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Installation and Performance Evaluation of a Solar Steam Cooking System for 1500 Students in the Hills– A Case Study

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Abstract

Community cooking is becoming costlier as the cost of cooking fuel is rising globally and impacting the environment by emitting greenhouse gasses which are responsible for global warming. India's main cooking fuel is LPG which is being imported and is a depleting natural resource. The use of fossil fuels results in the emission of GHGs. This necessitates the harness of solar energy for community cooking. The campus receives daily horizontal solar radiation of 3.66-7.53 kW/m^2 which can be harnessed for cooking food. A solar steam cooking system consisting of 22 solar dishes has been installed at the university campus to cook food for 1500 students. This generates heat of around 2.54 million Kcal/day and saves LPG amounting to 33,600 kg/year while reducing the CO_2 of 99,456 kg annually thereby mitigating climate change. Solar steam cooking will meet SDGs 7 and 13. The payback period for the solar steam cooking system will be 3 years.

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Carbon Dioxide; Climate Change; Cooking; LPG; Solar, Steam; Student, SDG.

Introduction

India's current energy consumption for cooking is around 1,104 TWh. Annual use of Liquified Petroleum Gas (LPG) on average, is 88.75 kilograms, 170 standard cubic meters (scm) of piped natural gas (PNG) and about 1,022 kWh of electricity. According to the Indian Energy Security Scenario portal of Niti Aayog, the estimated energy demand for cooking in 2047 would be around 410 to 599 TWh, following 'heroic effort' and 'least effort' scenarios respectively. According to this report, the future energy demand could be reduced mainly by using energy-efficient cooking systems and LPG will be a major fuel for cooking in urban areas apart from PNG, electricity and fuelwood and biogas as a fuel in rural areas. In India, 94% of people have access to LPG, more than 2.58 billion people have subsidised LPG connections, and 0.17 billion have non-subsidised LPG connections. Access to LPG in rural areas implies a shortage of LPG in urban areas and this will increase the use of electricity for cooking in urban areas.[1] Energy consumption depends upon the efficient

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production, access, and transport of fuels (LPG, electricity, fuelwood, etc.), the efficiency of cooking systems and consumer behaviour toward cooking.[2]

There is a correlation between the affordability, accessibility and adoption of non-polluting fuels and systems by the rural population.[3] Polluting and non-polluting cooking fuels have been classified by Stoner *et al*., 2021.[4] The clean cooking fuels are Solar, biogas, electricity, gaseous fuels, LPG, natural gas, and alcohol while polluting fuels are classified as solid biomass, fuelwood, agro-wastes and forest-waste, coal, and kerosene. Presently 63% of the world's population have access to non-polluting fuels (NPF) and technologies despite efforts by the United Nations which means 280 million people do not have access to NPF.[5] With this pace, 74% of the world's population will have access to NPF by 2030.[4] In India, 49% of people have access to NPF and 681 million people still use traditional cooking fuels.[6] With this pace, India could not achieve the SDGs target by 2030.

According to a study, LPG is the costliest fuel as the cost of 10 lts of water heating using LPG at present prices is approximately Rs. 8, Rs. 5.5 for the electric geyser and for fuelwood it is Rs. 2/- considering fuelwood costs Rs 4/kg.[7] India is moving towards achieving the United Nation's Sustainable Development Goal 7 as per capita emissions of CO_2 are 1.6 tonnes of India which is comparatively less than the global average of 4.4 tonnes. India's per capita energy consumption is 0.44 tonnes of oil equivalent (toe)] whereas the global energy average is 1.29 toe.[8]

Concentrated Solar Technology

Scheffler concentrators generate temperatures up to 150–300 °C. A Scheffler dish of 16 m^2 area has a thermal capacity ranging from 1,25,000 kJd^{-1} to 1,46,000 kJd-1 depending upon the DNI (Direct Normal Irradiation) during clear sky (The National Renewable Energy Laboratory, n.d.).

