Energy Storage Integrated Solar Stove

A case of solar Injera baking in Ethiopia

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Abstract*: *Many of today's solar cookers lack energy storage and their applications have been limited to day time use while the sun is shining. In addition these cookers need longer cooking time and are less versatile to users compared with the traditional wood stoves. This article presents tests of a solar stove with and integrated heat storage designed to satisfy a particular need of some east African countries to bake their daily food (Injera). The prototype was tested in the solar laboratories at NTNU and Mekelle University, and presented for community demonstrations in Mekelle. Steam is used as heat carrier between a receiver in the focal point of a concentrating dish and a solar salt based latent heat storage. The stored heat enables users to bake at any time. The storage has a capacity to retain usable thermal energy for about one to two days depending on the amount of insulation. This system can supplement the existing electric and biomass Injera stoves and provide inexpensive and clean energy solution for food preparation. Solar baking provides benefits in terms of human health, environmental strain and high costs associated with biomass fuel.

Keywords*: *concentrating solar, solar thermal, solar cooking, heat storage; PCM storage; Injera baking

I. Introduction

Ethiopia, a landlocked country in Africa, uses about 90% of traditional biomass fuel for cooking and 70% of Kerosene for lighting. Over the last two decades, the accessibility to the national grid of the country has increased but still only a few million households out of a population of more than 80 million are connected to the grid. In addition, the current power generating capacity of the country has not yet reached the energy demand of its growing economy. This has caused an energy deficiency throughout the country, which has also made the country to enforce a power rationing strategy, and this also limits the gross domestic product (GDP) of the country.

The biomass energy is mainly used to bake the country's common food type called "Injera" and its stew. Injera is commonly prepared from "Teff" (Eragrostis tef), and is consumed two to three times per day by most households. Generally, more than 50% of the biomass fuel is used to bake this food item. The kitchen used to bake Injera is highly polluted with smoke, soot, and products of incomplete combustion. The use of biomass fuel in a traditional stove has been affecting the health and school time of millions of women and children. It also puts pressure on the country's forest coverage leading to erosion and land degradation.

To reduce these negative impacts, the government and some nongovernmental organizations (NGOs) have started to introduce improved cook stove (ICS) designs. However, many of them were imported and did not meet users' expectations. Following this gap, the investment of importing ICSs has shifted to developing indigenous ICS designs.

Many developing countries burn biomass for domestic cooking and heating, but this fuel is the main sources of aerosol and gaseous pollutants. However, these impacts might be reduced by using ICS as shown in the study of U.C. Kulshrestha et al. [1], where a 32% reduction of aerosol and gases components was achieved. This study has also estimated about 41% of biomass was saved by using ICSs for cooking. In addition, affordability and design simplicity of ICSs have eased the burdens of biomass fuel collection and mitigated its social and environmental impacts as indicated in Kenya [2]. Despite the hardly published data of household fuel consumption in developing countries, Michael A. Johnson et al. [3] have shown that ICSs have saved about 27–66% of the energy consumed by traditional cooking stoves (TCS). Today, people prefer to use ICS; however, the use is limited due to the capital and operational costs. For example, a study in Bangladesh showed that about 83% of respondents in a survey preferred ICS over TCS [4].

Like most developing countries, Ethiopia is also dependent on using traditional fuels. More than 98% of its household energy comes from biomass and less than 2% from electricity and petroleum collectively [5]. The government has planned to disseminate nine million ICSs to improve the efficiency of biomass usage and build a sustainable market to realize this [6].

This program was expected to reduce 1,000 to 2,000 deaths per year from indoor pollution and 2.1 ton carbon sink per year per household. This is in line with the green economy strategy of the country. Moreover, the country's investment in power generation is expanding and electricity might be more commonly available in the near future.

In general, almost all efforts used to develop ICSs have been targeting at biomass as their primary energy sources. The efforts on developing solar cookers have been limited, and with focus mostly on direct cooking methods. The solar PV applications are increasing in Africa, such as Kenya and Tanzania [7] and the potential in Ethiopia is large [8]; but the research on solar thermal is still immature. Direct solar cookers have not been widely accepted due to their limitation to indoor and night use, longer cooking time and higher system price. Likewise, baking of especial food types such as Injera has not been possible on solar cookers. However, their introductions in some African countries have improved the energy security of some households [9]. The acceptance of solar cookers could be increased if indoor, indirect, and any time cooking regardless of the sun's presence is possible. This possibility can be provided by integrating heat storage in the cookers.

