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Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy

Report on field testing of standalone solar cooking appliance

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D10.8 Report on field testing of solar cooking appliances.

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Version N°1

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Abbreviations and Acronyms

Acronym	Description
WP	Work Package
PV	Photovoltaic
REREC	Rural Electrification and Renewable Energy Corporation
EPC	Electric Pressure Cooker
PTC	Positive Temperature Coefficient
DC	Direct Current
PAYGo	Pay-As-You-Go
hr	Hour
min	Minutes

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Executive Summary

The report details the research, development, and field testing of a standalone solar cooking appliance under PURAMS Task 10.2 of the LEAP-RE project. The objective was to optimize the performance of direct current (DC) electric pressure cookers (EPCs) by integrating Positive Temperature Coefficient (PTC) heating elements to improve energy efficiency. Traditional resistive heating elements in EPCs have high energy consumption, making them less viable for widespread adoption, particularly in off-grid settings where standalone solar systems are used. The study explored alternative heating technologies, focusing on PTCs due to their self-regulating properties, energy efficiency, and safety advantages.

The development process involved designing and fabricating hybrid and PTC-only hot plates using 3D modeling, 3D printing, and aluminum casting. The hybrid model retained resistive coils while incorporating PTCs, whereas the PTC-only model relied entirely on PTC heating elements. A dedicated electronic control circuit was developed to regulate power consumption and optimize heating performance. Laboratory tests were conducted to validate the performance of the PTCs, assess power consumption, and analyze heat distribution. Cooking tests, including boiling and frying of beans, rice, and beef, were carried out to compare the efficiency of the modified cookers against traditional models.

Field testing was conducted in collaboration with the Rural Electrification and Renewable Energy Corporation (REREC) at their e-Cooking testing facility. The results demonstrated that the PTC-only EPC significantly reduced power consumption while maintaining comparable cooking times to existing EPC models. However, inrush current spikes and challenges in precisely controlling the heating profile required further refinements in the control circuit and programming. The study highlighted the potential for standalone solar EPCs to become more accessible and sustainable by reducing system costs through lower power requirements.

The project successfully demonstrated an optimized cooking solution using PTC heating technology, showing a clear pathway for further improvements. Future work should focus on refining the design for mass production, improving energy efficiency through better control algorithms, and expanding testing across different environmental conditions. The insights gained from this study contribute to advancing clean cooking technologies and promoting sustainable energy solutions, particularly in off-grid and energy-poor communities.

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Keywords

Electric Pressure Cooker (EPC), Positive Temperature Coefficient (PTC), Optimization, Cooking Tests, Efficiency.

1. Introduction

1.1 Background

As of 2019, Kenya's electricity access rate stood at 75% which is a mix of grid and off-grid solutions (Dubey, Adovor, Rysankova, & Koo, 2020). This however doesn't mean that every connected household has access to electricity. Lack of productive uses of electricity especially in poor rural areas is one of the many factors contributing to this. The economic status of these households makes it difficult for electricity as a source of domestic power to compete with other cheaper sources such as biomass and heat from the sun. In cooking applications, biomass is widely used and has disproportionately affected these households and the surrounding environments in terms of poor health caused by inhaling smoke, time wasted collecting biomass and destruction of forests and trees. Use of solar directly, such as in solar concentrators and indirectly, such as in solar powered cooking appliances can help mitigate some of these problems.

DC EPCs systems use solar photovoltaic panels to convert solar irradiance to electricity for cooking. They can either use an inverter to connect to a battery or bypass the battery altogether and connect directly to the panels (standalone configuration). One of the challenges hindering DC EPCs is that even though they are very energy efficient and consume much less power compared to their AC counterparts, the power drawn is still high which means large panels and/or batteries are needed hence the already uncompetitive purchase price for the EPC alone increases. There've been several solutions used to mitigate this such as using PAYGo systems but have worked only in some contexts such as use for food vendors. Our objective was to find an unexplored technological solution that might reduce the power consumption, hence reducing the overall price of the PV system while having as little effect on the cooking time as possible compared to existing DC EPCs in the market.

Previously, the first design concepts of the EPC prototypes had been done. After conducting lab tests on two DC EPC variants i.e., VIA and MECS e-Want DC EPC and analysing data to find possible areas of improvements, we conducted desktop research to find possible ways to lower the power consumption without affecting the cooking time by much i.e., increasing the heating efficiency. MECS e-Want EPC rated at 480W was used as the base model. With very minimal modifications that could be made to increase the efficiency of the resistive element heater in the EPC, we conducted desktop research to find other possible heating technologies that could be used such as diodes and Positive Temperature Coefficient (PTCs). PTCs were a more robust choice offering many advantages such as self-regulation making them safer. Several lab tests were done as discussed under the PTC **Validation Tests** section to prove the concept and computer designs made concurrently.

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2. Methodology

2.1 PTC Validation Tests

A PTC is a type of electrical heater that uses a material with a positive temperature coefficient to turn electricity into heat. This means that its electrical resistance increases as the temperature rises. This unique property allows PTC heaters to self-regulate and control their temperature without needing external control systems.

PTC heating elements offer an efficient and safe way to convert electrical energy into heat. Their key advantage lies in their self-regulating properties. Unlike traditional heating elements that require external controls like thermostats, PTC heaters naturally limit their own temperature as they heat up. This occurs because the material of the PTC element, often barium titanate ceramics, becomes less conductive at higher temperatures, reducing the current and thereby slowing the heat generation process. Several PTCs rated 12V 200°C and 24V 200°C were procured. Each one was first tested to confirm they practically match their rating and their margin of error. A lab setup shown in **Figure 1** below was used to evaluate the following:

1. How varying the number of PTCs affects the duration it takes to boil the water.
2. Which configuration, series or parallel connection, is best suited for our cooker.
3. Which physical placement would yield the best heat transfer results.
4. How the maximum combined PTC temperature (measured using a temperature sensor below the pot) and water temperature varies when using different numbers of PTCs and configurations.
5. The profile for the power drawn for all the test conditions.

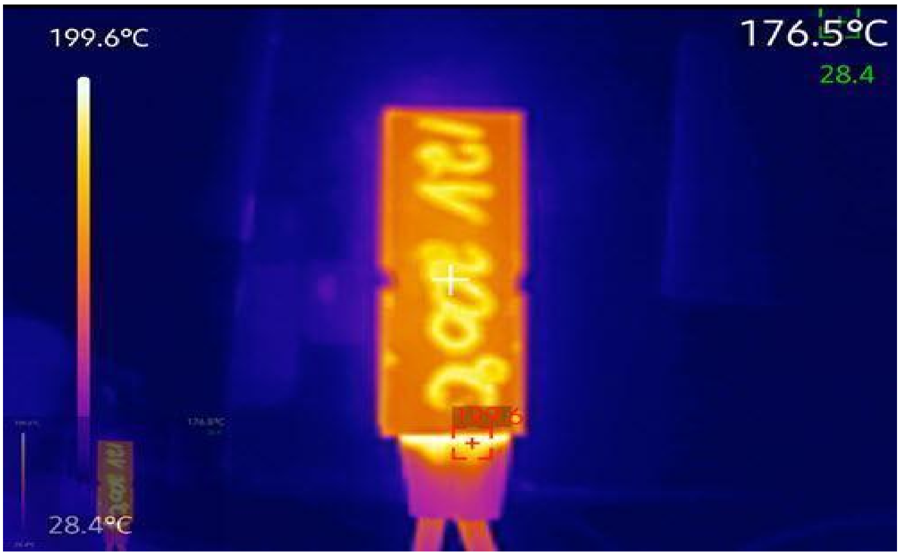

Figure 1: Lab test of a 12V 200^{0}C PTC

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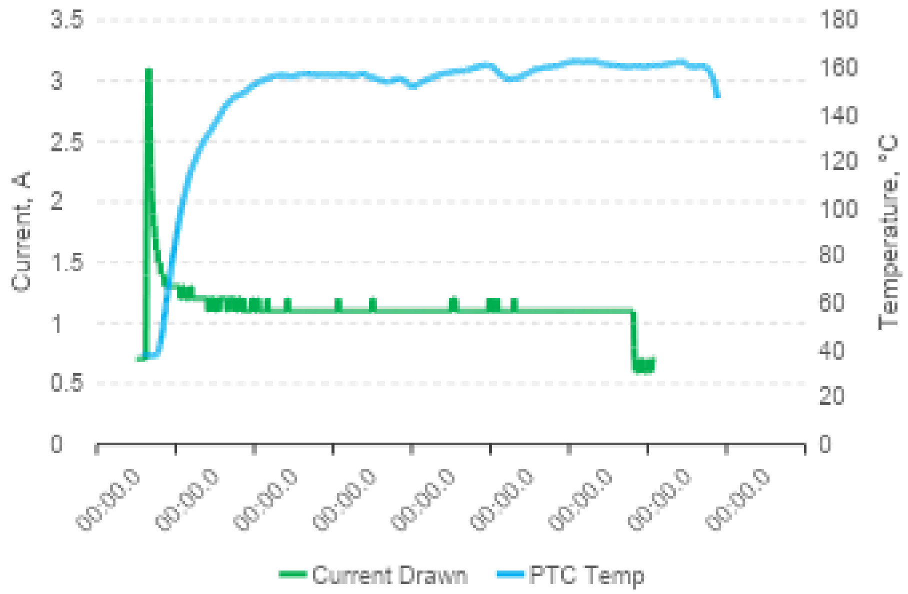
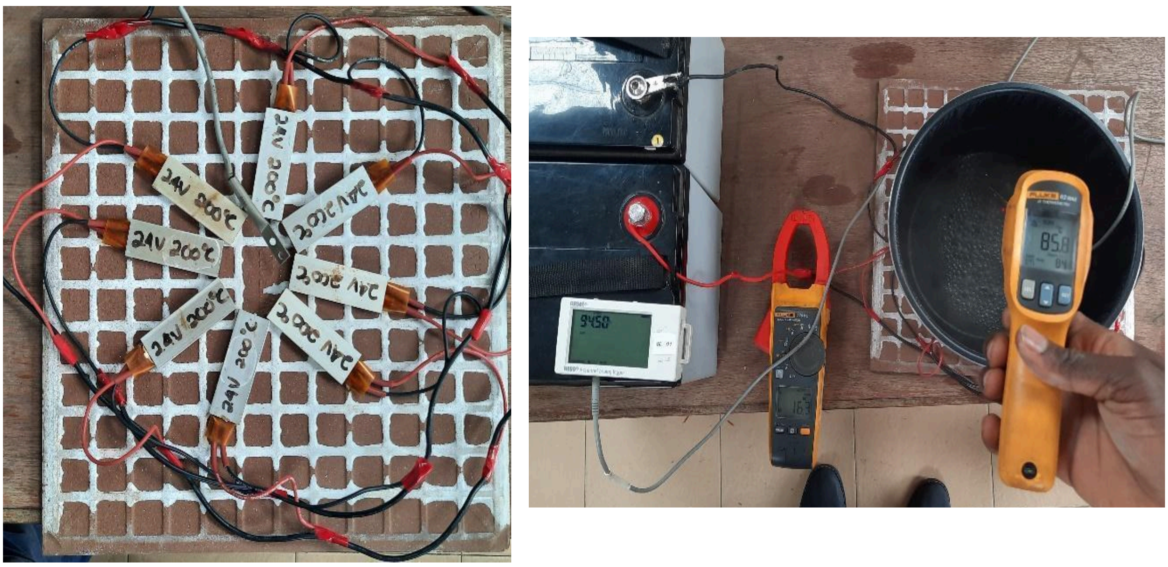


Figure 2: Current drawn and PTC temperature against time for a 24V 200^{0}C PTC

Figure 2 above shows how the current and temperature behaves over time. There's an initial spike in current (in-rush current) then the current drops and plateaus. Further tests involving boiling water were done using multiple PTCs to investigate our objectives in a simple setup as shown in Figure 3. Some of the analysed results can be seen in Figure 4 below.



