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Experimental and numerical investigation of a hybrid solar thermal-electric powered cooking oven

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ABSTRACT

The rapid development in technology and changing food habits have drastically altered the cooking method in recent years. Electric ovens are dominating the cooking sector in bakeries, restaurants, and domestic cooking. India holds the second position in terms of revenue generated by the sales of cookers and ovens. The electrical energy requirements are also adding up with electricity-based cooking. In addition, solar energy-dependent solar cooking appliances are available in the market, but they come with their own set of merits and demerits. This paper discusses the new concept and development of an Electric-Solar hybrid cooking appliance. The implemented control mechanism in the fully-featured hybrid OTG (Oven, Toaster, & Griller) oven shows the simplicity and ease of using solar energy in conjunction with electrical energy. The experimental and numerical results show that the temperature distribution inside an electric-solar hybrid oven saves energy up to 51% and takes much less cooking time than electric ovens and solar cooking appliances when operating in hybrid mode. The STEPCO (Solar Thermal-Electric Powered Cooking Oven) oven has demonstrated potential for a relatively quick return on investment, with a payback period of around 2.3 years in hybrid mode and 3.7 years in solar mode. Experimental testing has shown that the hybrid mode of the STEPCO oven achieves an impressive efficiency of 63%, which is significantly higher than that of the electric and solar modes, which are only 35% and 4.0%, respectively. Additionally, the STEPCO oven has the environmental benefit of emitting very little CO_2 during the cooking process when used in hybrid mode and zero CO_2 emissions when used in solar mode.

1. Introduction

For most of history, fossil fuels have been used in various forms to generate electricity, fuel vehicles, cook food, power machinery, and so on. These fossil fuels are known to increase carbon dioxide emissions into the atmosphere significantly. As a result, issues such as global warming and air pollution are increasingly becoming a menace. Carbon dioxide alone is responsible for 65% of greenhouse gases emitted globally due to human activities. According to the Inventory of U.S. Greenhouse Gas Emissions and Sinks, transportation (34%) and power generation (32%) account for the majority of CO_2 emissions [1]. To overcome these challenges, alternate sources of energy, especially renewable energy like solar, wind, water, geothermal, etc., are witnessing a steady rise [2,3–5].

According to a report published by the Department of Economic and Social Affairs, United Nations, in May 2021, one of the major challenges in achieving Sustainable Development Goal 7 (SDG 7, i.e., Affordable and Clean Energy) was the absence of adequate infrastructure that can support the decentralized availability of energy for communities [6]. As a result, 2.8 billion people did not have access to clean cooking in 2015, and this number is expected to decline only to 2.3 billion by 2030 [7]. The use of renewable energy, especially solar energy, would be a good option to mitigate this problem. It would be a good fuel source for several reasons, it is a good source of heat when concentrated, has an abundant supply in the environment, is readily available, and most importantly, is free of cost [8]. Solar energy is generally utilized in two forms: (a) via Photovoltaic cells for converting solar energy into electricity and (b) via extracting thermal heat from solar radiation. Trapping the solar radiations received from concentrated sunlight can give

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Nomenclature

S	Annual savings
CFD	Computational Fluid Dynamics
C	Cost of electricity per kWh
$(\tau_{ij})_{eff}$	Deviatoric stress tensor
dT	Difference between the final temperature of the food after cooking and the initial temperature of the food before cooking
$\vec{F}$	External body forces
p	First static pressure
$\overline{pg}$	Gravitational body force
m	Mass of the food
I	Mean radiation intensity
μ	Molecular viscosity
OTG	Oven Toaster Griller
P	Payback period of STEPCO
PCM	Phase change material
PMA	Poly Methyl Acrylate
RTE	Radiative transfer equation
STEPCO	Solar Thermal–Electric Powered Cooking Oven
c	Specific heat of the food
$\overline{\overline{\tau}}$	Stress tensor
t	The cooking time
E	The energy consumed by the oven in one daily cooking cycle
N	The number of days of power consumption by the oven
C_{oven}	The running cost of a conventional oven
C_{STEPCO}	The running cost of STEPCO
S_k and S_ε	The user-defined source terms
k	Thermal conductivity and
E	Total energy
EC	Total energy consumed
k	Turbulent kinetic energy
ε	Turbulent kinetic energy dissipation rate
I	Unit tensor
UF	Utilization Factor Value

temperatures similar to what can be obtained by other electric cooking appliances [9]. India being a tropical country receives 5000 trillion kWh per year and about 4–7 kW h per sq. m. per day of average incident solar radiation in most parts of the country [10]. Despite these advantages, solar cooking appliances are not very popular among households because of their bulky design, long cooking hours, continuously require the presence of a person to check the food and adjust the position of the solar cooker normally to the sunlight, cooking only at peak hours of sunlight in the afternoon, etc. [11]. To overcome these challenges, new models of solar cookers are being worked upon.

Solar cooking appliances are broadly categorized as (a) solar cookers with storage and (b) solar cookers without storage, as shown in Fig. 1. Solar cookers with storage are designed to make cooking possible even after sundown and on cloudy days. These cookers can store heat in the form of sensible heat or latent heat [12,13]. The cookers without storage are those types of cookers that work only when sunlight is available. These are further classified as direct solar cookers and indirect solar cookers.

Indirect-type solar cookers are those types of cookers in which the solar radiation is concentrated at a point. At this point, a thermal fluid is passed to absorb the heat. This heated fluid is then supplied to the place where cooking is to be done, for example, the kitchen [12–14]. Among direct solar cookers, the two most common types are box-type solar cookers and concentrating-type solar cookers [15]. Box type is one of the first forms of solar cooking appliances ever used. The major challenges of this type of cooker found in the existing works of literature are its bulky design and limited cooking options [8,13,15,16]. Mahavar et al. [17] designed a box-type solar cooker for small families. Design changes like replacing the common glass with Poly Methyl Acrylate (PMA) as a glaze material have improved the transmittance and robustness of the cooker. The authors claim that the cooker is inexpensive, and the payback period of this cooker is significantly shorter than the available box-type solar cookers. Studies like this show that modifications in the design of a solar cooker can significantly improve the application and efficiency of the appliance. One such modification which led to the betterment of the overall product can also be seen in Ref. [18]. Another type of direct solar cooker is the concentrator-type solar cooker [19,20]. This cooker is known to reach temperatures up to 300 °C, due to which the food kept inside these cookers could burn if left unattended [8]. To achieve high temperatures in this, the sunlight is directly focused on the center of the concentrator, which is difficult as the sun is not fixed at a position, and the concentrator has to be adjusted in a direction normal to the sun manually [21]. To make this process automatic and concentrate the maximum amount of solar radiation at the focal point, the sun tracking mechanism is used in concentrator-type solar cookers [21,22]. There are two commonly used sun-tracking systems: single-axis sun--tracking and dual-axis sun-tracking systems. Dual-axis sun-tracking systems have a complex control system that makes them expensive, need high maintenance, and have a longer payback period [23]. In E. K. Mpodi et al. [24], an automatic dual-axis tracking system has been developed in which dual-axis tracking in the vertical and horizontal axes is used for sun tracking. These systems are known for increasing the efficiency of sun-tracking, yielding higher temperatures by allowing the movement of the concentrator in more than one direction. On the other hand, single-axis sun-tracking systems are better known for their durability, low maintenance, and long life [23,24]. Another challenge is to be