Designs of thermal storage need to include considerations of some important factors such as technical properties, cost and environmental impact [10]. Research on latent heat storage using phase change materials (PCM) is also high on the agenda of solar power generation and other applications. The high phase transition enthalpy gives compact systems and the energy is available at a constant temperature (the melting temperature). Similarly, it is helpful to consider a combined use of latent and sensible heat storages to effectively utilize the stored energy in some applications. Two and three stage thermal storages are commonly used in solar thermal power plants. The sensible heat in such combinations help to preheat or/and superheat the heat transfer fluid (HTF) [11].

NOMENCLATURE

Abbreviations

birr	Ethiopian currency note
C	Effective heat transfer coefficient
GDP	Gross domestic product
HTF	Heat transfer fluid
ICS	Improved cook stoves
m	mass
NTNU	Norwegian university of science and technology
PCM	Phase Change Materials
Q	Heat
T	Temperature
t	Ton
TCS	Traditional cook stoves
a_m	Melted mass fraction
Δh_m	Heat of fusion per unit mass
Subscripts	
f	Final
i	Initial
l	liquid
m	Melting
P	Phase Change Materials
s	Solid

A South Africa's study on PCM heat storage for cooking application shows the need for further investigation and design improvements of the PCM storage [12]. A similar study of NTNU, Norwegian university of science and technology, has indicated the potential of PCM storage for energy intensive cooking, but it also suggested further studies in the area [13] and [14]. Both researches used a PCM mixture of $NaNO_3$ and KNO_3. Foong et al.'s [14] study of heat capacity found the common 60% $NaNO_3$- 40% KNO_3 mixture to be optimal (heat of fusion 108.67 ±1.47 (Jg-1)). The phase diagram numerically developed for this PCM was verified experimentally using differential scanning calorimeter (DSC) [13], [14] and [15]. Many refer to this mixture as "solar salt", which has a melting point of about 220°C. This PCM can also be suitable for Injera baking as Injera requires a temperature of 180-220°C to be well baked [16].

The solar salt based latent heat storage study of NTNU, for cooking applications, has included four different heat transfer concepts. One system coupled a parabolic trough to a heat storage using self-circulating oil as heat transfer fluid (HTF) [17]. This system demonstrates the three stages, sensible-latent-sensible, of thermal storage concepts also used for power generation [18]. A second system use air as heat carrier, with a rock bed as a heat exchanger to solar salt containers. A third system illuminates the solar salt storage directly [14]. The forth method, which is the basis for this paper, use steam as heat transfer fluid. Water is boiling in the absorber positioned in the focus point of a parabolic dish and the steam is condensing in a solar salt heat storage.

Storage charging and discharging methods is a general challenge [19]. Direct methods for Injera baking have been tested considering the bottom part of the pan as a receiver and focusing the solar radiation onto it [20], but without heat storage.

Acceptance of a solar Injera baking stove will depend on its simplicity and its resemblance to the classical cooking method (indoor use, baking time, Injera quality). The authors have been working on concepts to enable Injera baking from solar powered heat storage. This article discusses the test results of a small scale solar concentrator with integrated heat storage for Injera baking, and its future potential from a users' point of view.

II. MATERIALS AND METHODS

The use of solar energy for cooking can be increased if indoor cooking can be made at any time. Furthermore, the technology should not differ from the established cooking practices of the users. To achieve these basic demands, solar cooker designs eventually need to incorporate thermal storage and heat transport mechanisms. The temperature range of the solar salt melting point (about 220°C) is suitable for Injera baking. The overall heat storing capacity of the PCM and effective heat capacity values are given in Eq. (1-5) [14].

