A Techno-Economic Analysis of Solar *Injera* Baking Systems

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Abstract

The energy supply in Ethiopia is dominated by biomass energy, mainly for household consumption. A survey of 721 Ethiopian urban households presented here shows that about 55% of the household energy consumption is spent on cooking and additionally 37% is spent on baking. The final energy consumption per household yields about 8.8 MWh per year, which is quite high regarding the fact that no space heating is needed. Thus, solar cooking is crucial for CO_2 emissions reduction, and to limit deforestation and occurrence of health incidents related to cooking with biomass in Ethiopia.

Further, the paper presents an economic analysis of an advanced steam-based concentrating solar *Injera* baking stove that allows for indoor cooking. Despite the high investment costs of the solar stove, the levelized costs of useful heat, $LCoE_{useful}$, determined for a life span of 20 years turn out to be about 60% lower than the $LCoE_{useful}$ for baking with a typical biomass *Mirt* stove for the selected reference conditions in this case study.

Keywords: Ethiopia, end-use consumption share, solar Injera baking system, economic comparison

1. Introduction

The burning of collected fuelwood contributed 19.4% to the annual CO_{2e} emissions from agriculture and forestry and 17% to the overall annual CO_{2e} emissions in 2010 in Ethiopia. The strong dependence on burning biomass for cooking results in deforestation, fuelwood scarcity, and indoor air pollution. On top of that, diseases and health incidents due to biomass combustion for cooking are serious concerns especially in rural households as the kitchen and living room are usually the same. LaFave et al. (2021) attest that indoor cooking is accountable for the increased occurrence of respiratory infections, inveterate obstructive pulmonary disease, cataracts, and cardiovascular illnesses.

The residential sector electricity consumption, a large consumer compared to other sectors in Ethiopia, reached 4.2 TWh in 2018, which represents 46% of the total power consumption of the country. Another paper depicts that about 7% of the total national electricity consumption is used for *Injera* baking (Liyew et al., 2021). *Injera* is a spongy flatbread and staple food in Ethiopia, Eritrea, and Somalia. It is the main dish of these countries usually consumed with “wot” (Neela and Fanta, 2020). Wot is a traditional sauce made by boiling a mixture of either vegetables, meat, or cereals flour with different spices and additives.

Solar cooking technologies have the potential to reduce the use of biomass in the residential sector significantly given the ample solar irradiation throughout Ethiopia (Bayray et al., 2021). However, there are a wide variety of technical and economic barriers to the penetration of solar cookers, although many technologies have been developed during recent years, referred for example in Adem and Ambie (2017). Some studies also report that the cost of solar energy technologies is falling and the rate of adoption by rural households is increasing. Nevertheless, no solar *Injera* baking stove is available on the market yet. Further details of the economic analysis presented in this paper are published in Liyew et al. (2021).

The paper comprises two different studies: a survey on energy consumption in private households and a cost analysis of solar versus biomass and electric *Injera* baking stoves.

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2. Household energy end-use consumption

A representative survey on the individual final energy end-use consumption in 721 private households was carried out in three cities in Ethiopia using questionnaires and measurements. Twenty-five households are excluded from the evaluations as some very important variables are missing. The study applies a bottom-up engineering method, using information from the survey and data collected by additional assessments and metering as implemented by Larsen and Nesbakken (2004). The average final energy consumption for each household is determined by summing up the final energy for cooking, baking, boiling, water heating, lighting, and other electric appliances for all energy sources. The share of energy consumption of the end-uses is calculated as the ratio of the average consumption of the respective end-uses to the total average consumption. The summary statistics of the survey data are shown in Tab. 1.

Tab. 1: Summary statistics of the energy survey data (696 households). Data are presented as final energy.

