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Performance Studies of a Multipurpose Solar Energy System for Remote Areas

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ABSTRACT

Energy consumption for cooking, water heating, drying, heating and cooling of buildings, and water distillation in this developing world is a major component of total energy consumption in various households and commercial sectors. Demands and prices of fuels are increasing day by day. As an alternative fuel solar energy is a good option to utilize for various heating and cooling applications. Almost countries are using solar energy devices for the above mentioned activities through an individual component like, solar cooker, water heater, dryer, air heater, and solar still etc. A Multipurpose Solar Energy System (MSES) has been designed and fabricated especially for domestic use or for remote areas. All the experiments have been conducted in the climatic conditions of Moradabad (latitude -28058/ north and longitude - 78047/ east). MSES is proven a good alternate solar Combi-system for heating operations in a simple household. The obtained efficiency of the MSES is 29.21% with a payback period of 2.88 years, which is discussed with ecological and economical benefits of HSES.

Keywords*:* Solar energy, Hybrid system, Energy consumption, Performance testing.

1. INTRODUCTION

The burning or combustion of fossil fuels for heating operations introduces many harmful pollutants into the atmosphere and contributes to environmental problems like global warming and acid rain. Solar energy is an optimum solution as an alternate fuel and absolutely non-polluting, free of cost, and present in huge amount of the earth. The working principle is straightforward; the collector simply collects the radiation that falls on it and converts a fraction of it to other forms of energy [1]. Solar energy has been continued to utilize by various countries since 1900's. In the present era a variety of the techniques are there, to utilize solar energy in various aspects of households and commercial sectors. Cooking, water heating, desalination, power generation, heating and cooling of buildings, even lightening now can be operated on solar energy in different households and commercial sectors worldwide [2-6]. Although separate solar energy devices are individually capable for the principle purpose like; cooking and drying etc. Apart this, it has been noticed that specially designed hybrid solar energy systems (multipurpose devices or a combination of different devices) not only reduce the humanitarian efforts, but saves time, fuels, and provides economical and ecological benefits to its user as well as to the society. Likely systems are very beneficial to various societies in this present time, when the demand for oil and fuels is rapidly increasing with each new day. The use of the solar energy was started in the beginning of 1800's and it is continued to optimize the problems associated with heating and cooling processes. In the past an individual device/system was used for the purpose of cooking and other heating tasks. Later on some pioneers optimized their designing characteristics and designed them as a multipurpose device/system for heating and cooling operations [7-10].

Goyal et al. has been developed a techno-economic model for a hybrid solar forced- convection water heating system by considering two options (first was an instant electric heater while the second was the use of diesel as the auxiliary energy fuel). Calculations were made equivalent to the two envoy demand patterns, viz. (i) Hot-water demand of big residential buildings and (ii) industrial hot-water demand. Taking into account the life and all investment costs of the solar and auxiliary systems, the cost of useful energy was calculated for different values of collector area and tank capacity. The effect of subsidies on the optimum values of the collector area, tank capacity and the minimum cost of the useful energy was also discussed [11]. Nandwani designed a hybrid solar oven (electric cum solar oven) and described the working. This oven could be used for cooking and baking almost all types of meals at any time during the year employing solar and/or electric energy. The quality of the system was that it can be automatically switched from solar to electric energy when required [12].

Choudhury and Garghave been carried out the simulation study of a forced-circulation solar hybrid domestic hot water system that circulates air through a rock-bed air heater and employs an external air-to-water, transverse fin, shell-and-tube heat exchanger to transfer heat from the air to the water without the use of any auxiliary power. The performance was evaluated to the hot water demand of 4-person residential building. In addition, the study was extended to compute the pumping power expended in air and water circulation throughout the system [13]. Stahl et al. has built a self-sufficient solar house in Freiburg. The total energy demand for heating, electricity, and cooking was supplied by the sun. The combination of highly efficient solar systems with conventional means to save energy was the key to the booming operation of the house. The energy for electricity and hydrogen generation was supplied by solar cells. Hydrogen would be reconverted to electricity with a fuel cell or used for cooking [14].

Buildings integrated with *PV* systems presented compensation with respect to the non-integrated systems including reduced infrastructural asset, and lower cost for design and installation. Fuentes presented prelude results from the first 9 months of monitoring the Oxford solar house that was built, in particular, to evaluate the potential for *PV* to contribute cost effectively to domestic energy supply in the UK. It had a 4kW, *PV* system integrated into the roof structure and a $5m^2$ solar thermal domestic hot water. The house was designed to require a least of energy for heating, cooling and lighting [15]. Voss et al. has been explained to η_{exergy} as the key to buildings with reduced environmental impact. The combination of that approach with active and passive solar energy utilization could be lead to purchase energy demand close to zero. Highly efficient solar systems were combined with a hydrogen-based seasonal-storage system. Long-term storage of low-temperature heat was avoided by extensive passive solar energy utilization [16].

Tiwari et al. has been presented a new design of thin layer bed crop drying cum water heater and analyzed for making the whole system operate throughout the year. Energy balance equations for each component of the system were used to predict the analytical results. An additional mirror booster was used to enhance the intensity of heat energy. The water heater below the air heater systems will suppose to be acting as a storage material for drying the crop during off sunshine hours [17]. Nandwani have been made a solar hot box with 2 similar cabinets. It was used for, (i) comparing the behavior of a metallic slab filled with a PCM for short term heat storage (ii) the use of a selectively coated, as compared to a normal black painted, cooking pot, and (iii) for finding the U_L and thermal capacity of the box. Besides its use for research, the multipurpose device was used both to pasteurize up to 14-16 liters of water and for cooking [18], beside this he also designed a hybrid food processor that can be used for cooking, heating/ pasteurizing water and distillation of a small quantity of water and drying domestic products. After using it more than 3 years, the author found that to be a useful device, mainly for convenience, fuel saving, economical and also from an ecological point of view. The device could be used at any time with a backup of auxiliary power [19].

Kumar and Tiwari have designed and tested a new self-sustainable hybrid PV/T integrated active solar still. The *PV* system was used to generate electricity to run a pump (60W and 18V) heat the water in the collector. The proposed design of hybrid solar still could be used at any remote location because of its self-sustainability. It was observed that the hybrid solar still gives a higher yield than the passive solar still. Beside this, the daily distillate yield and η_{therm} of the hybrid solar still remain almost the same for all water depths in the basin by reducing the daily running period of the pump from 9 to 5 hours. The η_{exergy} of passive solar still varied from 0.4 to 0.5%, and varied from 2.24 to 2.6% in active mode with the increase in water depth [20]. N. Kumar et al. has been designed a truncated pyramid type solar cooker. It was designed for multipurpose owing the geometry of design rays hitting inside the cooker (walls) were reflected with high intensity to downwards a higher temperature was maintained at the absorber tray (bottom side). By making an increment in the depth of the cooker the device acts as a dryer for the domestic or homely purpose [21]. Wang et al. has been proposed a new combined cooling, heating and power system to be operated on solar energy. The effects of hour angle and the slope angle of the aperture plane for the solar collectors on the system performance were examined by applying genetic algorithm to find the maximum η_{exergy}. The system was reached the maximum η_{exergy} of 60.33% under the conditions of the optimal slope angle and hour angle [22].