$$Q = \int_{T_i}^{T_f} mC_p \mathrm{dT} \quad (1)$$

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT \quad (2)$$

$$Q = m\left[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)\right] \quad (3)$$

$$C_p = \begin{cases} 0.75 & T < 110^0C \\ 4.2 & 110^0C \le T \le 120^0C \\ 1.4 & 120^0C < T < 210^0C \\ 12 & 210^0C \le T \le 220^0C \\ 1.6 & T > 220^0C \end{cases} \quad (4)$$

$$Q_P = \int_{23}^{109} mC_p \mathrm{dT} + \int_{110}^{120} mC_p \mathrm{dT} + \int_{121}^{209} mC_p \mathrm{dT} + \int_{210}^{220} mC_p \mathrm{dT} + \int_{221}^{237} mC_p \mathrm{dT} \quad (5)$$

The salt in the heat storage is charged to liquid form and the heat released during the liquid-solid phase change is used for baking. In addition to the latent heat, the sensible heat stored in the solid form of the PCM and aluminum also adds to the heat storage. Latent heat storages can have low charging and discharging rates due to their low thermal conductivity. This requires fins to provide a large surface area for heat conduction from the salt to the upper frying plate. The storage is schematically shown in Fig. 2. A coiled heat transfer pipe is embedded in an Aluminum plate, which is the top part of the storage and also serves as the frying pan. 120 cylindrical aluminum rods of 20 mm diameter and 140 mm height provide the heat transfer to the salt during charging and from the salt during baking. The storage holds 20 kg salt.

A single pipe thermo syphon is not practical for our heat transfer distances. The current setup applies a closed loop system, where steam is generated in the heat absorber; it condenses to water in the storage and flows by gravity down and back to the absorber. The pressure was controlled by a relief valve to yield a maximum temperature of 250°C. Water provides a high latent heat, but the pressure has to be quite high (about 40 bar)to reach saturation temperatures above the solar salt melting temperatures.

The complete system shown in Fig. 1 has the following main components: a reflecting film covered parabolic dish collector (antenna basis), PCM storage with an aluminum top plate, solar tracker for the primary axis and manual tracker for the secondary axis. The auto tracker is a gear and pinion mechanism which was driven by a 9 volt motor which is powered from a 10 W solar PV panel attached to the system. The tracking motion was controlled by a photo sensor and a shading arrangement. A counter weight was used to counter balance the weight of the collector to ease the tracking motion. The four wheels fitted to the system were used for locomotion purpose. Fifteen K-type thermocouples were connected to the fins inside the storage, baking surface of the stove, inlet and outlet of the storage. The thermocouples in the storage were placed in three different zones. The three zones were top, middle and lower part of the storage. These were placed only in a quarter of the storage, considering the symmetry of the system, as shown in Fig. 2. These sensors measured the temperature development inside the storage and show the inlet and outlet steam temperature. The pressure relief valve helps to vent a pressure development beyond the preset pressure (45 bars).

