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Assessing the Embodied Energy of Box-Type Solar Cookers: A Sustainable Perspective

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Abstract: *As the global community intensifies its focus on sustainable and renewable energy solutions, the embodied energy of solar technologies becomes a critical aspect of evaluation. This study delves into the embodied energy associated with box-type solar cookers, a widely used and promising technology in the context of clean cooking. By analysing the energy inputs required for the production, transportation, and maintenance of these solar cookers, we aim to quantify and understand the environmental impact of their life cycle. The assessment involves a comprehensive analysis of materials, manufacturing processes, and transportation considerations. This helps us understand how much energy is needed for everything the cooker goes through in its whole life. Understanding the embodied energy of these devices is crucial for making informed decisions regarding their adoption, allowing stakeholders to assess the overall sustainability of solar cooking solutions.*

Key Words: *Box-type solar cooker, Embodied energy, Solar energy, Thermal performance.*

1. INTRODUCTION:

In particular, the environmental impact of renewable technologies—particularly as they relate to solar cookers—has come under increased scrutiny as the focus on sustainable energy options grows. This research focuses on a specific category of solar cookers—box-type solar cookers—and conducts a comprehensive analysis of their entire life cycle. By scrutinizing the materials used, manufacturing processes employed, and transportation considerations, this study seeks to illuminate the cradle-to-grave energy requirements associated with these cookers[1].

Human beings have four fundamental needs, namely food, shelter, clothing, and energy. Among these, the preparation of food, commonly known as cooking, stands out as a crucial household activity. Therefore, ensuring a sufficient energy supply is essential for the functionality and survival of human beings [2].

Food is a fundamental necessity for humans, providing essential nutrients and calories required for metabolic activities. Utilizing a solar cooker in food preparation ensures the retention of these vital nutrients and calories through proper heating, maintaining thermal energy within the cooker. Unlike traditional cooking methods such as LPG, kerosene stoves, induction cookers, microwave ovens, electric heaters, and conventional Chula's, solar cookers require minimal maintenance and pose no risk of accidents. Furthermore, the use of solar cookers eliminates the release of harmful gases during the cooking process, in contrast to the burning of conventional biomass, which is prevalent in South Asian countries like India, Pakistan, Nepal, and Bangladesh. This reliance on conventional biomass leads to indoor air pollution, resulting in significant health issues in the region[3]. Therefore, adopting solar energy for cooking at home emerges as a practical and environmentally friendly alternative.

Solar cookers rely on bright and sunny conditions to function effectively; however, their utility is restricted during periods of cloud cover and at night [4].

1.1 LITERATURE REVIEW : Few studies found in the existing literature discuss the embodied energy in the solar cooking process, particularly in the context of Solar Box Cookers (SBCs). Noumi (2004)[5], Angappan (2023)[6], B Koshti (2023)[7], Tawfik (2024)[8]. This study represents an initial attempt to evaluate the practicality of deploying box-type solar cookers in India. We employed a method called process analysis to estimate the energy feasibility of these cookers. This involved assessing the materials used and calculating the energy required for the processes involved in making the cooker.

The performance of a box-type solar cooker relies heavily on the materials chosen for its various parts, including glazing, insulation, casing, and the absorber tray. In an effort to enhance the efficiency of box-type solar cookers, a new design was created and tested. This particular design aimed to serve as a domestic solar cooker suitable for small families in the present social context. The evaluation focused on assessing how well the newly designed box-type solar cooker performs under current social conditions[9].

2. EXPERIMENTAL SET-UP: A double-glazed cooker designed and fabricated with reflector at the renewable energy laboratory MNNIT Prayagraj. Both the outer box and the inside box are constructed of galvanised sheet. The outer box dimensions measure 48cm × 48cm ×18 cm, while the inner box dimensions are 43cm × 43cm with a height of 14 cm. To provide insulation, the side spacing between outer and inner casing is filled with 2.5 cm of glass wool. The base also constructed from GI sheet and 4cm glass wool filled between upper and lower plate. To improve heat absorption, the inner tray was coated black using blackboard paint. Two 0.5 cm thick clear window panes were fitted over a wooden frame. To reduce thermal losses the gap of 1.5 cm was provided between glass covers. To create thermally insulated a rubber gasket was used wooden frame to ensure a leak-proof seal. The cooker's lid was a 0.5 cm thick plain mirror reflector that was fastened in place. The reflector can be positioned over the cooker and adjusted to different angles ranging from 60⁰ to 120⁰, depending on the season. Depending on the season, the reflector can be placed over the cooker and tilted at various angles between 60⁰ and 120⁰. The solar cooker has an aperture area of 18.49 cm^2. It can accommodate four cooking utensils, each with a diameter of 14 cm, made of stainless steel. The cooker is secured on an angle iron stand for stability.

Figure.1: Image of box type solar cooker

2.1 DESIGN SPECIFICATIONS: The design specifications of solar cookers encompass various factors, including the materials used, shape and size, reflector configuration and cooking chamber design. Each specification has a significant impact on the overall functionality, efficiency.

