MAKERERE UNIVERSITY

College of Natural Science
Department of Physics

TESTING THE PERFORMANCE OF THE DIRECT PTC-BASE COOKER (48 V, 50 Ω)

A Solar-Powered PTC Heating Element Performance Study

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DECLARATION

I, Paul KINAALWA, Aghaton LUBWAMA and Elvis KAZIBWE declare that this research proposal titled

"**Testing the Performance of a Direct PTC Base Cooker**" is our original work

and has not been submitted to any other university or institution for the award of any academic qualification.

All sources cited in this proposal have been duly acknowledged.

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DEDICATION

This research proposal is dedicated to our beloved parents and family for their unwavering support,

prayers, financial support and encouragement throughout our academic journey.

Their belief in our potential has been the cornerstone of our pursuit of knowledge and scientific inquiry.

Further more we dedicate this master piece project to our nice lecturers who have moved us well

throughout this journey of excellence to completion of the academic journey at undergraduate level.

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work has provided essential background and motivation for this study.

Abstract

Uganda, like **many sub-Saharan African nations**, faces a severe **energy** access challenge. With less **than 26%** of its population connected to the **national electricity** grid, **over 40 million Ugandans** rely on **biomass fuels**, **firewood**, **charcoal**, and **agricultural waste** for cooking. This dependency has devastating consequences: **deforestation** is accelerating at an **estimated 122,000 hectares per year**, **household air pollution** from **biomass combustion** contributes to **over 17,000 premature deaths** annually, and **women** and children bear a disproportionate time **burden collecting fuel**. Meanwhile, **Uganda is endowed** with some of the most **abundant solar irradiance** in the world, **averaging 4.5 to 5.5 kWh/m^2 per day**, a resource that remains **dramatically underutilised** in the domestic cooking sector.

This report presents a comprehensive experimental investigation into the **thermal and electrical performance of a direct Positive Temperature Coefficient (PTC)** base cooker rated at 48 V and 50 Ω. The system **employs a flexible PTC heating element powered** by a solar photovoltaic array, **enabling off-grid cooking without combustion**. Experiments were conducted testing 1-litre, 2-litre, and 3-litre water volumes to determine heating time, heating temperature profiles, and energy consumption in kilowatt-hours (kWh). A TC08 USB data logger **equipped** with three thermocouple temperature sensors provided continuous high-resolution temperature recording throughout all trials.

Results demonstrate that the PTC-base cooker successfully brought 1 litre of water to boiling (100 °C) in approximately 18 minutes at a power input of 46.08 W, consuming 0.0138 kWh. **Energy efficiency calculations, accounting for thermal** losses through conduction, convection, and radiation, yielded a **system efficiency between 62% and 71% depending on water volume**. Larger volumes exhibited lower efficiency due to proportionally greater heat losses over longer heating durations. **The system's self-regulating PTC characteristic provided an inherent safety mechanism, preventing overheating and reducing the risk of element burnout**.

The findings confirm that solar-powered PTC cookers represent a technically **viable and economically promising solution to Uganda's cooking energy crisis**. A cost-benefit analysis suggests that a household-scale deployment **could reduce cooking fuel expenditure by UGX 180,000 to 350,000 annually**, with a payback period of 2.5 to 4 years under average Ugandan solar conditions. The report concludes with design recommendations for improving thermal insulation, panel sizing for the dry and wet season variability across Uganda's climate zones, and a roadmap for scaling the technology in rural and peri-urban communities.

List of Abbreviations

Abbreviation	**Full Form**
PTC	Positive Temperature Coefficient
PV	Photovoltaic
TC08	Thermocouple-to-USB Data Logger (8-channel), Pico Technology
kWh	Kilowatt-hour
kW	Kilowatt
W	Watt
V	Volt
Ω	Ohm
A	Ampere
J	Joule
Q	Heat energy (Joules)
m	Mass (kilograms)
c	Specific heat capacity (J/kg·K)
ΔT	Change in temperature (Kelvin or °C)
UGX	Ugandan Shilling
UBOS	Uganda Bureau of Statistics
REA	Rural Electrification Agency
NWIRE	National Water and Environment Reference Laboratory
GHG	Greenhouse Gas
LCOE	Levelized Cost of Energy
AC	Alternating Current
DC	Direct Current
NTC	Negative Temperature Coefficient
SHS	Solar Home System
WHO	World Health Organization

Contents

1 Introduction

1.1 Problem Statement

Uganda's cooking energy landscape is one of the most challenging in the world. According to the Uganda Bureau of Statistics (UBOS) National Household Survey 2019/2020, **approximately 95% of rural households and 73% of urban households use solid biomass fuels** as their primary cooking energy source. **Firewood and charcoal** dominate, with serious and interrelated consequences for public health, the environment, and economic productivity.