Dependent Variable	Min.	Max.	Mean	Std. Dev.
Energy for *Injera* Baking (kWh/a)	0	27,729	3,264	2,768
Energy for *Wot* Cooking (kWh/a)	1,807	13,459	3,810	1,633
Energy for Tea/Coffee Boiling (kWh/a)	0	4,891	971	556
Energy for Lighting (kWh/a)	0	3,285	162	225
Energy for TV & DVD player (kWh/a)	0	461	171	96
Energy for Water Heating (kWh/a)	0	143	14	40
Energy for Bread Baking (kWh/a)	0	548	39	141
Energy for Other HH electric appliances (kWh/a)*	0	818	360	394
Total final energy consumption (kWh/a)	2,730	33,307	8,792	3,410

*Other HH electric appliances include electricity for refrigerators, blenders, and washing machines.

The daily solid biomass fuel and electricity consumption was measured and a conversion factor of 19.45 MJ/kg for the biomass and one for the electricity consumption was applied. The survey yields a mean final energy consumption of about 8.8 MWh/a per household and the average family size is 4.6±1.89. It reveals that more than half of the household energy consumption is spent on cooking (Wot + tea/coffee boiling) and additionally 37% is spent on *Injera* baking, as shown in Fig. 1. The final energy consumption per capita yields 1.76 MWh/a. This is quite high compared to the per capita final energy consumption in developed countries considering no space heating/cooling requirement in Ethiopia. This is mainly because of the smaller ratio of useful to final energy for biomass, which is the dominant energy source in Ethiopia.

The household energy end-use analysis shows that almost the entire final energy consumption is suitable for the use of solar heat using concentrating solar collectors. Fig. 2 shows an overview of the end-uses identified and their suitability for the integration of solar heat, as they all are low and/or medium-temperature heating processes. The end-use temperature levels were determined in other studies (Mekonnen et al., 2020; Tesfay et al., 2014).

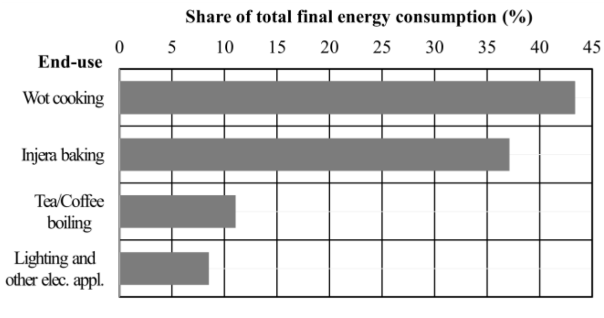

Fig. 1: A household energy end-use consumption share in urban Ethiopia

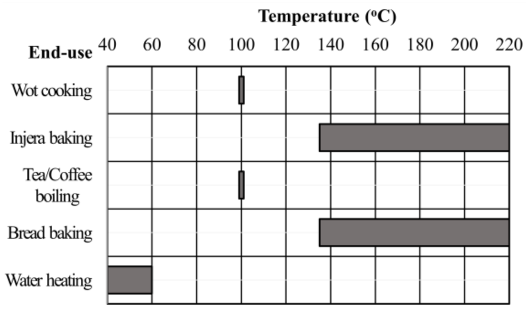

Fig. 2: Identified end-uses and its temperature level (Mekonnen et al., 2020; Tesfay et al., 2014)

3. *Injera* baking stoves

A plate temperature ranging between about 135 – 220 °C is needed for *Injera* baking. Inefficient three-stone open fire biomass stoves with a conversion efficiency of less than 10 %, based on final energy, are still the most common stoves used in rural Ethiopia. The thermal efficiency of the improved *Mirt* stove, shown in Fig. 3, ranges from 25–35 %. Electric *Injera* baking stoves, shown in Fig. 4a, are another competing and widespread baking technology. The rated power of an electric Injera stove is within the 3.7 – 4 kW range, with an efficiency of 40 – 50 % (Hailu et al., 2017). However, Jones et al. (2017) reveal that efficiency increment to about 30 % points can be achieved with improvements on the clay plate.