Installation of Community Based Solar Steam Cooking Systems in India

Capacity-wise, solar steam cooking system (SSCS) have been installed at three major religious locations in India for cooking food for pilgrims. An SSCS was installed at Brahma Kumari, Mount Abu having 106 concentrators of $16m^2$ each for 1500 persons/day and generating energy amounting to 16782 MJd^{-1}.[9] Another SSCS was installed at Sai Baba Sansthan, Shirdi with 73 concentrators of $16m^2$ each for 3000 persons per day and generating energy amounting to 11558 MJd^{-1}.[9] The system generates 3600 kg of steam daily thus, saving 0.1 million kg of LPG annually.[10] The efficiency of the system was found to be 66.67% with a 2-year payback period.[11] Similarly, an SSCS was installed at Tirumala Tirupati Devasthanam with 84 concentrators of $16m^2$ each for cooking food for 2000 people daily with energy generation of 10638 MJd^{-1}.[9] The system generates 4000 kg of steam at a temperature of 1800C daily.[10]

The university has 17 hostels scattered over a hilly terrain. Around 1200 students reside in these hostels. A large quantity of LPG is used to prepare food. With the increasing cost of LPG, the cost of food is also increased. To reduce the cost of food and the emission of greenhouse gasses, an SSCS has been proposed. To install a SSCS a common kitchen is required. The food during lunch and dinnerwill be served in all the hostels well in time and the breakfast will be provided in respective hostels as the steam is not available in the morning. The transportation of food from the common kitchen to different hostels well in time is another issue. A sufficient south-facing area including the rooftops for the installation of an SSCS consisting of 22 dishes is also required. The strategy to achieve these objectives has been discussed in section 2 and results have been presented in section 3.

Methodology

Climate of Himachal Pradesh

Himachal Pradesh is a hilly state in the extreme north of the Indian sub-continent lies between latitudes 30º22′N and 33º12′N and longitudes 75º45′ E and 79º04′ E having a geographical area of 55,673 km^2. The mean daily maximum temperature of 35.5ºC is observed in June which is the hottest month in plains and 28.7ºC in hilly locations. The mean daily minimum temperature of -1.7ºC to 7.3ºC is observed over the northeast region of the state and in the southern region, a temperature higher than 5ºC i s observed.[12]

Location

Dr. Y S Parmar University, Nauni is situated at an altitude of 1280 metres above mean sea level with a latitude of 30.86°N and longitude of 77.17°E in the foothills of the Himalayas, it experiences a maximum temperature of 36˚C and a minimum of -1˚C. Snowfall is quite rare. The university has an average of 285 sunny days annually recorded at the Conventional Meteorological Observatory of India Meteorology Department, GOI. The climatic data of Nauni taken from MNRE and IMD is presented in Table 1.

Table 1: Climate data of university campus

Month	Temperature (°C)	Average RH (%)	Solar radiation (kWh/m2/day)	Wind speed (m/s)
January	8.2	48.1	3.66	3.3
February	10.4	48.0	4.55	3.4
March	15.3	40.9	5.75	3.4
April	20.5	34.7	6.92	3.7
May	23.7	40.2	7.53	4.1
June	24.6	56.3	6.93	4.3
July	23.0	79.0	5.65	3.5
August	22.0	83.1	5.08	3.0
September	20.2	74.3	5.43	3.0
October	16.8	53.2	5.40	2.9
November	13.1	41.6	4.44	2.9
December	9.8	42.0	3.57	3.2
Annual	17.3	53.4	5.41	3.4

Table 1 revealed that the campus receives daily horizontal solar radiation of 3.66-7.53 kWh/m^2 per day which can be harnessed to reduce LPG consumption being used for cooking in 17 student hostels. The total LPG consumption in all the hostels is about 51,300 kg annually.

Keeping given the above an SSCS for 1500 students has been installed at the university campus for cooking food (lunch and dinner). Presently, food is cooked in each hostel separately. To cook food for 1500 students a common kitchen has been constructed.

Strategy to Install 22 Solar Concentrators

There are 22 solar concentrators in total out of which 18 concentrators are water-based for generating steam for boiling purposes and 4 concentrators are oil-based being used for frying food as Indian consume spicy food (Fig 1).