(a) **(b)**

Figure 3 (a): 8 PTCs in radial arrangement parallel connection; Figure 3 (b) Same setup achieving 950C pot temperature and 850C water temperature

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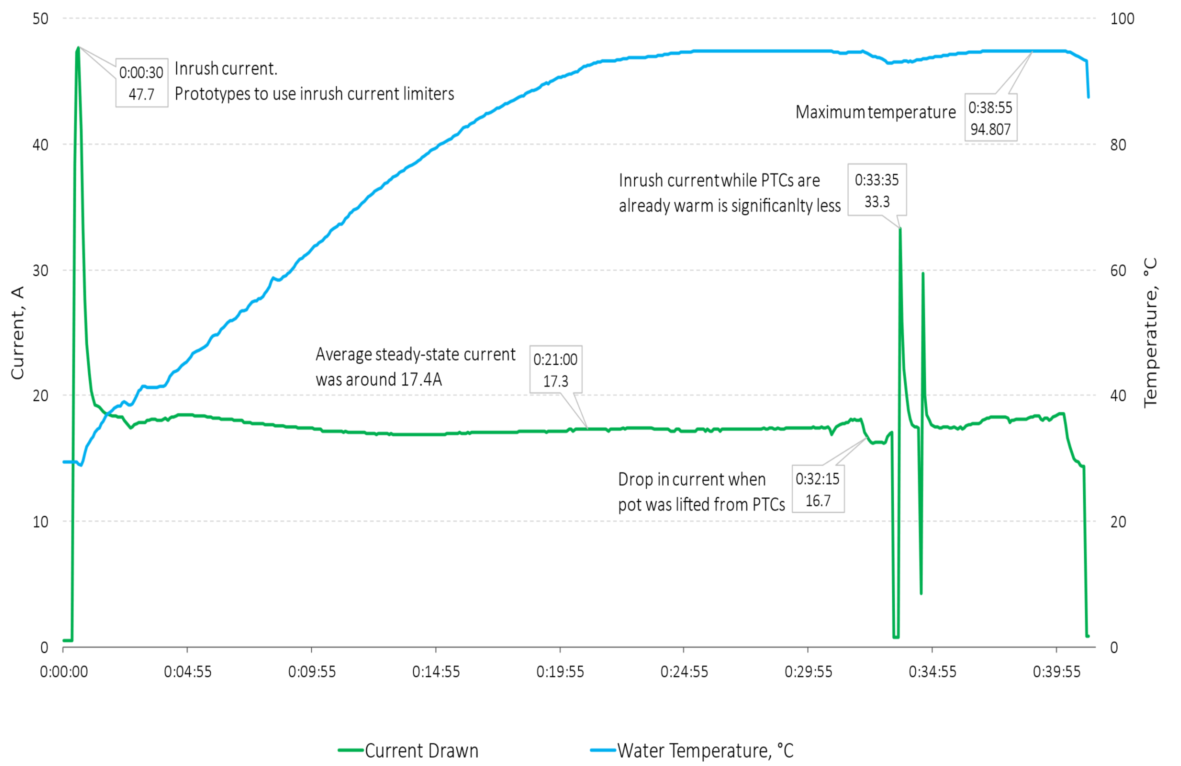

Figure 4: Current-Temperature relationship against time for the 8 radial arrangement parallel connected PTCs used to boil water

It was crucial to explore more on the combined behaviour of multiple PTCs. Some of the conclusions drawn were:

1. The inrush current more than doubles the steady-state current. Inrush current limiters are to be used to protect both the power source and the internal electrical components.

2. The settling-time (time taken for current to reach steady state) and the peak inrush current decreases with decrease in temperature difference.

With the water having boiled successfully, we concluded that PTCs can be a viable heat source for clean cooking appliances. The next step was to come up with multiple design concepts using PTCs, fabricate the prototypes and conduct field tests.

2.2 Hot Plate Fabrication

The original coil-based model was modified by adding PTCs heaters. The hot plate consists of two coils each rated 250W, 24VDC therefore consuming a total of 500W. Three PTCs were added with a consumption of 144W. The PTCs were designed to sustain heat after the resistive coils have attained a certain temperature and solely used when low energy cooking mode was selected.

The PTCs only hot plates were fitted with six PTCs with a cumulative consumption of 288W. The fabrication of the models involved three steps.

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1. 3D Modelling
2. 3D printing
3. Aluminium Casting.

2.2 3D Modelling

To quickly prototype a hot plate for the DC pressure cooker, model designs were created using CAD software which enabled the team to easily collaborate and coordinate, simulate and test different designs patterns, perform several design iterations while checking and fixing errors and tolerances. The process was an iterative one with design constraints especially on space and the shape of the PTCs.

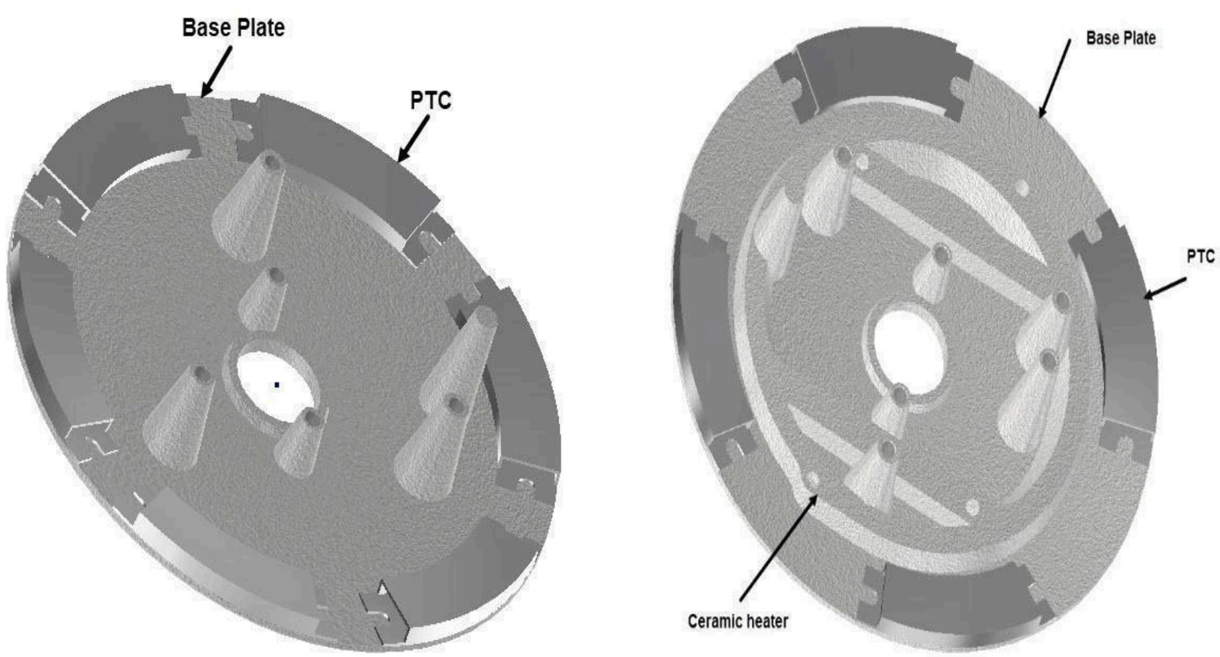

Figure 5: 3D CAD Models of Hybrid and PTC only designs

2.2 3D Printing

3D printing, also known as additive manufacturing, is a process that transforms digital designs into physical objects by building them layer by layer. This technology employs computer-aided design (CAD) software to create detailed models, which are then sliced into thin cross-sectional layers for printing.

3D printing utilises a variety of materials, such as (plastics, metals, ceramics) and techniques (FDM, SLA, SLS etc) useful for rapid creation of prototypes for product development. It also facilitates production of intricate shapes and structures that are challenging with conventional techniques.

The models were 3D printed using Fused Deposition Technology (FDM). The approach was chosen to provide faster prototyping, ability to test complex model patterns, lightweight and cost-effective. This process was crucial because it helped:

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1. Allow for spatial visualization of the model in case of any obvious defects.
2. Confirm that the hotplate and PTCs would fit in the cooker
3. Test that the curvature allowed the hotplate and the pot to lie flash with each other allowing for maximum contact and hence best heat transfer.
4. Evaluate the contact of the PTCs to the hotplate also for maximum heat transfer.
5. Test best plate thickness that would allow for fastening of the PTCs to the hot plate.
6. Upon successful evaluation, provide a pattern that can be used to create the mold cast.

a) Hybrid hot Plate

The hybrid design retained the original design with resistive coils and the PTCs were added on the edges.

Figure 6: Initial 3D printed models of hybrid hot plate. Bottom view (left) and top view (right).

b) PTC Only Hot plate

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This design eliminates the coils and several PTCs are fitted as the only source of heat.

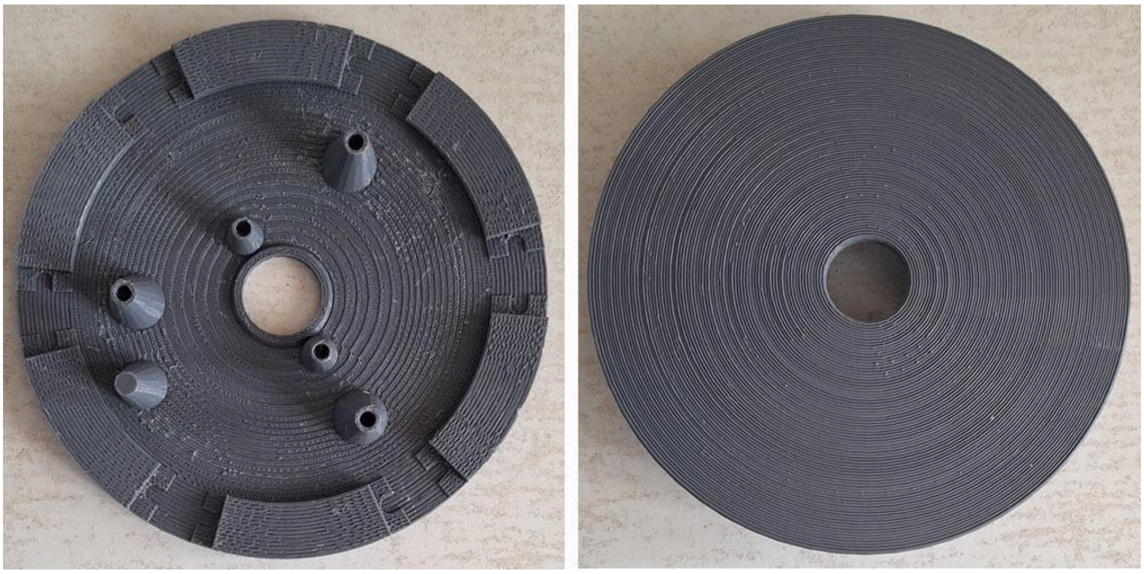

Figure 7: 3D printed model of PTC based hot plate. Bottom view (left) and top view (right)

After several iterations we had the final design. The final models were used as template to create the mold patterns. The patterns used for casting the hot plate was spliced into two halves to fit on the 3D printer machine platform and later joined using glue.

Figure 8: 3D printed model with a casting release agent to its surface

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2.2 Aluminium Casting and Machining

The casting of the hot plate was done locally using sand casting method and the aluminium was recycled from old engine blocks. Aluminium is an excellent metal for casting due to its ability to melt well and it has a higher thermal conductivity than iron or steel and a relatively low specific heat capacity, which means it heats up and cools down quickly when exposed to heat sources making it a good choice for designing a hot plate for this project.