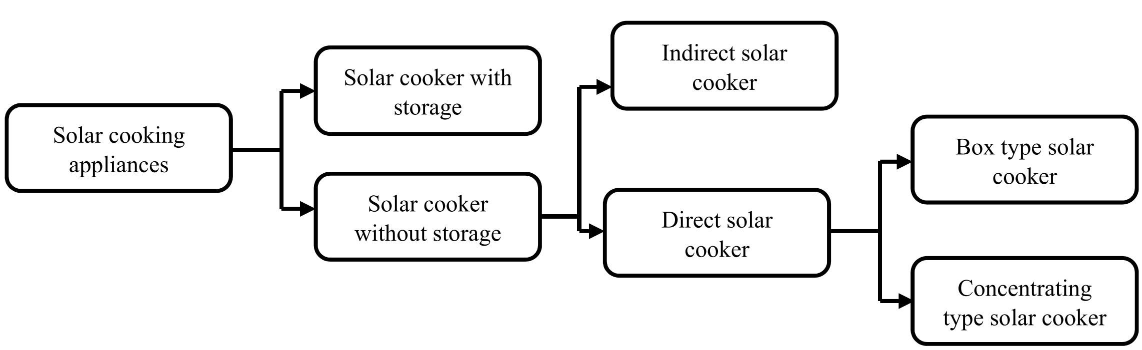


Fig. 1. Categories of solar cooking appliances.

able to use a solar cooker after sundown. In B. H. K. Ibrahim et al. [12], one such hybrid solution is presented where a two-way heat source is applied, one by using water as thermal fluid and the other via electricity. When there is no sunlight to power the cooker, the phase change material (PCM) storage unit is supplied with an electric supply [25]. The heated PCM acts as a source of heat for the cooker. E. Cuce [26] investigates the impact of microporous absorbers on the thermodynamic performance parameters of cylindrical solar cookers through numerical and experimental analysis. It includes a comprehensive thermal performance analysis for a typical spring day in Bayburt, Turkey, and three different porosity configurations are considered for the absorber surface. The results indicate that microporous absorbers significantly improve the energy and exergy efficiency of the cylindrical solar cooker, with a noticeable reduction in the time to boil. A. Saxenae et al. [27] explore the use of sensible heat storage materials, including blackened pebbles, small pieces of masonry bricks, and small aluminum balls, to enhance the thermal efficiency of a box cooker for solar cooking applications. The results indicate that the use of these materials can significantly improve the thermal efficiency of box cookers, with the model utilizing aluminum balls showing the best performance, with a thermal efficiency of 59.61%, cooking power of 75.21 W, and thermal storage capacity of around 9 h/day. P. M. Cuce et al. [28] focuses on the development of a new solar box cooker using natural and recycled materials to overcome the limitations of traditional solar box cookers in low-solar radiation regions like the Black Sea Region of Turkey. The study finds that the water temperature in the cooking pot is kept over 40 °C due to latent heat storage, and the thermal efficiency of the cooker varies from 7.47 to 4.54%. A. Aquilanti et al. [29] examine the thermal and optical performance of four solar panel cookers, including a novel design called the Kimono cooker. The cookers are assembled using inexpensive materials and tested in parallel under the same environmental conditions in Ancona, Italy, during three different periods of the year. It is found that the Kimono and Funnel cookers have the best performance at low-medium and medium-high sun elevations, with an average boiling time of 1.74 h and 1.66 h, respectively. The study suggests that solar panel cookers are affordable and easy-to-manufacture systems for sustainable and eco-friendly cooking practices.

Apart from solar cookers, electrical cooking appliances, especially ovens, have also been gaining popularity among urban households. These ovens have different types of heating technologies like convection, microwave, infrared, jet impingement, etc. [30,31]. Like other smart home appliances, ovens are also available with the integration of IoT (Internet of Things) [32]. These ovens can be remotely controlled through smartphone applications. They can perform baking and operations like roasting, air frying, proofing, dehydrating, and reheating food [33,34]. One of the major challenges with these cooking appliances is the source of their fuel. Though they utilize electricity as fuel without producing any by-products, the process of production of electricity has a significant carbon footprint. In India, close to 60% of electricity generation is still fossil fuel-based [35]. That is why we need cooking appliances that can be a step ahead of using clean energy by introducing renewable energy resources to run these appliances. J. L. Chukwuneke et al. [36] discussed the dual-powered baking oven. This baking oven can work on electricity as well as a regular LPG cylinder. Though this oven is dual-powered, the use of LPG makes it a fossil fuel-based cooking appliance. Several works of literature exist on such dual-powered ovens, but most of these ovens have demerits like bulky design, low efficiency, temperature limitation, limitation of types of cooking, ease of operation, etc. [14,36–39]. While many studies show the use of more than one fuel source in hybrid designs but none of them was able to replace more than one cooking appliance.

In this research, a hybrid Solar Thermal – Electric Powered Cooking Oven (STEPCO) has been fabricated and studied. It is a dual-powered oven having electricity and solar radiation as its two sources of heat. The basic design of this hybrid oven has been adapted from the traditional Oven Toaster Griller (OTG) ovens for the sake of ease of use. The Monte Carlo radiation model has been used to predict the temperature distribution inside the oven. A numerical analysis of the STEPCO has been performed to estimate the maximum temperature achievability of the oven for used dimensions and materials for assessing the suitability of the appliance for different cooking applications. Experimental studies have been done by cooking several food items like cake, rice, pizza, etc., and quantifying their cooking time, energy consumption, and energy efficiency. So, our study aimed to develop a hybrid oven that overcomes the limitations of existing solar cooking appliances. Specifically, we sought to address the low efficiency, high payback period, low energy savings, and sophisticated use associated with solar ovens. By fabricating an Electric-Solar hybrid cooking oven with simple use, high energy savings, low payback period, and high energy efficiency characteristics, we believe our study has successfully limited these drawbacks and improved upon existing technology. Additionally, we discussed the financial feasibility and payback period of the STEPCO oven.

2. Methodology

2.1. Numerical evaluation

The numerical investigation is used to determine the variation in the temperature inside the electric and solar hybrid cooking oven for the three different cases of cooking and cooking time for the various food materials.

2.1.1. Governing equation

In this case, the fluid is steady, and fluid movement is by free or natural convection; The following governing equations have been used in the Fluent 18.1 simulation [40].

Eq. (1) represents the continuity equation that is used to ensure that the mass of fluid in the oven is conserved [40]:

$$\frac{\partial}{\partial x_i}(\rho u_i) \tag{1}$$

The continuity equation was used to model the flow of air inside the oven and ensure that the mass of air entering the oven was equal to the mass of air leaving the oven.

Eq. (2) represents the momentum conservation integral equation that is used to determine the velocity of the fluid in the oven [40]:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \bullet (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \bullet (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{2}$$

Where p is the first static pressure, $\bar{\bar{\tau}}$ is the stress tensor, and $\rho \vec{g}$ and $\vec{F}$ are the gravitational body force and external body forces. The equation was used to model the flow of air inside the oven and ensure that the momentum of air entering the oven was equal to the momentum of air leaving the oven.