Kumar and Tiwari have presented the life cycle cost analysis for a single slope passive and hybrid PV/T active solar stills. Effects of different parameters like, interest rate, life of the system and the maintenance cost were taken into account. The comparative cost of distilled water produced from passive solar still was found to be less than a hybrid PV/T active solar still for a 30 year lifetime. The PBP's of the passive and hybrid PV/T active solar still were estimated to be in the range of 1.1-6.2 years and 3.3-23.9 years, respectively, while the energy PBP was estimated at 2.9 and 4.7 years, respectively [23]. N. Kumar et al. has been fabricated and tested a truncated pyramid geometry based multipurpose solar device that was used for domestic cooking and water heating. Cooking tests followed by B.I.S., were performed in different seasons and the device was found to meet the requirement set on 2 figures of merit [24]. Kumar et al. has developed an empirical relation to estimate the glass cover temperature for known values of water and T_{amb} in basin type hybrid PV/T active solar still. The relation was based on outdoor experimental results of water and T_{amb} in the range of 14°C to 92°C and 14°C to 36°C respectively. The proposed glass cover temperature was obtained with a maximum relative error of 1.12% compared to the value obtained through a numerical solution while the highest relative error in the evaporative mode of energy transfers from water surface was 1.2% [25].

2. DESIGN AND FABRICATION

The design deals with a simple and systematic arrangement for water heating, drying and cooking activities. By utilizing solar energy, this system is specially designed to reduce the manual efforts which are carried to handle dissimilar devices for cooking and other heating tasks in domestic zone. The overall dimensions of the MSES are, 184 × 122 × 44 cm^3, (this dimension is sub-divided into size of four individual components) while for the basin of the still aperture area is 112 × 61.6 cm^2, for the dryer aperture area is 76 × 60 cm^2, for open sun dryer aperture area is 112 × 42 cm^2 and for solar cooker it was 48 × 68 cm^2 for the bottom one. The frame of the system was made of galvanized iron and rectangular in shape at a height of 50 cm from the ground level. Four castor wheels are provided in the bottom end of frame support for the movement or place accordingly to track the sun. To prevent heat losses, glass wool was used as an insulator and inserted (2 mm thickness) in between the system's boundary and the aluminum casing sheet enveloped to the system. PVC pipes were used to drain and supply water to solar still cum water heater.

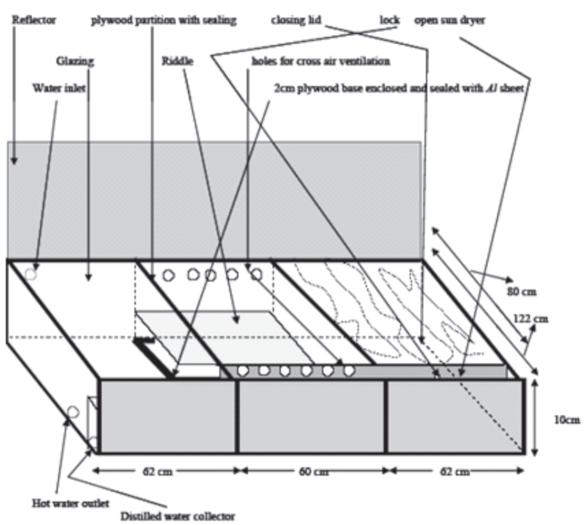

Figure 1: Schematic of HSES

All the components of MSES are completely separated by 2 cm thick plywood sheet. Same plywood was fitted in the bottom of the solar cooker and the dryer section, except solar still. An aluminum (Melting point -988 k, density -2706 kg/m^3, specific heat – 903 J/kg.k, thermal conductivity – 237 W/m.k) sheet of 2 mm thickness was fixed (rolled) all over inside the system and painted dull black for a good amount of heat stored. A riddle was used (1mm thickness) at a height of 5 cm from the bottom of the dryer to remove heavy water particle or moisture. Beside this, for the high rate of drying, small holes of 2 mm diameter for cross air ventilation, at a height of 40 cm, were provided while same at closing and the opposite side (made of 1.2cm of thermacole sheet) at a height of 18 cm from the bottom of the dryer. In the case of solar cooker, the side walls were trapezoidal shaped to expose to sun for better heat storage [26]. The cooker was single glazed with a pane of 2 mm thickness float glass as well as the whole system was i.e. MSES. The inner absorber tray was designed particularly for good sensible heat storage [27] and a rubber gasket of 1.5 mm thickness was placed in opening lid to make leak proof. Apart this, a high intensity planar reflector, 184 × 75 cm^2 of corrugated lacquered aluminium [28] was used to enhance the efficiency of the combined components of the system. The system was placed towards the south orientation [29], while the slope of the glazing for the whole system was 15^o. For the proper fixing (fitting) of the aluminium sheet to the walls and bottom of system a 1 mm diameter screws were used in the zigzag form. A good adhesive "M-Seal-trademark" was used to make the whole system leak proof. Various other design parameters and efficiency improving techniques has been studied and consider for making of MSES [30-33]. All the materials to fabricate the system were available locally at reasonable rates.

3. PERFORMANCE TESTING OF MSES

A solar still is a very simple way of distilling water, which is powered by the heat energy from the sun. Impure water is inserted into the container, where it is evaporated by the solar energy through transparent glazing (plastic sheet or toughened glass). The pure water vapor condenses on top and drips down to side due to a slope of glazing and then it is collected and removed. Solar still consists of an insulated black painted aluminum pan where impure water stands at shallow depth. The slope glazing was supported by an appropriate frame at a certain height usually less than the opposite one, covers the pan and is sealed tightly with an adhesive to make the system leak proof. During the water heating process inside the cabinet the water gets evaporated and due to this the salts and microbes present in the original water are left at the rear. After this condensed water trickles down the inclined glass cover to an internal assortment trough and out of a storage tank [35].

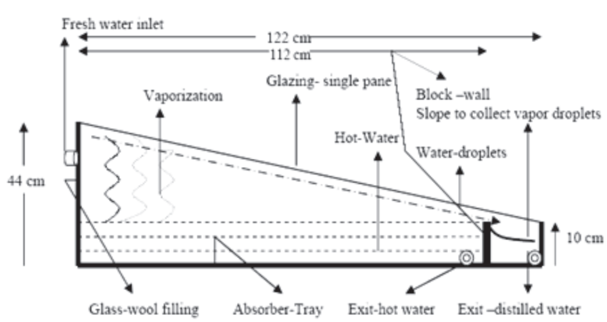

Figure 2: Schematic of solar still cum water heater

The performance testing of the first component of MSES (solar still cum water heater) has been carried out on a sunny day (05.03.2012) in the month of March. Heat energy from the sun was permissible into the collector to heat the water in single slope solar still block. The water evaporates only to condense on the underneath of the glass. When water evaporates, only the water vapor rises, leaving contaminants behind the slope of the glass directs the condensate to a collection trough (see in Figure 2), which in turn delivers the water to the outlet of the system then to a collection bottle scaled with liters.