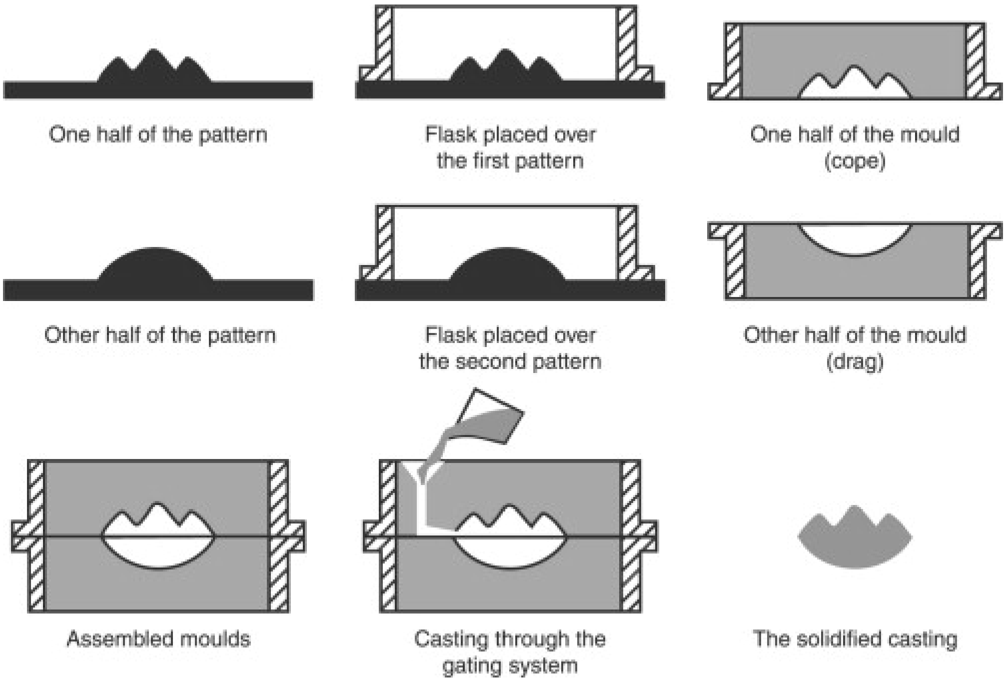

Figure 9: Illustration of sand-casting process (Lumley, 2018)

2.1.1 Hybrid hot plate casting and machining

Due to limitations of the local casting industry, casting with coils integrated was not possible therefore the original plate was used, and extra aluminium material was added to provide the required space for fitting the PTCs.

Machining was done to smoothen the added aluminium as well reducing the overall diameter. 3mm diameter holes were drilled for fitting the PTCs. The wiring for the PTCs was done parallel allowing the PTCs to be controlled independently. The wiring of the coils was not touched, and it was connected directly to the main control panel.

The cooking plate sensor and temperature sensor were fitted on the main plate.

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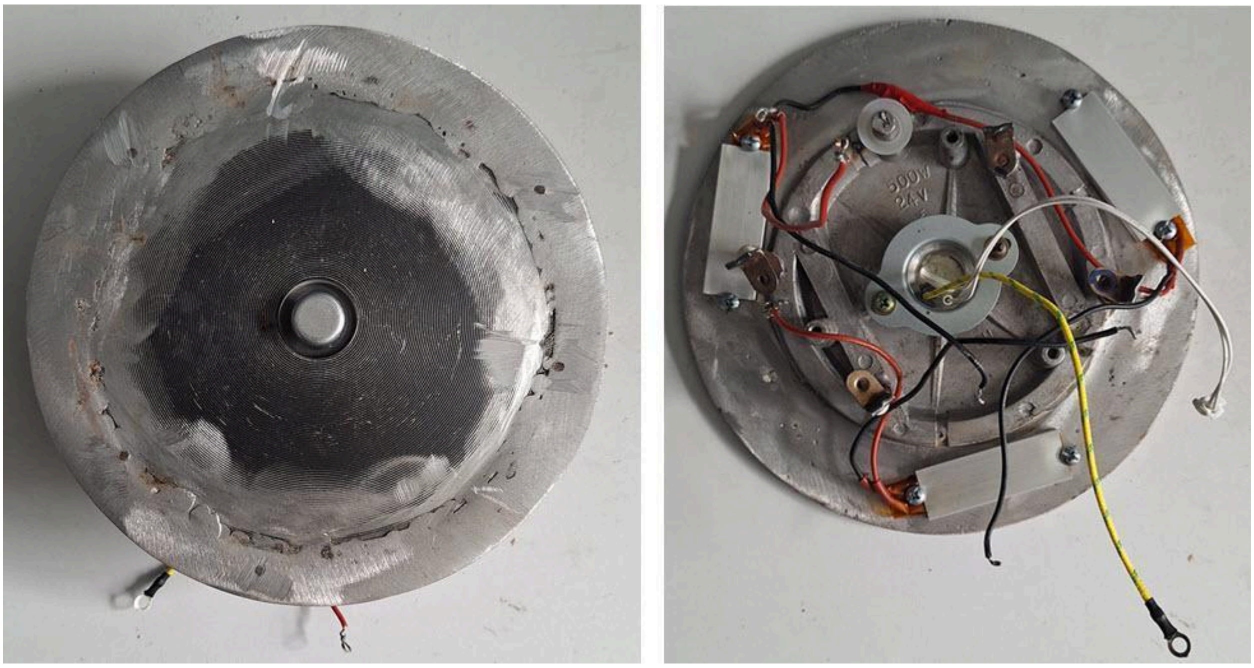

Figure 10: Hybrid hot casting with PTCs fixed

2.1.1 PTC-only hot plate casting and machining

The 3D printed model of the PTCs only heater was used to create the sand cavity, and then molten aluminium was poured. Due to local casting capability, it was not possible to put the holes in the plate stands and machining was done to smoothen the top surface, reduce diameter, drill mounting holes and PTCs fitting holes.

Figure 11: Aluminium casting for PTC-only hot plate before surface finishing

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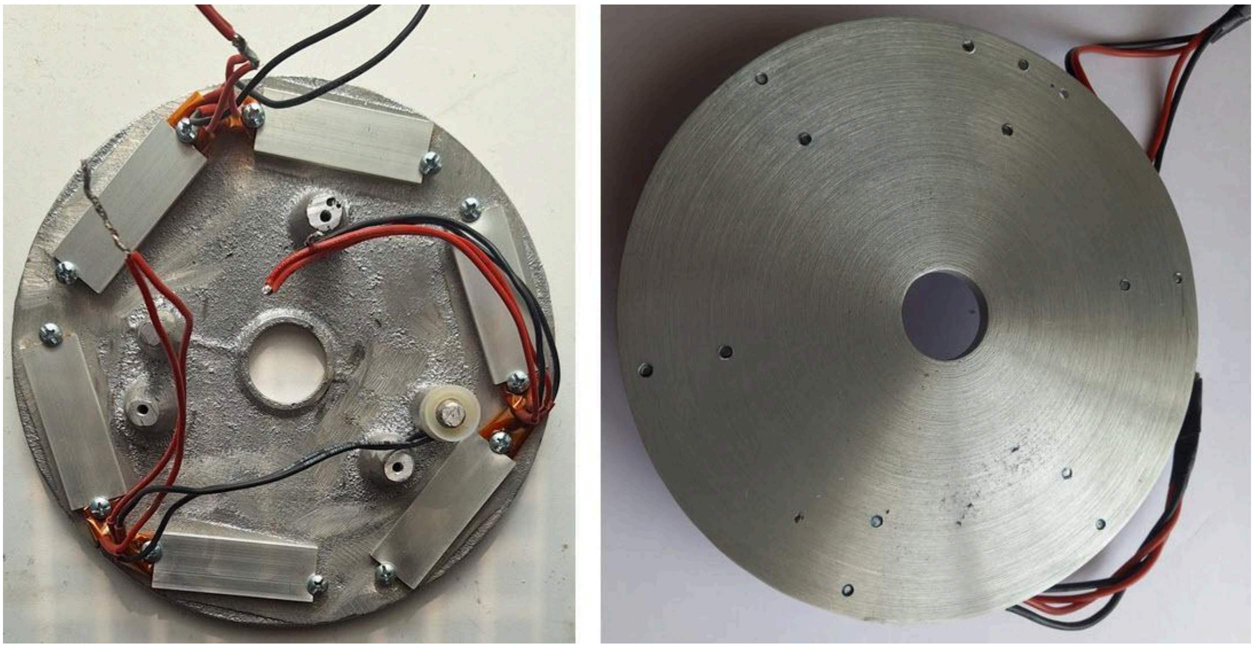

Figure 12: PTC-only hot plate machined and fitted with PTC heaters

A total of 6 PTCs were fitted on the bottom of the hot plate. The wiring was done in 3 pairs. Two PTCs were connected in parallel and directly connected to the electronic control board. This was to reduce the wiring required and make the setup more maintainable.

2.2 Electronic Control Circuit

From the lab experiments, PTCs consumed a significant amount of current when cold powered and then dropped to stable levels as the temperature rises as seen in **Figure 4** above. This current spike is large when several PTCs are chained together and to prevent that a dedicated electronic circuit with a microprocessor was designed and prototyped locally to control the current spikes and turn on and off the PTCs automatically.

Same control hardware circuitry is used in both hybrid and PTCs only circuits, but the control software is developed independently.

2.1.1 Hybrid hot plate circuitry

This configuration consists of a resistive coil and 3 PTCs. When the DC pressure is powered on after selecting the meal the cook. The control circuit senses the power signal and turns on the coils. As cooking continues the circuit continuously measures the temperature of the cooking pot and the state of the pressure valve.

At preset upper threshold temperature and the pressure valve is triggered the coils are turned off and PTCs turned on to sustain the heat. If the cooker heats drop to set lower threshold temperature the PTCs are turned off and the coils turned on.

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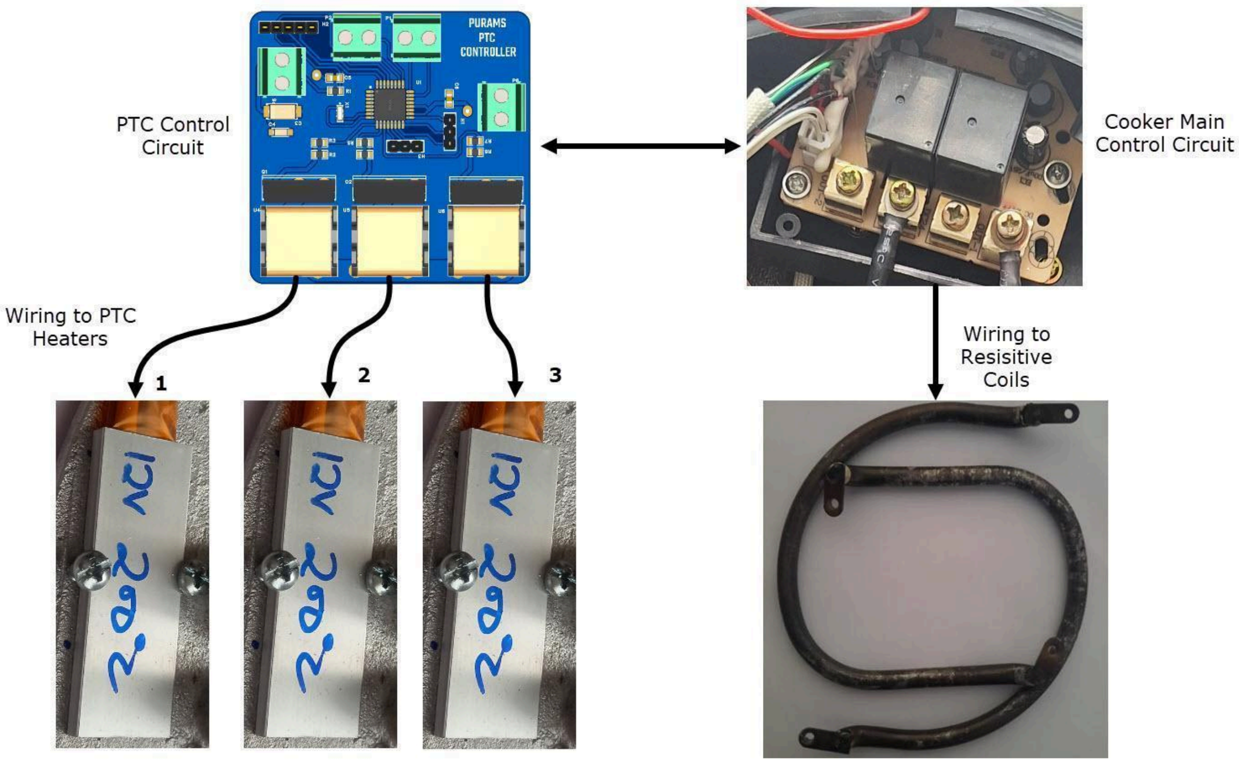

Figure 13: Wiring of hybrid EPC heating elements (Resistive and PTC heaters)

The control circuit also detects low power cooking mode and instead of turning one coil on which consumes 250W, only the PTCs are turned on consuming a total current of 144W. This saves energy in low cooking mode using the PTCs.

