## Title
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Authors
Ezimora, Ukamaka
Agorrilla, Ruth
Abrenic, Daniel Christian
et al.

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# Thru-Reflector-Wall (TRW) Solar Cooker Kitchens

Ukamaka Ezimora, Ruth Agorrilla, Daniel Christian Abrenica, Santiago Garcia

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This paper was written for ENGR 194, seeking to bring forth Joel H. Goodman's vision for solar cooker designs.

# Thru-Reflector-Wall (TRW) Solar Cooker Kitchens

Ukamaka Ezimora*, Ruth Agorrilla, Daniel Christian Abrenica, Santiago Garcia

*School of Engineering, University of California Merced, Merced, CA, USA*

HIGHLIGHTS

- Introduces a CPC funnel design made from accessible materials like press-molded clay and optical glass mirrors.
- Aims to develop a scalable production method for solar cookers that can be integrated into existing housing structures in developing nations.
- Focuses on creating a durable and affordable design that can endure year-round environmental conditions.
- Seeks to reduce dependency on precious, unsustainable materials, often used in solar cookers.

*Keywords:*
Clay ceramic
Environmental emission
Clean cooking
Sustainability
Manufacturing
Heat transfer
Solar concentrator

ABSTRACT

Joel H. Goodman is a retired assistant professor of architecture at the University of Minnesota who, motivated to bridge the gap between sustainable living and underdeveloped communities, began developing various solar cooker designs. To bring forth Goodman's vision, we were tasked with designing a solar cooker to be permanently integrated into a building and able to direct variable sun rays towards the cooking surface with its funnel-like shape. The cooker provides a sustainable alternative to traditional cooking methods such as wood and coal burning, which remain prevalent in underdeveloped regions despite their harmful environmental and health impacts. Solar cookers, like other clean cooking technologies, have the potential to significantly reduce greenhouse gas emissions, mitigate deforestation, and improve public health by reducing indoor air pollution. Furthermore, access to clean cooking methods reduces the time and effort required for fuel collection, which can increase societal productivity and lower mortality rates, particularly among women and children. The integration of solar cookers into architectural designs represents a sustainable solution that not only enhances the well-being of communities but also supports global climate change mitigation efforts by reducing reliance on nonrenewable energy sources.

## I. INTRODUCTION

In the 21st century, while most developed countries have access to modern cooking resources like electric stoves, there are still countries around the world that rely on traditional methods, such as coal and wood burning. Solar concentrator cookers are devices that use mirrors and lenses to concentrate the light from the sun and cook food. Similar to other clean cooking agents like electricity, ethanol, natural gas, and biogas, solar cookers foster beneficial outcomes for individuals, communities, and the environment. Many people in developing nations primarily use nonrenewable energy sources such as coal, crop waste, and kerosene. Specifically, about 2.3 billion people around the world have to rely on these unclean cooking methods, leaving a negative influence on societal productivity, environmental conditions, and human health [1]. According to the International Energy Agency (IEA), these unclean cooking methods contribute significantly to air pollution, resulting in approximately 3.7 million premature deaths annually [1]. The adverse effects are particularly pronounced for women and adolescents, who are often tasked with cooking in many societies [1]. In Sub-Saharan Africa, a staggering 81.5% of the population lacks access to clean cooking facilities [1]. Many of these areas lack the infrastructure necessary to implement the simplest solutions, such as electric stoves, microwaves, and similar appliances. For instance, in Sub-Saharan Africa, nearly 50% of the population in the region does not have electricity, further complicating the situation [1]. Meanwhile, Developing Asia accounts for 55% of the global population without clean cooking options; however the implementation of policies that promote liquefied petroleum gas (LPG) and clean air initiatives have improved those numbers [1].

TABLE I

Prospective countries for solar cooker implementation and selected pottery businesses identified within the regions.

| Country | Region | IEA % | Pottery Businesses |
|---|---|---|---|
| Ethiopia | Africa | 7.60% | • St. George Gallery<br>• Hasesa Crafts |
| Uganda | Africa | 0.70% | • Byentaro Ceramics<br>• Olivia Potter |
| Rwanda | Africa | 5.40% | • Gatagara Pottery<br>• Azizi Life<br>• Urumuri Pottery |
| Kenya | Africa | 20.40% | • Kazuri Bead Factory<br>• Ceramica Africa |
| Laos | Asia | 9.60% | • Lao Pottery House |
| Honduras | Central America | 49.50% | • Alfarería Lenca La Campa |

In Central and South America, access to clean cooking is generally better, though countries like Honduras still exhibit serious gaps, with 50.5% of the population lacking access [1]. A low IEA percentage may indicate that a country struggles with energy efficiency, which can result in higher energy consumption and increased greenhouse gas emissions. Furthermore, it may reflect a reliance on fossil fuels and limited integration of renewable energy sources, raising important concerns about energy sustainability and security. Table I shows prospective countries with low IEAs that could therefore benefit from solar cookers. Transitioning to clean cooking technologies can profoundly transform lives by reducing mortality rates among women and children and enhancing the overall quality of life within communities. Improved access to clean cooking solutions not only has the potential to elevate public health outcomes but also to increase societal productivity by reducing the time spent on fuel collection. Furthermore, by decreasing reliance on wood and charcoal, we can mitigate deforestation and lower greenhouse gas emissions, thereby playing a crucial role in climate change mitigation efforts. This paper will delve into some of the work that was done as a part of the ENGR 194, senior engineering capstone design course at UC Merced. Some aspects not addressed in this paper, but completed during the course, include step-by-step manufacturing details for large and small scales, along with economic and supply chain analyses.

