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Techno-Economic Study of Different Renewable Energy Based Cooking System

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ABSTRACT

Cooking and heating applications are major energy consumers in India. Cooking is an integral part of each and every human life as food is one of the basic necessities for living. The problem arises when fuel is either scarce or highly expensive. Half of the world's population is exposed to indoor air pollution, mainly because of burning solid fuels for cooking and heating application. The World Health Organization reports that in 23 countries 10% of deaths are due to just two environmental risk factors: unsafe water, including poor sanitation and hygiene; and indoor air pollution due to solid fuel usage for cooking. Therefore, it becomes necessary to use energy efficient, environment friendly and economically viable devices in household cooking practices. Hence the renewable energy based cooking devices like box type solar cooker, biogas plant and biomass metallic portable cookstove were undertaken to evaluate their thermal performance as per BIS standards and techno-economic feasibility in the Department of Mechanical Engineering, GITS, Udaipur.

The existing box type solar cooker was evaluated as per IS – 13429 (2000) part 3 for stagnation test which showed value of first figure of merit lower than 0.12, hence the solar cooker marked as B-grade solar cooker. The thermal efficiency of solar cooker was determined by water boiling test and found to be 26.7%. The exergy analysis was carried out and the exergy efficiency found about 2.61%. Production efficiency of 2 cubic meter biogas was found 76% while thermal efficiency of biogas burner stove was determined as per IS 8749 (2002) and observed 54.18%. The exergy efficiency of biogas stove was nearer to 3.18%. The thermal performance of biomass metallic portable cookstove was carried out as per IS 13152 (2013) and the thermal efficiency was found about 32.58%. The exergy efficiency was calculated and found about 3.79%.

The techno-economic analysis of selected renewable based cooking systems was calculated in terms of LPG stove and the result showed that the benefit cost ratio was inversely proportional to net present value and payback period. From selected systems biogas burner stove showed the higher benefit cost ratio and lower the net present value and payback period. It is concluded that if a beneficiary has sufficient cattle to operate a family size biogas plant, biogas technology is most appropriate for them. It will fulfill their cooking needs as well as manure for agriculture. Solar cooking technology is suitable for small family having 3-4 members. Solar cooking technology could be adopted easily by rural as well as urban households.

Key words: *thermal efficiency; exergy analysis; payback period; benefit cost ratio; net present value*

Nomenclature

Nomenclature	Meaning	Nomenclature	Meaning
A_{SC} or A	Aperture area of solar cooker (m^2)	T_{az}	Average Ambient Temperature (°C)
C_{pw} or C_w	Specific heat of water (kJ/kg. °C)	$\bar{T}_a$	Average ambient temperature (°C)
c_1 or CV_f	Calorific value of the fuel wood in kJ/kg. ^{0}C	t_1 or T_{wi} or T_{w1}	Initial temperature of water (°C)
c_2	Calorific value of kerosene, in kJ/kg	t_2 or T_{wf} or T_{w2}	Final temperature of water (°C)
Cp_{Al}	Specific heat of aluminium (kJ/kg. °C)	T_a	Ambient temperature (°C)

C_0	Capital Cost system (Rs.)	T_s	Sun temperature (°C)
D	Density of kerosene, kg/m^3	T_{fuel}	Temperature of burning fuel (°C)
d	Discount rate (10%)	T_{fp}	Final temperature of pot (°C)
E_i	Energy Input	T_{ip}	Initial temperature of pot (°C)
E_o	Energy Output	T	Life span of system (years)
F_1	First Figure of Merit	V	Gas consumption (l)
F_2	Second Figure of Merit	V_b	Volume of Biogas (l)
f_1	Initial temperature of water in first vessel (°C)	$UL_{,sc}$	Overall Heat Loss Coefficient of the box type solar cooker
f_2	final temperature of water in first vessel (°C)	W	Weight of utensil (kg)
f_3	Final temperature of water in last vessel at the completion of test in °C.	w_m *or* M_w	Mass of water (kg)
G	Quantity of water taken (kg)	w	Mass of water in vessel, in kg
Gs	Average solar radiation (w/m^2)	W	Mass of vessel complete with lid and stirrer, in kg
H	Calorific value of biogas (kcal/m^3. °C)	X	Mass of fuel consumed, in kg
I_s or $\bar{H}$	Average solar radiation incident on the aperture of the cooker (w/m^2)	x	Volume of kerosene consumed, in ml
M_1	Initial mass of the cook-stove in kg	P	Money value of the fuel saved per cooked (Rs.)
M_2	Final mass of the cook stove after burning for half an hour in kg	R	Rate of Return
m_{pot}	Mass of pot (kg)	T	Number of time period
N	Total number of vessels used	T_{pz}	Final Temperature of trey at steady state condition (°C)
N	Number of feed can be cooked in year	α	Repair and maintenance, % of capital cost
η0	Optional Efficiency	%	Percent
Ψ	Exergy Efficiency	°C	Degree Celsius

