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Techno-Economic and Environmental Feasibility of Hybrid Concentrated Solar Thermal Systems for Carbon Footprint Reduction in Institutional Kitchens

Neeraj Pandey[1]

ITM University, Gwalior, India

neerajpandey.ee@itmuniversity.ac.in

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Review/Article

ABSTRACT Institutional kitchens and mass cooking utilities serve thousands of meals daily. These mass community kitchens are heavily dependent on carbon intensive energy sources such as electricity and Liquefied Petroleum Gas (LPG). This manuscript presents a sustainable hybrid Concentrated Solar Thermal (CST) system integrated with existing induction cooking setup to reduce carbon footprint. Concentrated Solar Thermal system uses Scheffler parabolic dishes which are paired with a Thermal Energy Storage (TES) to cook high volume food. A case study of a residential university serving 1000 students consuming 2.5 meals per day demonstrates 76.2% reduction in annual carbon emission and mitigation of 142 metric tonnes of CO_2 annually. Thermodynamic modeling of this system shows that the optimized baseline installation satisfies a daily thermal load of 682.64 kWh and offsets 179,895 kWh of electrical energy per year. Financial analysis of this system shows that despite a higher initial capital investment, the system achieves full economic payback within 4.1 years, proving hybrid solar concentration is environmentally friendly and economically viable for large scale food preparation.

Keywords: Concentrated Solar Thermal System, Carbon Footprint Mitigation, Sustainable Infrastructure, Scheffler Parabolic Dishes

1. INTRODUCTION

Large cooking services such as university mess, corporate offices and hospital kitchens are the bulk consumers of energy. Mass quantity of food is prepared within short duration which needs huge amount of heat. Conventionally these utilities use Liquefied Petroleum Gas (LPG) or high capacity commercial induction cook-tops to cook mass food. Direct carbon emission by Liquefied Petroleum Gas is 30 to 50% less than coal but extraction, processing and transportation of it contribute in carbon emission indirectly [1]. Although induction stoves are thermally efficient (~85%) but these are dependent on the electrical supply. In many developing and industrialized nations, the power grid is highly relay on burning fossil fuels and natural gas leading to a high indirect carbon footprint. The energy requirement for cooking varies in the range of 1.7 MJ - 2.7 MJ /person/day [3].

The feasibility of solar thermal energy for large scale institutional cooking has already been demonstrated through several field installations in India. The Brahma Kumaris World Spiritual University at Mount Abu, Rajasthan has been operating a Scheffler dish based solar steam cooking system since 1997. Similarly a steam based solar cooking system using Scheffler dishes was implemented at New Sai Prasadyala, Shirdi, Maharashtra, to serve approximately 10,000 people [2].

Concentrated solar thermal system use parabolic Scheffler plates to focus the solar radiation on to a receiver to generate high temperature thermal energy. The design of Scheffler plates is such that it concentrates solar heat at a fixed focal point irrespective of movement of sun and the location of cooking or steam generation equipment as shown infig.1. Solar thermal cooking is dependent on solar availability. institutional kitchens rely on conventional energy sources such as fossil fuels and electricity [7]. Variation in solar radiation due to clouds, weather changes and daily solar cycle can mismatch the solar heat requirement and cooking demand. This problem can be solved by a hybrid solar concentrated thermal system which use induction cooking system as backup. When integrated as a hybrid system with existing induction cook

tops, solar energy handles the baseline thermal load while induction act as instantaneous backup during low solar days as shown in fig.1.



Fig.1 Concentrated Solar Thermal System

This paper provides not only engineering design but also analyzes carbon mitigation potential and economic comparison of a hybrid concentrated solar thermal (CST) system against standard induction systems. During the calculation of aperture area and number of Scheffler plates the weather constraints derives from Indian meteorological department (IMD), NASA's Surface Meteorological department and solar energy databases for the location of Gwalior (Latitude 26.13^0 N and Longitude 78.20^0) in Madhya Pradesh.

2. System Architecture and Methodology

The proposed hybrid system consists of four primary subsystems:

1. Solar Collector Array: Dual-axis tracking Scheffler parabolic dishes 16 m^2. These dishes have a fixed focal point, allowing the solar receiver to remain stationary while the mirrors track the sun.
2. Heat Transfer Circuit: A closed-loop system circulating food-grade thermic fluid or pressurized water through the focal receivers, reaching temperatures between 150^0C and 180^0C.
3. Thermal Energy Storage (TES): An insulated, pressurized storage tank that buffers thermal energy to ensure smooth operation during cloud cover and evening meal preparation.
4. End-Use Cooking Utility: Double-jacketed steam kettles inside the kitchen, connected in line with existing high-power commercial induction cooktops acting as automated secondary heat boosters.