The basin area of the still was 112 × 61.6 cm^2. The vertical heights of the outer glass cover of the still were 44 cm and 10 cm with a slope of 15° along the breadth of the still. The height of the water inside the still was maintained at 9 cm by an auto flow arrangement above this height. A trough was placed to collect distilled water on the separation wall of still as in figure 2. The hot water inside the still was used for the dual purpose, as inside the chamber it was continued to phase change (evaporation) as well as the water was heating, that can be taken for cooking purpose for the 3rd component of the MSES. Definitely the use of pre hot water reduces the time taken for cooking and can be used for other works like drinking (in cold season) and washing. Water, glass and vapor temperatures were recorded with the help of calibrated copper constantan thermocouples and a digital temperature indicator.

The thermal performance of a basin type solar still is usually based on the model proposed by Dunkle, in which a heat balance on the basin water, and on the cover glass, while a convective, radiative, and the evaporative heat transfer was established between water and glass. The energy balance equations for different components such as glass cover, water mass and base liner of a single slope passive solar still are [36-37];

Glass cover

$$h_{iw} (T_w - T_g) = h_{ig} (T_g - T_a) \quad (1)$$

Water mass

$$\alpha'_w I(t) + h_w (T_b - T_w) = (MC)_w \, .dT_w/dt + h_{iw} (T_w - T_g) \quad (2)$$

Basin liner

$$\alpha'_b I(t) = h_w (T_b - T_w) + h_b (T_b - T_a) \quad (3)$$

The thermal behavior of the solar still cum water heater has been identified by calculating hourly productivity of the solar still and the $\eta_{overall}$,with the help of two major heat transfer models of thermal modeling of solar stills [37-38]. It has been observed through the literature survey that most experiments are conducted to a solar energy device like solar still, results in measured efficiencies greater than the theoretical ones and the predicted performance based on the efficiency and heat losses obtained through experimental testing. Hence for each individual component of the MSES, the calculations are made to obtain instantaneous efficiency. Following equations are used to calculate the efficiency of the still and other related parameters [39-41].

[*Values obtained from calculations, by using above theory, are taken on an average for a particular day of the experimental testing, as for, evaporative heat transfer coefficient,* h_{ewg} *= 16* $W/m^2 °C$*, Latent heat of vaporization of water, L =2260 kJ/kg,* A_p *is the aperture area of the basin liner, and* I_g *is the solar radiation intensity incidental on the glass cover, I = 714* W/m^2*,* T_{wat} *- temperature of water,* T_{igt} *-temperature of inner glass,* T_{ogt} *-temperature of outer glass cover,* m_w*- mass of distilled water,*α'_b *= Fraction of solar energy absorbed by blackened surface* α'_w *= Fraction of solar energy absorbed by water mass*].

Table 1: Performance parameters of solar still cum water heater

Time (Hrs)	I (W/m^2)	T_{wat}°C	T_{igt}°C	T_{ogt}°C	T_{amb}°C	Ws (m/s)	O/P (ml)
10.00	660	46.1	40.5	32.0	27	3.01	142.68
11.00	690	53.1	46.1	34.5	30	2.98	178.36
12.00	700	58.2	51.2	36.8	32	2.76	178.36
13.00	710	62.4	54.5	39.7	34	3.06	201.12
14.00	740	65.9	55.7	41.2	37	3.09	259.95
15.00	800	68.6	57.7	44.2	39	2.81	277.73
16.00	750	66.3	56.3	43.1	38	2.98	254.86
17.00	730	63.7	53.3	42.3	36	3.09	264.99
18.00	720	61.6	50.8	37.2	31	2.95	275.24
19.00	680	52.9	45.4	32.3	28	3.11	191.1

The values obtained, after making calculations for the distilled water daily output was observed 2.41 liters per day that was measured through a scale marked bottle (in liters) after finishing of the test at 19.15 hrs of the same day. The overall efficiency of the first component of the MSES (solar still) was obtained 31.5%. The quality of the distilled water was checked through two different TDS meters for pH value ((Model-CD600 range 10/1990) and Ppm value (Model-pH600 range 0.0 to 14.0 pH) which were measured at 100 and 8 respectively.

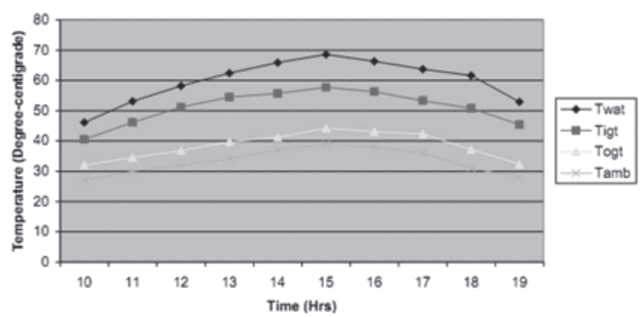

Figure 3: Performance curves of solar still cum water heater

During the conduction of experiments, the temperature of hot water inside the solar still cum water heater was noted for a maximum value of 69°C, which is a good value to initiate the cooking in the third component of MSES. Because, we are using already pre-heated water for cooking it is obvious that the solar cooker will definitely reduce a little amount of time spent on cooking in it (discussed in section 3.3). Beside this, this pasteurized water can be used for washing of vegetable and fruits before drying, for which the hot water is not required. This water can also be used for drinking purposes in the cold climates or other works as to make tea and soup, if the supply of water to the inlet of the solar still cum water heater is fresh.

4. TESTING OF THE SECOND COMPONENT (DRYER) OF MSES

Drying is the oldest method of food preservation and solar food dryers are an appropriate food conservation technology for a sustainable world. By reducing the moisture contents of substance to 10% to 20%, bacteria, yeast, mold, and enzymes are all prevented from spoiling it. During the drying of substance the means is to remove moisture or heavy water particles as quickly as possible at a temperature that does not seriously affect the flavor, texture and color of the food. The flavor and most of the nutritional values are preserved and concentrated. Vegetables, fruits, meat, fish, and herbs can all be dried and preserved for more than a few years in many cases. Solar dryers have the same basic components as do all low temperature solar thermal energy conversion systems [41-42]. Solar dryers can be classified into two major groups, namely:

1. Active drying systems (hybrid solar dryers).
2. Passive drying systems (natural-circulation solar dryer).

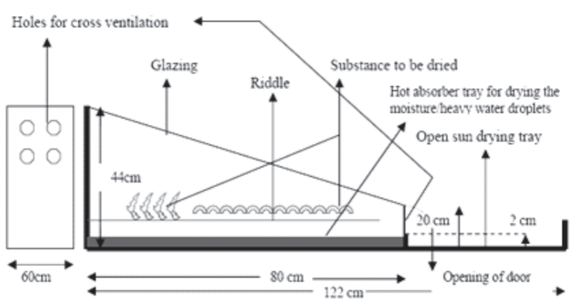

Figure 4. Schematic of solar dryer

Natural convection type solar dryers significantly reduce drying time compared to open air sun drying, but their quite small holding capacity is a major constraint. In these solar dryers, air movement is due to natural circulation. Substances get heated due to direct absorption of heat or due to high temperature in the enclosed space and then moisture evaporated from the substances, escapes out of the chamber by natural circulation of air [43-44].