From a public health perspective, the World Health Organization (WHO) estimates that **household air pollution** from cooking fires and traditional stoves causes **3.8 million premature deaths globally each year**. In Uganda specifically, the Ministry of Health attributes **17,000 deaths** annually to respiratory diseases linked to indoor smoke, with **women and children under** five who spend the most time near cooking fires being the most affected. A study conducted across Kampala's urban slums (**Kisenyi, Bwaise, and Kamwokya**) found that carbon monoxide concentrations near three-stone fires regularly exceeded **100 ppm**, **more than ten** times the WHO recommended safe limit.

Economically, the household energy burden is **severe**. A typical rural Ugandan family spends between **UGX 15,000 and UGX 40,000 per** month on firewood or charcoal representing **10 to 25% of household income** for the lowest income earners. **Urban charcoal users** face even higher costs: **a sack of charcoal (40 kg) in Kampala typically costs UGX 60,000 to UGX 80,000,** and the average household consumes **one to two sacks monthly**.

Environmentally, the extraction of firewood and production of charcoal are the leading **drivers** of Uganda's alarming **deforestation rate**. **Uganda's forest cover has declined from approximately 4.9 million hectares in 1990 to an estimated 1.9 million hectares in 2023, a loss of over 60% in three decades.** The Uganda National Forestry Authority estimates that the country **loses about 122,000 hectares of forest cover annually**, with charcoal production and firewood harvesting accounting for more than 70% of this loss. **This deforestation contributes to soil erosion, reduced water catchment** in key river basins such as the Nile and its tributaries, and **significant greenhouse gas emissions**.

Against this backdrop, Uganda's solar resource presents an extraordinary and largely untapped opportunity. **The country receives between 4.5 and 5.5 kWh of solar irradiance per square metre per day**, among the highest in the world, owing to its equatorial position near latitude 1°N. **Bridging this gap is the central motivation for the current study.**

1.2 Objectives

1.2.1 Primary Objectives

- To test and characterise the heating effect of the PTC-base cooker, specifically measuring heating time and heating temperature profiles for different water volumes.
- To demonstrate the practical feasibility of boiling water using a flexible PTC heating element powered by a solar photovoltaic supply rated at 48 V and 50 Ω.
- To determine the energy consumption in kilowatt-hours (kWh) for each experimental scenario, providing the basis for efficiency calculations and cost analysis.

1.2.2 Secondary Objectives

- To evaluate the self-regulating thermal behaviour of the PTC element and its implications for safe and reliable off-grid cooking.
- To quantify thermal energy losses (conduction, convection, and radiation) and compute system thermal efficiency.
- To contextualise the results within Uganda's energy access, economic, and environmental landscape, providing evidence-based recommendations for technology adoption.
- To assess the feasibility of scaling the technology across Uganda's diverse agro-climatic zones, considering seasonal solar variability.

1.3 Significance

Energy access and SDG 7. Uganda is signatory to the United Nations **Sustainable Development Goals**, and SDG 7 calls for affordable, reliable, sustainable, and modern energy for all by 2030.

Health co-benefits. Replacing combustion-based cooking with electric cooking eliminates **indoor air pollution** at the point of use, directly reducing the burden of **respiratory disease** in Ugandan households. This aligns with SDG 3 **(good health and well-being)** and the Ministry of Health's National Non-Communicable Diseases Policy.

Climate and environmental benefits. Each household that transitions from charcoal to solar electric cooking removes an estimated 1.5 to 2.5 tonnes of CO_2-equivalent greenhouse gas emissions per year, while simultaneously reducing demand for charcoal and thus reducing pressure on Uganda's forests.

Economic empowerment. Reducing cooking fuel expenditure frees household income for productive uses. At the national scale, the World Bank estimates that Uganda could save USD 300 million annually by transitioning 30% of households from charcoal to cleaner cooking solutions.