The circuit monitors the pressure sensor and a cooking complete signal from the main cooker control board. If the cooking complete signal is triggered, the circuit turns both the coils and PTCs off.

```
start program
Initialize sensors and turn off heaters
Read temperature and pressure sensor
if at lower threshold
   turn ON coils
   turn Off PTCs
else if at upper threshold
   turn OFF coils
   turn ON PTCs
if cooking complete
   Turn off cooker
else
   repeat program
```

Figure 14: Screenshot of the pseudocode for the hybrid circuit software

Figure 15: Hybrid circuitry with both main and PTC circuits wired and connected and fitted in the DC pressure cooker

2.1.1 PTC-only hot plate circuitry

PTCs circuitry has PTCs only as the heating element. The design has 6 PTCs and to control an inrush current of ~40A, the circuit turns the PTCs one at a time with a preset delay. 2 PTCs are connected in parallel to create a single input and the result is 3 pairs of PTCs connected independently to the control circuit.

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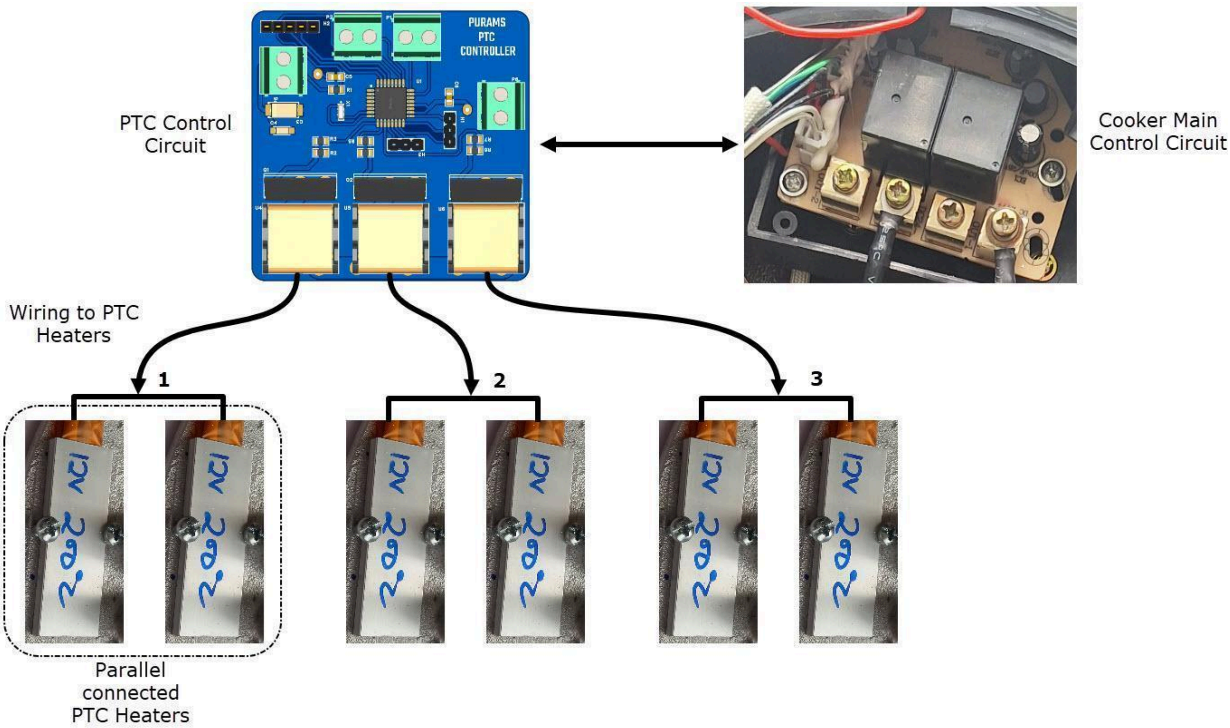

Figure 16: Paired PTCs and 3 pairs connected to control board

The control circuit is connected to the main control board so that it can receive cooking and control signals.

```
start program
Initialize sensors and turn off heaters
Read temperature and pressure sensor
if cooking signal received
   turn on PTC pair 1
   wait for 10 seconds
   turn on PTC pair 2
   wait for 10 seconds
   turn on PTC pair 3
else
   turn off all PTCs
if cooking complete
   turn off PTCs
else
   repeat program
```

Figure 17: Pseudocode for the hybrid circuit software

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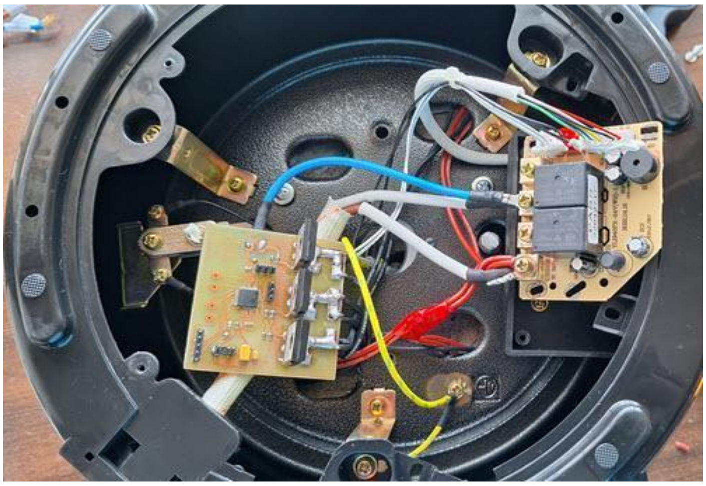

Figure 18: PTCs only circuit, with both main and PTC circuits wired, connected and fitted in the DC Pressure cooker

```
/**
* switch on ptcs with delay
*/
void switchOnPTCs() {
  switchControl(PTC_1, ON);
  debug("PTC 1 ON.");
  delay(PTC_DELAY);
  switchControl(PTC_2, ON);
  debug("PTC 2 ON.");
  delay(PTC_DELAY);
  switchControl(PTC_3, ON);
  debug("PTC 3 ON.");
}
```

Figure 19: A section of PTC-only control software.

Six PTCs were modified with 3 fixed with hybrid hot plate and the rest 3 with PTCs only hot plate. The 3 pairs enabled the team to test and validate the cooking data as well as analyse the energy efficiency of the new modified DC pressure cookers.

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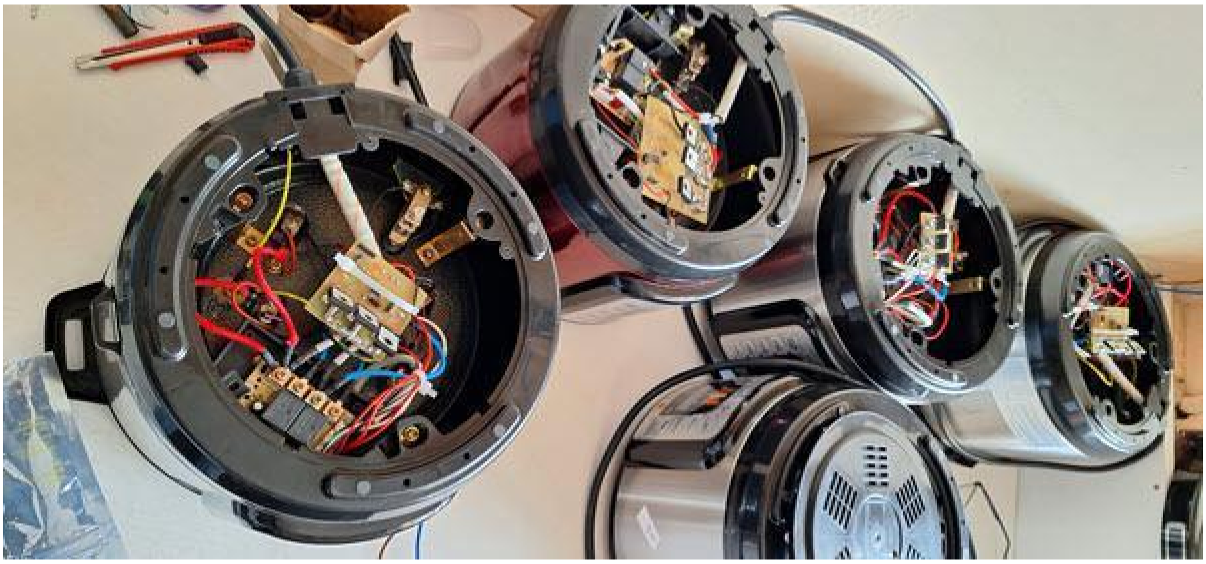

Figure 20: Modified DC EPCs ready for cooking tests

2.2 Battery and Solar Setup

The modified DC EPCs are rated 24V. Two 12V batteries were connected in series to provide an output of 24V and a capacity of 200AH. Two solar panels with a total output of 48V-500W and an MPPT charger were connected to recharge the battery after or during cooking tests.

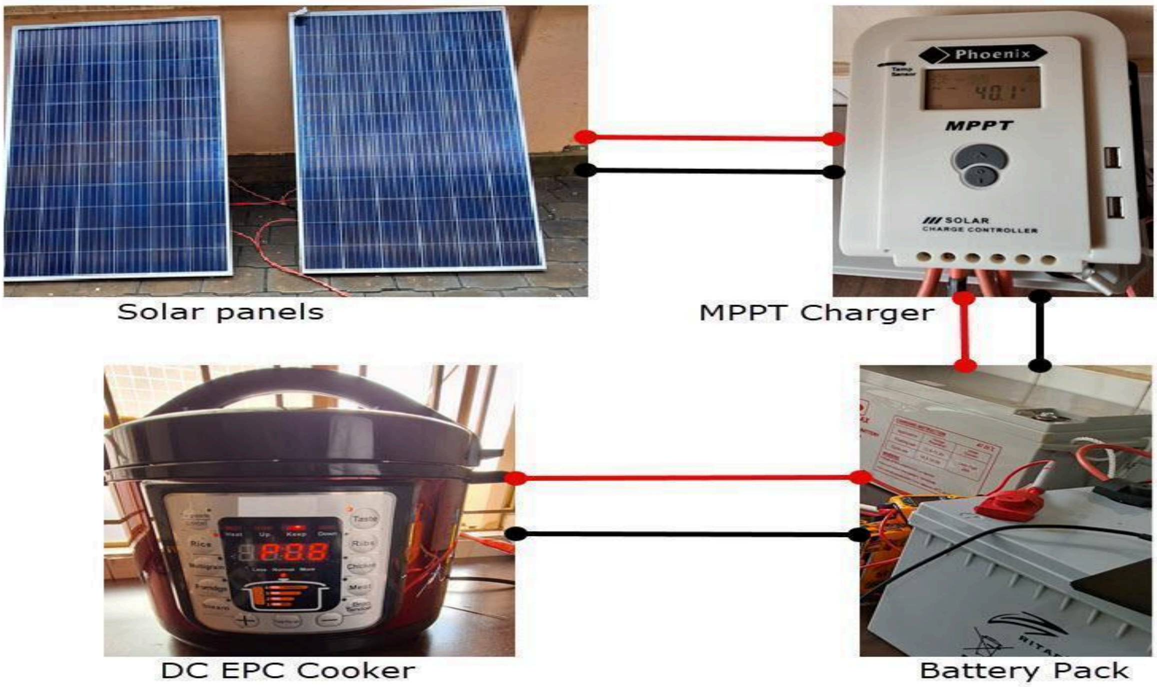

Figure 21: Solar PV system configuration

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2.2 Cooking Pot Internal Temperature Measurement

The DC EPC has an external temperature sensor that touches the cooking pot and provides the control circuit with temperature information so that cooking temperature can be regulated and controlled in case of over temperature situations.