In HSES, the second component is solar cabinet dryer, which operates on natural convection mode of heat transfer. In this component, a riddle of size 76 × 60 cm^2 has been inserted through a sliding arrangement at a height of 5 cm from the base of the system, to make the removing as well as inserting of it easily. A sensitive balance with the range of (0-1000 grams) and sensitivity of ±1.5% is used for weighing purpose of substance to be dried. For the performance testing of the solar cabinet dryer, potato slices and bread slices were used on different days. The testing procedure was conducted on a typical summer day in the month of May on 10.03.2012. To calculate the efficiency of this component via air mass flow rate [45-46] and the air velocity inside and outside the dryer chamber, a good sensitive hot wire anemometer with an accuracy of ±1% was used to measure these values.

Thermal performance evaluation of a solar collector is momentous for its fascinating. This is associated with its thermal efficiency, and defined as the ratio of the useful energy of the incident solar radiation, for solitary period. This useful energy is closely linked to the thermal losses of the device and its surroundings, resulting from different modes of heat transfer. In the steady state, a solar dryer thermal performance is expressed by;

$$\eta = Q_u/A_cI_t = F_R\,(\alpha.\tau) - F_RU_L\,[(T_i - T_\alpha)/I_T] \quad (6)$$

$$F_R = m.C_p/A_cU_L\,[1- e^{\,AcULF'/m.Cp}] \quad (7)$$

Where, the average overall heat loss coefficient (U_L) based on the aperture area for the dryer is obtained (at no load) equals to 14.62 W/m^2K, by using Equation (8):

$$I\,(\alpha.\tau) = U_L\,(T_s\text{-}T_a) \quad (8)$$

The system drying efficiency is calculated from the ratio of the energy required to evaporate the moisture of the commodity to the heat supplied to the drier and noticed equals to be 27.5% on the hourly average basis, by equation (9). For evaluating the performance of component second of HSES, one kilogram of thin potato slices, with 75% initial moisture contents are used as a substance to be dried, while final moisture contents required to be equal to 13%. The total time taken for the complete drying of the potato slices is observed 62 hours, while the dryer was operated 7 hours of good sunshine per day.

$$\eta_d = w.l/A_c.I \quad (9)$$

[Where, w (moisture evaporated) = 0.04 kg, *l* (Latent heat of vaporization of water) = 2260 $kJkg^{-1}$, I = I_{avg} = 722 w/m^2, transmissivity -absorptivity product = 0.9 × 0.9 = 0.81, A_c aperture of dryer].

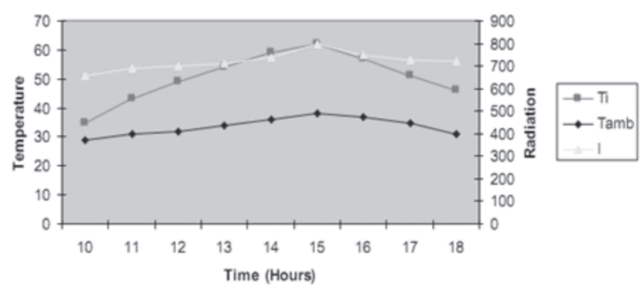

Figure 5: Performance curves of solar dryer

In this type of cabinet dryers there are some limitations towards its operating ranges such as; its small capacity with a limited use to small scale applications. Streaking of, substances due to direct exposure to the solar heat intensity (radiation) and moisture condensation inside is glazed reduces its transmittivity that affects the moisture removal rate. Beside this, there is a restricted use of selective coatings on the absorber tray (collector) [47].

5. TESTING OF THE THIRD COMPONENT (COOKER) OF MSES

Cooking is the prime need of all human beings globally and the use of the cooking fuels (LPG, Kerosene, electricity, fuel-wood and agricultural waste) along with different cooking devices (LPG burner, kerosene stoves and traditional chulhas), typically depends on particular household incomes. A large variety of cooking devices are used in India based on prevailing climatic conditions and the socio-economic settings. Traditional low cost cookstoves are widely used for cooking and other heating activities by rural people, which have very low thermal efficiencies and are extremely polluting. Solar cooking is an optimum solution to minimize these problems by its easy operation and eco-friendly nature. Several types of the solar cookers are available in the markets like solar box cooker, solar parabolic cooker and solar ovens among which the box type solar cooker is used mostly. By providing good subsidies, various state governments of different countries are promoting solar cookers and other solar energy devices. The use of different types of solar cookers [30], for cooking purposes is spreading widely in this developing world particularly in villages and remote areas.

In the current hybrid system, the third component is a solar box cooker. Two parameters have been recommended to evaluate the performance of a box-type solar cooker by American Society of Agricultural Engineers in 2003. These are the F_1 (first figure of merit), and F_2 (second figure of merit). The first figure of merit depicts optical efficiency and is the ratio of optical efficiency to heat loss factor; it is evaluated by a stagnation test without load (no substance placed inside the cooking pots). The second figure of merit, F_2, gives an indication of the heat-exchange efficiency factor and involves heating of a full load of water (inside the cooking pots). Beside this the cooking power of solar cooker was also discussed and can by calculated by equation (13). The performance testing of the solar cooker (3^{rd} component of MSES) is carried out on both conditions i.e., on load and no load. Two performance evaluating parameters F_1 and F_2 [48-49], are obtained at 0.12 and 0.56 respectively after conducting the experiments. The efficiency of the cooker was observed 34% [50] in the ambient conditions of Moradabad. 1 kg of fresh water was used as a cooking substance in two modified and similar cooking vessels [51]. Readings of experiments were taken at every 20 minutes while total testing time was one hour, followed by ASAE standards [52]. The key feature of this component is its highly sensible storage tray (absorber plate) [27]. The testing results obtained from this component were for a particular day 15.03.2012. All the values for performance rating are obtained by using the following equations. It was noted that the performance of this component was found satisfactory for cooking, during good sunshine hours i.e., between 12.20 to 14.40 hours. A six wire thermocouple meter was used for temperature measurement while solar intensity was measured from solarimeter.