Concentrating solar collectors are suited for providing higher heating power per aperture area. This makes them suitable for *Injera* baking. In this study, the steam-based concentrating solar *Injera* stove, shown in Fig. 4b, is selected for economic evaluation as it is suitable for indoor cooking. It also allows cooking without in-between defocusing while pouring the dough on the plate. Nevertheless, it has a rather simple design and low costs, as it is designed without storage. It works as an indirect solar cooking system where water (steam) circulates. Using water as a working fluid enhances the thermal performance of the system due to its high specific heat capacity and high density. The system uses the natural fluid circulation principle with a boiling process at the receiver and condensation at the stove.

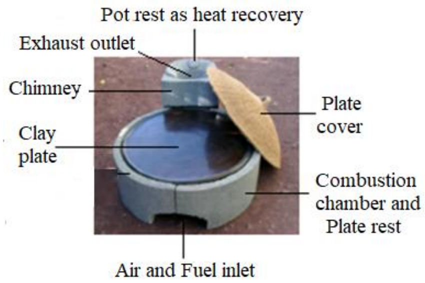

Fig. 3: ***Mirt*** **improved biomass stove** (Adem and Ambie, 2017)

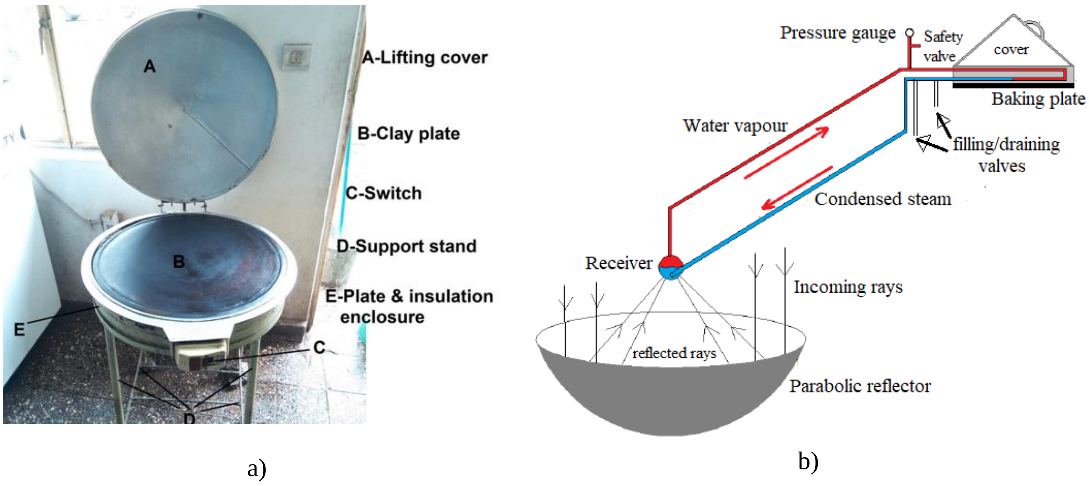

Fig. 4: a) Electric Injera baking stove (Hailu et al., 2017) **b) Block diagram of Steam-based concentrating solar Injera baking stove** (Tesfay et al., 2014)

4. Levelized costs of heat for *Injera* baking

The levelized cost of energy (LCoE) is the discounted costs associated with a technical solution over its lifetime divided by the discounted energy produced, consumed, or saved (Louvet et al., 2019). The LCoE refers to the useful energy as well as the final energy for the stoves, i.e. the biomass and the electric energy. The average discounted price of final energy is also calculated for 20 years of investigation and compared with the LCoE. Different sizes of baking stoves influence the LCOE, however, to simplify the evaluations the calculations are based on the energy consumption of average family size of five members in Ethiopia. Furthermore, a 100% solar fraction is assumed as Ethiopia receives adequate sunshine hours due to its proximity to the equator.