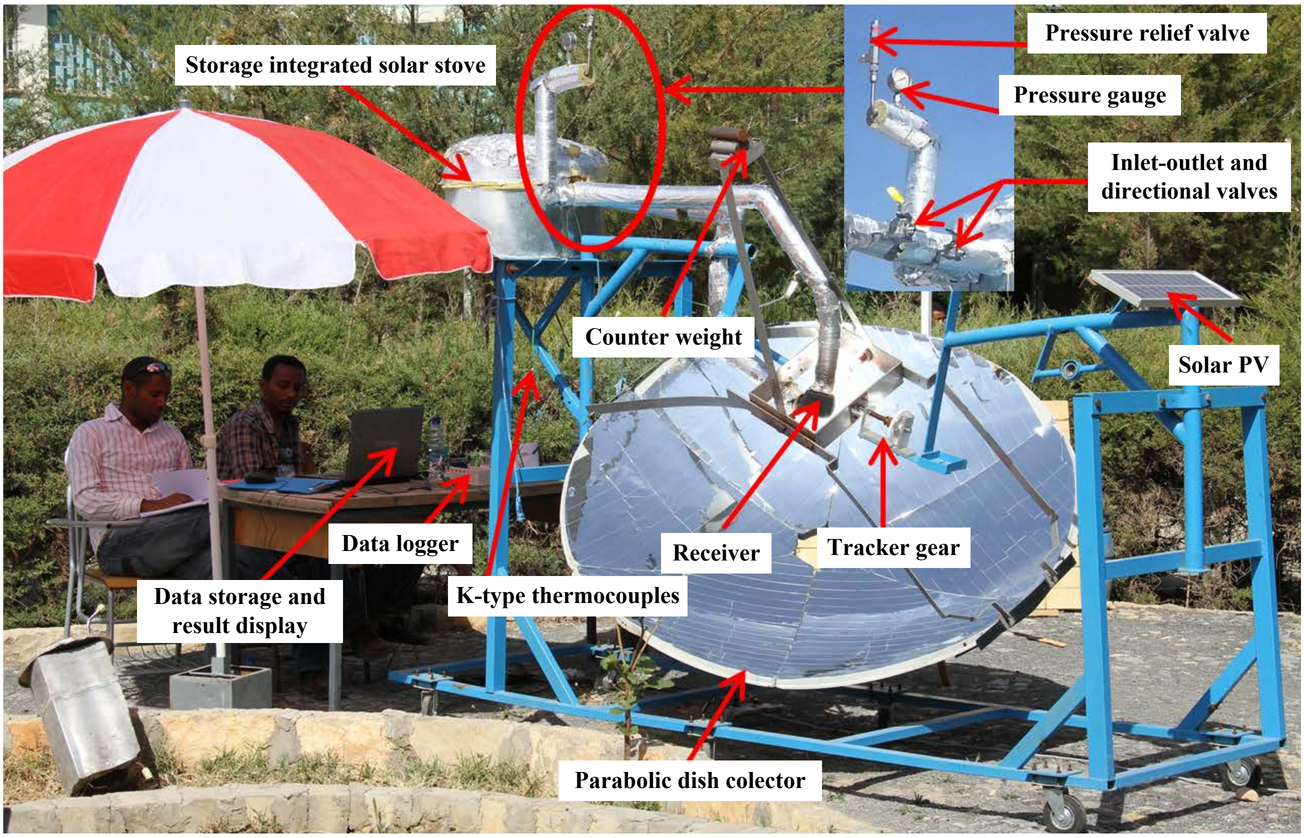

Fig. 1 Working prototype of storage integrated solar stove

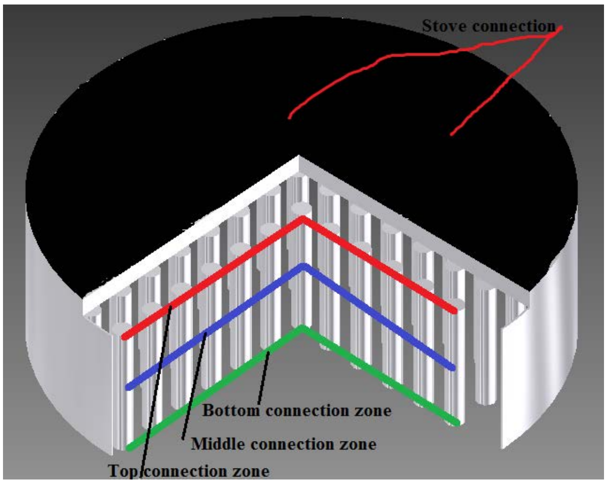

Fig. 2 placement of thermocouples in PCM storage

The temperature developments of the thermocouples at different positions were observed in time, graphically and digitally. These thermocouples were connected to a national instrumentation data logger. The data logger was interfaced to a laptop where the data was stored and results were displayed during and after the experiment. LabView version 2010 software was used to design the measurement program and record the data. The flow of the natural circulation in the closed loop stainless steel pipe was controlled by three valves. The pressure of the working fluid was regulated by a preset pressure relief valve. The instantaneous pressure development was read from the pressure gauge, which was fitted near to its relief valve. A manual hydraulic pump was used to feed, pressurize, and flush the system at the beginning of every experiment. The flushing process made the system free of any trapped air. If air is trapped in the system the temperature and pressure reading of the system will not agree with the standard steam table value.