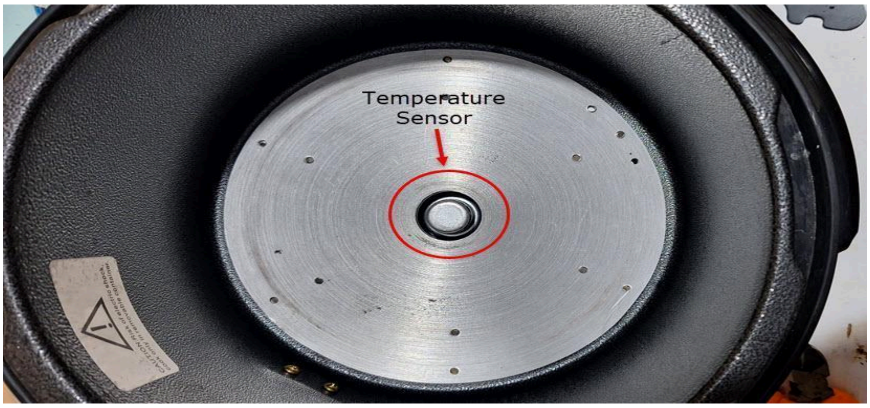

Figure 22: Location of cooking pot presence and temperature sensor

To test the heat transfer efficiency of the modified hot plates the internal temperature of the cooking pot was logged. The team used a thermochron, 4K sensor.

The Thermochron sensor has a temperature range of -40°C to +85°C, with an accuracy of ±1°C in the range of -30° to +70°C and ±1.3°C outside of that range. The resolution of the DS1921G's readings is 0.5°C. It can read up to 2048 values at a logging rate of 1 minute to 255 minutes.

(a) **(b)**

Figure 23: (a) A thermochron, 4k sensor for cooking pot internal temperature measurements. (b) LinkkUSBi Touch and hold reader for thermochron sensor.

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Figure 24: PC software for analysing the data collected from the thermochron sensor

Figure 25: Water boiling test

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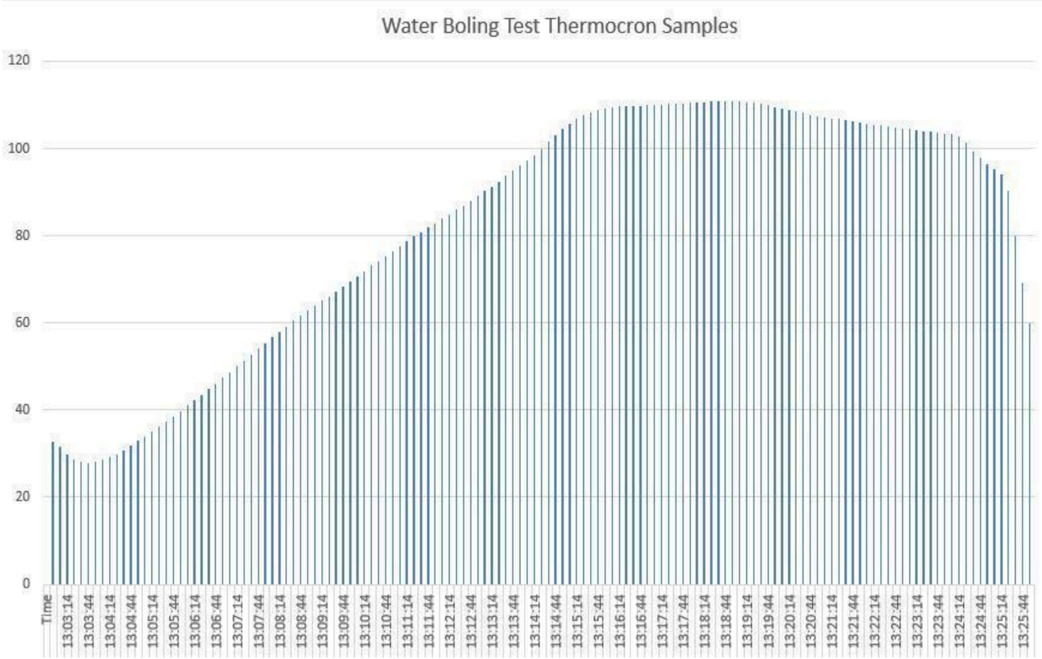

Figure 26: Graph of water boiling samples.

Food Comparison AC (2021 Research) vs Solar EPC Cooker

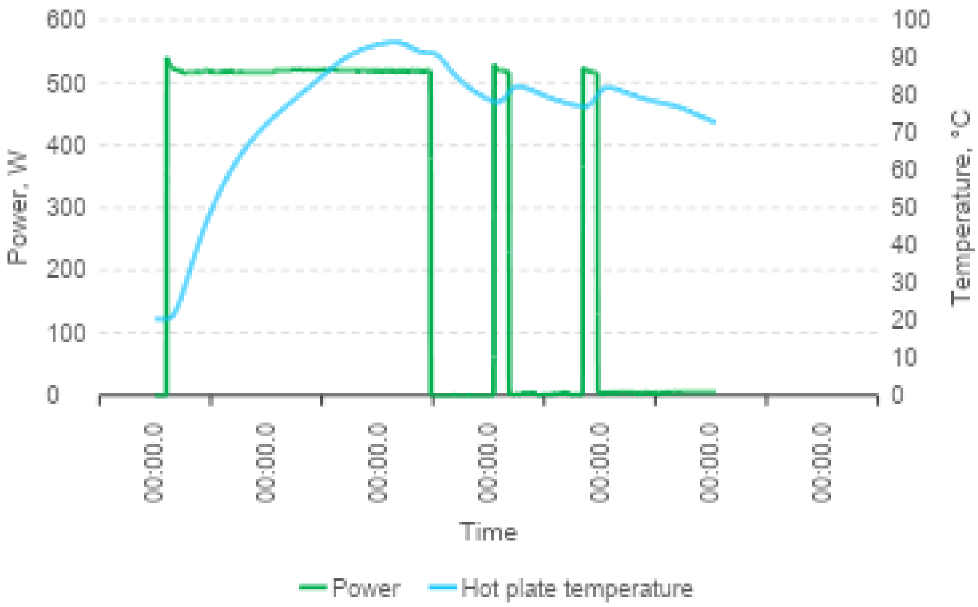

Figure 27: Boiling beans

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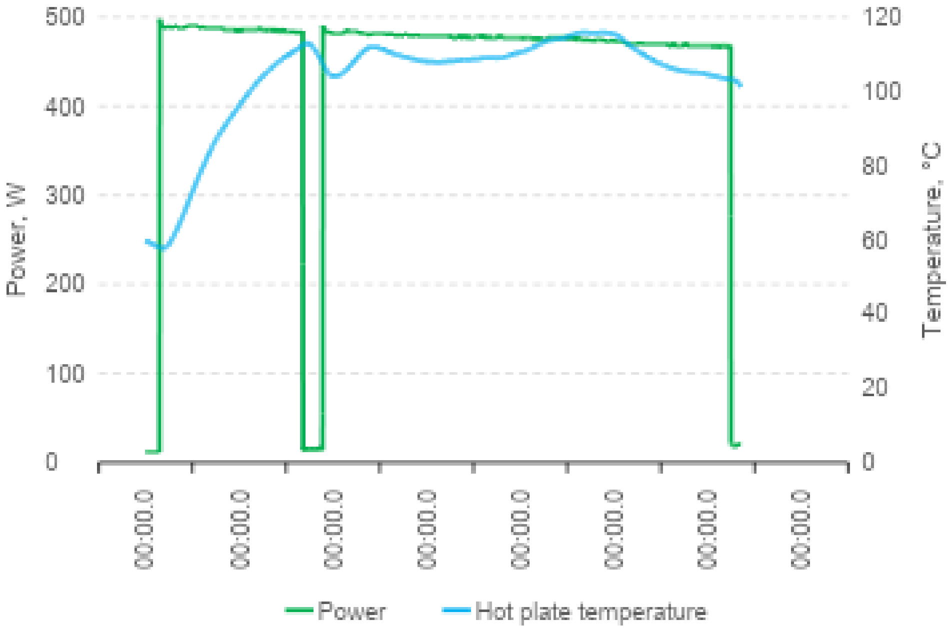

Figure 28: Beans Frying

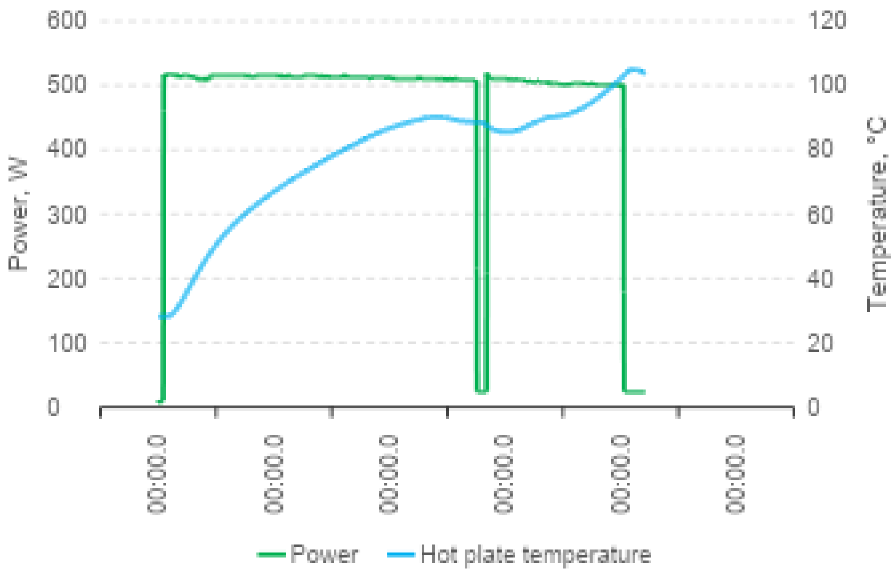

Figure 29: Ugali cooking

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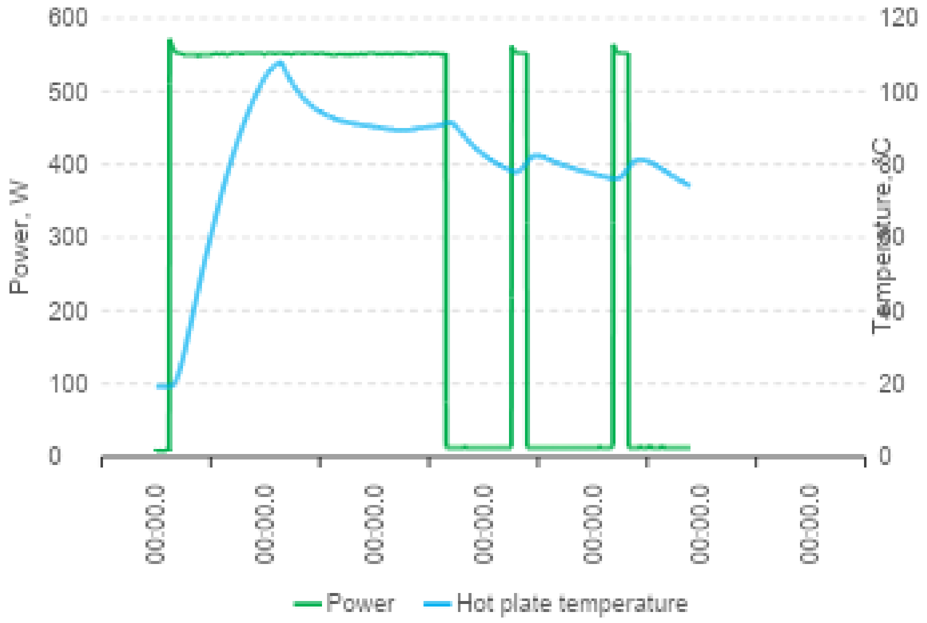