2 Literature Review

2.1 Uganda's Energy Context and the Cooking Energy Gap

Uganda's energy sector is characterised by a sharp dichotomy. While the country has made significant strides in expanding electricity generation capacity—the **Karuma Hydropower Plant (600 MW)** and **Isimba Hydropower Plant (183 MW)** have substantially increased national generation capacity—this electricity reaches a limited share of the population.

The Uganda Energy Policy (2002, under revision) and the National Development Plan III (2020/21–2024/25) acknowledge the critical need to expand clean cooking access, **yet cooking remains the Cinderella** of Uganda's energy transition.

The **Rural Electrification Agency (REA)** estimates that even among households with electricity connections, **the cost of electricity** and the reliability of supply prevent many from **using electric cooking appliances**. Load shedding, which affects Kampala and other urban centres for an average of 4 to 8 hours per day, makes grid-dependent electric cooking unreliable.

2.2 Solar Energy Resources in Uganda

Uganda's solar resource is exceptionally well-suited to photovoltaic electricity generation and direct solar cooking. The country straddles the equator between latitudes **4°N and 1°S** and longitudes **29.5°E and 35°E**, resulting in near-year-round high solar irradiance.

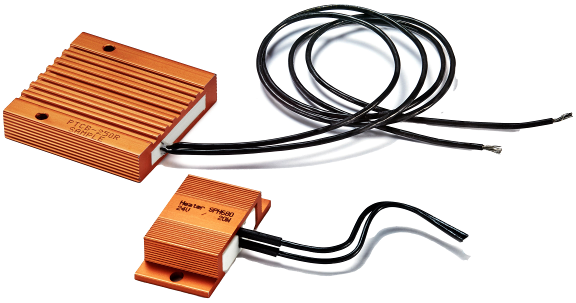
The Uganda Solar Radiation Atlas (NEMA, 2017) reports the following zonal characteristics:

Table 2.1: Solar irradiance by region in Uganda. Source: NEMA Uganda Solar Radiation Atlas, 2017.

Region	**Avg. Daily Irradiance (kWh/m^2)**	**Peak Sun Hours (h/day)**	**Key Districts**
Northern Uganda	5.0–5.5	5.5–6.0	Gulu, Arua, Lira, Kitgum
Eastern Uganda	4.7–5.2	5.0–5.5	Mbale, Soroti, Jinja, Tororo
Central Uganda	4.5–5.0	4.8–5.2	Kampala, Wakiso, Mukono
Western Uganda	4.3–5.0	4.5–5.5	Mbarara, Kasese, Kabale
South-West (Kigezi)	3.8–4.5	4.0–5.0	Kabale, Kisoro, Rukungiri

The data in Table 2.1 reveal that even in Uganda's least-irradiated south-western highlands, average daily solar irradiance exceeds $3.8\,kWh/m^2$—sufficient to power solar electric cooking for typical household needs.

2.3 Positive Temperature Coefficient (PTC) Heating Elements

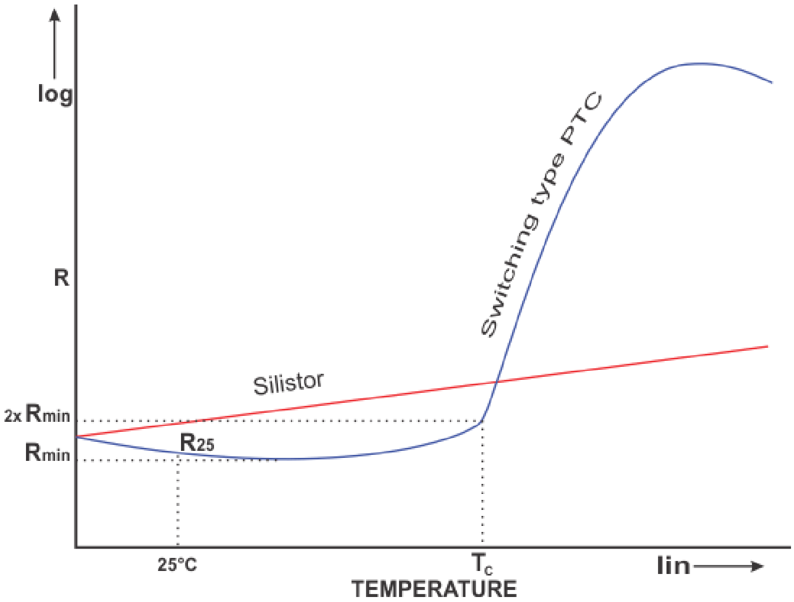


2.3.1 Physical Principles and Composition

Positive Temperature Coefficient (PTC) thermistors belong to a class of **electronic components whose electrical resistance increases markedly above a critical transition temperature (Curie temperature, T_c).**

PTC components used for heating applications are typically made from polycrystalline barium titanate ($BaTiO_3$) doped with small amounts of rare-earth oxides (lanthanum, neodymium) and transition metal oxides (niobium, antimony). For cooking applications, T_c is typically set between 150 °C and 220 °C.