Table I: Materials Used to Build the Prototype

No	Description	Dimension	Working pressure [bar]	Design capacity [bar]
1	Stainless steel (SS) pipe	10mm diameter and 1mm thickness	40	100
2	Pressure gage	-----	45	80
3	Stainless steel Pressure relief valve	Designed for 10 mm SS pipe	45	100
4	Stainless steel valve	for 10 mm SS pipe	45	75
5	Parabolic dish (satellite antenna)	1.8 m diameter	---	---
6	Mild steel Receiver	d= 100 mm h=100 mm, and t= 4 mm	40	NA
7	Mild steel support structure	Designed to carry a mass of 150 kg	NA	NA
8	Bearings	d=30 mm, D= 60 mm and w= 20 mm	NA	NA
9	DC motor	9V Designed to rotate 20kg	NA	NA

III. Results and Discussions

A. Injera baking using solar energy

Cooking using solar energy is not a new technology. Many designs of solar cookers exist and cookers are available across the world, and would be expected to be used in areas where electricity is not available and biomass is scarce. However, most of the technologies are unable to keep the stove hot enough and long enough to bake special foods such as Injera. The technology in this study enabled users bake Injera from a stored solar energy. The energy from the sun was collected during the day and stored in the PCM storage where it can be used whenever needed, similarly as for modern electric stoves.

Injera baking on the heat storage has been tested for a fully charge storage (utilizing the latent heat storage) and for a partly charged storage (using the sensible heat). Fig. 3 shows the temperature recordings during baking of Injeras for the case of a quite low temperature in the storage (sensible heat storage). The surface temperature drops as the batter is poured on the plate and rises during the cooking process. The Fig.3 also shows cases which failed due to cooking initiated before the surface temperature had reached sufficiently high values. The interesting fact to be noted in Fig. 3 is that Injeras could be successfully cooked even at quite low initial surface temperatures.

The baking times in Fig. 3 are comparable to the times for electrical stoves. However, baking from a fully charged storage was even quicker as shown in Fig. 4. During baking from the stored latent heat, the temperature of the storage remained nearly constant until about nineteen Injeras were baked. Only the top part of the storage then decayed slightly. The averaged baking surface temperature decreased linearly as shown in Fig. 4.

When the storage was discharging, a gradually decreasing baking surface temperature was observed. Energy is removed from the top part of the storage; some waiting time would eventually equalize the temperature in the storage. The Injera baking process from a fully charged storage was run for about an hour, see Fig. 4.