INTRODUCTION

Energy is essential for economic and social development. In India the cooking and heating applications are major energy consumers. Cooking is an integral part of each and every human being as food is one of the basic necessities for living. The problem arises when fuel is either scarce or highly expensive. The problems are more pronounced in most of the developing countries, particularly in the remote and rural areas. Cooking accounts for a major share of energy consumption in developing countries including India. As we know for cooking 1 kg of food we need 7 to 22 MJ energy [1]. Commonly used sources of energy for cooking are firewood, crop residue, cow dung, kerosene, electricity, liquefied petroleum gas (LPG), biogas, etc [2]. Half of the world's population is exposed to indoor air pollution, mainly the result of burning solid fuels for cooking and heating. Cooking causes deforestation, health hazard and other social and economic issues. The World Health Organization (WHO) reports that in 23 countries 10% of deaths are due to just two environmental risk factors: unsafe water, including poor sanitation and hygiene; and indoor air pollution due to solid fuel usage for cooking. The toxic emissions are very pronounced in developing countries where most of the people use conventional sources. Wood cut for cooking purpose contributes to the 16 million hectares (above 4% of total area of India) of forest destroyed annually. The cooking energy demand in rural areas of developing countries is largely met with bio-fuels such as fuel wood, charcoal, agricultural residues and dung cakes, whereas LPG or electricity is predominantly used in urban areas [3] In under-developed countries, women have to walk 2 km on an average and spend significant amount of time for collecting the firewood for cooking [4-5]. Energy usage for cooking is always associated (directly or indirectly) with emissions that affect both environment and health. So it is necessarily required to use renewable energy sources for cooking namely Solar Energy, Biogas Energy and Biomass Energy (cook stove).

Solar energy is considered a suitable alternative for variety of applications. Solar energy is abundantly available worldwide and it is possible to cook noon meal for 4 to 5 members and saves about 3 to 4 cylinders of LPG every year, while the life of solar cooker is 10 to 20 years. For testing of solar cooker an 8 lit/m^2 load is taken according to BIS. The solar cooker having 20–25% efficiency and temperature in the range of 70 to 110 °C.Biogas is one of the promising sources of alternate energy at domestic/farm level in rural area [1] .They studied the production of biogas at different total solids content in cattle dung. They recommended dung water mixture having 14 per cent TS for water scarcity areas. They reported that the modified biogas plants for solid state digestion of cattle dung required very little or no water for mixing with the cattle dung and generated 50 per cent higher gas as compared to common biogas plants. Typically 1 kg of cow dung yields about 0.03 m^3 of biogas per day [6]. The biomass cookstove is another alternative for cooking application.

Keeping above points in mind, research work was carried out for performance efficiency, exergy efficiency and techno-economic analysis of cooking devices namely box type solar cooker, biogas burner stove and biomass metallic portable cookstove.

MATERIALS AND METHODS

Thermal Performance of cooking systems

Solar Cooking (Box Type Solar Cooker)

The thermal performance of box type solar cooker was carried out as per IS – 13429 (2000) part 3 [7]. The thermal performance test was conducted according to BIS standards and values of F_1 and F_2 [7-8] were calculated. The values of F_1 and F_2 were reported based on arithmetic average of at least 3 test values which did not have variation more than 0.002.