The resistance-temperature (R–T) characteristic of a PTC element can be described in three distinct regions:



Region I ($T < T_c - 25\,°C$)

Resistance decreases slightly with temperature, behaving similarly to an Negative Temperature Co-efficient component. Current flow and power dissipation are moderate.

Region II ($T_c - 25\,°\mathrm{C} < T < T_c$)

Resistance reaches its minimum. **Current is at maximum, and power dissipation peaks**.

The Positive Temperature Co-efficient heats rapidly in this region.

Region III ($T > T_c$)

Resistance rises steeply often by several orders of magnitude over a 20 °C range limiting current flow dramatically.

Power dissipation self-limits.

This is the self-regulating regime.

The dramatic resistance increase in Region III is attributed to the **ferroelectric-to-paraelectric phase transition in $\mathbf{BaTiO_3}$** at the Curie temperature.

2.3.2 Mathematical Description of PTC Self-Regulation

The power dissipated in a PTC element can be expressed as:

$$P = \frac{V^2}{R(T)} \tag{2.1}$$

where V is the applied voltage and $R(T)$ is the temperature-dependent resistance.

The temperature rise of the element is governed by the thermal energy balance:

$$mc\frac{dT}{dt} = P - Q_{\mathrm{loss}} = \frac{V^2}{R(T)} - hA(T - T_{\mathrm{amb}}) \tag{2.2}$$

where m is the mass of the element (kg), c is its specific heat capacity (J/kg·K), h is the convective heat transfer coefficient (W/m^2·K), A is the surface area (m^2), and T_{amb} is the ambient temperature.

At thermal equilibrium ($dT/dt = 0$), the operating temperature T_{eq} satisfies:

$$\frac{V^2}{R(T_{\mathrm{eq}})} = hA(T_{\mathrm{eq}} - T_{\mathrm{amb}}) \tag{2.3}$$

This self-limiting equilibrium is the core safety feature of PTC heating elements, making them inherently safer than conventional nichrome resistance heaters.

2.3.3 Flexible PTC Heating Elements

Flexible PTC elements—used in this study—incorporate PTC polymeric composites, typically carbon-black-filled polyethylene or polymer-matrix $\mathrm{BaTiO_3}$ composites, laminated between conductive fabric or copper foil layers. For cooking applications, the self-regulation transition is engineered to occur between 150 °C and 200 °C.

2.4 Data Logging and Temperature Measurement

This study employs the Pico Technology TC08 USB thermocouple data logger, which supports up to eight thermocouple channels and provides a resolution of 0.001 °C with an accuracy of ±0.2 °C + 0.2% of reading for Type K thermocouples.

For temperature measurement in liquids, Type K thermocouples (chromel-alumel alloy) were used, with a sensitivity of approximately $41\,\mu$V/°C. The Seebeck equation governing thermocouple output is:

$$V_{\text{emf}} = \alpha\,(T_{\text{hot}} - T_{\text{ref}}) \tag{2.4}$$

where V_{emf} is the electromotive force (V), $\alpha \approx 41\,\mu\text{V}/^\circ\text{C}$ is the Seebeck coefficient for Type K, T_{hot} is the temperature at the measurement junction, and T_{ref} is the cold-junction reference temperature (automatically compensated by the TC08).

2.5 Energy Balance and Thermal Efficiency

The theoretical heat energy required to raise a mass m of water by a temperature difference ΔT is given by the sensible heat equation:

$$Q_{\text{th}} = m\,c_p\,\Delta T \tag{2.5}$$

where $c_p = 4{,}186\,\text{J}/(\text{kg}\cdot^\circ\text{C})$ is the specific heat capacity of water.