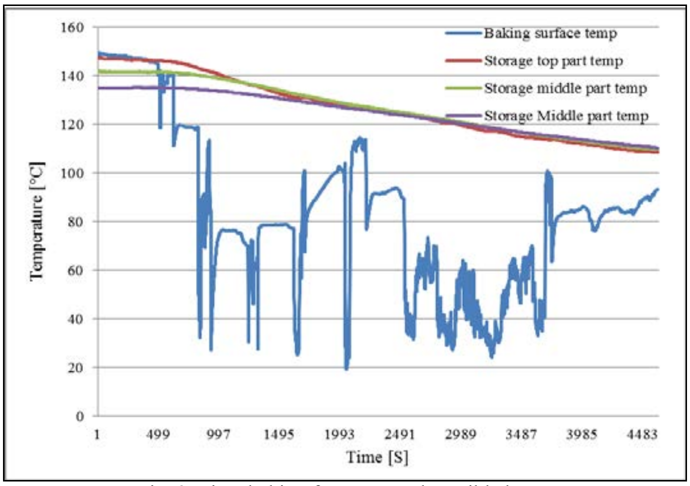

Fig. 3 Injera baking from a stored sensible heat

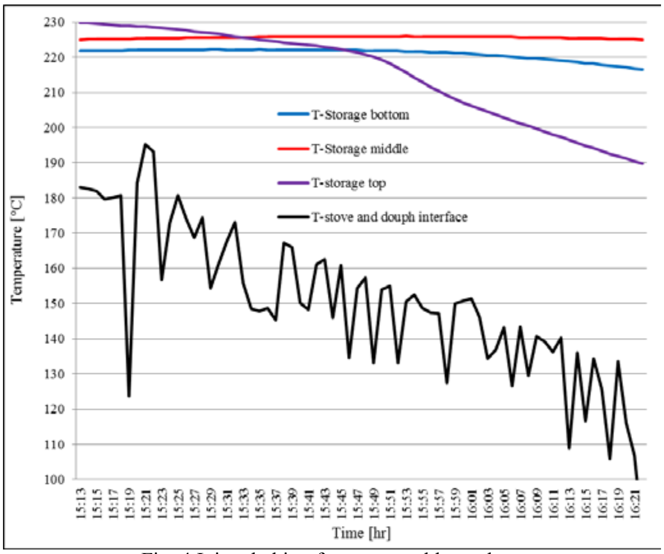

Fig. 4 Injera baking from a stored latent heat

During this time nineteen Injeras were successfully baked from the stored heat at an average baking time of three minutes per Injera. The remaining heat was used to bake bread. The Ethiopian bread is known for its circular shape and was baked on the circular stove surface as for Injera. Bread baking requires lower temperatures compared to Injera baking. Injera needs a high heat flux to evaporate part of its water content, which in return determines its quality. On the other hand, users prefer a slow energy flow at a relatively lower temperature during bread baking and they rarely cover the stove. This helps the bread expand its volume which in return affects the quality of the bread. Once the bread reaches its maximum volume expansion in good time its pleasant aroma comes out automatically, which tells the readiness of the bread. On the average, bread baking took about forty minutes to be well baked in the traditional biomass stove setting. In this study, from the remaining heat of the storage it was possible to bake five breads. Each of the breads took different baking time. The first bread was very quick and took only about thirty minutes, but the second, third and fourth required thirty nine, fifty two and sixty seven minutes respectively. At last the fifth bread required 1.2 hours to bake. The more the storage is depleted, the longer the baking time becomes. The heat loss during bread baking was also quite large compared to Injera baking because the bread thickness hindered the sealing effect of the lid. The total baking test was run for five hours and finally the storage was left at about 150°C to decay naturally.

The storage integrated solar stove used here was designed for an average household with five members. The total cost of the prototype system is very high for the low income majorities. However, the system has no or low running and maintenance cost compared to existing stoves. The stove's design life was estimated to about fifteen years, depending on the endurance of the reflective surface of the parabola.

This innovation is the first successfully tested technology for steam based solar Injera baking. The system was demonstrated to invited guests of different universities and industries in Ethiopia.


Fig. 5 Solar Injera baking and testing

Furthermore, the technology and its Injera baking process was shown to invited guests and communities of Mekelle University, Ethiopia. The first solar baked Injera and solar cooked stew was served to the attendees. The event has demonstrated the potentials for solar energy research to solve energy problems; this attempt indicated a prominent achievement to many Ethiopians. The attendees were overwhelmed by the technology and they recommended for an immediate outreach program. They have also raised their technical concerns of the technology by comparing it to the conventional electrical stove. The solar stove demanded an elevated height from the ground in order to allow the HTF circulate naturally in its closed loop. This height is an unavoidable feature as long as the system works as a self-circulating system. However, the magnitude of the height might vary from place to place, based on the latitude of the places. The same system in two different geographic locations therefore will have two different heights.

The unavoidable height of the system can be regarded as a negative feature of the technology. Fig. 5, from top left to bottom right, shows system setting and baking height, baking process, the typical solar baked Injera, testing of the prepared food by staff and students respectively. In this demonstration event; more than twenty staffs, more than fifty students of Mekelle University and three from media were attended and tested the prepared food. The engineering students were attracted by the event and the technology. The technology was able to hold the attention of many students; and students who came from rural areas were the most inspired once.

B. Energy expense assesment and solar stove potential

An interview based survey on energy consumption and its monthly expenses were collected from three hundred twenty one households, ten hotels, two hospitals and three boarding schools of Mekelle city. This paper has analyzed only the households' responses of the survey. The household energy survey was conducted by dividing the households in to three income classes. These are: low, middle and higher income classes. The low income class represents for households, who lead their life from daily labor income, and they do not own private house. The middle income households are those who have permanent job and a medium income, they may or may not own private houses.