The stress tensor $\bar{\bar{\tau}}$ is given by Eq. (3) [40].

$$\bar{\bar{\tau}} = \mu\left[\left(\nabla \vec{v} + \nabla \overrightarrow{v}^{T}\right) - \frac{2}{3}\nabla . \vec{v} I\right] \tag{3}$$

Where μ is the molecular viscosity, and I is the unit tensor. The second term on the right-hand side is the effect of volume dilation.

The Reynolds analogy concept was used in turbulent momentum transfer for numerical modeling of turbulent heat transport. The modeled energy equation is computed by Eq. (4), which is used to determine the temperature distribution inside the oven under different cooking conditions [40].

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}[u_i(\rho E + p)] = \frac{\partial}{\partial t}\left[\left(k + \frac{C_p \mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j} + u_i(\tau_{ij})_{eff}\right] + S_h \tag{4}$$

where k and E represent the thermal conductivity and total energy, respectively.

Eq. (5) is used to evaluate the deviatoric stress tensor $(\tau_{ij})_{eff}$ which is used to model the viscous forces acting on the fluid inside the oven [40].

$$(\tau_{ij})_{eff} = \mu_{eff}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) - \frac{2}{3}\mu_{eff}\frac{\partial u_k}{\partial x_k}\partial_{ij} \tag{5}$$

k-equation [40]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial t}(\rho k u_i) = \frac{\partial}{\partial t}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{6}$$

ε-equation [40]:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + C_1\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{7}$$

S_k and S_ε are user-defined source terms.

K-ε model is a semi-empirical model based upon the model transport equation to determine the turbulent kinetic energy (k) and turbulent kinetic energy dissipation rate (ε). When the flow is fully turbulent.

The values of the standard constants are as follows:

$$C_{2\epsilon} = 1.92, \sigma_\epsilon = 1.3, C_\mu = 0.09, C_{1\epsilon} = 1.44, \sigma_k = 1.0 \qquad 1.0$$

The above-mentioned equations are true for the steady state of the fluid. In the case of the transient state, only time variables will be added to the given equations, and the rest all will remain the same. The equations were solved using the Fluent 18.1 simulation software. The simulations were performed on a desktop computer with an Intel Xeon processor, 64 GB RAM, and an NVIDIA GTX 1080 GPU running on the Windows 10 operating system, and the results were post-processed using ParaView 5.6 software.

2.1.2. Monte Carlo Radiation model

The Monte Carlo radiation model generally simulates such processes that have physical interactions between the system and photons. Initially, the arbitrary plane for the source of the photons has been selected and tracked throughout until photons get absorbed by some other material. Whenever the photons undergo some "event," i.e., scattering, absorption, and surface interactions, etc., the whole system is updated. An arbitrary source for the photon generation is selected based upon the emitted radiation, and each band being used is independent of the non-grey model.

To be used the radiative transfer equation (RTE), the Monte Carlo model considers the intensity of radiation, which is directly proportional to the differential angular flux of the photons, and uses the radiation field as a photon gas. For this gas, a is the probability per unit length such that photons are being absorbed at the given frequency. So, the mean radiation intensity, I is directly proportional to the distance travelled by a photon in the unit volume in unit time [40].

2.1.3. Boundary conditions

In steady-state and transient conditions, the heat is generated inside the oven by giving the heat generation rate to the filaments. In order to model the solar interaction with a simple oven, a computational domain of five times the actual dimension is used. For the solar interaction, the Monte Carlo Radiation model is used.

To couple both pressure and velocity, a SIMPLE algorithm is applied. SIMPLE is used for solving the pressure equations by using a semi-implicit method for compressible and incompressible fluid flow. The second-order upwind scheme of the SIMPLE algorithm is used.

2.1.4. Grid independence study

Uniform structured mesh is used across the geometry. A grid independence study was carried out for the average temperature inside an oven for the transient conditions. The minimum number of elements was 5,50,000; below the minimum number of these elements, the solution stability and numerical accuracy changes, as seen in Table 1.

Table 1
Grid independence test for average temperature.

Sr. No.	Elements	Average Temp. (K)	Simulation Time (Mins)
1.	3,00,000	456.34	45
2.	5,50,000	458.26	60
3.	7,20,000	458.28	85
4.	9,50,000	458.30	120
5.	11,50,000	458.31	150
6.	13,90,000	458.31	220

The size of the elements implemented in this study was 7,20,000. A grid size of more than 7,20,000 shows no significant difference in temperature results, but higher computational time and effort were observed, as shown in Table 1. The volumetric mesh has hexahedral elements. For grid independence of the solutions, the model was run for the six different sets of cells.

2.2. Experimental evaluation

2.2.1. The design aspects of solar thermal – electric powered cooking oven (STEPCO)

The STEPCO has been designed according to the needs of the household and commercial outlets like restaurants and bakeries. The design aimed to provide a familiar OTG oven-like experience to the user. The other aspect considered was the used materials that can keep the overall weight of the oven on the lighter side to make it portable.

The selected design allows STEPCO to have performance equivalent to that of an electric OTG, and also, at the same time, it can be operated in solar and hybrid-powered modes. The main heating chamber has three sides of aluminium alloy and the remaining three of toughened glass. The three-glass sides are the top, bottom, and door (front side). The top and bottom surfaces of the heating chamber are made of transparent, toughened glass to allow entry of concentrated solar radiation. This ensures sufficient solar thermal heating of the oven when operating in solar or hybrid mode (Fig. 2). The heating elements present in the oven are responsible for providing electrical heating. They are used only when operating STEPCO in electric/hybrid mode. A microcontroller-based smart control system controls the operation of these elements. This control system is responsible for the control and operation of various parts of the oven. It comprises of a thermocouple to detect the temperature and relays used as switches for turning on and off the various parts of the oven like heating elements, convection fan, etc. Its optimized algorithm allows it to handle the switching between solar and electrical heating inputs while operating in hybrid mode. To ensure equal heat distribution, a convection fan is placed on one side of the aluminium wall. The solar radiation was measured using a pyranometer, while the ambient temperature was measured using a temperature sensor along with a data logger.

The 3D diagram and the practical experimental setup of the oven can be seen in Fig. 2 (a) and 2 (b). Table 2 represents the technical specification of the STEPCO. In hybrid mode, STEPCO is placed in the focal point of a concentrating-type parabolic dish. Dimensions of this solar parabolic trough collector are mentioned in Table 3. Since the tracking of the dish is manual, it must be changed every 15–20 min while using it. It has a delivery power of 0.6 kW. The temperature at the bottom of a good heat-conducting vessel kept at the focus point of the solar parabolic dish may reach up to 400 °C with higher solar irradiation.

2.2.2. Working of electric-solar hybrid cooking oven

The STEPCO works in three modes, namely: Solar Mode, Electric Mode, and Hybrid Mode. Its functions are controlled by a smart control system, which decides based on the power source to operate in the three modes.