## II. CONTEXTUAL FRAMEWORK

### *A. Previous Solar Cooker Designs*

Solar powered cooking devices, which convert sunlight into electricity have shown promise through their ability to power a variety of devices, from ovens to stoves, as well as their ability to store energy and allow for solar cooking even in gloomy weather. However, solar energy is less accessible, especially in rural areas where the batteries or electricity infrastructure may not be available. Solar concentrator cookers can be not only a practical solution for many communities, but a better one, as they can reach high temperatures quickly, making them efficient for cooking. Some solar cookers have even been developed with heat storage capabilities. For instance, Goodman [2] employed case studies and comparative analysis of design proposals to evaluate the performance of small-scale heliostat systems that utilize thermal storage systems such as molten salt or firebricks. Goodman’s results indicated that small heliostats integrated into long-span hanging roof designs can effectively meet mid-to-high temperature heat demands, serving as an efficient solution for solar energy needs [2]. Similarly, Schwarzer and Vieira da Silva [3] explored the development of solar cooking systems with or without temporary heat storage, showing that systems utilizing heat storage can efficiently replace traditional firewood-based cooking methods. The researchers designed a solar cooking system with integrated reflectors, installed prototypes across diverse settings in India, Mali, Chile, and Nicaragua, and evaluated performance by assessing both sensible and latent cooking power along with overall heat transfer efficiency [3]. Although the heat storage system provided additional benefits, like indoor cooking and the ability to cook during the night using stored heat, the high cost of fabrication and the difficulty of sourcing materials in non-industrialized countries pose challenges for large-scale adoption without external financial support [3].

### *2.2 A Novel CPC Building-Integrated Design Made with Non-Precious Materials*

Previous studies have highlighted challenges such as the high cost of fabrication [3, 4], difficulty in sourcing specialized materials in non-industrialized countries [3], and maintaining performance under low sun elevation and suboptimal conditions [2, 3, 4]. The parabolic designs have shown promise in cooking under suboptimal conditions, such as the snowy mountains of the alps. In snowy mountain environments, parabolic solar cookers are positioned to optimize direct sunlight, with the reflective snow aiding heat concentration, enabling efficient, high-temperature cooking despite cold conditions. The large size of a standard parabolic reflector posed a challenge for those lacking the space to put such a device; however the compound parabolic concentrator (CPC) is more compact, but still reaps the optical benefits of the original parabolic design [5]. This study builds on the work of Goodman [2] by expanding the evaluation of building-integrated solar cookers to include a diverse range of geographic and cultural contexts, aiming to identify an adaptable solution that is feasible given the resources available in non-industrialized countries.

*B. Metal Material/Manufacturing*

Due to its effortless versatility, sheet metal is a common material of choice for simple solar concentrator designs. Using sheet metal in solar concentrator cookers proves to be effective because sheet metal can be coated with reflective materials, enhancing its ability to focus sunlight. This increases the efficiency of heat concentration, which is crucial for solar cooking, making metal a highly relevant material in their design and construction. Another benefit of this material is ease of fabrication. Sheet metal is readily manipulated through cutting, shaping, and assembly, providing great flexibility in design [6, 7]. This adaptability facilitates the development of a range of concentrator forms, including parabolic dishes and solar ovens. Traditionally, mechanical and hydraulic presses have been used for metal forming; however, a transition to smart metal forming processes is underway, improving the sustainability of the process [6]. Metal can be expensive in its raw form, so recycled metal would be a more realistic solution for our purposes. Recycled construction waste can provide metal materials, but recycling necessitates specialized technologies and adherence to quality standards set by end users and authorities [8]. With shorter lifespans for electrical and electronic equipment due to heightened consumer demand, electronic waste could also be transformed into a valuable resource [9]. Weidenhamer et. al (2017) have found that locally made aluminum cookware, often produced from recycled scrap metal in low and middle-income countries, is a significant and previously unrecognized source of metal exposure, particularly lead, during normal cooking processes. To mitigate health risks, source-separated materials with known origins and compositions should be used. However, there will always be complications such as additives and contamination risks [8, 10]. Hence, recycled metal has been shown to pose a greater risk to public health, contradicting the primary objective of a solar concentrator cooker.

*C. Pure Clay and Clay Composites*

Clay is an eco-friendly building material known for its excellent thermal insulation properties. Additionally, it is abundant in developing countries, cost-effective, and provides durability, making it a sustainable option for solar cooker construction. Results have shown that compositing clay with other materials can make a positive impact to the clay's material properties [11, 12, 13, 14]. If implementing this as a long term solution, it is recommended that the composite material be adapted to what is available in the local region. For instance, coconut shells are widely available in tropical regions. It is important to note that in general, compositing a material reduces its ability to be recycled; however, natural materials like clay are not likely to be reused. Therefore, the reduced recyclability of clay is not relevant [15].

*D. Clay Manufacturing*

For the clay mold, recommended manufacturing methods for an implemented solution include press molding, slip casting, or ceramic injection molding, which are arranged from least to most industrialized processes. All of these processes are suited for components with precise shapes. The most industrialized method is ceramic injection molding which involves feeding a mixture of ceramic powder and a binder into a heated mold under high pressure, where it solidifies into the desired shape, followed by debinding and sintering to remove the binder and densify the ceramic [16]. Another method is clay slip casting, which involves pouring liquid clay (slip) into a plaster mold, allowing it to form a layer along the mold's surface as the plaster absorbs water, then draining the excess slip and letting the cast harden before removing it from the mold [16]. A benefit of slip-casting is that it allows the creation of complex shapes. However, it can take a long time for one piece to form, depending on the size of the mold and the desired thickness [16]. The least industrialized method is a press mold. With press molds, these structures can be easily created at home by individuals with limited clay crafting experience, during classes at local workshops, or scaled up for production in a local factory. After molding the clay, it needs to be dried, then fired. It has been demonstrated that the firing temperature significantly affects the physical properties of fired clay [18]. Clay bricks fired at higher temperatures (up to 1200°C) show increased compressive strength and reduced water absorption [18]. The firing duration also had a noticeable, albeit lesser, effect on these properties [18]. Our regions of interest with hot climates may be humid and have a lot of moisture in the air. This can affect the mechanical properties of the clay material. Researchers have found that the air's moisture content significantly affects compressive strength and elastic modulus, with the reduction in compressive strength ranging from 1% to 18% depending on the specimen configuration and moisture conditions [19]. Thus, firing at a higher temperature is crucial to minimize the water absorption from the environment, which can weaken the clay's strength.