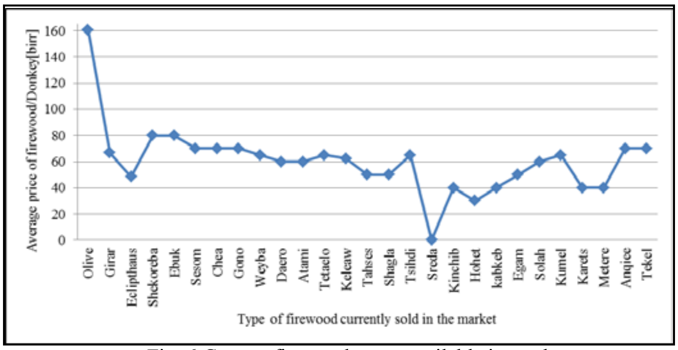

Fig. 6 Current firewood types available in market

All of the higher income households who participated in this survey possess a private residential house, electric stoves for Injera baking and for stew cooking. The majority of the middle income households own private house, electric stove for Injera baking but they use biomass for stew cooking and hot water supply. However, some middle income households who do not own private residential house use biomass for baking, cooking and hot water supply purpose. The lower income class was a mixed group, in which many of the households do not own residential house and some live in newly established villages and do not have access to electricity. This class use biomass for all types of cooking and baking applications. They use electricity only for lighting, with some exceptions that use kerosene for lighting.

The market price of the biomass was collected from six open market places of the city. Officially the government has banned tree cutting throughout the country. However, illegal flow of biomass fuel continues even today. The diversity of firewood species in the market currently has reached to twenty seven, which was limited to only a few options in the past. This number is now two to three times compared to the options of ten years ago. The increased firewood diversity comes as a result of two reasons: the first is because of the disappearance of some common firewood species. And the second reason is associated with the ever increasing firewood price as shown in Fig. 6.

Biomass energy was very inexpensive in urban areas and was collected for free in rural areas about two decades ago. However, today it is purchasable in both places. When the rural started to purchase biomass, its price impact on cities grew sharply as shown in Fig. 7-8.

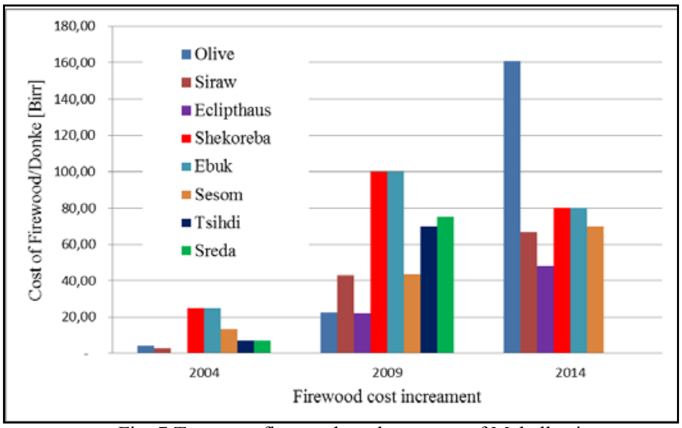

Fig. 7 Ten years firewood market nature of Mekelle city

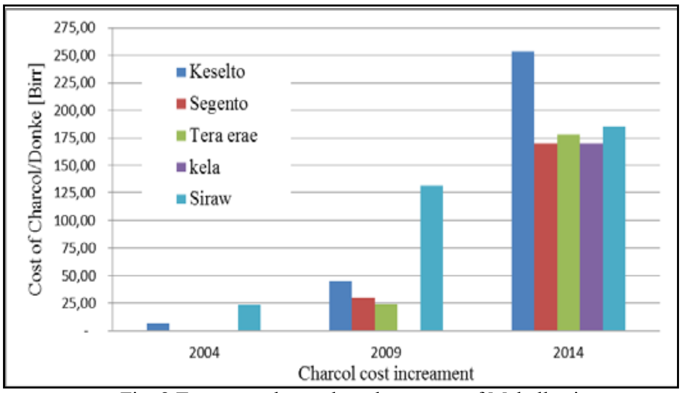

Fig. 8 Ten years charcoal market nature of Mekelle city

The marked increase in the price of firewood in 2009 was as a result of the power shortage and continuous power interruption happened in the country. During this period the country's economy was highly affected by the lack of energy. It was during this period the country started to follow the power ration strategy. This year was a challenging time for many of the country's industries, which were forced to decrease or close their production capacity because of power shortage.