Table 1. Specification of box type solar cooker (BSC)

Parameter	**Specification of box type solar cooker(BSC)**
Direction	East – West
Placed	MNNIT Prayagraj, India, Renewable energy laboratory
Coordinates	25.4358° N, 81.8463° E
Meteorologic conditions	Warm and Humid
Outer box	North wall- Galvanized iron (18×48cm) South wall- Galvanized iron (18×48cm) East wall - Galvanized iron (18cm×48cm) West wall- Galvanized iron) (18×48cm) (18cm×48cm) Top cover- Galvanized iron (48cm ×48cm)

Inner box	North wall- Galvanized iron (14cm x 43cm) South wall- Galvanized iron (14cm × 43cm) East wall- Galvanized iron (14cm × 43cm) West wall- Galvanized iron (14cm × 43cm) Top glass – Double glass (46.8cm×46.8cm) Base- Aluminum (43 cm × 43 cm)
Mirror	Simple plane (46cm×46cm)

3. METHODOLOGY:

Solar data was collected during summer seasons in Prayagraj (U.P.) through experimental observations. The methodology for the box-type solar cooker is outlined as follows:

- Experimental measurements were taken for solar intensity on the top cover along with temperatures recorded at various locations within the solar cooker.
- Utilizing the obtained experimental data, an analysis of the thermal performance and solar data for the solar cooker was conducted.
- Calculation of embodied energy.

4. RESULT:

4.1 PERFORMANCE OF SOLAR COOKER (THERMAL PERFORMANCE)

Figure of Merit (F_1)

F_1 assesses solar cooker performance, considering optical efficiency (η_o) and heat loss factor (U_L).

$$F_1 = \frac{\eta_o}{U_L} \quad (1)$$

η_o measures the cooker's ability to utilize solar radiation for cooking, while U_L gauges thermal energy escaping through the cover.

Experimentally $$F_1 = \frac{T_p - T_a}{I_a} \quad (2)$$

T_p = Stagnation temperature of the absorber plate (ºC)

I_a = Average solar radiation (W/m^2)

Full-Load Test (F_2)

The Full-Load Test evaluates solar cooker performance, using water-filled pots and excluding the reflector to calculate F_2. Initial water temperature (60-95ºC) and final temperature (90-95ºC) are measured. The test includes 10-minute interval measurements of solar irradiation, environmental temperature, and cooking fluid temperature, offering crucial data for assessing the solar cooker's efficiency and effectiveness in practical cooking scenarios (Buddhi et al., 1999).

$$F_2 = \frac{F_1(m_w C_{pw})}{A_p t} \ln \frac{1-(1/F_1)((T_i - T_a)/I_a}{1-(1/F_1)((T_f - T_a)/I_a} \quad (3)$$

where, $m_w C_{pw}$ represents mass and heat capacity of water, A_p denotes the aperture area of the solar cooker, and t signifies the total time taken to reach the temperature T_f from the initial temperature T_i.

Cooking power- The cooking power of a solar cooker, product of 3 components (mass of fluid ×specific heat× temperature difference). This product is then divided by the time interval between measurements, typically 600 seconds (10 minutes). This calculation yields the heat energy generated by the solar cooker during that specific time period.

$$P_c = \frac{mc_p(T_{w1} - T_{w2})}{600} \quad (4)$$

Table 2. Thermal performance of BSC

F_1	F_2	cooking power
$F_1 = 0.11$	$F_2 = 0.23$	42 W

4.2 EMBODIED ENERGY

Embodied energy is a examine of the total energy expended in the production of a material or product, encompassing activities such as mining, manufacturing, and transportation distance. The main components of a solar cooker include the reflective material (such as aluminum foil), insulation material, cooking pots, and support structure.

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The table provides information on various components used in a particular in BSC. The components listed in the table. The total embodied energy for all these components is calculated as 2723.37 MJ.

Table 3. Components of BSC and its embodied energy

S.no.	Material	Mass (kg)	Mass Density (kg/m3)	Energy Density (MJ/m3)	Embodied Energy (MJ)
1	Galvanized iron sheet	8.39	7850	240	49.97
2	Toughened glass	2.07	2600	19.74	40.88
3	Mirror	1.02	2500	15.9	16.21
4	Aluminum frame	0.60	2700	279	167.4
5	Cooker Stand	6.3	7800	49.968	314.8
6	Black paint	0.2	880	90.4	18.8
7	Glass wool	0.36	20	316.6	114
	Total	18.94	24350	1011.6	722.0

4.3 PAYBACK PERIOD OF BSC

The payback period is a metric used to determine the time required for the returns or profits from an investment to recuperate the initial investment cost. In box type solar cooker(BSC), the payback period evaluates on the bases of LPG cost (₹1,155.50 on 19 April 2023, Prayagraj, Uttar Pradesh, INDIA), and fabrication cost of MBSC is 4500.27 that is nearly five times the cost of one cylinder.

The payback period can be determined as associated with energy consumption. One home LPG cylinder's energy, weight, calorific value, burner efficiency, total energy needed to cook one meal for a family of 4-5 people, and the portion of food that can be cooked in a Solar cooker are all included.