### *E. Solar Reflectors*

Now that a base material has been chosen for the solar concentrator, a reflector material is needed to help concentrate light and allow the solar concentrator to function. There are three important factors to consider when choosing a reflector: reflectivity, typical environmental conditions, and required maintenance. A highly reflective material will concentrate light much better, allowing for a more efficient solar cooker. While several materials show promise for use in solar applications, durability and resistance to environmental degradation vary significantly among the different materials [20, 21]. Environmental factors that can cause degradation include humidity, temperature, UV radiation, and airborne contaminants [21]. An important consideration is that degradation mechanisms such as abrasion, erosion, edge corrosion, tarnishing, and delamination can significantly impact a reflector's performance [21]. Traditional thick glass mirrors are the most reliable and effective reflector materials, and were therefore selected for this study [20]. When building the prototype, the specific mirror selection was not a primary concern, as long as it met the basic requirement of being glass with a metal backing.

## III. CHOSEN SOLUTION

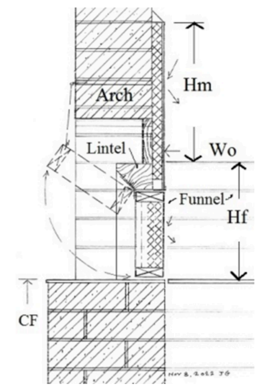



Fig. 1. Schematic of building-integrated solar cooker. Copyright [2022] by [Joel H. Goodman]. Reprinted with permission.

The team conducted a series of design explorations, spanning from online simulations to real-world cardboard models, to brainstorm new designs while also examining previous literature and our client's prior designs. This structure is intended to be secured to an outdoor kitchen as a building-integrated structure, as requested by Joel H. Goodman, shown in Fig. 1. For the solar cooker to operate effectively while remaining in the same position the whole year, the angles of the CPC have to be optimized. The angles for the four steps were decided to be 83°, 75°, 70°, and 35.13° to approximate a parabola. These angles were synthesized from existing parabolic solar cookers with accompanying ray tracing studies showing high efficiency of solar radiation retention [22, 23, 24].

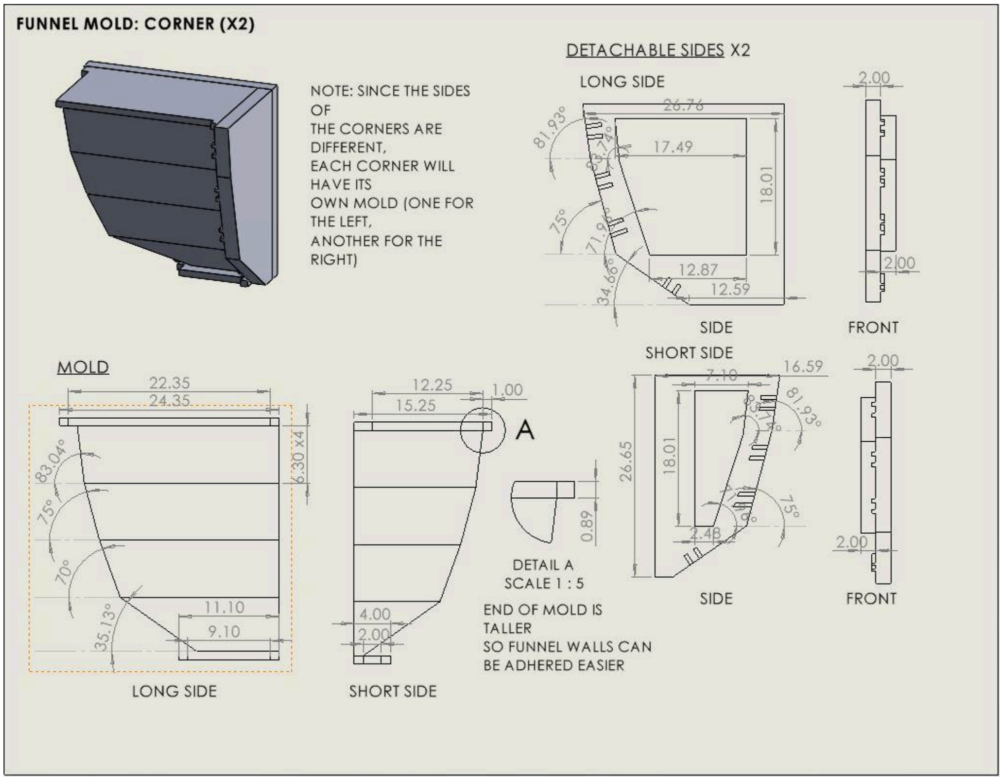



Fig. 2. CAD design drawing of a clay press mold, dimensioned in inches, used to create two corner funnel pieces. The mold is designed for forming the corner walls of the funnel.