First Figure of Merit (F_1): [9]

$$F_1 = \frac{\eta_0}{U_{L,sc}}$$

Second Figure of Merit (F_2): [9]

$$F_2 = \frac{F_1(M_w C_w)}{A\,\tau} \ln \left[\frac{1 - \frac{1}{f_1}\left(\frac{T_{w1} - \bar{T}_a}{\bar{H}}\right)}{1 - \frac{1}{f_1}\left(\frac{T_{w2} - \bar{T}_a}{\bar{H}}\right)} \right]$$

Energy Input: $E_i = I_s * A_{sc}$

Energy Output: $E_o = w_m . C_{pw}(T_{wf} - T_{wi})/\Delta T$

Exergy Analysis:

For the steady-state flow process during a finite time interval, the overall exergy balance of the solar cooker written as: Exergy Input = Exergy Output + Exergy loss + Irreversibility [10].

Exergy Input: [11]

$$\varepsilon_i = I_s \left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] A_{sc}$$

Exergy output: [11]

$$\varepsilon_{out} = m_w \frac{Cpw\left[(Twf - Twi) - Ta\, \text{In} \frac{Twf}{Twi}\right]}{\Delta T}$$

Biogas Cooking (Biogas Burner stove)

The thermal performance of biogas burner stove was carried out as per IS – 8749 (2002). Calculation of performance efficiency of biogas based burner stove, the water boiling and evaporation test taken as follows [12-13]

$$\eta = \frac{(G + W)(t_2 - t_1)}{VH} X100$$

Exergy Efficiency of Biogas burner stove:

The exergy analysis of biogas burner stove was calculated by using following methods.

Exergy input - [Exergy recovered + Exergy loss] - Exergy consumption = Exergy accumulation

Exergy Input:

$$\varepsilon_i = V_b . c_1 (1 - \frac{T_a}{T_{fuel}}) * \eta$$

Exergy Output:

$$\varepsilon_{out} = m_w . C_p (T_{wf} - T_{iw})\left(1 - \frac{T_a}{T_{fw}}\right) + m_{pot}\, Cp_{Al}(T_{fp} - T_{ip})(1 - \frac{T_a}{T_{fp}})$$

Biomass Cooking (Biomass portable metallic cookstove)

The thermal performance of biomass metallic portable cookstove was carried out as per IS – 13152 (2013) Part 1. Thermal efficiency of a cookstove may be defined as the ratio of the heat actually utilized to the heat theoretically produced by complete combustion of a given quantity of fuel. The biomass fuel used for performance test contain moisture about 5± 1 percent. The room temperature was maintained about 25 ± 5 °C. The Babul (*Acacia Nilotica*) size (3cm x 3cm) was selected for experiment.

$$Burning\ Capacity\ Rate = 2(M_1 - M_2)$$

$$Heat\ Input\ per\ Hour = 2(M_1 - M_2) * CV_f$$

$$Heat\ Utilized = (n-1)[(W * 0.896) + (w * 4.1868)](f_2 - f_1)[(W*0.896) + (w * 4.1868)](f_3 - f_1)$$

$$Heat\ Produced = 4.1868[(X_{c1}) + (xdc_2/1000)$$

$$Thermal\ Efficiency = (Utilized\ Heat - Heat\ Produced) * 100$$

Exergy analysis

The exergy analysis of biomass cookstove was carried out by following formula and the procedure used as follows: The experimental setup were done while doing performance evaluation of cookstove according to BIS standards.

Exergy Input: [1]

$$\varepsilon_i = m_{wd} . c_1 \left(1 - \frac{T_a}{T_{fuel}}\right) * \eta + xdc_2$$

Exergy Output: [1]

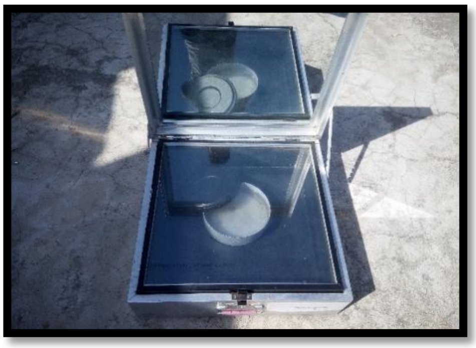
$$\varepsilon_{out} = m_w . c_p \left(T_{fw} - T_{iw}\right)\left(1 - \frac{T_a}{T_{fw}}\right) + m_{pot} Cp_{Al}(T_{fp} - T_{ip})(1 - T_a/T_{fp})$$

$$Efficiency = (Exergy\ Output - Exergy\ Input)$$

Apparatus used for evaluating performance of cooking devices

Solar Cooker

Size of Cooker - 0.45m*0.45m, Cooker body casing – Aluminium, Cover Plate - 2 transferring glass 0.88 % (Transmissivity), Mirror - Single mirror having 0.91% (Reflectivity), Pots - 4 pots of aluminium with black paint, Insulation - Glass Wool Cost - 3500/- (as per market cost)