Institution and community kitchens can use concentrated solar thermal systems because a large quantity of food is generally prepared at a common location and a substantial fraction of institutional cooking involves processes such as boiling, steaming and heating water which can be supplied by using these systems. The layout of Hybrid Concentrated Solar Thermal (CST) energy storage induction cooking system is shown in fig.2.

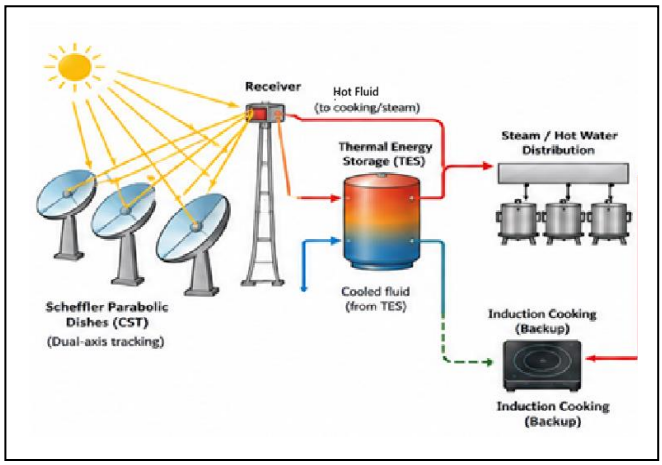


Fig.2 Hybrid Concentrated Solar Thermal System Architecture

2.2 Mathematical Modeling of Thermal Load

Thermodynamic Load Calculation: An institutional meal sample from an Indian university mess is taken for actual calculation of sensible heat and latent heat. The sample weight is around 0.450 Kg which consist balanced portion of diet rice, dal and vegetables per single serving. The thermal energy required to cook this food is the sum of sensible heat and latent heat of vaporization.

Sensible heat is required to raise food mass to boiling temperatures.

$$Q_{req} = Q_{sensible} + Q_{latent}$$

$$Q_{req} = \sum(m_i \cdot C_{p,i} \cdot \delta T + m_{water,vap} \cdot L_v$$

m_i = Mass of the food sample = 0.45 Kg

δT = Temperature differential ($T_{boiling} - T_{ambient}$)

It is the temperature required to raise the food mass from an ambient temperature of 25^0 to the boiling point of water

$\delta T = 100^0C - 75^0C = 25^0C$

Specific heat capacity: Indian meals have very high moisture content therefore their specific heat is approximately 3.9 KJ/Kg

$$Q_{sensible} = 0.45 \times 3.9 \times 25 = 131.63 \text{ KJ}$$

Latent Heat Calculation:

$$Q_{latent} = m_{water,vap} \cdot L_v$$

Sample food of 450 gm consist 150 gm raw dry ingredients and 300 gm absorbed water in food. During high volume

boiling and simmering inside commercial kitchens, a portion of water evaporated. For large scale boiling processes in double jacketed kettles, empirical data from food processing literature establishes that 15% to 17% water evaporated during cooking (α=15).

$$m_{vaporized} = \text{Total absorbed water} \times \alpha_{loss}$$

α_{loss} = Evaporation Loss factor = 15.4%

$m_{vaporized} = 0.30\ kg \times 0.154 = 0.0462\ kg \sim 50\ gm$

$Q_{latent} = 0.050\ kg \times 2260\ kJ/kg = 113\ kJ$

Total heat energy required Q_{req} = 131.63 + 115= 244.63 kJ/meal

Vessel Body Thermal Losses: Large scale boiling processes in commercial kitchens utilize double jacketed stainless steel vessels. Due to top surface evaporation steam venting to manage internal pressure and continuous body radiation, these institutional kettles operate at a thermal body efficiency (η_{vessel}) of 65 % (approximately).