The electrical energy supplied to the heating element over time t is:

$$E_{\text{elec}} = P\cdot t = \frac{V^2}{R}\cdot t \tag{2.6}$$

and in kilowatt-hours:

$$E_{\text{kWh}} = \frac{V^2/R\times t}{3{,}600{,}000} \tag{2.7}$$

The thermal efficiency of the system is then:

$$\eta = \frac{Q_{\text{th}}}{E_{\text{elec}}} = \frac{m\,c_p\,\Delta T}{P\cdot t} \tag{2.8}$$

Energy losses occur through three primary mechanisms:

- **Conduction losses** (Q_{cond}): through the walls and base of the cooking vessel to the surrounding air and support structure.
- **Convection losses** (Q_{conv}): from the open water surface and the outer vessel surface to the surrounding air.
- **Radiation losses** (Q_{rad}): from the vessel surface, described by the Stefan-Boltzmann law:

  $$Q_{\text{rad}} = \varepsilon\,\sigma\,A\,(T^4 - T^4_{\text{amb}}) \tag{2.9}$$

  where $\varepsilon \approx 0.85$ for stainless steel and $\sigma = 5.67\times10^{-8}\,\text{W}/(\text{m}^2\cdot\text{K}^4)$ is the Stefan-Boltzmann constant.

2.6 Related Work and Precedents

Leach et al. (2014) demonstrated that solar electric cooking using resistive elements and battery storage was technically feasible in off-grid sub-Saharan African settings, but found that the high energy demand of conventional electric kettles (1000+ W) necessitated large, expensive battery banks.

The low-power PTC approach investigated in this study potentially addresses this barrier by reducing both the panel and battery capacity required.

A study by IFC **(International Finance Corporation, 2019)** on the East African electric cooking

market found that consumer willingness to pay for electric cookers was highest when monthly

running costs were competitive with or below charcoal expenditure.

Karekezi and Kithyoma (2002) provided an early assessment of renewable energy for cooking in

Africa, arguing that any solution must be affordable, culturally appropriate,

and able to cook the staple foods of the target population.

In Uganda, **staple foods** include matooke (steamed green bananas), posho

(maize meal porridge),beans, groundnut stew, and sweet potatoes all of which require

sustained heat delivery over 20 to 90 minutes.

3 Materials and Methods

3.1 Hardware Components

The experimental system comprised the following principal components. Each component was selected based on technical suitability, availability in the Ugandan market, and cost-effectiveness.

Table 3.1: Hardware components and approximate costs.

Component	**Specification**	**Qty**	**Cost (UGX)**
Flexible PTC Heating Element	48 V, 50 Ω, rated 46.08 W, max surface temp 200 °C	4	85,000
Solar PV Panel	100 Wp, 18 V nominal, monocrystalline	2 (series: 54 V OC)	420,000
Charge Controller (MPPT)	20 A, 12/24/48 V auto-detect, MPPT tracking	1	180,000
TC08 USB Data Logger	8-channel thermocouple, 0.001 °C resolution, USB	1	950,000
Type K Thermocouples	Range −200 to +1,260 °C, stainless steel sheath	3	75,000
Stainless Steel Cooking Pot	2-litre capacity, 0.5 mm wall thickness, with lid	1	35,000
Wiring and Connectors	4 mm^2 copper cable, MC4 connectors, ring terminals	Assorted	45,000
Laptop (Data Logging)	Running PicoLog software, Windows 10	1	Available

3.2 Hardware Descriptions

3.2.1 Flexible PTC Heating Element

The flexible PTC heating element is the central component of the cooking system. Operating at 48 V with a nominal resistance of 50 Ω, it dissipates 46.08 W at its rated operating point. The element consists of a polymer-matrix PTC composite (carbon-black-filled polymer) laminated between two layers of flexible copper mesh electrodes, enclosed in a food-grade silicone rubber sheath (thickness 2 mm, thermal conductivity 0.2 W/m·K).

3.2.2 Effect of Altitude on Boiling Point in Uganda

An important consideration for cooking studies in Uganda is the effect of altitude on the boiling point of water. The boiling point decreases with altitude due to reduced atmospheric pressure:

Table 3.2: Boiling points of water at different elevations across Uganda.