The economic analysis of the solar *Injera* baking stove is performed by taking the *Mirt* stove as well as an electric stove as reference technologies to evaluate the LCoE. The costs accounted for are the initial investment, maintenance cost, salvage values, and the fuel expenditure of the individual technologies. The analysis is computed by considering the initial investment capital for all three technology options financed by a loan fund. The total investment cost of the solar baking device is estimated as the sum of the market prices of the solar dish (including fluid loop), miscellaneous components, and the manufacturing cost because such kind of stove is not available on the market yet. As operating costs, local biomass and electricity prices with proper correction for market inflation rates are regarded. Both export and domestic electricity prices are considered for the economic analysis while substituting the electric stove with the solar *Injera* stove. The important considerations for the levelized cost of heat analysis are summarized in Tab. 2. The levelized cost of heat is calculated according to eq. (1).

$$\mathrm{LCoE} = \frac{I_0 + \sum_{t=1}^{T} \frac{O_t + M_t}{(1+r)^t} - \frac{S_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \qquad \text{(eq. 1)}$$

Where the symbols in the equation are the initial investment (I_0), operation cost (O_t), maintenance cost (M_t), and salvage value (S_t), period of analysis (t), nominal discount rate (r), useful energy consumption (E_t), final biomass consumption (E_t), and final electricity consumption (E_t). The maintenance cost includes costs of the parts considered for replacement like the lifting cover made of mud for the *Mirt* stove; the switch and the resistor for the electric stove; and the baking pan assembly, the heating elements, the valves, and the pressure gauge for the solar *Injera* baking system. The replacement costs increase over time according to the market inflation rates.

Tab. 2: Summary of input data for the levelized cost of heat analysis

Parameter	Value
Biomass consumption of a household of five family members (the basis for *Mirt* stove)	5,372 kWh/a
Electricity consumption of a household of five family members (the basis for electric *Injera* stove)	486 kWh/a
Useful (heat) energy consumption of a household of five family members	72 kWh/a
The average number of *Injera* baked in a household of five family members	3,120 pieces/a
Inflation rate	12.5 % (in 2019/20 EFY*), 12 % (in 2020/1 EFY and onwards)
Nominal discount rate	7 %
Export electricity price	14 US¢/kWh
Domestic electricity price (2019-2023 plan)	3.7 US¢/kWh (in 2019/20 EFY), 4.4 US¢/kWh (in 2020/1 EFY), 5.7 US¢/kWh (in 2021/2 EFY), 7.0 US¢/kWh (in 2022/3 EFY)
Biomass fuel price (the basis for *Mirt* stove)	2 US¢/kWh
The investment cost for the *Mirt* stove	15.3 US$
The investment cost for an electric *Injera* stove	75.5 US$
The investment cost for concentrating solar *Injera* stove	399 US$
Period of analysis	20 years

*EFY=Ethiopian Fiscal Year

The levelized cost of useful heat, LCoE_{useful}, is evaluated based on the heat transferred from the baking plate to the *Injera*. Tab. 3 shows that in this case study LCoE_{useful} for baking with the solar device is 1.76 $ per kWh. This cost is nearly 60 % lower than the LCoE_{useful} for baking with the *Mirt* stove, and about 52 % lower than baking with an electric stove when taking into account export electricity prices. When domestic electricity prices are regarded, the overall cost for solar baking is about the same as for baking with electricity. The levelized costs of energy differ mainly due to the different fuel costs, large inflation rates of more than 12 %, and different efficiencies of the stoves. The latter results in a distinctively higher biomass final energy consumption than electricity consumption.

The levelized cost of a kWh of biomass, LCoE_{final}, that is saved when a *Mirt* stove is replaced by the selected solar stove is 0.04 $/kWh. Similarly, the cost of a kWh of saved electricity when an electric *Injera* stove is replaced by the selected solar *Injera* stove is 0.26 $/kWh. Substituting *Mirt* stove by solar stove provides less costly heat when considering the substituted biomass energy. The substitution brings a price reduction of about one-third of the average discounted price of biomass. The average discounted price of biomass over 20 years of analysis period is about 0.06

$/kWh; whereas the average discounted price of electricity is 0.14 $/kWh with the domestic price and 0.39 $/kWh with the export price.