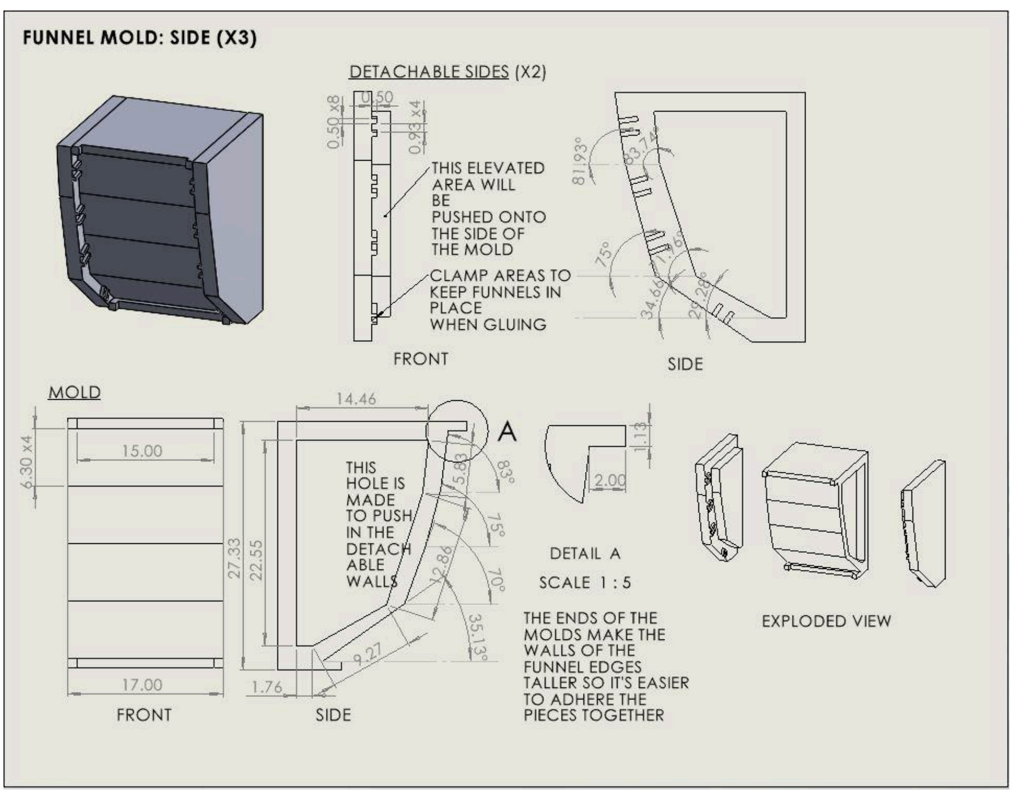



Fig. 3. CAD design drawing of a clay press mold, dimensioned in inches, designed for forming three straight walls of the funnel.

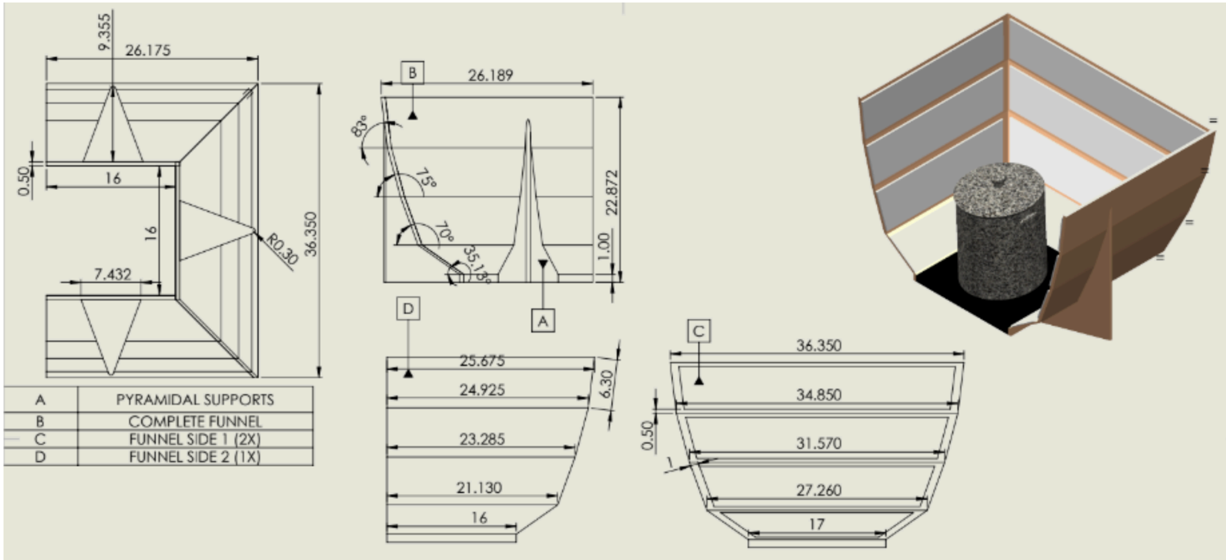



Fig. 4. Final product drawing dimensioned in inches. The design includes the clay funnel, made from fired clay using press-fit molds, inner mirrors adhered to the funnel with epoxy adhesive, and cookware positioned on the cooking surface.

The CPC funnel is composed of five distinct parts, formed through press-molded clay. The corner mold produces two pieces, while the remaining three pieces are created using the side mold. The dimensions of the clay funnel and molds are outlined in Fig. 2, 3, and 4, with the molds designed to accommodate clay sheets that would be pressed and dried into shape. As illustrated in Table II, a number of clay types were compared. Bentonite was identified as the most suitable additive for our project due to its appropriate pH and wide availability. A kaolinite-bentonite clay mixture was selected as the preferred choice for this application. When investigating the pH values and Cation Exchange Capacity (CEC) of both the clay and the mirrors that will be used together, it was observed that the interaction between these materials could lead to gradual wear of the clay structure over time. When flat glass mirrors are glued to the fired clay, differences in the composition of the metal backing of the mirror and the clay can cause early corrosion, significantly reducing the mirror's reflectivity. This occurs due to ion exchange between the two components and their differences in alkaline content.

To mitigate this issue, bentonite was selected for its relatively similar pH to the metal backing of the mirror, which helps reduce reactivity and slow down the corrosion process. Additionally, adhesives like water- and epoxy-based adhesives tend to "dry out" and shrink during curing, potentially placing undue stress on the fragile glass. Instead, a polyurethane-based adhesive was chosen for this project, as it chemically cures without shrinking, ensuring a stable bond between the mirror and the fired clay. The system consists of a CPC funnel structure, a fixed trapezoidal reflector, and a movable East/West-facing reflector. The funnel redirects the sun's rays toward the cooking surface, while the fixed reflector directs any escaping rays back into the funnel for increased exposure.