Biogas Burner Stove

Manufacturer - RUPAK Enterprise, New Delhi, Burner - Double burner of free cutting brass, Body Material - Stainless steel and brass. Price ranges - Rs.950/- (as per market cost)

Biomass cookstove

Manufacture - ShriramDeoPrakrutikUrjaPvt. Ltd. Bhopal,
Name & Model - DattuChulha, Thermal efficiency - 33.57 %, CO - 2.82 g/MJd,
TPM - 187.992 mg/MJd,
Cost - 4200 /- (as per market cost)

Techno-economic Analysis

The techno-economic analysis of solar based cooker, biogas based burner stove and biomass based cookstove was calculated separately [14-15].

Net Present Value (NPV): [14]

$$NPV = \left(\frac{np - C_0 \alpha}{d}\right) \left[\frac{(1+d)^t - 1}{(1+d)^t}\right] - C_0$$

Pay Back Period (PP): [14]

$$= \frac{C_0}{(np - \alpha C_0)}$$

Benefit Cost Ratio (BCR): $= \frac{Total\ Benefit}{Total\ Cost}$ [14]

RESULTS AND DISCUSSION

Thermal Performance of Cooking Systems

The thermal performance of selected renewable based cooking systems was done according to BIS standards.

Solar Cooking:

The stagnation temperature test that is, no load test was started at 10.30 am local time till the maximum plate temperature (124 °C), which occurred at 13.00 pm, was achieved. The following values were obtained in order to compute: Initial tray temperature = 27 °C, Final tray temperature = 124°C, Solar Radiation = 912 W/m^2. Equation (1) was used to compute. However, the obtained value of F_1 is 0.11where the allowed standard F_1 test states that if the value of F_1 is greater than 0.12, the cooker is marked as A-Grade and if F_1 is less than 0.12 the cooker is marked as a B-Grade solar cooker. The selected solar cooker is marked as a B-Grade solar cooker.

Table - 1 Observations recorded in performance of solar cooking.

S. No.	Parameters	Values
1	Outside Ambient Temperature	23 °C
2	Final Steady cooker trey temperature	124 °C
3	Average Solar radiation (Global)	912 W/m^2
4	Mass of Water	1.62 kg
5	Specific Heat of water	4.186 kJ/kg. °C
6	Aperture area of Solar cooker	0.45m x 0.45m
7	Time difference	4 h

Energy input and energy output values calculated as 0.68 MJ and 0.18 MJ respectively. Therefore Energy Efficiency was found to be 26.89 %. Fig. 1 shows the graphical representation of Energy and Exergy Efficiency with respect to time. The average exergy efficiency was found to be 2.61 %.