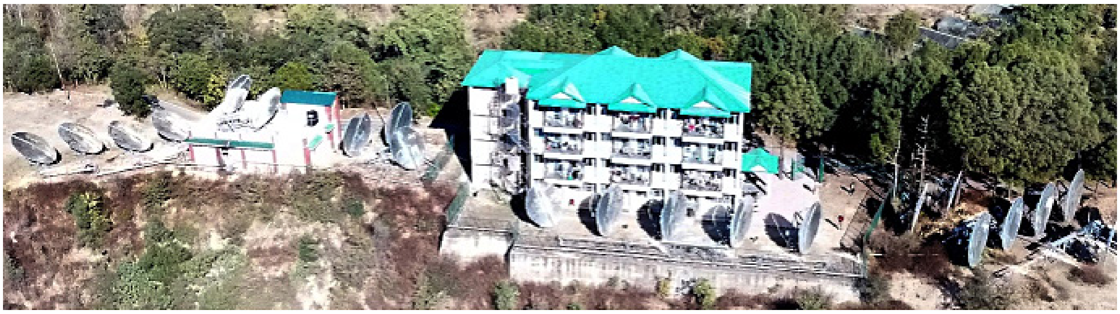

Fig 1: View of solar concentrators installed near the kitchen

Four oil-based dishes have been installed on the left side of the kitchen. The five-meter distance between the concentrator and receiver is maintained and the same distance is also kept between two concentrators. Each dish has one receiver to generate steam which is connected to a header through an insulated MS pipe of 1.25 cm in diameter. Two concentrators were installed at the top of the kitchen, three between the kitchen and the girl's hostel, five in front of the girl's hostel and eight at the adjacent hilltop. This is because the required space was not available near the kitchen.

Solar concentrators are fixed in the south direction however, the shading effect of hills is also taken into account. The tracking is adjusted in the morning, and the concentrators automatically move with the Sun in one direction (East-West), concentrating all the solar radiation exactly on the receivers connected to the Hyder. The concentrators are fixed at different points because of the space available.

Specifications of Solar Concentrator

The Scheffler Dish consists of aluminium mirror reflectors fixed on a steel framework. The mirrors are fixed to have a paraboloidal shape and reflect the incident solar radiation to the receiver. The mirror size is 15x7.5x0.3cm (950-1000 per dish) with a high-quality silver back coating.

Receiver

The receiver is fixed at the focal point of the concentrator. The receiver is spherical dome type and made up of boiler grade mild steel / SA516 ASTM1. The inner diameter is 37.55 cm, the outer diameter is 40 cm and the 7.5 cm of width. The receiver is insulated with a cladding thickness of 6 cm. The reflected solar energy from the concentrator is absorbed by the receiver and transferred to the working fluid circulated in the receiver to generate steam. The size of the receiver is designed in such a way that it can absorb maximum reflected solar radiation from the concentrator.13 The steam generated in receivers is collected in the header with high pressure. The steam accumulated in the header is taken to the kitchen through insulated pipes of 2.5 cm dia.

Header

The header is a circular pipe of MS iron with a diameter of 15 cm and a thickness of the iron sheet is 10mm. The length of the The header is kept at about 1.2 m per concentrator (Table 2). All the Hyders are connected to the kitchen inlet. The total length from the last concentrator to the kitchen is around 90 meter and the distance between the oil-based concentrator and the kitchen is 20 meters.

Table 2: Sizing of the header for carrying steam

Length of Hyder (m)	No of concentrators attached
2.5	3
2.5	2
6.0	5
8.5	6
2.5	2

The oil-based concentrators do not have a header but a tank is provided with these concentrators. The steam coming out of the receiver is fed to the header through a thermosiphon system and carried to the kitchen. The pipes, receivers and headers are insulated with glass wool covered with aluminium sheet to reduce heat losses. Pressure gauges, water level temperature indicators, level controllers, safety valves, and steam separators are provided with the system for safety and to measure different parameters. Each header is connected to the freshwater supply.

Motors

One DC motor of 50W power is fixed with four oil-based concentrators to rotate dishes with the movement of the Sun automatically. One DC motor of 0.5 HP has been provided with four oil-based concentrations to regulate the flow of oil to the kitchen. One DC motor of 50W power is fixed with two concentrators installed at the top of the roof, one with three concentrators installed between the kitchen and girl's hostel, two motors with four concentrators installed at front of the hostel and three are fixed with 9 contractors installed at a hilltop. A solar panel of 75 W and a battery is provided with each motor. The weight of the motor is 1.3 kg with a motor noise level of less than 45 dB.