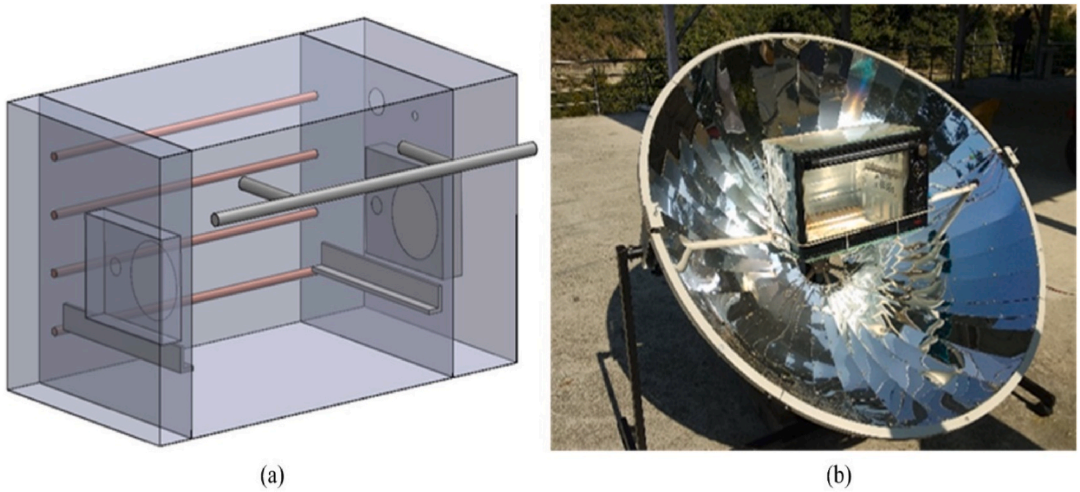


Fig. 2. (a) 3D-Model of the electric-solar hybrid cooking oven, and (b) Experimental setup of the developed electric-solar hybrid cooking oven.

Table 2
Technical details of electric-solar hybrid cooking oven.

Sr. No.	Parameters	Details
1	Heating Chamber (a) Dimensions	46 cm*35 cm*38 cm
	(b) Thickness of aluminium alloy sheet	0.1 cm
	(c) Thickness of toughened glass	0.4 cm
2	Heating Elements	4 cylindrical rods, 500 W (each)
3	Microcontroller	Arduino Uno
4	Thermocouple	K- Type, MAX6675
5	Relays	5 V

Table 3
Dimensions of solar parabolic trough collector.

Sr. No.	Parameters	Details
1.	Aperture diameter	1.4 m
2.	Focal point	0.28 m
3.	Reflectivity of the anodised aluminium sheet	0.75%

a) **Solar Mode:** In this mode, the STEPCO is placed on the focus point of a solar concentrator dish to concentrate the falling solar radiations on the oven. Here, no other power supply is needed.
b) **Electric Mode:** In this mode, the STEPCO is directly plugged into a power switch, and the cooking is through electrical heating only.
c) **Hybrid Mode:** In this mode, the STEPCO is placed on the solar concentrator dish with an electrical supply. Here the oven tries to achieve its set temperature through solar radiation, which is reflected by the parabolic dish on the oven. Through continuous monitoring of temperature with the help of a thermocouple, the control system decides when additional heat is required to achieve the set temperature. In such a case, electrical compensation is given to achieve the set temperature. It can be noted that the electrical compensation is provided only when the desired temperature is not achieved through solar thermal heating. This ensures uninterrupted cooking and energy saving.

All the experiments were conducted twice to ensure that the measurements were accurate, and the reported values are the average of the two measurements with a standard deviation of less than 1.0. In addition, we acknowledge that the accuracy of our results may be somewhat affected by the relatively large time steps (30 min) used in our measurements. While we chose this time step based on the capabilities of the measurement equipment available to us at the time.

3. Results and discussion

In this section, the data of the numerical study, as well as the experimental measurement results, have been presented. Computational Fluid Dynamics (CFD) analysis has been performed to observe the temperature distribution inside the oven and optimize the design accordingly. The experimental results obtained for solar, electric, and hybrid modes of cooking have been discussed and compared with the simulation results.

3.1. Numerical study results

3.1.1. CFD analysis of variation of temperature in the STEPCO during electric mode

Fig. 3 represents the variation of temperature with respect to time. As time increases, the temperature inside the oven is also increasing. The heat generation rate of the heating filament of the oven keeps on increasing and reaches its maximum value after 10 min. After 10 min, the temperature of the oven becomes constant.

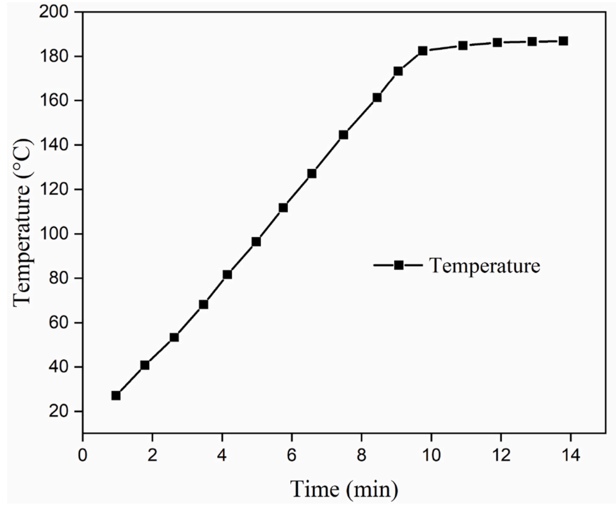
Fig. 3 (b) and 3 (c) show the average temperature distribution contour inside the STEPCO in electric mode. An average temperature of 185.13 °C is obtained, giving an input electrical power of 2000 W inside an oven after a time period of 10 min. The maximum temperature is obtained on the heating element and near the heating elements.

3.1.2. CFD analysis of variation of temperature in the STEPCO during solar mode

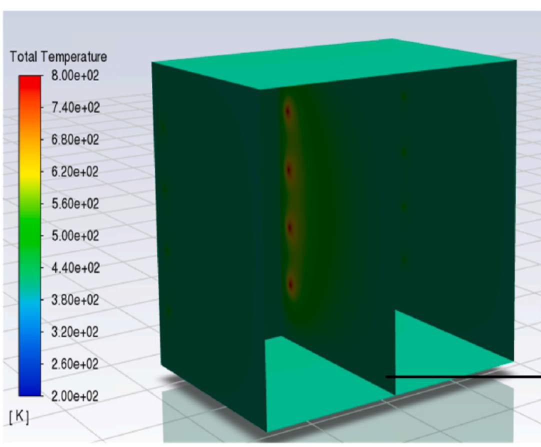
Fig. 4(a) represents the average temperature distribution inside the STEPCO under the solar mode. In solar mode, we obtained uniform temperature and heat distribution inside the oven. The average temperature inside the oven during the solar mode is 117 °C, as shown in Fig. 4 (a). In solar mode, the solar radiation is concentrated with the help of a solar concentrator dish, which provides overall better heating on all sides of the solar oven. Fig. 4 (b) shows the temperature inside STEPCO with increasing solar radiation. As the solar radiation increases, the temperature inside the STEPCO keeps on increasing and reaches the maximum value of 148 °C at 1050 W/m^2 solar radiation and 37 °C ambient temperature.