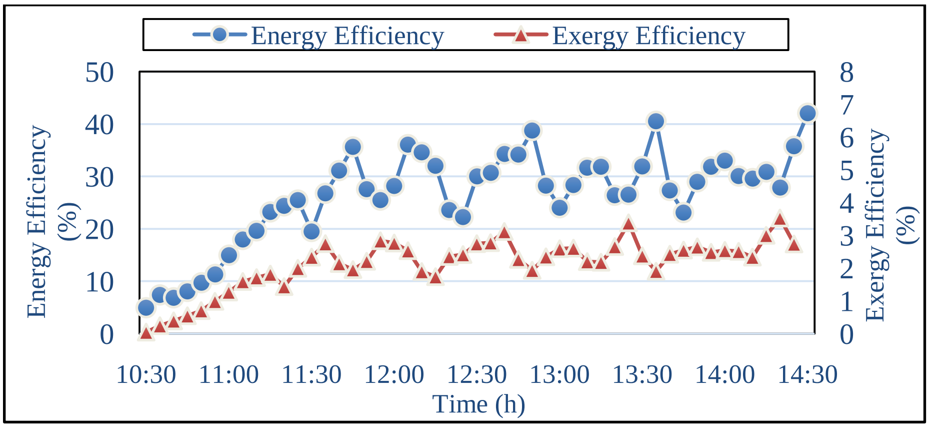


Fig. 1 Energy and Exergy Efficiency with respect to time

Biogas Cooking

The performance evaluation was carried out in the morning and readings were taken after every 5 minute of interval and depicted in Table 2. The maximum temperature of water in vessel was about 91 °C within 22 minute of total 30 minute test. The ambient temperature of room was 24 °C. The initial and final temperature of water was observed as 27 °C and 91 °C during test. Therefore the thermal efficiency was found to be 54.18 %. The 3.7 kg of water in vessel placed on burner. From Fig. 2 it was found that initially the energy and exergy efficiency was low but then increased with passage of time and then deceased at the end of test. The average exergy efficiency was observed as 3.18 %.

Table - 2 Observed data in performance of Biogas Burner Stove

S. No.	Parameters	Values
1	Quantity of Water in Vessel	3.7 kg
2	Water equivalent of the vessel complete with lid and stirrer	4.225 kg
3	Initial and Final Temperature of water	27 °C & 91 °C
4	Gas consumption	117 l.
5	Calorific value of Biogas	8 kcal / l.
6	Specific heat of aluminum	900 J/kg °C
7	Flame temperature or gas temperature	326 °C

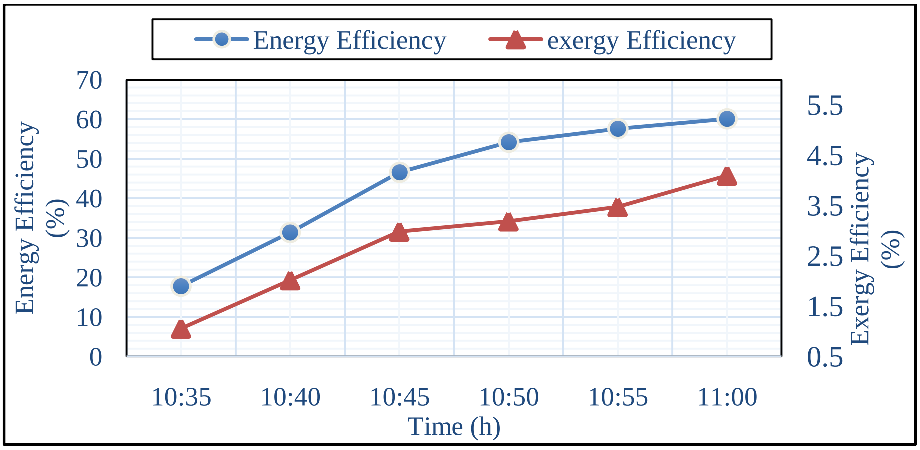


Fig. 2 Energy and Exergy Efficiency with respect to Time

Biomass Cooking:

The heat input rate was calculated and found as 3775 kcal/ h. As a selected cookstove was continuous feeding type thus first fill cookstove ¾ height with biomass then dividing fuel into 10 equal lots. The heat produced by cookstove was calculated as 10018.464 kJ and heat utilized for water boiling as 3264.11 kJ. The thermal efficiency of biomass portable metallic cookstove (*DattuChulha*) was found to be 32.58 %.

Table - 3 Observed data in performance of Biomass metallic portable cookstove

S. No.	Parameters	Values
1	Initial Weight of cookstove with fuel	6.868 kg
2	Weight of water taken	4.8 kg
3	Initial and Final Temperature of water	24 °C & 95 °C
4	Final Temperature of water in last vessel	40 °C
5	Calorific value of Wood (*Acacia Nilotica*)	19250 kJ/kg. °C
6	Calorific value of kerosene	35000 kJ/kg. °C
7	Density of kerosene	820.1 kg/m^3
8	Temperature of burning fuel	326 °C
9	Final Weight of cookstove with fuel	6.113 kg
10	Total fuel consumed for test	0.924 kg

The ambient temperature (32 – 36 °C), vessel (32 – 143 °C), handle (28 – 69 °C) and flame temperature (248 – 687 °C) were observed during performance.