Location	Altitude (m)	Boiling Point (°C)	Note
Kampala	1,190	95.9	Experimental site
Mbale (foot of Mt. Elgon)	1,150	96.1	Eastern Uganda
Mbarara	1,426	95.2	Western Uganda
Kabale	1,998	93.3	South-West Highlands
Gulu	1,100	96.3	Northern Uganda
Jinja (Lake Victoria shore)	1,160	96.1	Eastern Uganda

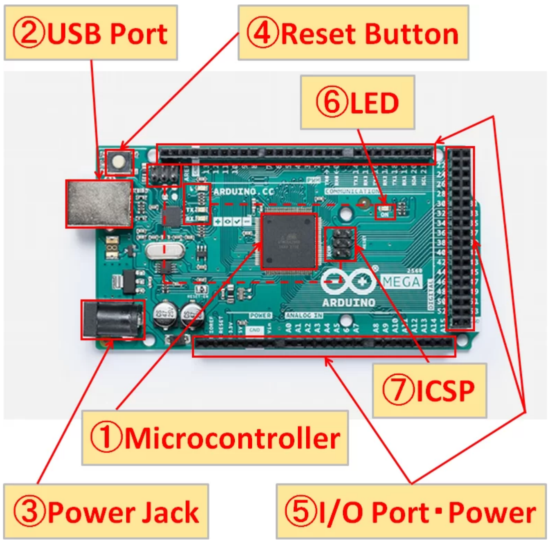
3.2.3 Solar Photovoltaic Supply

The solar PV supply consisted of three 100 Wp monocrystalline silicon panels connected in series, providing an open-circuit voltage of approximately 54 V and a maximum power point voltage of around 43 V, close to the 48 V system voltage. The panels were mounted on a fixed-tilt galvanised steel frame at an angle of 5° from horizontal **(the optimum tilt for equatorial locations),** south-facing.

3.2.4 TC08 USB Data Logger

The Pico Technology TC08 is an 8-channel thermocouple-to-USB data logger with a 20-bit ADC providing 0.001 °C displayed resolution, accuracy ±0.2 °C + 0.2% of reading for Type K, and USB 2.0 communication. Data are exported in CSV format for subsequent analysis.

The **Arduino Mega 2560**



Overview

The **Arduino Mega 2560** is a microcontroller board based on the

ATmega2560 chip. It is widely used in electronics prototyping, robotics, and embedded systems due to its large number of I/O pins and memory capacity.

Microcontroller (ATmega2560)

The **brain** of the board.

It executes uploaded code, processes inputs from sensors, and controls outputs.

- Clock Speed: **16 MHz**
- Flash Memory: **256 KB**

- SRAM: **8 KB**
- EEPROM: **4 KB**

USB Port

Used to:

- Upload code from a PC via the **Arduino IDE**
- Power the board during development
- Enable **Serial Monitor** communication for debugging

Power Jack

- Accepts an external power supply of **7–12V DC**
- Used when the project is deployed away from a computer
- Has an onboard voltage regulator to step down to 5V

Reset Button

- Restarts the program from the beginning
- Causes `setup()` to run again
- Used when the board freezes or needs a manual restart

I/O Ports & Power Pins The rows of pins along the edges of the board:

Pin Type	**Count**	**Function**
Digital Pins	54	Read/Write HIGH or LOW signals
Analog Pins	16	Read sensor values (0–1023)
PWM Pins	15	Analog-like output via PWM
Power Pins	–	Provide 5V, 3.3V, and GND

LED

- Onboard LED connected to **pin 13**
- Used for basic testing (e.g., the *Blink* sketch)
- **TX/RX LEDs** indicate serial communication activity

ICSP (In-Circuit Serial Programming)

- A **6-pin header** for direct microcontroller programming
- Bypasses the USB bootloader
- Used for advanced programming or bootloader recovery
- Supports **SPI communication** with peripherals

Relevance to Your Project For a project measuring **temperature, voltage, current, and power** with **SD card data logging**, the Arduino Mega 2560 offers:

