science, Engineering and Technology*, vol. II, no. 1, pp. 236-239, May 2015.

[14] C. R. Robertson, Fundamental Electrical and Electronic Principles, 3rd ed., Elsevier, Ed., Oxford: Newnes publications, 2008.

[15] C. Tse, "Basic circuit analysis," 17 June 2022. [Online].