$$\frac{539 \times 9.81}{10.97 \times 3.04} \tag{10}$$

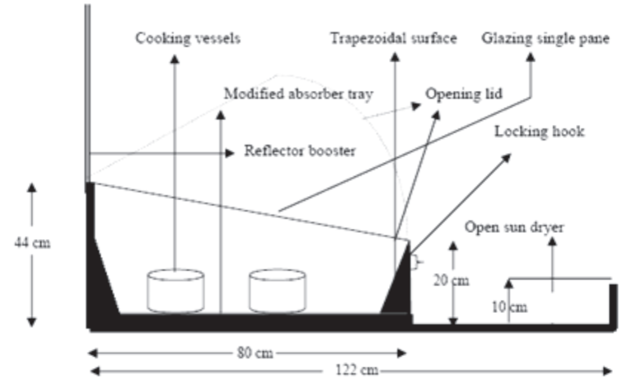

Figure 6: Schematic of solar box cooker

$$F_2 = \frac{F_1(MC)_w}{At} \ln\left[\frac{1-\frac{1}{F_1}\left(\frac{T_{w1}-T_a}{H}\right)}{1-\frac{1}{F_1}\left(\frac{T_{w2}-Ta}{H}\right)}\right] \tag{11}$$

$$\eta = MC\Delta T / A.H.\ \tau \tag{12}$$

P_i (*cooking power*) = $M.C_v$ [T_2 (*final water temperature*) –T_1 (*initial water temperature*)]/600 (13)

[*Where,* $T_p = T_{stag}$ *= stagnation temperature,* T_a *= ambient temperature,* $I = H_s$ *= insolation on a horizontal surface, M = mass of water, C = heat capacity of water, A = aperture area, t = time,* T_{w1} *= water temperature at the initial state,* T_{w2} *= water temperature at final state =* T_{wat}*, H = horizontal insolation (average), τ – time taken in testing = 3600 seconds*]

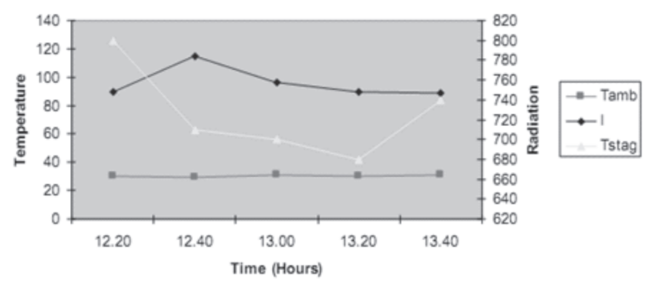

Figure 7: Performance curves of solar cooker at no load

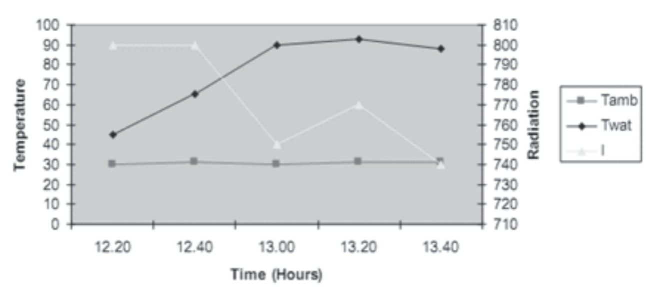

Figure 8: Performance curves of solar cooker on load

On the other hand, to estimate the savings of time by using preheated water (near about 60^{o}C) for cooking, two similar cooking vessels, A and B, were taken for the purpose. One was carrying a, 250 grams of thin potato slices with pre hot water (near about 60^{o}C), while another one was carrying same substance with fresh water (near about 20^{o}C). At the early start of cooking, both the vessels, A and B, were placed at the same time in the box cooker in ambient conditions of 32^{o}C and in insolation of 715 W/m^2. After 90 minutes vessel A, was found with a good ripped substance, while vessel B was taken 105 minutes for that to be a good quality rip from the starting of operation. A total time of 35 minutes was notified in the form of savings by using pre hot water with 250 grams of substance to be cooked.

6. TESTING OF THE FOURTH COMPONENT (OSD) OF MSES

Last one component of the MSES, is a solar open dryer. Open sun drying is the most commonly used methods to preserve agricultural products like grains, fruits and vegetables in most developing countries. Such drying under intimidating climate conditions lead to severe losses in the quality of the dried product [53]. Open sun drying suffers from quality considerations still it enjoys a cost advantage. Selection of the right drying system is thus important in the process of drying agricultural products.

Basically, to use the ideal space of the MSES, this was agood option to utilize the extra portion gap, by bringing it to a utilizing form or gain some useful work and hence it has been utilized as an open sun dryer. The size of this component is 42 × 112 cm^2. The hole of 2mm diameter, are provided for ventilation in absorbing tray, while a strong and rigid support is already provided to bear up the load for 2 to 5 kg or accordingly nature of the substance to be dried. The testing of this component was simply carried out by using the using the weight loss method through the sensitive balance apparatus. Open sun drying sample was weighed every two hours on the first day of drying and every one-hour the next day, to measure the moisture content.

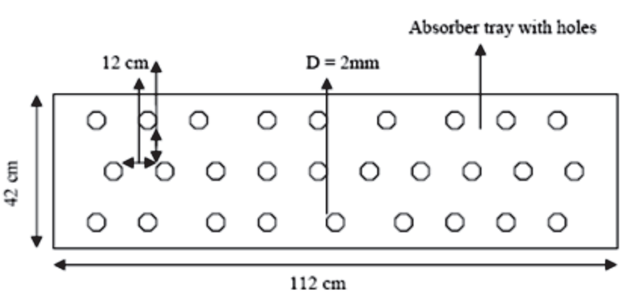

Figure 9: Cross section of open sun dryer

Under the open sun drying it was observed that the maximum moisture evaporation took place in 1-8 hours of drying time. This is due to the higher moisture existing at the start of drying and the process utilized the solar concentration for evaporation. Therefore, the temperature of the substance did not rise much more than ambient due to the cooling effect by evaporation of the moisture. During the night hours the temperature of the substance remained very close to ambient and less moisture evaporation took place. Beside this, a float glass was used to cover it, to escape it from moisture (contents present in the air), in the night hours. For the testing of the fourth component [54-55] a half kg green chilies were taken to be dried. The temperature of the absorber plate of open dryer was almost near about ambient temperature due to open to the environment. The energy balance equation on the crop surface for the moisture evaporation in open environment can be expressed by;

$$\eta = Q_u/A_cI_t = F_R\,(\alpha.\tau) - F_RU_L\,[(T_i - T_\alpha)/I_T] \tag{14}$$

$$\alpha I\,(t)A_t - h_{rc}(T_c\text{-}T_e)A_t - 0.016h_c\,[P(T_c)\text{-}\gamma \wedge AI\,P(T_e)]A_t - h_i\,(T_c\text{-}T_a)A_t = M_cC_c \wedge AI\ f \tag{15}$$

Energy balances equation of moist on air above the crop

$$M \wedge c - \wedge M_t + 0.016/h_c\,[P\,(T_c) - \gamma P(T_e)]A_t = h_2\,\{T_s\text{-}T_a\}\,A \tag{16}$$