TABLE II
List of potential funnel clay materials, their regions of abundance, pH levels, and Cation Exchange Capacity (CEC) [17].

| **Material Name** | **Chemical Composition** | **Regions of Abundance** | **pH** | **CEC (per 100 g)** |
|---|---|---|---|---|
| Kaolinite | $Al_4Si_4O_{10}(OH)_8$ | All regions below | 4.5 | 10 meq |
| Halloysite | $Al_2Si_2O_5(OH)_4$ | Oceania | 6-7 | 20-60 meq |
| Illite | *(K,H3O)(Al,Mg,Fe)2(Si,Al)4O10[(OH)2,(H2O)]* | Asia, Central America | 3-9 | 25-100 meq |
| Montmorillonite | $(OH)_4Si_8Al_4O_{20}\cdot nH_2O$ | Central America | 5.6 | 20-40 meq |
| Bentonite | Al2O3·4(SiO2)·H2O | Africa | 8-10 | 75-80 meq |

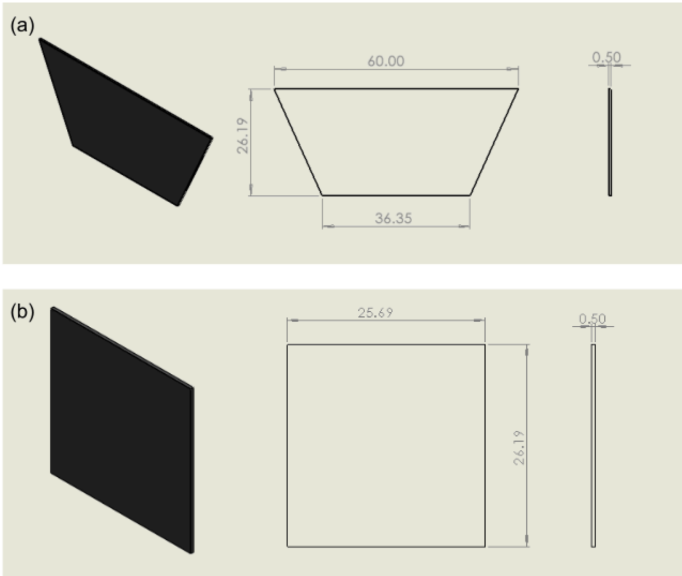



Fig. 5. Design drawings, dimensions in inches, showing (a) Trapezoidal wall reflector dimensions, (b) East-West portable reflector dimensions.

This fixed reflector is made of the same mirrors used in the funnel, with exact dimensions shown in Fig. 5(b). The East/West movable reflector as illustrated in Fig. 5(b), is adjustable to accommodate the sun's movement throughout the day.

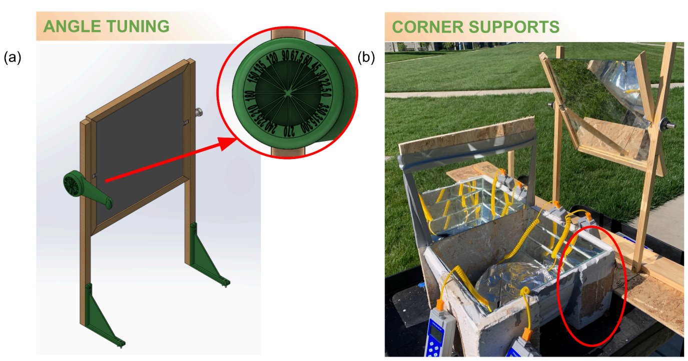



Fig. 6. Revisions to the final design. (a) A plastic handle attached to a nut and bolt system for precise angle adjustments; alternatively, a protractor can be used for tuning, (b) Prototype of the solar cooker during field testing with added corner supports.

As the sun rises in the East, the reflector is positioned on the west side to focus escaping rays back into the funnel, and it is moved to the east side as the sun sets. The reflector is equipped with a variable dial, allowing users to adjust its angle as shown in Fig. 6(a). Although the solar cooker is designed to remain outdoors, it is operated from inside a building through an opening in the wall, similar to the setup of an oven (Fig. 1).

## IV. METHODS

### *A. Manufacturing*

Our initial design was scaled down to 50% of its original size for production. The dimensions of the produced solar cooker was 14.875-inches x 12.5-inches. For prototyping purposes, gray PLA material was utilized in conjunction with an FDM 3D printer to produce our press molds.

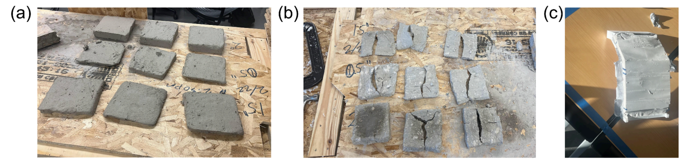



Fig. 7. Material testing of bentonite-kaolinite clay slabs with dimensions of 6 in. x 6 in. and thicknesses ranging from 0.5 in. to 2 in. (a) Wet clay, (b) Dried clay, showing uneven drying and cracking over time, (c) Use of plaster as an alternative material for creating the funnel prototype.

Testing was conducted using 9 sets of 6 x 6 inch bentonite clay samples as shown in Fig. 7. However, the samples dried too quickly, leading to the development of cracks. Due to a relatively low project budget and a tight timeframe, we opted to use plaster of Paris instead of bentonite clay for our final product. In SolidWorks, a static Von Mises stress simulation study was conducted to test the strength of supports for the corners of the structures. Catastrophic failure was observed at the seam, or corner where the two sides met, so the design was revised to implement a more robust support structure that used more material compared to the original design. The five fired clay pieces are arranged and adhered to each other using 3M brand polyurethane-based 540FL adhesive. Following the construction of the funnel, the glass mirror is then cut and adhered using the 3M 540FL adhesive. The glass mirrors were carefully hand-cut by the research team to fit the funnel, using a diamond-bit rotary-tool and adequate respiratory protection. The exact dimensions of the 12 mirror pieces can be gleaned from Fig. 4, which depicts the fully dimensioned constructed funnel. For the adjustable external reflector, the glass piece was encased in a wood frame to ensure safe handling during use.

### *B. Simulation Setup*

Before testing, simulations were conducted to obtain hypothetical values for comparison with the actual test results. The software used was SolidWorks Flow Simulation. The primary simulations were based on solar radiation, and the parameters tested included temperature, heat power (stored), and radiative heat flux. These simulations were run at a 50% scale to correspond with the prototype size. Simulations were conducted for both Merced, California (the experimental testing location), and Tegucigalpa, Honduras (the target location).