Tab. 3: Levelized cost of energy (LCoE) referred to useful and saved final energy

Technology description	LCoE ($/kWh)
Mirt stove, cost per kWh useful heat	4.30
Electric *Injera* baking stove, cost per kWh useful heat*	3.70
Electric *Injera* baking stove, cost per kWh useful heat**	1.90
Solar *Injera* baking device, cost per kWh useful heat	1.80
Solar *Injera* baking device, cost per kWh saved biomass	0.04
Solar *Injera* baking device, cost per kWh saved electricity	0.26

*with export electricity prices **with domestic electricity prices

5. Conclusion

The survey of nearly 700 urban Ethiopian households reveals a mean annual final energy consumption of about 8.8 MWh/household. Of which, about 55 % of the total final energy consumption is spent on cooking and boiling, about 37 % for baking, and about 8.5 % for other household applications including lighting. The end-use analysis of the households shows that currently, almost all end-uses are suitable for the use of solar heat using concentrating solar collectors.

The economic case study presented in this paper reveals that *Injera* baking with the investigated indoor solar baking device without storage is significantly less expensive for the considered reference conditions than baking with common baking technologies when regarding the entire life span of the solar device. According to the evaluations, the $LCoE_{useful}$ for the *Mirt* stove and an electric baking stove (considering export prices) is more than twice as high as the $LCoE_{useful}$ of the investigated concentrating solar baking device. Also, substituting *Mirt* biomass stove with concentrating solar Injera stove provides substantial cost reduction compared to the average discounted price of biomass within a 20-years analysis period.

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7. References

Adem, K.D., Ambie, D.A., 2017. A review of injera baking technologies in Ethiopia: Challenges and gaps. Energy for Sustainable Development 41, 69–80.

Bayray, M., Gebreyohannes, Y., Gebrehiwot, H., Teklemichael, S., Mustefa, A., Haileslassie, A., Gebray, P., Kebedom, A., Filli, F., 2021. Temporal and spatial solar resource variation by analysis of measured irradiance in Geba catchment, North Ethiopia. Sustainable Energy Technologies and Assessments 44, 101110.

Hailu, M.H., Kahsay, M.B., Tesfay, A.H., Dawud, O.I., 2017. Energy consumption performance analysis of electrical mitad at Mekelle City. Momona Ethiopian Journal of Science 9, 43–65.

Jones, R., Diehl, J.C., Simons, L., Verwaal, M., 2017. The development of an energy efficient electric Mitad for baking injeras in Ethiopia, in: Proceedings of the 25th Conference on the Domestic Use of Energy, DUE 2017.

LaFave, D., Beyene, A.D., Bluffstone, R., Dissanayake, S.T.M., Gebreegziabher, Z., Mekonnen, A., Toman, M., 2021. Impacts of improved biomass cookstoves on child and adult health: Experimental evidence from rural Ethiopia. World Development 140, 105332.

Larsen, B.M., Nesbakken, R., 2004. Household electricity end-use consumption: Results from econometric and engineering models. Energy Economics 26, 179–200.

Liyew, K.W., Habtu, N.G., Louvet, Y., Guta, D.D., Jordan, U., 2021. Technical design, costs, and greenhouse gas emissions of solar Injera baking stoves. Renewable and Sustainable Energy Reviews 149, 111392.

Louvet, Y., Fischer, S., Furbo, S., Giovannetti, F., Helbig, S., Köhl, M., Mugnier, D., Philippen, D., Veynandt, F., Vajen, K., 2019. Economic comparison of reference solar thermal systems for households in five European countries. Solar Energy 193, 85–94.

Mekonnen, B.A., Liyew, K.W., Tigabu, M.T., 2020. Solar cooking in Ethiopia: Experimental testing and performance evaluation of SK14 solar cooker. Case Studies in Thermal Engineering 22, 100766.

Neela, S., Fanta, S.W., 2020. Injera (An Ethnic, Traditional Staple Food of Ethiopia): A review on Traditional Practice to Scientific Developments. Journal of Ethnic Foods 7.

Tesfay, A.H., Kahsay, M.B., Nydal, O.J., 2014. Design and development of solar thermal Injera baking: Steam based direct baking. Energy Procedia 57, 2946–2955.