Energy used for the meal preparation per person is 900 kJ.
The energy required for five members family and one meal = 5 × 900 = 4500 kJ per day.
Assume 80% of the food may be made in a solar cooker, even though the entire meal cannot be cooked there.
Energy consumed in cooking food = 4500 × 0.80 = 3600 kJ per day

$$\text{The calorific value of LPG} = 50000\,\frac{\text{kJ}}{\text{kg}}$$

$$\text{Amount of LPG in one domestic cylinder} = 14.2\ \text{kg}$$

$$\text{Amount of Energy in 14.2 kg LPG} = 710000\ \text{kJ}$$

$$\text{Burner Efficiency} = 60\ \%$$

$$\text{Amount of usable Energy in one LPG cylinder} = 426000\ \text{kJ}$$

$$\text{Days domestic cylinder can fulfill demand} = \frac{\text{Amount of usable Energy in one LPG cylinder}}{\text{amount of energy required for preparing meal per day}} \qquad (5)$$

$$\text{Days domestic cylinder can fulfill demand} = \frac{426000\ \text{kJ}}{3600\,\frac{\text{kJ}}{\text{day}}} = 118.33\ \sim 118\ \text{days}$$

Cost for energy consumption of 118 days = ₹1,155.50 ~ 10/ day
To recover the cost of BSC (₹4500), i.e., Payback Period = 450 days ~ 1.5 years (Considering 300 days in a year)
In terms of Embodied Energy,
Embodied Energy of BSC = 722.0 MJ
Amount of Useful Energy produced by BSC per day = 3600 kJ

$$\text{PaybackPeriod} = \frac{\text{Embodied energy of BSC}}{\text{Amount of useful energy produced by BSC per day}} \qquad (6)$$

$$\text{PaybackPeriod} = \frac{722.0\ \text{MJ}}{3600\,\frac{\text{kJ}}{\text{day}}} = 200.5\ \text{days}\ \sim 200\ \text{days}\ \sim 0.66\ \text{years}$$

(Considering 300 days in a year)

Table 4: Cost and energy payback period of BSC.

S.no	Parameter	MBSC
1	Cost payback	0.66 years
2	Energy payback	2.52 years

5. FINDINGS :

- Embodied Energy Assessment: The research successfully conducted a thorough embodied energy assessment of box-type solar cookers, encompassing the entire life cycle from production to disposal. The findings revealed that the total embodied energy for the components of a conventional box-type solar cooker was calculated to be 722.0 MJ.
- Design Specifications Impact: The study underscored the critical role of design specifications, including materials, shape, size, reflector configuration, and cooking chamber design, in influencing the overall functionality and efficiency of box-type solar cookers.
- Performance Evaluation: The experimental set-up and performance evaluation of a specific box-type solar cooker highlighted the importance of design modifications for enhanced efficiency, demonstrating the practical utility of solar cookers under real-world conditions.
- Cooking Processes Classification: The classification of thermal cooking processes into two categories based on required temperatures provided valuable insights for optimizing box-type solar cookers, particularly in meeting the needs of specific cooking methods.
- Payback Period Analysis: The economic assessment, considering both LPG cost and fabrication cost, indicated that the payback period for the box-type solar cooker was approximately 0.66 years in terms of energy consumption and 1.5 years in terms of cost recovery.
- Environmental Implications: The research illuminated the environmental implications of box-type solar cookers, emphasizing the importance of considering factors such as energy consumption during manufacturing, transportation, utilization, and end-of-life processes.

6. RECOMMENDATIONS:

- Material Optimization: Explore alternative materials with lower embodied energy for the construction of box-type solar cookers, aiming to reduce the overall environmental impact.
- Continuous Design Improvement: Encourage ongoing research and development to enhance the design of box-type solar cookers, focusing on improving efficiency and adaptability to diverse cooking needs.
- Awareness and Adoption Campaigns: Launch awareness campaigns to educate communities about the benefits of adopting box-type solar cookers, emphasizing both economic and environmental advantages.
- Policy Integration: Advocate for the integration of solar cooking technologies in national and regional renewable energy policies, providing incentives for manufacturers and consumers to invest in sustainable cooking solutions.

7. CONCLUSION:

This paper has provided a comprehensive examination of the embodied energy associated with box-type solar cookers, focusing on their life cycle from production to disposal. The study aimed to contribute valuable insights into the environmental impact of these cookers, emphasizing the need for a sustainable perspective in the evaluation of renewable energy solutions.

Through a meticulous analysis of materials, manufacturing processes, and transportation considerations, the research shed light on the cradle-to-grave energy requirements of box-type solar cookers. The assessment of the cookers' performance, as well as the introduction of a new design for enhanced efficiency, further enriched the understanding of their practical utility.

The study also delved into the design specifications and performance evaluation of a specific box-type solar cooker, providing valuable data for assessing functionality, efficiency, and practicality under real-world conditions.

Moreover, the research considered the embodied energy of various components used in the construction of a conventional box-type solar cooker, offering a detailed breakdown of their energy consumption. The payback period analysis, considering both LPG cost and fabrication cost, further highlighted the economic and energy efficiency aspects of adopting box-type solar cookers.

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