Backup System

An LPG-based boiler has been provided with a solar steam cooking system having the capacity to generate steam 150 kg/hour so that cooking may continue during non-sunny days. An electric heating system of 15-16 kW has been provided with oil-based vessels as a backup system.

Vessels

Three vessels have been provided for boiling food and two vessels for frying purposes. Single jacket rice vessel is made of stainless steel 18/8 304 Grade, with a water capacity of 125 ltr and 20 kg rice can be cooked one time. The outer shell has a diameter of 52.5 cm, a height of 60 cm and with bottom 2 mm stainless steel 304 grade sheets. The vessels are provided with a lid made up of 1.2mm thick (304 grade) stainless steel. Double jacket boiling vessel having 60 ltr capacity. The outer shell is a stainless steel 304-grade sheet with a thickness of 2mm. The vessel has a diameter and height of 50cm each with an inner shell made up of sustainable steel 304-grade sheet having 2mm thickness. In oil-based vessels, a rectangular jacket is provided at the base of a vessel for hot oil storage. Safety valve and steam regulator valves have been provided in the kitchen.

Results and Discussion

Performance of the SSCS

Campus receives an average DNI at the installation site of 5.33kwh/m2/day which can be utilized to generate steam for cooking. The steam required on pressurized hot water (ltr/day) is 1000kg/day and the pressure bar is 2.5 kg to 3.5 kg at a temperature of 125-140 ^{0}C. Each parabolic dish could generate around 56 Kg of steam in a day depending on the solar radiation and steam pressure. The requirement of steam on pressurized feed water (lire/day) is 1250 kg/day. The total capacity of flow rate is 150 kg/hour. The design of the system is to make a minimum pressure of 6 kg/cm^2

Solar dish has a receiver at its focus to intercept the incident solar radiation and track the sun on a single axis. The system is equipped with a thermal system and security measures. The dishes are installed in series and parallel combinations connected to different steam headers depending on the size of the system.

Integration Strategy

The Solar System is designed to provide steam at a pressure of 6.5 bar to 7.5 bar, which will carry steam into the kitchen through insulated pipes and cook food in a vessel installed in the kitchen. The energy output is 2.54 million/day peak at STC. The solar field of 18 dishes shall steam the water in a closed loop configuration and which will be stored in the steam Hyder for the cooking of food during lunch and dinner. This would reduce LPG consumption during Sunny hours. The solar steam generation process from solar and backup system installation is shown in the block diagram (Figure 2).