Figure 30: Beef boiling

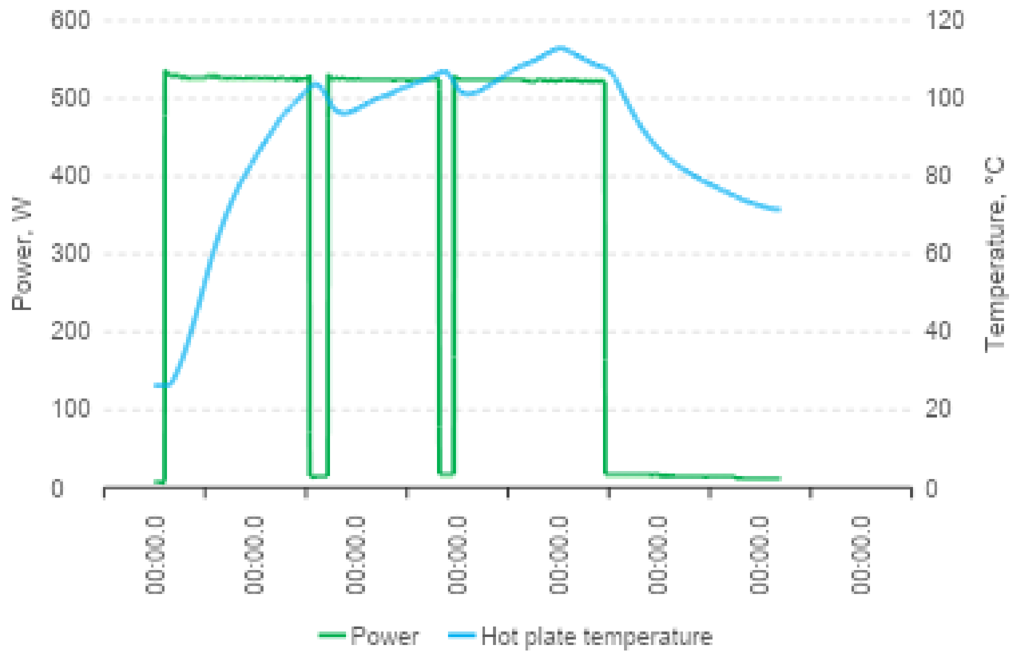

Figure 31: Beef Frying

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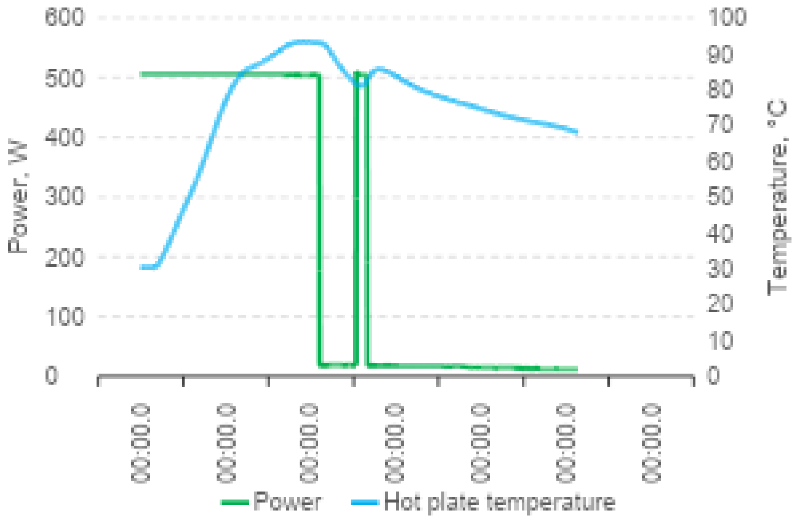

Figure 32: Rice cooking

2.2 Kitchen Test Setting

Before controlled cooking tests could be done, safety tests had to be performed to look for operational anomalies, fabrication defects and wring assemblies. This mainly included boiling one litre of water and 1 ½ cups of rice. We were keen to look for any unusual behaviour such as smoke (due to burning wires or soldering flux), short circuits and steam leakages before proceeding with the cooking tests. Configuration of the heating system was done at this stage such as tweaking the heating code to make sure the different heating elements switched on as intended.

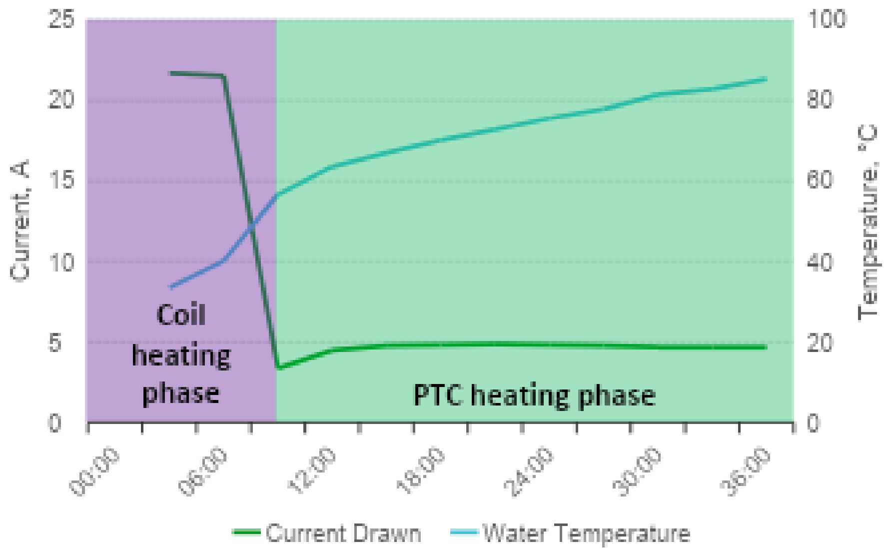

Figure 33: Water boiling test results using the hybrid EPC during the initial prototype tests

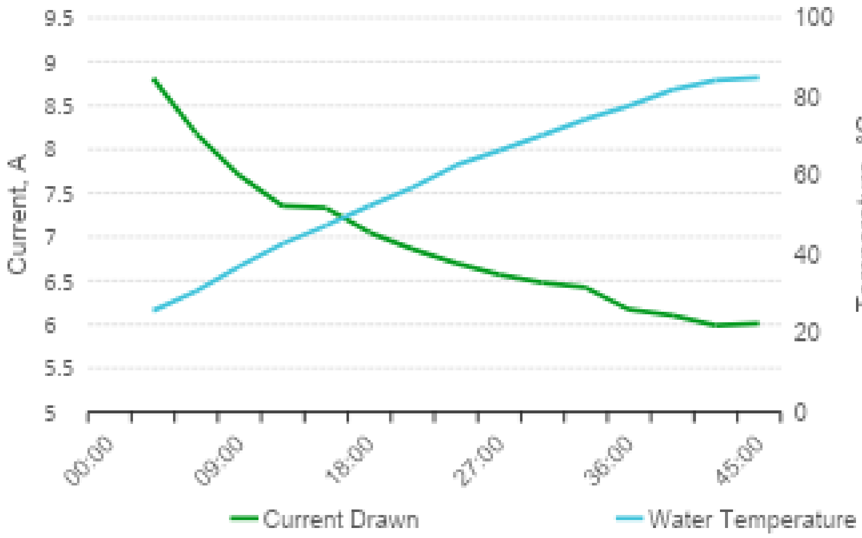

Figure 34: Water boiling results from the PTC-only EPC during the initial prototype tests

The meals for cooking tests were selected so that we can ideally test boiling under pressure, sauté and cooking under pressure. We prepared a cooking plan comprising of beans, beef and rice. These are common foods cooked in Kenya and easily make it on the dinner tables for families. The tests would be done during July-August period, which are normally the coldest months in Kenya. This intentionally planned to simulate the worst-case scenarios when the irradiance is lowest.

Figure 35: Strathmore University handing over the prototypes to the REREC at Jamhuri Center, Nairobi

Field tests in Kenya were conducted with collaboration with REREC. Having been part of the PURAMS project, and the government agency mandated with electrification of rural areas in Kenya, REREC has played a crucial role in promoting cleaner cooking technologies in Kenya. We relied on their experience to conduct unbiased field tests. SU provided REREC with two pairs of the EPC prototypes and the PV system at their test facility at Jamhuri Energy Center in the outskirts of Nairobi.

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The cooking setup was made up of 2 solar panels rated at 345 watts 24V and 2 batteries rated at 12V 200AH. The panels were directly connected to the cooker to simulate a standalone-use scenario. The batteries were to be used only when needed to sufficiently cook the meals.

Figure 36: Clean cooking setup at REREC's testing facility

The field tests were done to gather qualitative and quantitative feedback from users to improve the user experience. Some quantitative metrics observed were:

1. Time taken to cook
2. Energy consumption
3. Final food temperature

Some of the qualitative metrics to be observed were:

1. General ease of use
2. Quality of food cooked (taste, texture, temperature etc)
3. Safety measures

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Table 1: Field testing and data collection plan

Initial Battery Voltage	Final Battery Voltage	Initial Food Weight (g)	Final Food Weight (g)	Final Food Temperature	Total Cooking Time
Ingredient One		**Ingredient Two**		**Ingredient Three**	
Cups	**Quantity (ml)**	**Cups**	**Weight (g)**	**Dry Weight (g)**	**Soaked Weight (g)**
Comments:					

From the data collected, it was possible to calculate the power consumed, cooking temperature at different stages of cooking, know how much of much ingredient we used. This data is important when making a comparison to other systems. To keep the data uniform for all test scenarios, we made a template for tests as shown in Table 1 together with the ingredient's quantities. A short orientation was done to show how the system should be connected and how to operate the different modes. Cooking instructions were kept to a minimum in order not to interfere with the user experience. The testers were also asked to record the taste and texture of the food, and the overall user experience for both the EPCs and how they compare to each other.