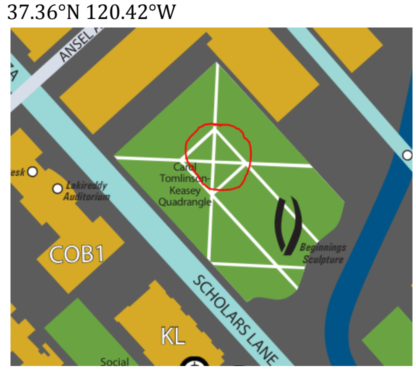
*C. Experimental Setup*

The prototype testing involved setting the solar cooker on a cart with the East/West reflector positioned on one side, placed in the middle of the quad in front of the New Beginnings campus statue, as shown in Table III, where the sun is optimally located in the Northeast. In the center of the solar cooking device, an aluminum pan filled halfway with water was covered with aluminum foil during the boiling process. The setup included four thermocouples, with two placed in the pan and the other two positioned on top of it. Testing was conducted in two time intervals: morning from 9:34 to 11:46 AM and afternoon from 12:13 to 2:00 PM. Conducting cooking tests at various times provided a better simulation of typical cooking durations and yielded more realistic results in terms of maximum temperatures. During the testing periods, we recorded data on a datasheet every 5-6 minutes, noting the temperatures (in Celsius) from all four thermocouples. The thermocouples were used to measure the temperature of specific components of the heat transfer system, enabling us to calculate important parameters like heat flux and thermal efficiency. Two thermocouples were placed in the aluminum pan, while the other two were positioned outside of it. External factors that may have contributed to the differences between theoretical and actual values, were noted.

## V. RESULTS

As illustrated in Fig. 8(b), as the size increases, the maximum temperature, minimum incident radiant flux, and maximum incident radiant flux also increase in a linear relationship, indicating that the solar cooker's performance is directly affected by its size. However, when the external reflector is positioned at a 67.5-degree angle, the correlation between the minimum temperature and the size of the cooker weakens. Overall, this suggests that the solar cooker operates more efficiently and effectively when constructed at full scale. From the simulation results shown in Fig. 9, we discovered that the functionality of the solar cooker may improve in Tegucigalpa, Honduras, due to differences in the sun's position and the higher levels of solar radiation in the region. Fig. 10 illustrates the variation of heat power throughout the entire duration of testing. It can be inferred that the actual measured values were significantly lower than the simulated values, likely due to factors such as wind speed, atmospheric temperature, and variations in sun positioning. Additionally, the simulations were conducted under the assumption of ideal conditions.

TABLE III
Recorded parameters from field testing.

| | |
|---|---|
| DATE | 04/30/2024 |
| LOCATION | 37.36°N 120.42°W   |
| TEST SUBJECT | Water inside an aluminum pan |
| TIME | **Morning**: 9:34 am - 11:46 am<br>**Afternoon**: 12:13 pm - 2:00 pm |
| ATMOSPHERIC TEMP. | 19°C - 24°C |
| WIND SPEED | 9 mph - 13 mph |
| E/W ANGLES | 67.5° - 90° |

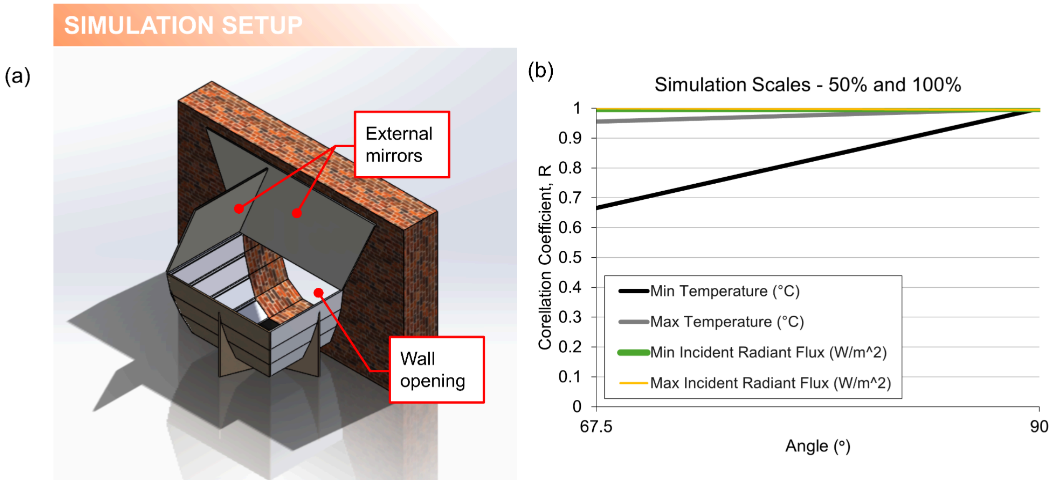
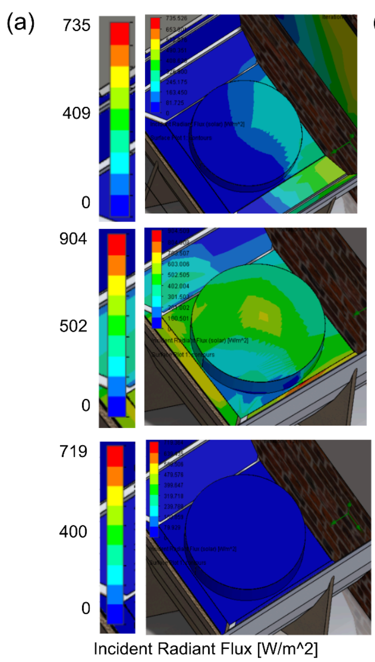
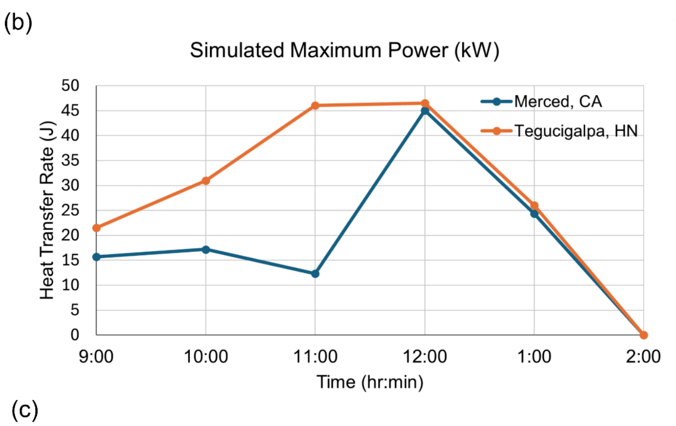



Fig. 8. (a) Structure of the solar cooker, featuring both the fixed mirror reflector and the East-West portable reflector. (b) Analysis of simulation results showing a positive correlation between the size of the components at 50% and 100% scales.