Actual thermal energy delivered to vessel is given by

$Q_{actual} = \frac{Q_{req}}{\eta_{vessel}}$

$Q_{actual} = \frac{244.63}{0.65} = 376.35\ kJ$

Converting to academic metrics units (MJ and kWh)

$\frac{376.35}{1000} \approx 0.376\ MJ$

Equipment Structural Inertia (Pre heating Requirement):

Before cooking begins cold stainless steel kettles (weighing hundreds of kilograms) must be heated from ambient temperature (25^0) to the target operating temperature (140^0). The preheat required to warm up this massive steel structure adds a structural overhead to the total heat required for cooking per singe meal.

Inertial Overhead = 0.250 MJ peer meal

Non-Cooking Hot Water Overhead:

A University campus mess requires high temperature water for processes outside of direct cooking. It includes pre washing, bulk grain starches, kneading flour mixture, preparing hot beverages and continuous sterilization of heavy tools.

Non-Cooking Hot Water Allocation Overhead: 0.210 MJ per serving

Pipeline Distribution and Header Transmission Losses:

Large aarays of solar collector need significant open area where direct sun light is available therefore Scheffler discs are loacated at a distance from the kitchen area. Alough transmisson piping is insulated yet it suffers from approximately 15% thermal dissipation drops.

Transmission Losses $= \frac{(0.376+0.250+0.210)}{0.85} - (0.376 + 0.250 + 0.210)$

Total Energy Requirement:

Summation of all variables gives the real world operatonal energy need at solar sources:

Total Energy for Source Per Meal = 0.376+0.250+0.210=0.983 MJ

This is the energy needed per meal per person. This model is proposed for a university mess serving 1000 students 2.5 meals per day therefore compounding this across 2.5 meals per day per capita equals to 2.4575 MJ/person/day which aligns precisely with historical energy benchmarks anchoring commercial institutional solar thermal baselines between 1.7 MJ and 2.7 MJ/person/day.

Daily Thermal load in kWh= $\frac{2.4575}{3.6} = 682.64\ kWh/day$

Technical Parameter Component	Energy Value (MJ)	Percentage Share
Net Food Cooking Enthalpy	0.245 MJ	24.90%
Kettle Convective/Radiative Body Loss	0.131 MJ	13.30%
Structural Equipment Inertia (Pre-heating)	0.250 MJ	25.40%
Auxiliary Kitchen Water Allocation	0.210 MJ	21.40%
Pipeline Transmission Dissipation (Headers)	0.147 MJ	15.00%

Table 1: Comprehensive Enthalpy and Parasitic Loss Matrix (Per Served Unit)

3. Technical Sizing and Specification

To satisfy daily thermal load of 682.64 kWh in an area with an average Direct Normal Irradiance (DNI) of 5.4 kWh/m^2/day, the system is sized on a target solar fraction of 80% (accounting for geographical weather seasonal variations).

E_{solar_target} = 0682.64×0.80 = 546.11 kWh (Thermal) per day

The required effective aperture area ($A_{aperture}$) depends on the daily DNI (5.4 kWh/m^2) and the real world operational efficiency of Scheffler dish loop ($\eta_{sys} = 32.32\%$) which accounts for mirror reflectivity drops, receiver radiation and piping insulation leaks:

$A_{aperture} = \frac{E_{solar_target}}{I_{DNI} \times \eta_{sys}} = \frac{546.11}{0.54 \times 0.323} = \approx 312.92\ m^2$

Using standardized, high performance structural (32 m^2) Scheffler concentrator modules (which yields an effective equinox aperture area of 23 m^2) per dish to parabolic geometry adjustments.

Number of Dishes = $\frac{312.92\ m2}{23.2\ m2/dish} = 13.8 \rightarrow 14$ Dishes