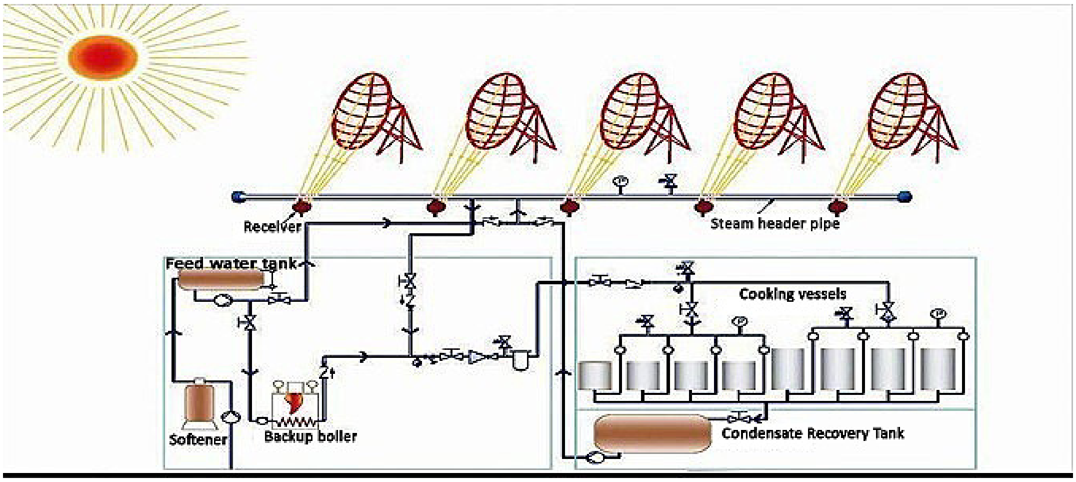

Fig. 2: Schematic block diagram of solar steam cooking system

Steam Generation in the SSCS

The steam generation depends upon the Direct Normal Irradiance (DNI) of the location. The monthly average DNI values are given in Table 3. The lowest DNI values (3.03 and 3.09 kWh/m2/day) were received in July and August and the highest (7.16 kWh/m^2/day) in

October. The average heat delivery per dish will be in the range of 20,846 to 49,260 Kcal/day. The heat generated in oil-based dishes will be in the range of 83,384 to 197,040 Kcal/day. The steam generated in 18 dishes will be 670 to 1,583 kg/day. The estimated steam requirement for 1500 students is around 1000kg/day. However, it will also depend upon the food habits of the students and the ambient temperature of the water. During July and August, the LPG will be used as a backup to meet the cooking requirement of 1000kg/day. The total 22 dishes generated heat of around 585,044,840 Kcal annually. This will not only save the consumption of LPG but also reduce the GHG emission thereby mitigating climate change.

Table 3: Month-wise estimated steam generation based on Direct Normal Irradiance

Month	Monthly Average DNI (kWh/m²/day)	Average heat delivery per dish Kcal/per day
January	4.97	34,193
February	5.26	36,188
March	6.50	44,720
April	6.47	44,513
May	6.06	41,692
June	4.56	31,372
July	3.03	20,846
August	3.09	21,259
September	4.80	33,024
October	7.16	49,260
November	6.30	43,344
December	5.85	40,248

Case Study

A meal was prepared during lunchtime in which 7 kg of Rajma (*Phaselous vulgaris*) and 12 kg of Rice were cooked along with frying of gravy (mixture of tomato, onion, garlic and ginger with certain spices). Steam pressure was maintained at 2kg/cm^2 recorded using a pressure gauge meter fixed inside the kitchen. The temperature of steam for frying was maintained at 145^{0}C recorded through a sensor-based temperature recorder. The time taken to cook rice was 30 minutes and Rajma was cooked in 1 hour and 45 minutes. The food was served to 200 students in the hostels.

Food Distribution Strategy

The food is cooked in the newly built kitchen for 1500 students and is distributed in the hostels during lunch and dinner. Since the hostels are scattered, the e-cart is used to carry food to the hostels. The breakfast and chapatti cooked in the existing kitchen of the hostels. Presently students are managing their mess but now it will be handled by a contractor.

Energy Saving

The cost of the SSCS is USD 131,579. The current price of a domestic LPG cylinder of 14.2 kg is USD 12.5[14] and a commercial cylinder of 19 kg is USD 29.64[15] India's import of LPG stood at 1.26 million tonnes in February 2022.[16] Presently LPG consumption in all the hostels is around 51300 kg emitting CO_2 of 151,848 kg annually. On average, the cost of 51300 kg LPG is around USD 63,099.

Sustainable Development Goals

The solar steam cooking system meets SDGs 7 (Affordable and Clean Energy) and 13 (Climate Change). It provides sustainable clean and modern cooking energy and simultaneously reduces GHGs thereby mitigating climate change. The solar cooking system is a sustainable source as solar energy is available everywhere whereas LPG is likely to be depleted in the near future and has many environmental and economic concerns.

Conclusions

The use of fossil fuels for community cooking causes the emission of GHGs thereby resulting in global warming. The LPG is being imported into India, there is a huge burden on the exchequer. The harnessing of solar energy for community cooking is a sustainable alternative and cost-effective. The SSCS installed at the university campus for 1500 students in hilly terrain will not only save LPG of 33, 600 kg/year amounting Rs. 28.56 lakhs but also reduce the CO_2 of 99,456 kg annually and also benefit the students in terms of the cost of food and quality. The cost of the system will be recovered in three years. The solar steam cooking system will meet Sustainable Development Goals 7 & 13.

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Conflict of Interest

The author declares no conflict of interest.

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