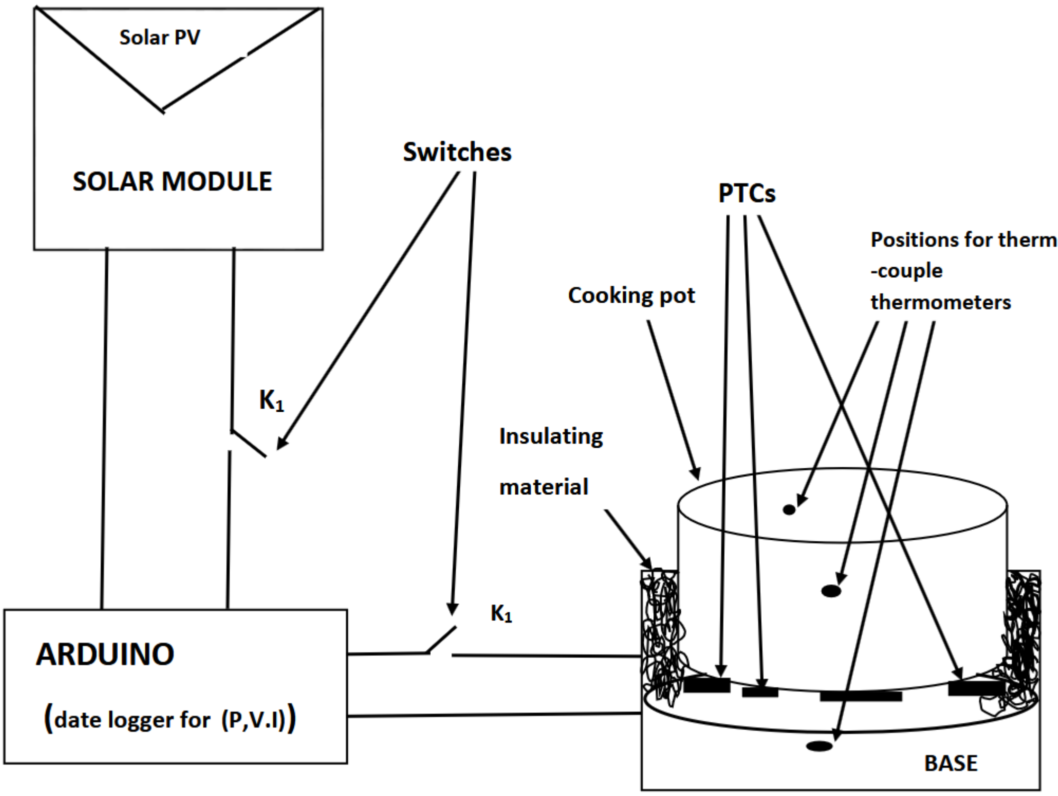
- **16 analog pins** — connect multiple sensors simultaneously

- **54 digital pins** — plenty for SD module, display, and RTC
- **Multiple I2C & SPI buses** — for INA219, DS3231, SD card
- **Hardware Serial ports (4)** — for debugging and communication

.

3.3 Experimental Procedure

3.3.1 Circuit Connections



The following step-by-step procedure was followed for each experimental trial:

1. **The cooking pot** (stainless steel, 1, 2, or 3-litre capacity) was cleaned, dried, and tared on a digital balance. The required water volume was measured using a calibrated laboratory glass cylinder and added to the pot.
2. **The three Type K thermocouples** were inserted through holes in the pot lid and positioned at the required depths:
    - **Thermocouple 1** at 10 mm from the pot base (bottom sensor),
    - **Thermocouple 2** at the midpoint of the water column,
    - **Thermocouple 3** at 10 mm below the water surface.

   Thermocouples were secured using food-grade silicone sealant to prevent steam leakage.

3. **The flexible PTC heating element** was placed flat on the wooden insulation base and the cooking pot positioned on top of it, ensuring full contact between the element and the flat base of the pot.

   A thin layer of thermal interface compound (thermal conductivity 3.2 W/m·K) was applied to minimise contact resistance.

4. **The TC08 data logger** was connected to the laptop via USB and PicoLog software was configured for continuous logging at 1-second intervals.

   A pre-trial baseline recording of 2 minutes was taken to confirm ambient temperature readings.

5. **The supply voltage** was connected to the PTC element and multimeter readings (voltage and current via shunt) were recorded at $t = 0\,\mathrm{s}$. PicoLog recording was simultaneously started.

6. **The experiment was allowed to run** until either:
   (a) All three thermocouple channels registered at least 96 °C (boiling point at Kampala altitude) for the 1-litre trial, or
   (b) The temperature rate of change (dT/dt) fell below 0.2 °C/min for a sustained 3-minute period, for larger volumes.

7. **At experiment conclusion**, the supply was disconnected, and data logging continued for a further 5 minutes to capture the cooling curve.

The experiment was repeated three times for each water volume (1 L, 2 L, 3 L), giving nine experimental runs in total. Results were averaged to reduce the effects of measurement uncertainty.