3.2. Experimental results

The STEPCO has been tested for its maximum achievable temperature on a sunny day (The experiments were conducted on April 11, 2022) through solar thermal heating using a solar concentrator dish. It has been tested for cooking in the three modes of operation, namely



(a)



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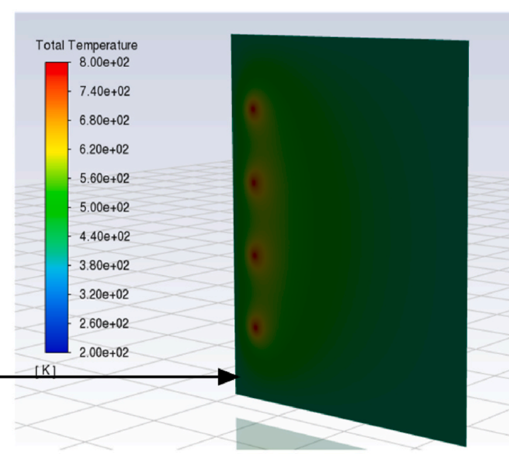
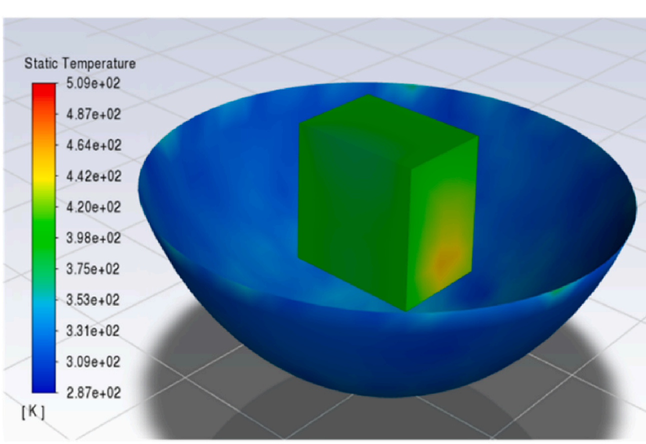
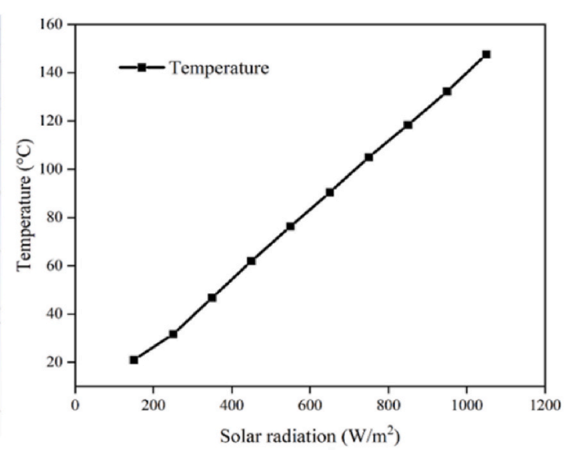


(c)

Fig. 3. (a) Variation of temperature with respect to time (b) Temperature distribution over the midplane inside the oven (c) Enlarged view of temperature distribution over the midplane.



(a)



(b)

Fig. 4. (a) Average temperature distribution inside oven under solar mode (b) Temperature inside STEPCO with respect to solar radiation.

solar, hybrid, and electric modes, to record the time taken energy consumed and energy efficiency with the recording of available solar irradiance. The eatables mentioned in Table 4, in their given quantities, were cooked for the purpose of all STEPCO experiments.

3.2.1. Stagnation test and thermal performance comparison

In this experiment, the STEPCO was kept in solar mode on a sunny day to check the stagnation temperature it can attain in a specified time. Fig. 5 represents the temperature inside the STEPCO oven, the ambient temperature, solar radiation, and daytime graph for the day of the experiment. Table 5 lists the maximum attained temperature, ambient temperature, time of the day, solar radiation, and date of the experiment by STEPCO (in solar mode) in comparison with the other solar cookers in existing literature [17,41–46].

The peak temperature achieved inside the STEPCO was 148 °C. The maximum ambient temperature during the experiment was 37 °C. The experimental value matches with the numerical simulation result reported in Fig. 4 (b). However, there is a small variation between the two sets of data. The margin of variation between the two sets of data is less than 10%. This variation could be due to several factors, such as environmental variability, instrumental error, or human error. However, the margin of error is relatively low, so we can say that the experimental value matches with the numerical simulation. It can be observed from Table 5 that despite STEPCO being a hybrid device, it is at par in thermal performance with the solar cookers developed by various other authors mentioned in Table 5.

3.2.2. Comparison of STEPCO performance in different cooking modes

In this experiment, four items, namely rice, milk, cake, and pizza, were prepared in the STEPCO in solar, electric, and hybrid modes. During solar and hybrid mode operation, the average irradiance on that particular day and time was recorded, and it is shown in Table 6. It was observed that baking processes required comparatively less time than that taken for food items, which involve boiling the food, as shown in Fig. 6 (a). Also, due to the slow and steady rise in temperature, pasteurization of milk was possible. It can be seen that when the average solar irradiance was high, faster cooking was possible.

The energy consumed and cooking time observed in the electric mode were found to be similar to conventional electric OTG ovens available in the market. From Fig. 6 (a), it can be observed that the cooking is significantly faster in the electric mode as compared to the solar mode, as it can generate higher temperatures inside the oven.

In hybrid mode, the items were cooked on a sunny day, with the cooker having both an electrical power supply and solar thermal heating. It can be observed from Fig. 6 (b) that the cooking time in this mode was close to the cooking time of the electric mode. Simultaneously, the energy consumption was significantly reduced in this mode compared to the electric mode. In all three modes (i.e., solar, electric, and hybrid), solar energy is accounted in energy calculations (although it is a free source of energy).

The performance of STEPCO varies depending on the mode in which it is being operated. Parameters like cooking time, energy consumed, and energy efficiency change drastically in shifting from one mode to another. But it can be seen clearly from the above findings that the novel hybrid mode of the STEPCO is the most efficient mode in all three. The STEPCO shows an average of 53% energy saving in hybrid mode when compared to its electric mode. The electric mode of the STEPCO can be roughly considered as a conventional OTG electric oven readily available in the market. STEPCO resulted into 57%, 53%, 48%, and 54% energy saving with respect to electric mode cooking operation for rice, milk, cake, and pizza, respectively. This means the STEPCO has a 53% energy-saving advantage over the other ovens available in the market. We can see that the cooking is significantly faster in STEPCO's hybrid mode operation. Time-saving of 57%, 58%, 80%, and 45% were recorded in hybrid mode with respect to solar mode operation for rice, milk, cake, and pizza cooking operations, respectively. This means that the STEPCO takes approximately 60% less time to cook as compared to the box type of solar cooker available in the market. The energy efficiency of the STEPCO oven was estimated using Eq. (8) [48].

$$\text{Energy efficiency} = \frac{\text{Useful energy gained by food}}{\text{Total input energy}} \tag{8}$$

The total energy input is given in Fig. (6 b), and the useful energy gained by the food can be calculated using Eq. (9) [49].

$$\text{Useful energy gained by food} = \frac{m * c * dT}{t} \tag{9}$$

where m and c are the mass and specific heat of the food, respectively. While dT is the temperature difference over small time steps (t) during the cooking the food and the heat gained calculated respectively. The experimental results show that the STEPCO oven has an efficiency of 63%, 35%, and 4.0% in hybrid, electric, and solar modes, respectively. These results indicate that the hybrid mode of the STEPCO oven is significantly more efficient than the electric and solar modes. Table 7 shows a comparison between the efficiency of the hybrid mode of the STEPCO oven and other reported values of relevant solar cookers. The findings demonstrate that the hybrid mode of the STEPCO oven has a higher efficiency than the other solar cookers compared in the table. The above experimental study shows that the STEPCO overcomes the two main challenges faced by solar cooking appliances and electrical ovens, i.e., cooking time, energy consumption, and efficiency.