(c)

| LOCATION | MAX. TEMPERATURE (°C) | MAX. RADIATIVE FLUX (W/m$^2$) | MAX. HEAT POWER (kW) |
|---|---|---|---|
| Merced, CA | 93.77 | 703.507 | 45.06 |
| Tegucigalpa, HN | 98.86 | 726.215 | 46.51 |

Fig. 9. (a) Simulation of solar radiation on the cooking surface using SolidWorks, measuring the incident radiant flux. (b) Calculation and comparison of the theoretical maximum heat power for Merced (testing region) and Tegucigalpa (target region), plotted based on the testing protocol. (c) Calculation of actual heat power and radiative flux of the solar cooker derived from temperature measurements taken during testing.

(a)

| PARAMETER | THEORETICAL | ACTUAL |
|---|---|---|
| MAX. TEMPERATURE (°C) | 93.77 | 40.1 |
| MAX. RADIATIVE FLUX (W/m$^2$) | 703.507 | 184.31 |
| MAX. HEAT POWER (kW) | 45.06 | 11.81 |

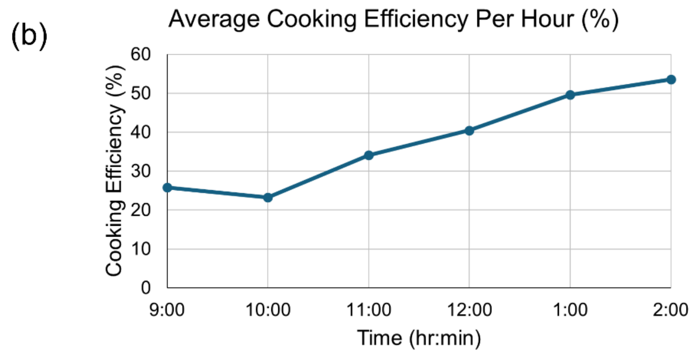



Fig. 10. (a) Comparison of theoretical versus actual results observed in experiments under conditions in Merced, CA. (b) Plot illustrating cooking efficiency from 9 AM to 2 PM.

Equation (1) is Fourier's Law of Heat Conduction, where $q$ is heat flux in W/m$^2$, $k$ is thermal conductivity in W/mK, $\Delta T$ is change of temperature in Kelvin, and $\Delta x$ is the thickness of cookware walls in meters. Equation (2) solves for the heat transfer rate in W/s, where $Q$ is heat power in W, $A$ is area of the cookware in m$^2$, σ is the Stephan-Boltzmann constant, and ε is surface emissivity. Equation (3) solves for the overall utilization efficiency of the cooker [25]. Here, $m_f$ is the mass of the cooking fluid, $c_f$ is specific heat of fluid, $T_{f,max}$ is the maximum temperature of the cooking fluid,, $T_{fi}$ is the initial temperature of the cooking fluid, $I_{av}$ is average solar intensity during the time interval, $\Delta t$ is the time taken by the fluid to reach maximum temperature, $A_t$ is the surface area of the lid of the vessel, $A_c$ is the effective collector (aperture) area, and $\eta_r$ is the mirror's reflectivity.

$$q = \frac{k\Delta T}{\Delta x} \qquad (1)$$

$$\frac{Q}{At} = \sigma\varepsilon(T_2^{\ 4} - T_1^{\ 4}) \qquad (2)$$

$$\eta_u = \frac{m_f c_f (T_{f,max} - T_{fi})}{I_{av}\Delta t[A_t + (A_c - A_t)\eta_r]} \qquad (3)$$

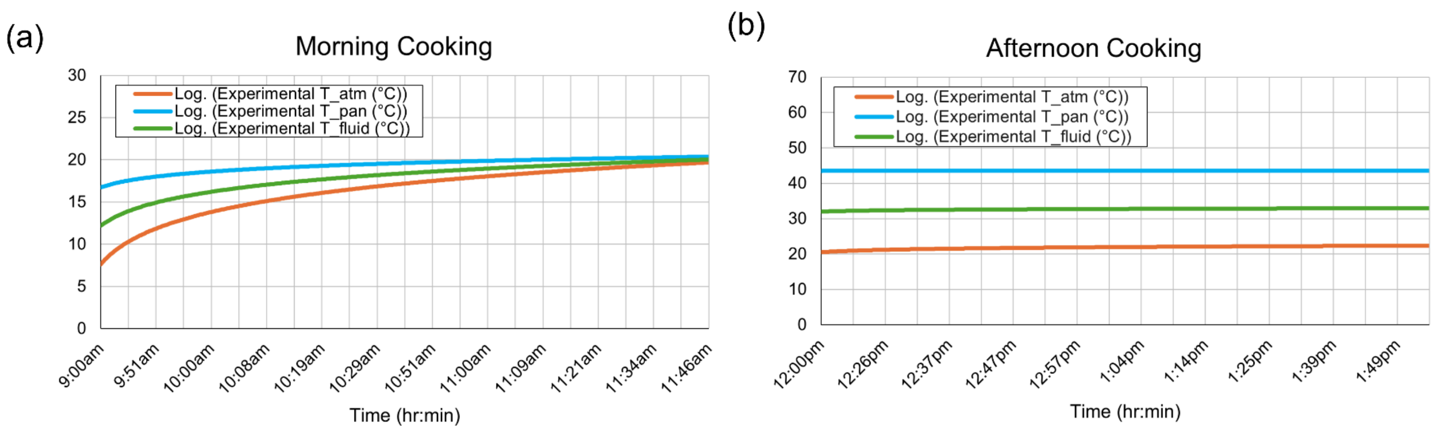



Fig. 11. Logarithmic trend lines representing temperature trends during morning and afternoon cooking sessions. (a) In the morning cooking phase, temperatures converge to a single value, approaching equilibrium. (b) In the afternoon, temperatures are higher and demonstrate greater stability.