Moisture evaporated can be evaluated as

$$m_{ev} = 0.016/\wedge h[P\,(T_c) - \gamma P(T_e)]A_t \tag{17}$$

[*A_t -area of tray (m^2), h_{rc}-radiative and convective heat transfer coefficients from crop surface to environment (W/m^2°C), P(T) -partial vapor pressure at temperature T (N/m^2), T_c -crop temperature (°C), T_e -temperature above crop surface (°C), M_c -mass of the crop (kg), I(t) -solar intensity (W/m^2), m_{ev}-moisture evaporated (kg), h_c-convective heat transfer coefficient of crop (W/m^2 °C), h_i-convective heat transfer coefficient from crop to air (bottom loss) = 5.7 (W/m^2°C), h_2-convective heat transfer coefficient due to wind = 5.7 + 3.8V (W/m^2°C), Q_e -rate of heat utilized to evaporate moisture (J/m^{2}s)*]

Average drying rate, *D* [kg/s], is determined from a value of 0.05 kg/sec, from the mass of moisture to be removed by solar heat and drying time by equation (8), [56].

$$D = m/\tau_d \tag{18}$$

[Where, D- drying rate, τ_d – time taken in drying]

Apart this, another test was conducted with a less moisturizing containing substance. A, 400 grams (initial weight) bread slices were taken to be dried in open sun energy. After placing them in the open sun dryer for 8 hours (from 10.00 am to 18.00 pm) of full sunshine, their final weight was noticed to be 290 grams. The quality of the dried products in hybrid drying notably improved compared to open sun drying as well as solar drying due to the fact that drying was uninterrupted until the final moisture content was attained. This eliminated possible moisture re-absorption and mould growth during overnight storage of the product during open sun drying and solar drying. Traditionally, farmers used the open-to-the-sun or natural drying technique, which achieves drying by using solar radiation, ambient temperature, relative humidity of ambient air, and natural wind. In this method, the crop is placed on the ground or concrete floors, which can reach higher temperatures in open sun, and left there for a number of days to dry. Capacity wise, and despite the very rudimentary nature of the process, natural drying remains the most common method of solar drying. This is because the energy requirements, which come from solar radiation and the air enthalpy, are readily available in the ambient environment and no capital investment in equipment is required. The process, however, has some serious limitations [57-58].

In the open sun drying, there is a considerable loss due to various reasons such as rodents, birds, insects and micro-organisms. The unexpected rain or storm further worsens the situation. Further, over drying, insufficient drying, contaminated by foreign material like dust dirt, insects, and micro-organism as well discoloring by UV radiation are characteristic of the open sun drying. In general, open sun drying does not fulfill the international quality standards and therefore it cannot be sold in the international market. With the awareness of inadequacies involved in open sun drying, a more scientific method of solar-energy utilization for crop drying has emerged termed as controlled drying or solar drying [59].

6. TESTING OF THE MSES AS A UNIT

There are so many methods, approaches and software are available to develop a model to evaluate the thermal performance of solar energy devices and likely systems [60]. But the most common method is to develop a thermal model by using energy balance equations to evaluate the thermal behavior of any solar thermal system. The testing of the MSES as a full unit has been carried out, after the performance evaluation of each one component as individually. To evaluate the whole system as a unit, tests are conducted on load and no load conditions. On no load condition, the system was operated ideal, so all the components were empty, while for on load test, 1 kg of water was placed in cooking vessels in the solar cooker, 1 kg of thin cylindrical slices of potato were placed on riddle inside the dryer cabinet as well as in the open sun dryer, and a 15 kg of water was filled in still cum water heater.

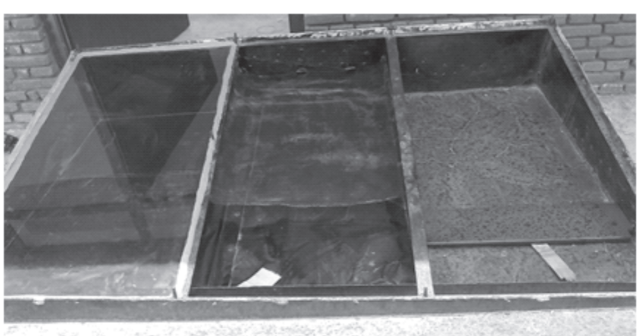

Figure 10: Frame cabinet of HSES during fabrication

To obtain the efficiency of MSES, energy balance equations are used and the system was operated at full sunshine hours from 10.00 to 17.00 hours. To get the whole system stagnation, the system was operated ideally, on no load. Three thermocouples were used to measure the stagnation temperature by placing them inside the component MSES1 (solar still), MSES2 (dryer), and MSES3 (solar cooker), while forth one wire was placed on absorber tray in the open sun dryer. Beside this, one wire was used to read out ambient temperature along with mercury in glass thermometer for comparison.

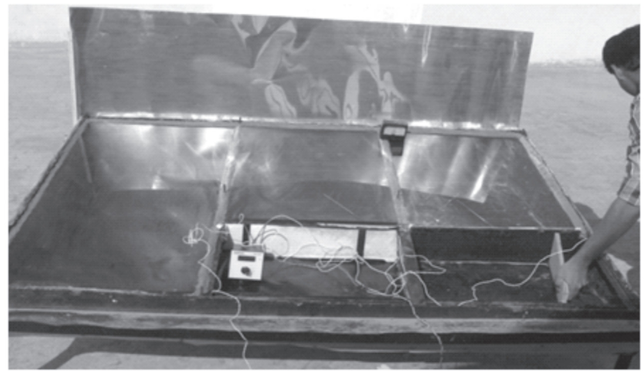

Figure 11: Performance testing of HSES

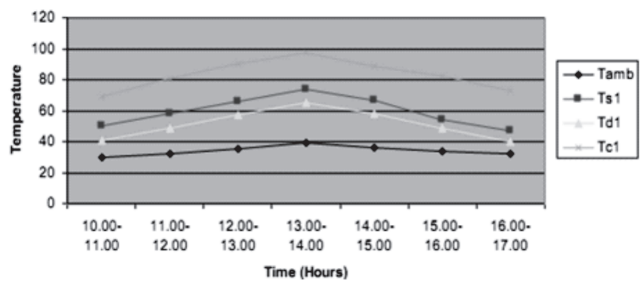

Figure 12: Performance curves of HSES at no load

The energy balance of the HSES is almost comparable to the normal solar energy device. The total energy input to the whole system due to the sun Q_s:

$$Q_s = Q_{loss} + Q_{use} \quad (19)$$

$$Q_{use} = Q_s - Q_{loss} \quad (20)$$

$$Q_{use} = I \times A_p \times (\tau\alpha) - A_p \times U_L \times (T_{ws} - T_{amb}) \quad (21)$$

$$Q_{use} = A_p \times [I \times (\tau\alpha) - \{I\,(\alpha.\tau)/(T_{ws} - T_a)\} \times \{(T_{ss} + T_{ds} + T_{cs})/3 - T_{amb}\}] \quad (22)$$

U_{loss} is the overall heat loss coefficient (W/m^2 ^{o}C) mainly due to conduction, convection and radiation. Experimentally we can also measure the useful energy by;

$$Q_{use} = (M.C.\Delta T)_{still} + (M.C.\Delta T)_{dryer} + (M.C.\Delta T)_{cooker} + (M.C.\Delta T)_{osd} \quad (23)$$