3.3. Economic feasibility study and payback period of STEPCO

The focus of this research was not only to develop a hybrid energy-efficient cooking appliance but also to make it affordable for markets of developing countries like India. As the adaptation of electrical cooking is increasing rapidly, especially in the domestic cooking sector, the product demand is also increasing at a drastic rate [42]. Nowadays, a fully featured conventional microwave oven costs around INR 12,000 to 15,000. With a cost of just INR 12,000, the STEPCO (which comes along with a solar parabolic collector dish) is right in the middle of the competition. Also, if we consider the renewable energy aspect of it, we can easily observe that it not only justifies its cost but also it will have a shorter payback period to become effectively free of cost.

Though the STEPCO has many advantages over existing appliances in the market, while being used in solar and hybrid mode, it requires a bit of adaptation time for those who only use conventional cooking methods. Energy savings and payback period of this oven in comparison to other conventional cooking methods and fuels will be a good incentive for its wide acceptability. To measure the energy-saving and payback period of the hybrid oven, it is important to consider the utilization of renewable and low-cost solar energy and high-cost electrical energy in STEPCO. The energy utilized for cooking using a conventional electric oven will be completely saved when STEPCO is operated in solar mode. When the same STEPCO is operated in hybrid mode for time-saving and performance-driven functionality, there would be a small amount of electrical energy consumption.

The payback period estimation for STEPCO depends on a) the annual power consumption of STEPCO, b) the annual power consumption of conventional electric oven, c) the cost per kWh of electricity d) the cost price of STEPCO.

Table 4
Quantity of Items cooked in STEPCO.

Sr. No.	Item	Quantity
1	Rice	400 g
2	Milk	500 ml
3	Cake	500 g
4	Pizza	8-inch (small size)

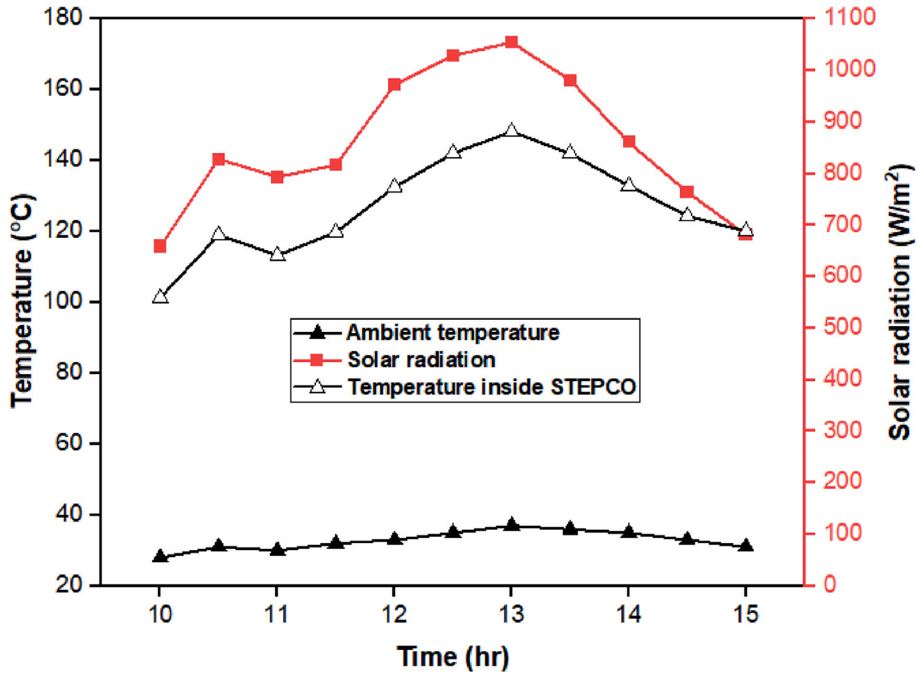


Fig. 5. Variation of the temperature inside the oven, the ambient temperature, and the solar radiation with respect to time for solar mode with no load.

Table 5
Thermal profile comparison of STEPCO (in Solar Mode) with other solar cookers.

Sr. No	Reference	Stagnation Temperature (°C)	Ambient Temperature (°C)	Time	Solar Radiation (W/m^2)	Date of Experiment
1.	Vaishya J et al. [37]	122	32	12:00	1020	23 September
2.	Nahar N [36]	132	28	14:00	760	–
3.	Negi B et al. [38]	140	27	12:00	750	March
4.	Mirdha U et al. [40]	163	37	13:30	–	–
5.	Kumar S [39]	138	37	13:40	858	–
6.	Harmim A et al. [41]	140	48	12:00	960	23 July
7.	Mahavar S et al. [17] SFSC-1	144	35	13:30	945	17 June
8.	Mahavar S et al. [17] SFSC-2	144	42.5	13:20	859	20 May
9.	Cuce P et al. [28]	82.5	28.2	09:00	588.2	–
10.	Cuce E et al. [47]	100	–	12.00	925	June
11.	E. Cuce [26]	140	16.9	15:10	–	25 April 2018
12.	STEPCO	148	37	13:00	1050	11 April

Table 6
Irradiance during solar-aided cooking.

Items	Hybrid (W/m^2)	Solar (W/m^2)
Rice	953	985
Milk	1030	1040
Pizza	1000	845
Cake	970	930

The annual energy consumption of an oven is expressed by Eq. (10) [53].

$$EC = E \times N \tag{10}$$

Where E is the energy consumed by the oven in one daily cooking cycle (in kWh)

N is the number of days of power consumption by the oven.

The annual operation expenditure of the oven is given by Eq. (11) [54].

$$A = c \times EC \tag{11}$$

Where c = cost of electricity per kWh.

EC = Total energy consumed.

On comparing the annual operation expenditures of a conventional oven with STEPCO, the annual savings on using the STEPCO is expressed in Eq. (12) [55].

$$S = C_{oven} - C_{STEPCO} \tag{12}$$

The running cost of a conventional oven (OTG), denoted by C_{oven}, is estimated to be INR 10999 per year if the oven is used for 1 h per day. In comparison, the running cost of STEPCO, denoted by C_{STEPCO}, in hybrid mode is estimated to be INR 5771 per year for the same usage and INR 7757 per year in solar mode. Therefore, the annual savings on using the STEPCO in hybrid mode and solar mode equals to INR 5228 and INR 3242, respectively. These findings indicate that the STEPCO oven can provide significant cost savings compared to a conventional oven, particularly when used in hybrid mode. All these calculations are obtained on cooking the rice, milk, cake, and pizza.