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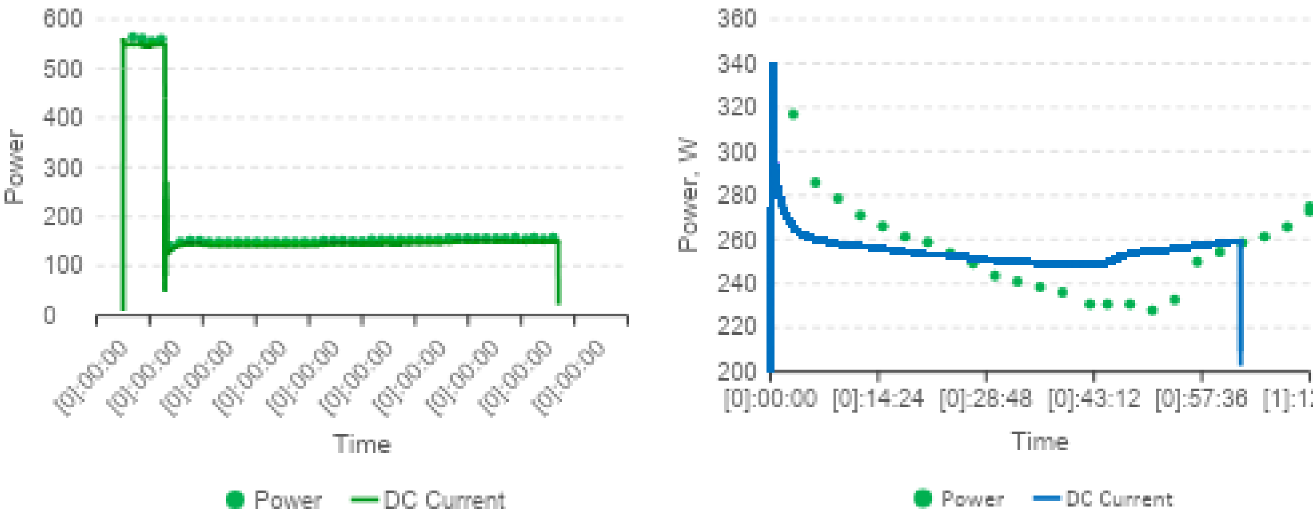
Figure 37: Solar Powered cooling demonstration at REREC's testing facility

3. Results

3.1 Bean Boiling Tests



(a) Hybrid EPC test **(b) PTC-only EPC test**

Figure 38: Power consumption during a cooking test for boiling beans

Three beans boiling tests were done for each prototype fine-tuning the heating systems as we went along until we got the best possible results. The beans had been soaked through the night to make them much easier for cooking. It is important to mention that soaked beans were twice the weight of the dried ones at 1 kilogram. Steam was observed after 47 minutes into the hybrid test shown in **Figure 38 (a)**. Both the resistive coils

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were switched on for the first 13 minutes and the PTC elements took over the cooking from there until the beans were properly done at 2hrs 16min. Field test data shows boiling under 2 hours was possible.

The boiling using the PTC-only EPC took 1hr 15min. One of the cookers had a damaged MOSFET (used to switch on the PTC heating elements) and power only got to two pairs of PTCs, which made it perform poorly compared to the other test by more than an hour.

For both prototypes, steam build-up was sufficient to pressurize, with the PTC-only cooker pressurizing after 45min.

3.1 Beans Cooking Tests

The PTC-only EPC took an average of 1hr 30min to fully cook the beans though the time could have been slightly shorter. This time is broken down to about 50minutes of sauteing after which a slightly less than a liter of water was added together with boiled beans. The lid was finally closed and after 9min for pressure build up it, the valve closed, and pressure cooked the remaining time. The final food temperature was about 77.5°C as shown in **Figure 40**.

The hybrid EPC performed similarly to the PTC-only cooking at an average time of 1hr 35min. The pressure had built enough to continue cooking without any additional heat at 1hr 9min.

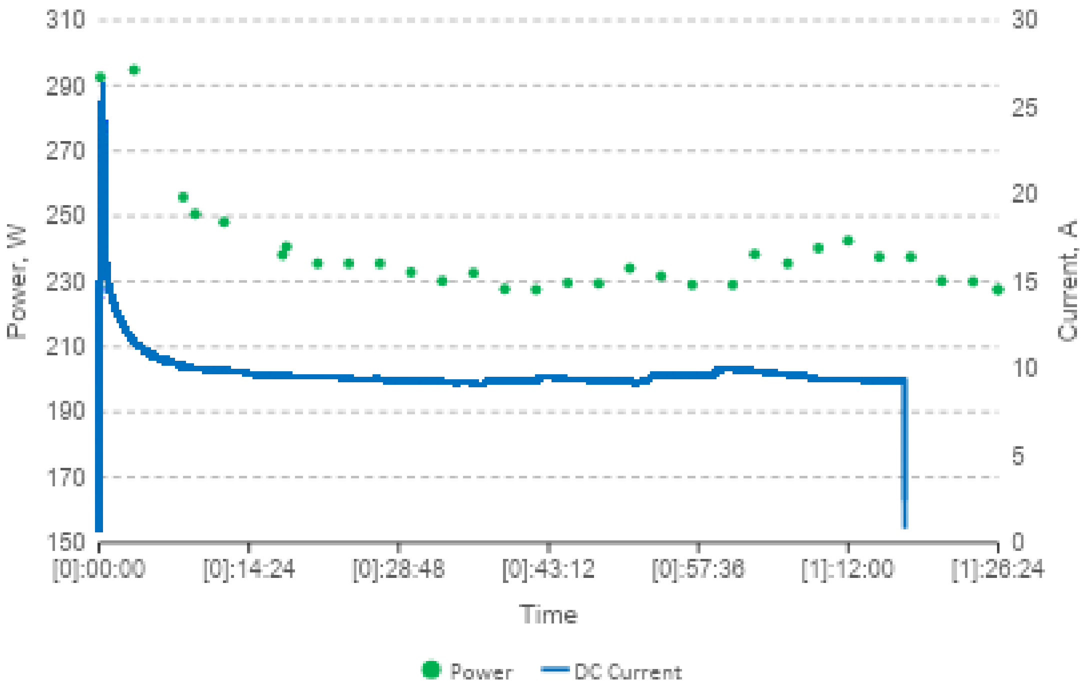

Figure 39: Beans cooking test with PTC-only cooker

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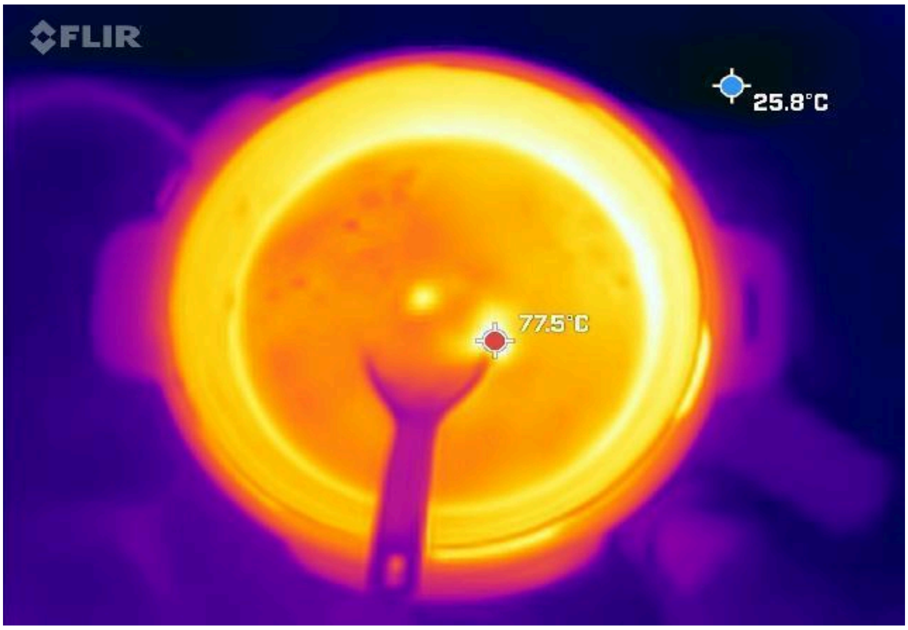

Figure 40: Final beans temperature for the PTC-only EPC test

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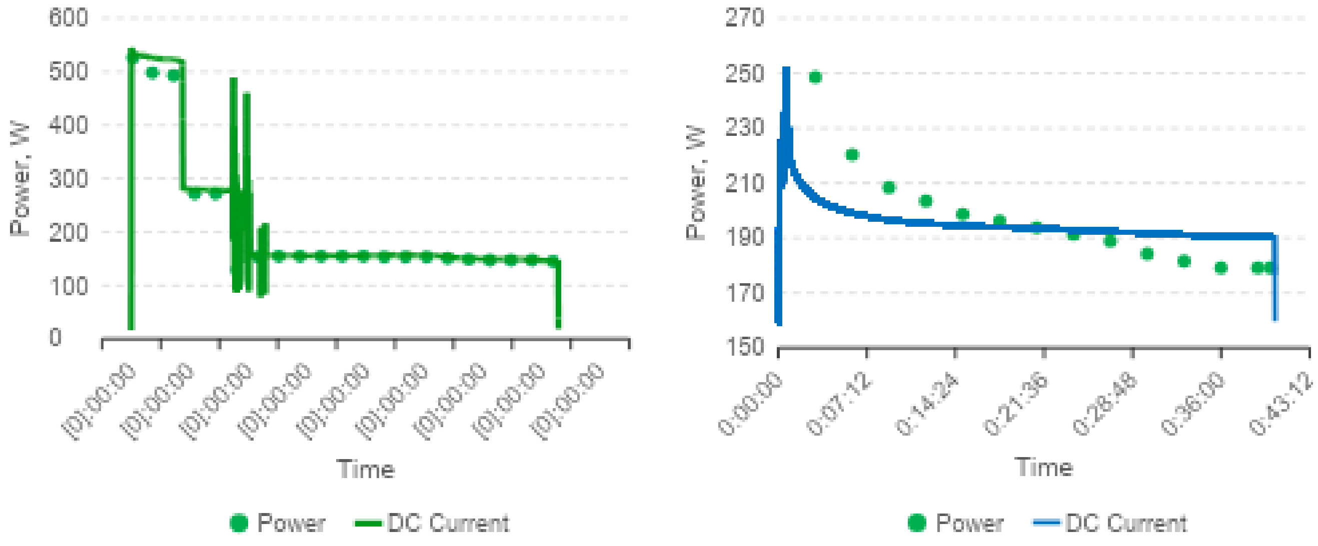
3.1 Rice Boiling/Cooking Tests



(a) Hybrid EPC test **(b) PTC-only EPC test**

Figure 41: Power consumption during a cooking test for boiling rice

Initially, the hybrid EPC was unable to sufficiently cook the rice since all the steam would escape. After troubleshooting, we discovered that the heating would occur slowly making it insufficient to rapidly heat the water to steam and lock the valve. In some instances, the water would dry up quickly when using a ratio of 1:1. The ratio was adjusted to 1.5 cups of water for every cup of rice. After reprogramming, the EPC would sufficiently cook the rice within an hour. Steam appeared before the half hour mark. The heating could be optimized to cook in much less time. The final food temperature was above 85°C. as shown in **Figure 42**.

Rice was well cooked after 40minutes cooking using the PTC-only EPC. The final food temperature was 92.6°C. Initially the heat was not enough to pressurize and lock the valve, hence the water dried up and the rice was undercooked.