The 2009 power shortage of the country has made many households to rely on biomass to cook and bake their daily meal. In this period, not only firewood but also charcoal showed a significant price increment as shown in Fig. 8. In addition to the power shortage, the shortage of man power to fetch firewood has contributed to the biomass price increment. In the past, rural area children and youngsters had limited opportunities to attend school; hence they were spending their time on fetching firewood and charcoal to help their family. However, since recently the coverage of education in rural areas has increased; which now keep many children in school. This in return reduced the supply of biomass to cities and caused an increase in price. Moreover, demographic growth, urbanization, and deforestation have contributed their share to raise the price. Subsequently, the price of firewood and charcoal continues on increasing. Today's firewood and charcoal price was below ten birr per donkey three decades ago. Such price increase has become desperate in some parts of the country, where the cost of cooking has become higher than the price of getting food items.

The analysis of the survey shows that the cost of biomass fuel is higher than the cost of electricity. From this analysis, biomass fuel is not expected to be the primary choice for energy source. However, low accessibility of electricity and limited options of other alternative energy sources have led to a continuation of the use of biomass. The average annual energy expense graph of Fig. 9 shows that the low income class paid the highest among the others. This was mainly because many households of this class lived in rented houses, where landlords did not allow them to use electricity for cooking and baking. Secondly it was due to the steadily increasing biomass fuel price. The third reason was their low income, which disabled them to invest and own electric stoves and enjoy their benefits. However, the middle income classes have moderate energy expense, which was because of the mixed energy use.

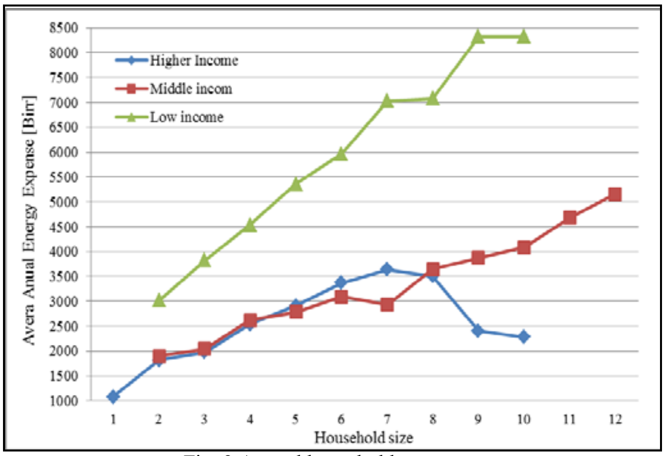

Fig. 9 Annual household energy expense

On the other hand, the rich class has paid the lowest annual energy expense. In addition, the energy expense of this class has declined irrespective of family size, which was the result of energy efficiency awareness and implementing schedules of the power authority to operate energy intensive appliances. Electricity is also inexpensive, with a current price of 0.2 birr per kWh (0.01 dollar per kWh). Generally the result of the survey has supported the need for an energy shift from biomass to electricity, which will have environmental, and health impacts and improved economics.

Many of the households participated in this survey were also asked for their view towards a solar Injera stove. The majorities of the respondents were very positive and showed high interest in owning such technologies immediately. However, some of them were highly concerned on its initial price, robustness and its service time. Very few were very skeptical about it as they have never heard or seen a similar technology. The survey also demonstrates the need for dissemination of solar technology. A proper awareness program would help to promote the new technology effectively.

The integrated solar Injera stove has shown to have competitive technical performance compared with modern stoves. However, its higher initial price might deter households' interest to own it. This technology needs a continuous improvement and systematic awareness creating strategies.

IV. Conclusion and Recommendation

This study has demonstrated the capability of a solar concentrator with PCM heat storage to bake the unique Ethiopian food Injera, which was a challenging application. The storage integrated solar stove technology can be competitive with existing electric Injera stoves, regarding baking time and quality of the Injera. This can made it an acceptable solution by many biomass users. The solar stove prototype has a high initial price; however, this price could hopefully be reduced through an optimized production method. A survey among households in the region showed that biomass prevails as a primary energy source, even after a strong increase in the price of biomass has made it more expensive than electricity. Although solar cookers have been available for a long time, the survey shows that a continuous awareness creation program of solar technology would be useful. The deteriorating situation with biomass fuel should open for more use of solar based cooking systems.

Acknowledgment

The Authors express their appreciation to Mr. Yirga H. Tesfay for his help to feed the data from energy consumption survey of Mekelle City to computer.

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