The energy and exergy efficiencies were evaluated based on the water temperature using respective analysis and plotted against the heating time as in Fig. 3 and 4 respectively for each vessel and for the individual as shown in Fig. 5. It can be seen from Fig. 3 that the energy efficiency increased with time for the first vessel, where as it decreased first sharply and then slightly and again sharply for the last vessel (vessel 3). On the other hand, for second vessel (vessel 2) the energy efficiency first sharply decreased then gradually increased, attained its peak and then slightly decreased as the heating/boiling time increased. The Similar results were observed for the exergy efficiency with a slight difference than that of the energy efficiency for the second vessel (vessel 2) and it was found in the range of 4.5% to 7.5% which is observed from fig. 4. The overall average exergy efficiency was found to be 3.79 %.

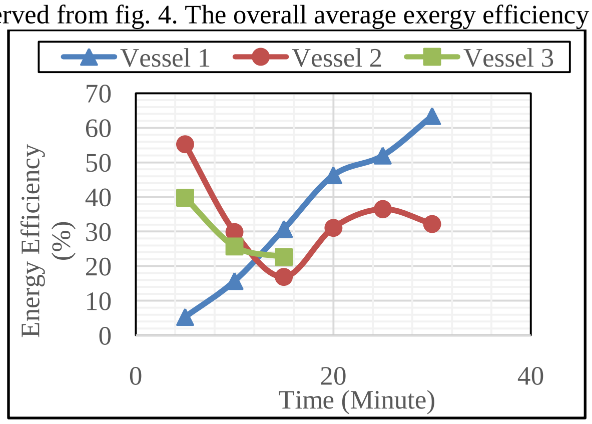


Fig. 3 Energy Efficiency vs. Time of different vessels for cookstove

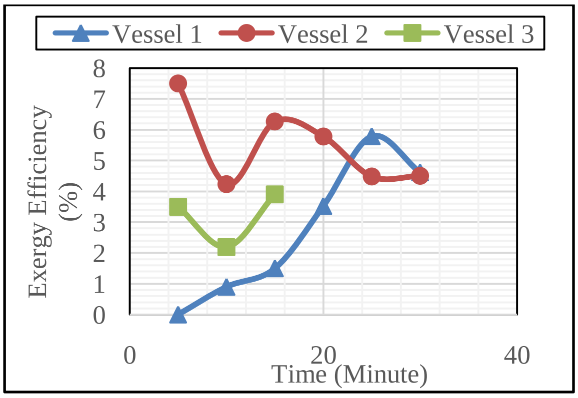


Fig. 4 Exergy Efficiency vs. Time of different vessels for cookstove

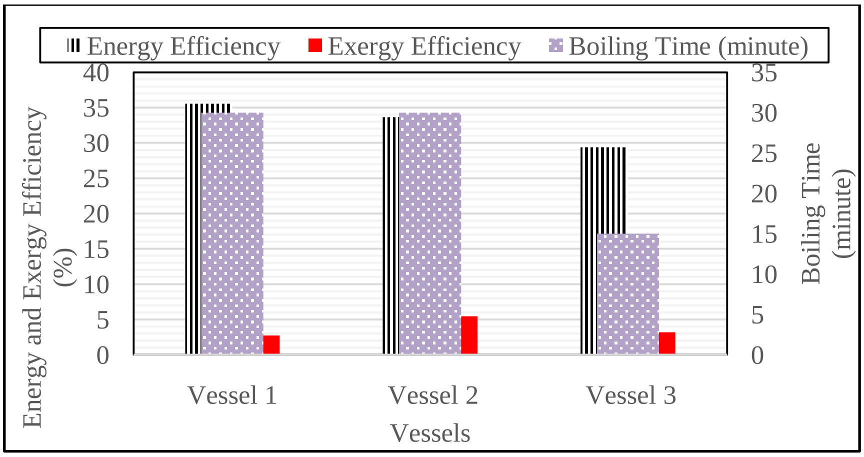


Fig. 5 Variation of efficiencies and time for different vessels in the Cookstove

TECHNO ECONOMIC ANALYSIS OF COOKING SYSTEMS

The techno-economic analysis of renewable based cooking systems was calculated in the term of Net Present Value (NPV), Payback Period (PP) and Benefit cost ratio. These parameters were found with respect to conventional fuel i.e. LPG. It gives techno-economic feasibility of systems.