Using Eq. (13), the payback period of STEPCO is estimated [56].

$$P = \frac{\text{Cost of STEPCO}}{S} \tag{13}$$

Using the annual savings on the STEPCO oven in both hybrid and

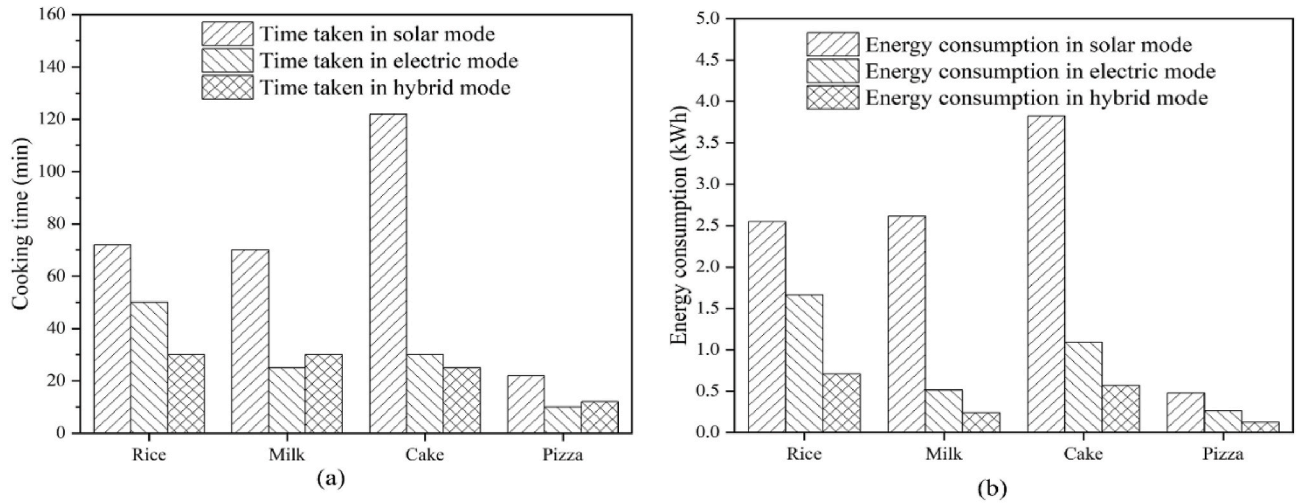


Fig. 6. (a) Cooking time in solar, electric, and hybrid mode for rice, milk, cake, and pizza (b) Energy consumption in solar, electric, and hybrid mode for rice, milk, cake, and pizza.

Table 7
Comparison of energy efficiency of STEPCO (in Hybrid Mode) with other solar cookers.

Sr. No	Reference	Energy efficiency (%)
1.	P. M. Cuce et al. [28]	7.47–4.54
2.	E. Cuce and P. M. Cuce [47]	30
3.	E. Cuce [26]	34.6–21.2
4.	S.B. Joshi, and A.R. Jani [50]	38
5.	E. Cuce & P. M. Cuce [51]	38.04
6.	A. Kumar et al. [52]	52.2
7.	STEPCO	63

solar mode and the cost of STEPCO (INR 12000) as input values in Eq. (13), the payback period of the oven can be estimated. The results show that the payback period of STEPCO in hybrid mode is approximately 2.3 years, while the payback period in solar mode is approximately 3.7 years. These findings suggest that the STEPCO oven can provide a relatively short payback period, particularly when used in hybrid mode, making it a potentially cost-effective and financially viable option for households and businesses seeking to reduce their energy costs.

In Herez An et al. [57], the author has performed a survey of the cooking patterns of households in a given town, which concludes the average cooking requirements of a regular household. The UF value stands for Utilization Factor Value. It is the percentage fraction of utilization of STEPCO divided by the percentage fraction of utilization of standard oven for cooking in a day. The payback has been calculated by taking a standard Electrical OTG oven as a reference. From Fig. 7, it is evident that if more than 50% of cooking is being performed using STEPCO for both solar as well as hybrid mode, then its cost can be recovered shortly.

3.4. Environmental impact

The CO_2 emission from cooking for a month has been analyzed for the study of the environmental effects of using STEPCO. Taking the case of India, the comparative data presented in Fig. 8 (a), 8 (b), 8 (c), and 8 (d) shows even electrical cooking has a significant carbon footprint considering 60% of electricity produced in India is still fossil fuel based [35]. The UF value stands for Utilization Factor Value. It is the percentage fraction of utilization of STEPCO divided by the percentage fraction of utilization of standard oven for cooking in a day. Fig. 8 shows that if more than 50% of cooking is being performed using STEPCO for

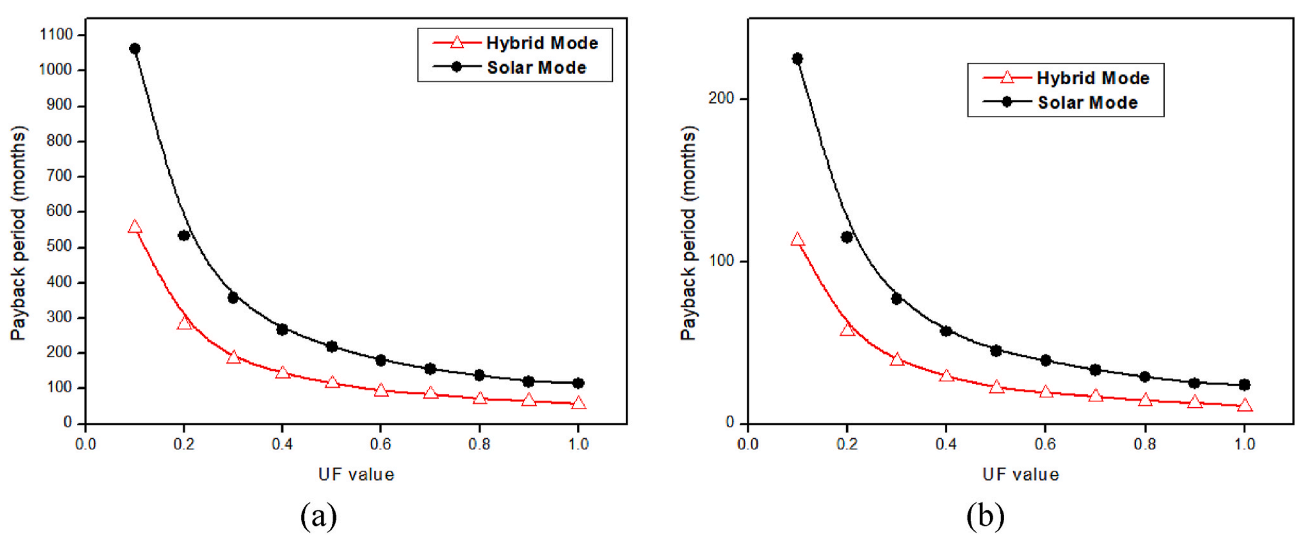


Fig. 7. (a) Payback period projections in the minimum usage scenario (cooking of only one meal that contains one pot of rice in a day for a year), (b) Payback period projections in an average household usage scenario.