By obtaining this useful data from the experimental measurements and standard variables like specific heat and latent heat, one can calculate approximately the effective efficiency of the MSES for the given process

$$\text{Effective efficiency} = Q_{use}/ Q_{in} \quad (24)$$

$$= [(M.C.\Delta T)_{still} + (M.C.\Delta T)_{dryer} + (M.C.\Delta T)_{cooker} + (M.C.\Delta T)_{osd}] / I.A_p.\, T_t (25)$$

= **29.21%**

[*Where, Ap- aperture area of HSES, T_{ws} – average stagnation temperature of the whole system, T_{ss}, T_{ds}, and T_{cs} - are the stagnation temperatures of still, dryer, and cooker respectively, T_t - processing time, I – average insolation during testing of HSES, beside this, the temperature of the open sun dryer was noticed almost same as the ambient temperature and fluctuation was noticed and considered only for 1^0C, specific heat of air in the dryer is taken as 1004*]

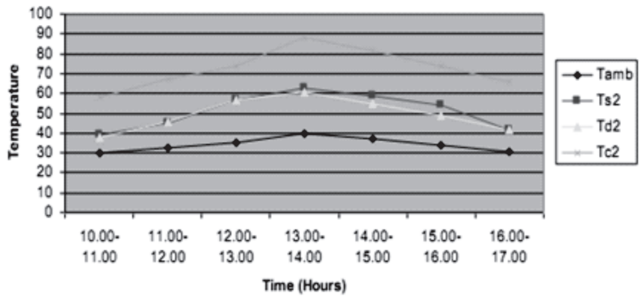

Figure 13: Performance curves of HSES at 'on load'

6. PAYBACK PERIOD

The PBP gives an estimate of how long the individual system/device will be exposed to that possibility. It provides a measure of liquidity since it shows how long an investor will have to wait before the initial cash outlay will be available for reinvestment or consumption. Advantages of the payback period suggest that it could be used as a guide in the financial evaluation of a solar energy system. The PBP provides information about the risk of the investment and its liquidity. By providing this more complete information, the homeowner is aided in making a more intelligent economic evaluation. In the present case the PBP is calculated on the basis of simple analysis payback period [61]. The life of the system is assumed between 10 to 15 years under safe operating conditions. To obtain the PBP, only electricity is considered. The whole system cannot be run on any individual alternative fuel like LPG, kerosene, fuel wood and coal, except electricity. The reason is that a solar dryer can't be operated on LPG, kerosene, and likely fuels and it becomes more complicated to operate all the components of HSES on different individual fuel. Hence only electricity has been considered to obtain approximate savings by it and PBP. Hence, the net saving per year is calculated in terms of saving of electricity and in turn of money. A total amount of rupees four thousand approximately is spent on fabrication of the MSES.

By calculating the net power required to operate the whole solar energy system [62], one can easily find the net saving of electrical power. To operate the solar cooker the net power required is 65 Watts means if an electrical coil of 65 Watts connected to the absorber tray then it will give the same cooking performance as mentioned previously in section 3.3, similarly for solar dryer it became 60 Watts, while there is no need for the open sun dryer to supply electrical power because of high heat losses. For a water heater, an 80 Watts coil is required to start good evaporation or to heat the 25 liters of water up to 60 to 65^0C in 3 to 4 hours. The total system requires a power of 0.21 kWh. In the climate condition of Moradabad, we have 275 days with good sunshine throughout a year, in which at least six hours are pretty good to use solar energy devices (11.00 am to 16.00 pm). Hence considering all those factors the total timing of the system used in a year, is 275 days multiplied by 6 hours. The cost of electricity in the area of experimental work is rupees 4 per unit. Now

PBP = (total investment on the system/ net saving per annum)
= 2.88 years

Table 2: Breakdown of the cost of HSES

Item	Quantity	Approx. Cost (INR)
Aluminium sheet	3 m^2	900
Glass wool	8 kg	160
Plywood	122 × 122 × 2 cm^3	800
G.I (frame angles)	15 kg	300
Adhesive	1 kg	50
Cardboard paint	1 liter	40
Float glass	184 × 122 × 0.2 cm^3	220
Riddle (iron made)	76 × 60 × 0.1	40
Lacquered *Al* sheet	1.2 m^2	330
Miscellaneous (PVC pipes, screws, rubber gasket, castor wheels, paint brush, etc.)	-	500
Labor charges (15% of total cost)	-	500
Total	-	3340 + 500 = 3840 $\simeq$ 4000

7. ECOLOGICAL AND ECONOMICAL BENEFITS

There are a lot of benefits of using solar energy in various aspects [63]. This source of energy is free of cost and available in an enormous amount on earth. Solar energy is continuing to utilize, in power generation, heating, cooling, and cooking in almost of working and living places [64]. Other aspects of it are; drying of foods and crops, water distillation, solar energy collectors etc. [65]. By using solar energy we can save a huge amount of various fuels and capital. Beside this, solar energy is a clean fuel and due to combustion free, it is non polluting fuel too. We not only save the money and fuels but also can maintain a good health by using it and keep away from various harmful diseases which are generated by the burning of biomass [66-67]. It is a typical task to estimate the actual savings from actually existing solar energy systems/devices worldwide. In the present case, the savings of other regular fuels used for heating can be estimated on the basis of net saving of money. It has been estimated that near about 58 kg of LPG, 99 liters of kerosene and 231 kg of fuel wood will be saved as an individual fuel per annum for the MSES for a total cost of 1386 (INR). It is also a noticeable point that the initial cost of solar energy devices (passive type) is reasonable in comparison of other fuels used for heating and cooling. Solar energy reduces our energy reliance on fossil fuels, produces no air or water pollutants, and no greenhouse gas emissions. Solar energy also uses little to no water, thereby saving our precious water resources. Solar is modular and can be sized to fit a wide array of applications and needs [68-70]. Solar energy contributes to energy security and self-reliance. It can be used to provide heat, light, and electrical power in two main types of solar energy systems; (i) passive systems which refers to the collection of heat and light while passive solar design for instance uses the sun's energy to make homes and buildings more energy-efficient by eliminating the need for day- time lighting and reducing the amount of energy needed for heating and cooling, while active solar energy systems refers to storing and converting this energy for other uses, either as photovoltaic electricity or thermal energy [69-73].

Solar energy technologies generate electricity without producing any type of pollution and can reduce carbon emissions by offsetting the need for carbon-producing fuels. This source of energy really gives us a tremendous eco-friendly environment. By using the sun's energy we can minimize the reducing figures of forests on our planet as well as can save a good amount of capital. Solar energy not helps only in above manner but also provide fair chances of employment in power plants and other thermal stations, while some of leading industries in India, are very well established in manufacturing of solar thermal products like, solar cookers, solar water heaters, PV cells, solar lanterns and air-conditioners etc. Even many state governments and ministries of almost countries are provided subsidies on purchasing of solar energy devices as well as a tax rebate on the same articles [74]. This energy is really a boon or a full bag of advantages for us and we must use it maximum for our needs.