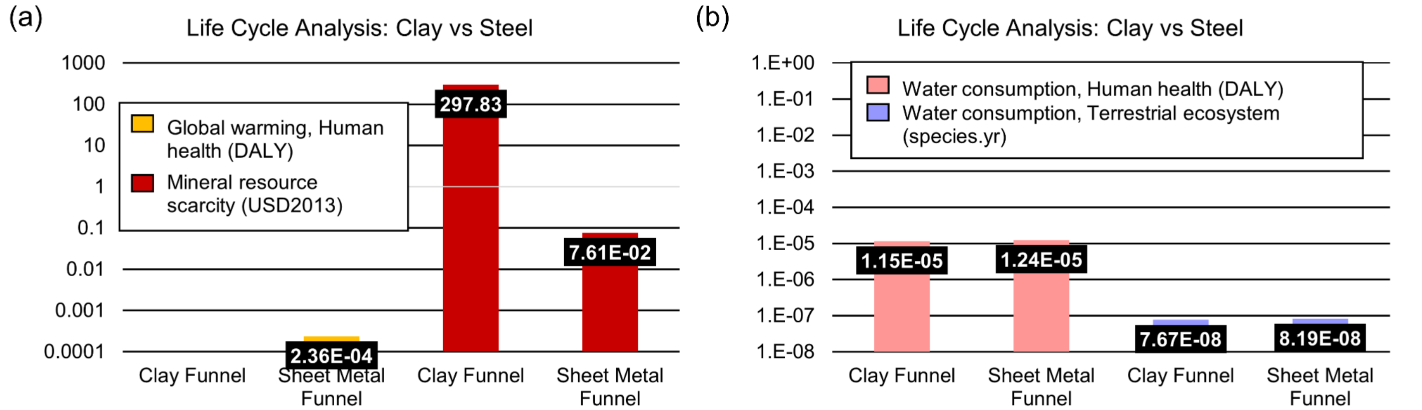



Fig. 12. (a) Comparison of the effects on global warming and natural resources. (b) Comparison of the effects on water consumption in both the ecological and human spheres.

Translating the heat transfer terms into practical cooking considerations, temperature refers to how hot the cooking surface can get, while heat flux indicates the total amount of heat that can flow through the cooking surface. Maximum cooking efficiency was determined by the highest temperature reached hourly, ranging from a minimum of 23.18% efficiency to a maximum of 53.52%, as calculated using (3). Despite the less-than-ideal conditions, the solar cooker was still able to achieve between one-quarter and half of its maximum capabilities. As demonstrated in Fig. 11(a), during the start of the cooking process, the temperatures of the air, pan, and water converge to reach equilibrium. Later in the cooking process, Fig. 11(b), the temperatures become more distinct. The temperature of the fluid, or air is the coldest, and the temperature of the aluminum pan is the hottest. We assume that the pan retains heat and transfers it to the water, allowing it to become warmer than the ambient temperature.

The results of the LCA show the comparison of our novel clay CPC solar cooker compared to the standard sheet metal parabolic solar cooker. In the Life Cycle Assessment (LCA) simulation, several parameters were defined to evaluate their environmental impacts. The hypothetical units were 5,000 funnels produced and 200 plaster molds used. The materials considered for the clay product include sawn lumber sourced from Honduras. The production process for the clay product involves bisque firing in kilns, with smaller table top kilns typically drawing between 1.5 and 1.8 kilowatts. Inputs for the LCA included base plaster, water, flat glass mirrors, glue adhesive, sawn lumber for external reflectors, fire clay, and electricity used during kiln firing, with the ReCiPe 2016 Endpoint (H) impact assessment method applied to transform life cycle inventory results into indicator scores for Human Health, Environmental Damage, and Resource Loss. Our analysis revealed that the clay funnel exhibited a Disability-adjusted Life Year (DALY) of 0, indicating no impact on human health, while the sheet metal funnel had a DALY of 2.36E-04, suggesting a greater effect on global warming and human health. In life cycle assessment (LCA), mineral resource scarcity refers to the potential depletion of mineral resources that could impact future generations, highlighting the importance of sustainable resource management. While the clay funnel incurs significant monetary costs associated with mineral resource scarcity, the sheet metal funnel is composed of precious materials, raising concerns about its long-term sustainability. In contrast, clay is abundant, non-precious, and highly sustainable, making it a more viable option for minimizing environmental impact and ensuring resource availability for future generations. Notably, both products had similar water consumption impacts on human health and terrestrial ecosystems, though the clay funnel showed slightly lower consumption rates. This comprehensive assessment highlights the environmental trade-offs associated with each material choice in the production of funnels, offering insights into sustainable manufacturing practices.

## VI. CONCLUSIONS & FINAL RECOMMENDATIONS

In summary, our solution presents an environmentally friendly and affordable approach to addressing the UN's clean cooking challenge. Tropical and subtropical regions are particularly well-suited for innovations in solar cooking due to their abundant solar resources. This project involved developing a method for manufacturing and distributing a sustainably produced solar cooker that can be seamlessly integrated into existing housing structures in developing nations. The design and its components are intended to be durable enough to withstand year-round environmental conditions and made from accessible materials. Our work is scalable, allowing for adjustments in production size. By utilizing abundant materials, we aim to reduce reliance on unsustainable precious materials, thereby improving the carbon footprint of our novel solar concentrator cooker. Given the differences in material availability and manufacturing infrastructure, a cross-country approach is essential. To enhance the total heat power and efficiency of the solar cooker in future iterations, several innovations could be implemented. These include mechanisms to block, suppress, or minimize wind flow across the funnel, the addition of a reflective cookware door, modifications to the trapezoidal wall reflectors, and improvements in heat storage.

### CRediT authorship contribution statement

**Ukamaka Ezimora:** Investigation, Supervision, Methodology, Validation, Formal analysis, Writing – Original Draft, Review & Editing. **Ruth Agorilla:** Investigation, Methodology, Validation, Formal analysis. **Daniel Christian Abrenica:** Investigation, Supervision. **Santiago Garcia:** Investigation, Supervision.

### Data availability

Data will be made available on request.

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