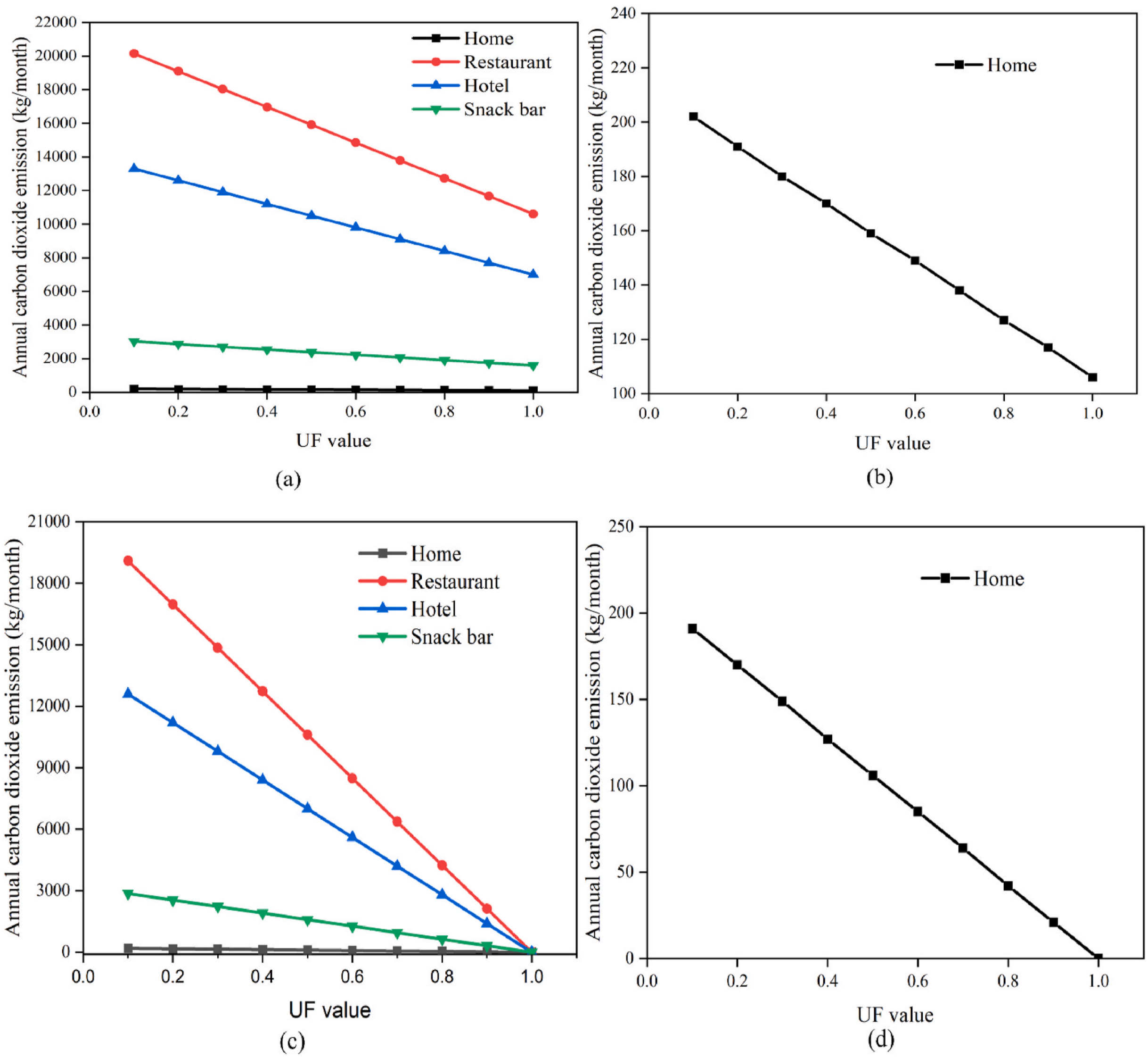


Fig. 8. (a) CO_2 emission due to percentage use of STEPCO in hybrid mode for home, restaurant, hotel, and snack bar, (b) CO_2 emission due to percentage use of STEPCO in hybrid mode for home, (c) CO_2 emission due to percentage use of STEPCO in solar mode for home, restaurant, hotel, and snack bar, (d) CO_2 emission due to percentage use of STEPCO in hybrid mode for home.

both solar as well as hybrid mode, then its CO_2 emission will be small. The Fig. also show that if the cooking process is done completely using STEPCO, the emitted CO_2 will be very small if the STEPCO operates in hybrid mode, and it will equal zero if the STEPCO work on solar mode. The emission of CO_2 from the STEPCO oven can be determined by its energy consumption and the source of the electricity used to power it. The amount of CO_2 emitted per kilowatt-hour (kWh) of electricity varies depending on the type of power plant used to generate the electricity. In this study, it is assumed that all the electricity being consumed in any form is being produced by the thermal power plant. The amount of CO_2 emission is estimated using Eq. (14) [58].

$$CO_2 \text{ emissions (kg)} = \text{energy consumption (kWh)} * CO_2 \text{ emission factor (kg / kWh)} \quad (14)$$

The CO_2 emission factor can be found on government websites or from the power company [58].

From Mittal M et al. [58], it can be seen that to produce 1 kWh of electricity from a thermal plant, 0.9 kg CO_2 is released. The variation in carbon emission due to the use of STEPCO has been shown in comparison to a standard OTG oven. The cooking requirement estimate for home, restaurant, hotel, and snack bar has been calculated based on the data reported by A. Herez et al. [57].

4. Conclusions

The available solar cookers can be commonly used, but newer methods to make the solar cookers useable in the absence of sunlight are a better way for the technology to move forward. The hybrid nature of cooking appliances gives a new dimension to cooking technology. This has resulted in the development of hybrid ovens. Such integration of technology allows a gentle shift from one type of cooking technology to another. In this article, we utilize a STEPCO oven which is a hybrid oven that utilizes solar energy and electricity. The following are the important finding of the study.

- The maximum temperature achieved in the electric oven in the simulation study is validated by experiments. The experimental and numerical results show that the temperature distribution inside an electric-solar hybrid oven and saves energy up to 51% and takes much less cooking time than electric ovens and solar cooking appliances, respectively when operating in Hybrid Mode.

- The oven has been shown to be efficient and effective in cooking food, as it was able to achieve the desired temperature in a shorter amount of time than a traditional oven. The oven was also effective in cooking a variety of food items, including cake, rice, and pizza.
- The STEPCO is hybrid oven is competitively priced at INR 12,000, while the conventional microwave oven costs around INR 12,000 to 15,000. This makes STEPCO oven an affordable and accessible option for households and businesses looking to adopt more sustainable and eco-friendly cooking practices.
- The STEPCO oven demonstrated significantly higher energy efficiency in hybrid mode (63%) compared to electric mode (35%) and solar mode (4%).
- The study finds that the payback period of the STEPCO oven is estimated to be around 2.3 years when used in hybrid mode and 3.7 years when used in solar mode, indicating that the oven can offer a relatively short payback period, particularly when used in hybrid mode.
- It will also contribute to a decrease in centralized electricity generation, and hence, modern technology will be based on sustainable energy. By promoting the use of sustainable energy sources in cooking, the STEPCO can contribute to reducing carbon emissions and dependence on fossil fuels. Technologies like this are not only user-friendly, eco-friendly, and durable, but they are also a step towards achieving the ambitious renewable energy goals of the country.

Credit author statement

Prashant Saini: Conceptualization, Formal analysis, Visualization, Writing – original draft, **Sushant Pandey:** Formal analysis, Visualization, **Shruti Goswami:** Methodology, Visualization, **Atul Dhar**: Conceptualization, Methodology, Writing – review & editing, supervision, **M. E. Mohamed:** Visualization, **Satvasheel Powar**: Conceptualization, Methodology, Validation, Resources, Writing – review & editing, supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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