Table - 4 Specifications recorded and consider for Techno Economic Analysis

	Cooking Devices Used		
Dimensions	**Box Type Solar Cooker**	**Biogas Burner Stove**	**Biomass Cookstove**
Capital Cost (Rs.)	3500	950	4200
Repair and maintenance cost (%)	5	5	5
Discount Rate (%)	10	10	10
Life span (years)	5	2.4 (3000-4000 working hour)	5
Number of Days food can be cooked	300	365	365
Fuel saved per day (with respect to LPG) Rs/day.	15.57	7.10	10.92

The Net Present Value or Net Present Worth for the systems was calculated on the basis of present investigation and the interest rate considered for the system and the profit achieved in year. A box type solar cooker, biogas burner stove and biomass metallic portable cookstove were taken for calculation of NPV/NPW. With respect conventional cooking system i.e. LPG stove.

Table - 5 NPV, PP and BCR of Renewable based Cooking Systems

Renewable energy based cooking systems	**Net benefit from conventional fuel LPG**		
	NPV (Rs.)	**PP (Years)**	**BCR**
Box type Solar Cooker (Portable)	13494.9	0.77	1.33
Biogas burner stove RUPAK	4239.76	0.37	2.72
Biomass metallic portable cookstove (DattuChulha)	10072.65	1.11	0.949

Table 4 shows the Net Present Value of box type solar cooker was found to be higher than that of biomass cookstove and biogas burner stove. The Payback Period for the systems was calculated on the basis of capital cost of systems and the discount rate considers for the system and the profit achieved in year. A box type solar cooker, biogas burner stove and biomass metallic portable cookstove were taken for calculation of Payback Period (PP) with respect to conventional cooking system i.e. LPG stove. Table 4 shows the Payback Period of biomass cookstove was found to be highest than that of box type solar cooker and biogas burner stove. The Benefit Cost Ratio (BCR) for the systems was calculated on the basis of net benefit of system with respect to conventional system i.e. LPG and the total cost of the system. Table 4 shows the Benefit cost Ratio of biogas burner Stove which was found to be higher than that of biomass cookstove and box type solar cooker.

The techno-economic analysis of different renewable based cooking systems was calculated and the result shows that higher the benefit cost ratio will lower the net present value and payback period. From selected systems biogas burner stove shows the similar result which are tabulated in Table 5.

Findings

1. The selected different renewable based cooking systems were studied according to BIS standards.
2. The first figure of merit and second figure of merit was found that 0.11 and 0.58 respectively. The thermal efficiency of box type solar cooker was obtained as 26.89% and 2.61 % was the exergy efficiency.

3. The thermal performance of biogas burner stove was calculated in term of energy efficiency and exergy efficiency and found to be 54.18 % and 3.18 % respectively.
4. The heat produced by cookstove was calculated as 10018.464 kJ, and heat utilized for water boiling as 3264.11 kJ. The thermal efficiency was found to be 32.58 %.
5. The overall average exergy efficiency for biomass cookstove was found to be 3.79%.
6. The energy payback time of cooking systems was calculated with respect to embodied energy and found that the biogas burner stove shows higher time i.e. 5.41 years than that of box type solar cooker and biomass cookstove which shows 4.08 years and 1.40 years respectively.
7. The Net Present Value (NPV) was compare with conventional fuel (i.e. LPG-Stove) and was found that box type solar cooker as Rs. 13494.9 which was higher than biogas stove and biomass stove as Rs. 4239.76 and Rs. 10072.65 respectively.
8. The payback period with respect to LPG-stove; resulted that biogas burner stove was found to be lower as 0.37 years than that of solar cooker and biomass cookstove as 0.77 years and 1.11years respectively.
9. The benefit cost ratio of biogas burner stove was found higher as 2.72 than that of solar cooker and biomass cookstove as 1.33 and 0.949 respectively, by comparing with LPG-stove.

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