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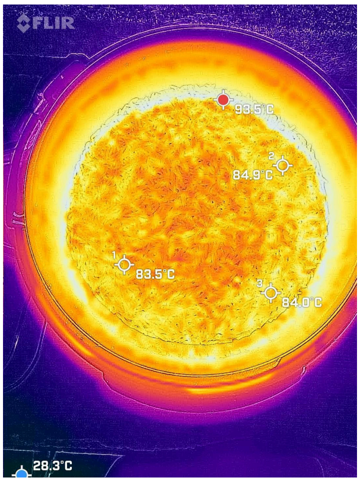
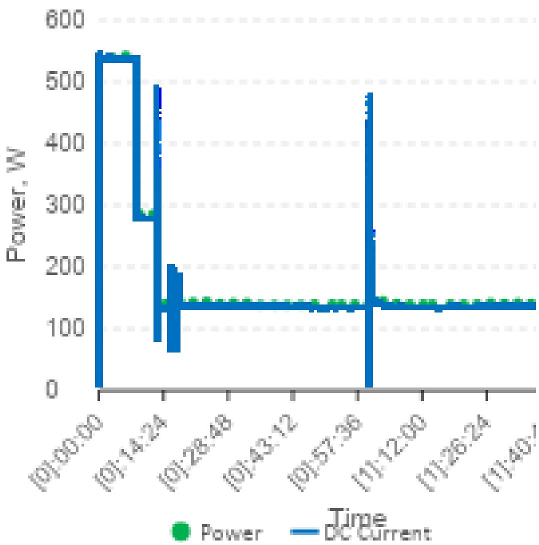
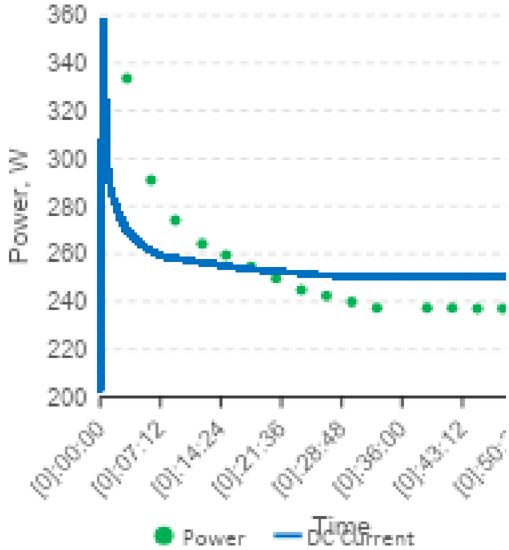


Figure 42: Final rice temperature for hybrid EPC test

3.1 Beef Boiling Tests



(a) Hybrid EPC test



(b) PTC-only EPC test

Figure 43: Power consumption during a cooking test for boiling beef

Raw beef, with slight seasoning and 2 cups of water were added to the EPCs and closed. Steam could be observed after 40min of boiling initially using the hybrid EPC; however, the pressure buildup was not sufficient to close the valve and pressurize the system. Even after 1hr of continuous heating, the meat was still undercooked. The mode was reprogrammed, and two more tests were done. The EPC successfully pressurized, and the meet was fully boiled after 1hr 45min of continuous boiling. The final food temperature was 82°C.

It took the PTC-only EPC less than 1hr 30min to fully boil the meat. The cooker managed to pressurize after 36min of boiling. The heating phase was about 1 hour, after which the

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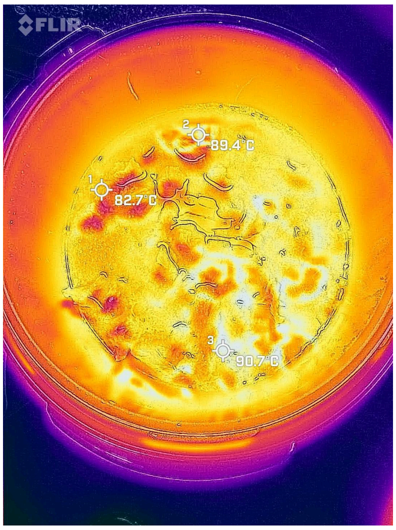
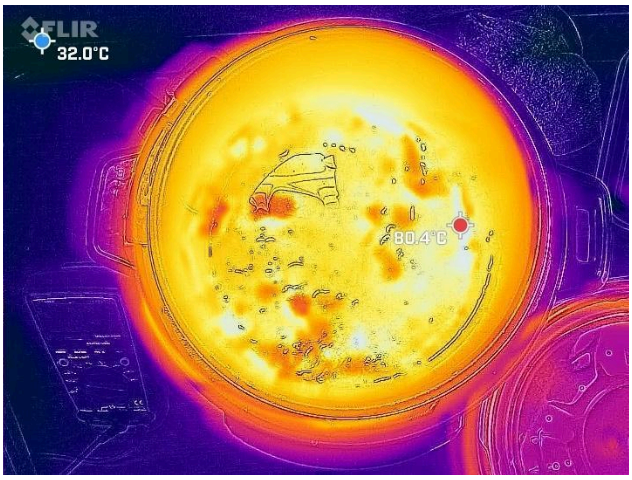
meat was boiled only by pressurized steam without any additional heating. The final food temperature was 80°C.



(a) Hybrid EPC test



(b) PTC-only EPC test

Figure 44: Final food temperature during a cooking test for boiling beef

3.1 Beef Cooking Tests

Food was sautéed for 50 minutes after which the lid was closed for a while. Steam was already observed 15 minutes after the lid was closed. A cup of broth was added and the lid closed. The EPC took another 10min to pressurized, another 20 minutes to switch to pressure cooking and 40min to depressurize. The entire process took 1hr 45min to fully cook the beef as shown in **Figure 45**. The time taken to build up pressure and later depressurize could be optimized to make the cooking shorter.

The PTC-only did much better, overcooking the beef in 1hr 24min. The sauté phase only lasted 39min and locked immediately after the lid was closed. The heating, however, continued causing the emergency valve to open and allow the steam to escape. After 20 minutes of heating, the cooker eventually switched off to cook only by steam. The pressure subsided completely after 24 minutes, and the beef was overcooked. With more optimization, the cooker will cook in less time.

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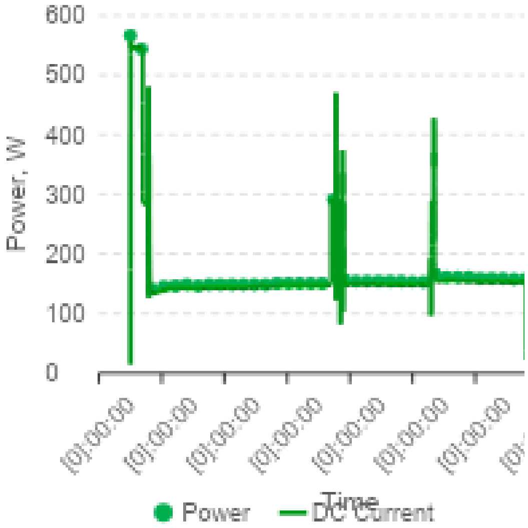

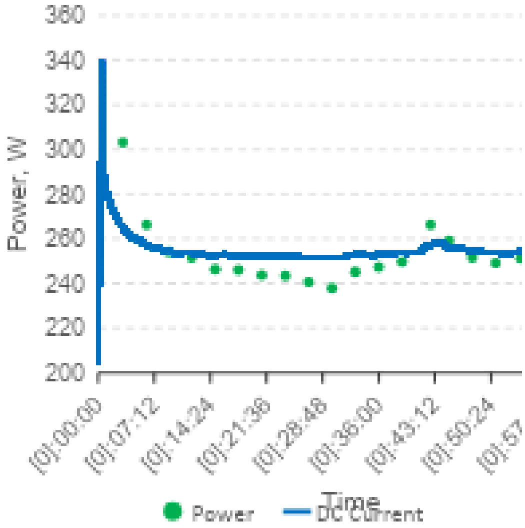

(a) Hybrid EPC test **(b) PTC-only EPC test**

Figure 45: Power consumption during a cooking test for cooking beef

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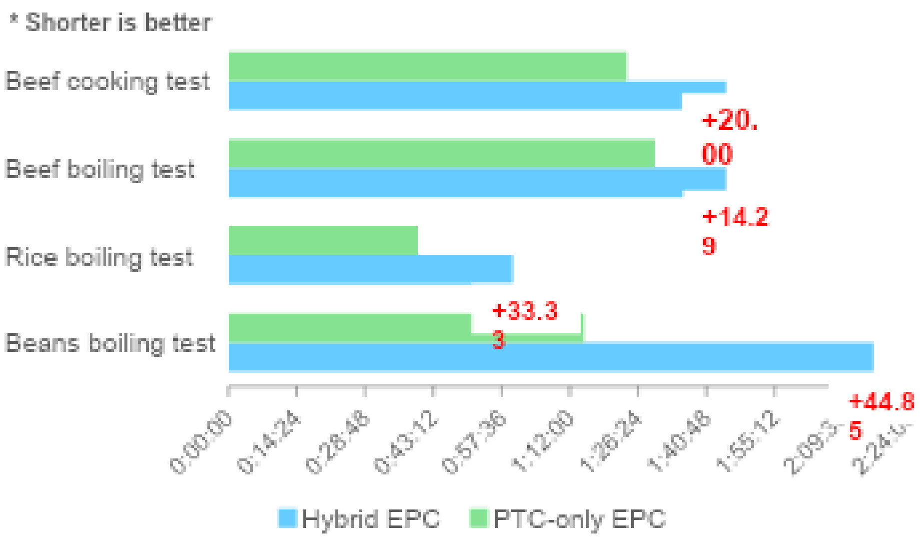
3. Discussion

The results indicate that the PTC-only EPC outperformed the hybrid EPC in all tests, averaging almost by half the time in some instances as shown in the figure below. A 10-30% improvement should be expected in most scenarios. Comparing power curves for both



Cookers show that they have similar peak currents at about 20 amperes, however, the peak power drawn by the hybrid EPC is estimated at 480 watts while the PTC-only is about 300 watts. This is because the hybrid EPC initial heating phase uses both coils rated at 24V 20A. This metric is important because it makes the PTC-only better suited for smaller sized PV systems.

Despite this advantage, the inrush current is still higher than it needs to be. It can be reduced to less than half using inrush current limiters on all the PTCs. This would level out the power curve below 300W. Assuming the average power rating at 260W and oversizing the panel at 300W, cost of the standalone system (battery storage excluded) would be estimated to be about $120 to $170. The hybrid and existing EPC are rated 480W and would require much larger panels, almost twice the size of that fitted with the PTC-only EPC. Even with the cost savings, the EPC is expensive compared to existing lower tier cooking technologies such as the improved cookstoves.

Although EPCs have a certain degree of automation, meaning one doesn't have to monitor food as it cooks, they can be complicated to use especially when measuring ingredient quantities. Rigorous testing and programming must be done to find the tight margins in which to configure modes for cooking different foods. PTCs power curve is continuous making it much harder to accurately control the heating curve. This was experienced while boiling rice. Using the recommended water to rice ratio of 1:1 would lead to gradual escaping of steam making the food dry before being properly cooked. All cooking modes would need to be reprogrammed and a cookbook with new ingredient quantities made. This would improve the user experience.

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4. Conclusion

This report highlights the test reports undertaken to optimize the 5 litre 24 VDC solar cooker developed by Foshan Shunde e-Want Electrical Technology Ltd for Modern Energy Cooking Services (MECS).

Extensive research was done to optimize the hot plate by completely redesigning the cooker and replacing it with more efficient heating elements. Furthermore, in addition to the main control panel, an extra intelligent microprocessor-based control hardware was added to improve hot plate performance. Based on the lab experiments conducted, the modified cookers provide valuable insight on the new ways to improve conventional DC pressure cookers. The test results show a significant decrease in energy consumption while cooking the same type of foods in regions served by the MECS project, such as Ugali, Rice, Beans, Tea, and Beef.

The prototyping iteration undertaken has utilized locally sourced materials and suppliers. This provided a quick and cost-effective way to test the DC EPC while allowing greater flexibility in performing iterations until a desired cooker performance was achieved. The final prototypes are a hybrid hot plate which utilizes both the resistive coils and the PTCS and PTCs only design.

As the project has achieved greater milestones, some challenges and limitations were encountered; the process is recommended for large-scale manufacturing as it provides better tolerance, surface finishes and possibility for complex designs. This would enable it to insert the PTCs inside the casting design and produce a whole integrated unit. This would more greatly improve heat distribution and thermal transfer efficiency.

As the project has modified an existing DC EPC mainly focusing on the hot plate, some limitations occurred in modifying the main control circuit as the manufacturer was not willing to allow modification. A custom-built control circuit would be better as the cooking algorithms will be optimized for the new improved hot plates.

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