7. RESULT AND DISCUSSION

Mostly hybrid solar energy systems are typically designed and developed by integrating with PV modules [75]. A good power backup is always required for solar energy devices for efficient operation in low ambient temperature conditions or in bad climate conditions. There are very few solar hybrid systems which directly operate only on solar energy. Reason is that, on passive mode such solar energy devices have low thermal efficiency while an integrated PV hybrid system has better efficiency over than passive type solar energy hybrid systems. But the major problem is that PV modules are available in markets for much higher cost and impracticable to afford by poor one. Accept this, to operate a solar cooker, solar dryer, and solar water heater cum still on auxiliary power as a solar Combi-system, a large PV module is required to operate the whole system as a unit. Beside this, if people from rural areas purchased an individual solar device for water heating, distillation, cooking and drying (after providing a good subsidy by the government) than the total cost of all these devices is much more than discussing HSES. If the comparison can be made between these systems (individual components and HSES) then a variation of ± 5 % in thermal efficiency may be possible due to combi-system in comparison of using separate solar energy devices. The mean is that it works with a minor change in thermal efficiency or slow processing.The results obtained, after experimental testing and analysis of the HSES as a unit as well as its individual components are found adequately. The system was operated on both conditions on load and on no load for efficiency evaluation. The whole system efficiency obtained after performance testing was found 29.21%, while for solar still cum water heater 31.5%, for solar dryer 27.5%, and for solar box cooker it was 34%. A total amount of 4000/- Indian rupees was estimated after fabricating of HSES. The system is specially developed for rural areas or people below the poverty line.

It has been practically observed that many households used more than one energy source for heating activities like kerosene, LPG, fuel-wood, and agriculture waste, in which kerosene and LPG are the two subsidized petroleum products used as a prime source of household energy. Coal and biomass has also been found a less consumed source of a cooking fuel. A survey was carried out to know the consumption of fuels for heating purpose in three different types (LIH-lower income household, MIH- Medium income household and HIH- Higher income household) of households in native place for a period of three months. In a LIH, an approximately consumption of LPG was noticed for 14 kg and for kerosene it was 6 liters per month while wood fuel was the third commonly fuel used for cooking with a maximum consumption in LIH among all. Coal was used for water heating along with fuel wood, while the dry leaves or wood chips were observed to use as an initial lighter (to pre ignition). An amount of approximately 800 (INR) has been spent on different fuels used for cooking and other heating activities by an LIH per month as shown in table [3]. MIH were found to clean cooking fuels like LPG mainly, and electricity while the other fuel like kerosene, coal and fuel wood has been noticed for a small consumption in the other heating tasks. An average amount of 925 (INR) has been spent on different fuels used for heating process by a MIH per month. The last one household was observed to be based mainly on LPG, a neat cooking fuel, while electricity (geyser) was used for water heating and other heating works as to make warm drinks and baking. This household spends an average amount of 3000 (INR) per month on heating activities. Having all the concepts of consumption of various fuels for a variety of heating works in different households, it outcomes that LIH has a limited budget to spend of fuels. By considering all those factors regarding the consumption of fuels and average expenses on them by different type of households, the HSES has been designed and fabricated purposely for the people who have a lower budget or unable to afford them due to limited monthly budget. It doesn't mean that rest two households (MIH and HIH) can't use it. It can be an additional system for them for any special purpose as dying and distillation.

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This system has been fabricated by locally available materials in a very simple and user friendly way. There is no international standard is considered for its designing as a whole unit except performance testing of solar cooker (Because cooking is the prime need of every household hence the cooking device must have good efficiency). The feasibility of the system is suitable to all levels of households and climate conditions (on an average value, ambient temperature varies between 22^0C to 45^0C, the wind speed goes up to 3.70 m/s maximum, the sun gives good heat intensity at least for 5 hours with 500 W/m^2 and beside this, for purchasing of likely solar devices a local "Prathama Bank" followed by the Indian government provide loans for solar energy device or systems) round the year of Moradabad city. This system is feasible to utilize solar heat energy and can be used throughout the year in parallel of other heating device/systems like LPG burner, kerosene stove etc. The calculated PBP for the MSES is 2.88 years. All the components were found in a fine satisfaction for different household heating activities and safe working. Beside this, a good amount of other regular fuels was estimated in the form of savings per annum as 58 kg of LPG, 99 liters of kerosene, 231 kg of fuel wood or an amount of rupees 1500. The initial start of the different activities of like water heating, drying and cooking was found low and time taken but after operating of one hour on good ambient conditions (i.e more than 30^{o}C of T_{amb} and 700 W/m^2 of solar intensity) a significantly improvement was found in the performance of MSES.

Table 3: Total expenses and consumption of fuels in different households per month (the cost of the fuels is taken, as fixed in March 2012)

Heating	LIH		MIH		HIH	
Fuel @ (₹)	Quantity	Cost (₹)	Quantity	Cost (₹)	Quantity	Cost (₹)
LPG @ 24.30	14 kg	345	20 kg	486	25 kg	607.5
Kerosene @ 12.00	6 liters	72	5 liters	60	5 liters	60
Coal @ 30.00	5 kg	150	2 kg	60	–	–
Wood @ 6.00	20 kg	120	5 kg	30	6 kg	36
Biomass @ 2.00	2 kg	4	–	–	–	–
Electricity @ 3.90	–	–	200 W	78	500W	1950
Others*	–	100		200		300
Total		791		914		2953

All the individual components were also found good in working in good ambient conditions. The water inside the solar still was reached at near about 60^{o}C in early two or three hours while the daily output of the distilled water was near about 2 to 3 liters/day, depending upon ambient conditions. The second component, solar dryer was also successful dried the potato slices, cabbage, green thin chilies and bread slices successfully with a slow processing. The maximum time was taken in 1 kg of green chilies i.e, two and half day. The processing of OSD was too slow and a direct effect of wind speed was notified on the processing. The third one component was found more efficient in comparison of other components of the same device. It was successfully achieved a fine stagnation near about 115^{o}C in early one hour. It cooked rice and pulse with a good taste while a total time taken was observed approximately three hours. For the efficiency enhancement of MSES for a good year round performance, a suitable PCM for thermal storage beneath the absorber tray [76], or using a transparent insulation material [77] inserted between double glazing, or by integrating with good auxiliary system (electrical back up) [78] can be used by installation or by providing those features in MSES in any climate conditions. There will be a little rise in total cost of the system (and are under study) for fabrication.

Abbreviations

MSES—Multipurpose solar energy system
PV—Photovoltaic
PCM—Phase change material
PBP—Payback period
OSD—Open sun dryer

Symbols

η_{exergy} – Exergy efficiency
η_{therm}– Thermal efficiency
U_L – Overall heat transfer
T_{amb} – Ambient temperature
Ws – Wind speed
α – Absorption coefficient
τ – Transmission coefficient
Q_s – Net heat energy
Q_{loss} – Total heat energy loss
Q_{use}– Total heat energy used

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