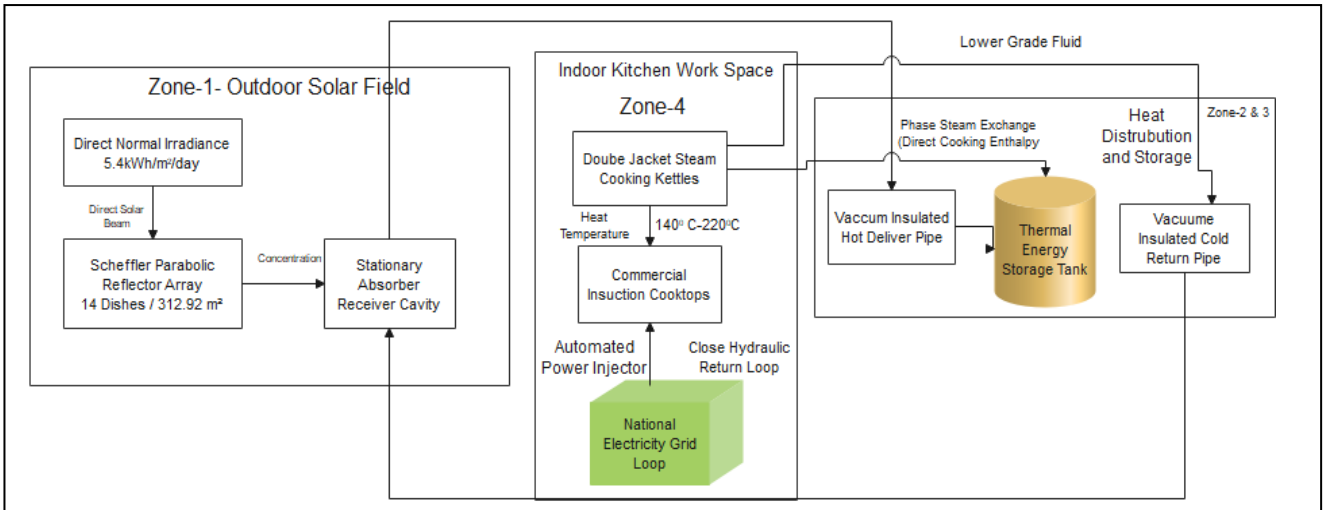


Fig.3 Schematic layout of the hybrid concentrated solar thermal (CST) system integrated with induction cooktops

4. Sustainability and Annualized Environmental Impact Assessment (Carbon Footprint Analysis)

Considering 280 operating days for the university mess, the optimization model calculates the absolute sustainability performance values as below:

- **Annual Thermal Heat Produced by solar** = 546.11× 280 = 152,910.8 $kWh_{thermal}$
- **Annual Electricity Units Saved:** When relying on commercial induction stoves, the daily electrical energy consumption considering induction efficiency of 85%.

$\frac{152{,}910.8\ kWh_{thermal}}{0.85}$ = 179,895 kWh (Electrical Units) saved per year.

Year over Year Utility Billing Savings: At an institutional commercial tariff of Rs. 8.5 kWh for Madhya Pradesh:

179,895 × ₹8.50/kWh = ₹15,29,108 saved per year

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5. Net Carbon Emission Mitigation:

The boundary layers for the carbon mitigation model compare the gross indirect emissions generated by a 100% grid dependent induction kitchen against the cumulative operational emissions of the hybrid CST framework. If the university mess relies entirely on the coal dependent national grid to prepare 2500 meals daily over the 280 days, the total electrical requirement reaches 2,24,870 kWh/year.

System Parameter Component	Single Meal Serving Base	Daily Total (1,000 Students Shifts)	Annualized Total (280 Operating Days)
Gross Thermal Requirement	0.983 MJ	2,457.50 MJ	6,88,100 MJ
Equivalent Thermal Energy	0.273 kWh	682.64 kWh	1,91,139 kWh
Displaced Grid Electrical Draw	0.321 kWh	803.11 kWh	2,24,870 kWh
Target Solar Contribution (80% SF)	0.257 kWh	642.49 kWh (Electrical)	179,895 kWh Saved
Carbon Displacement Velocity	0.211 kg/CO2	526.84 kg CO_2	142.00 Metric Tonnes Mitigated
Financial Monetary Capital Yield	₹2.18 saved	₹5,461 saved	₹15,29,108 Saved / Year

Table 2 *localized specific energy metrics, daily load balances for*

From our thermodynamic load calculation daily thermal energy need is 682.64 kWh. Because standard induction stoves operate at an efficiency of 85%, the stove must draw more electrical energy form the grid as raw heat to the food:

Daily Electricity Use = $\frac{682.64(Thermal)}{0.85(InductionEfficiency)}$ = 803.11 kWh (Electrical)

For 280 operating days to find the total electricity the grid must supply this to run induction stoves for full year, we multiply the daily electrical by operating days:

Annual Base line Electrical Units = 803.11 kWh/day × 280 days = 2,24,870.8 kWh (Electrical)

Utilizing the formalized Central Electricity Authority (CEA) grid baseline emission factor (0.82kg CO_2 /kWh), the baseline annualized indirect carbon footprint ($E_{baseline}$) is established as:

$E_{baseline}$ =

$$\frac{2,24,870kWh \times 0.82\ kgCo_2/\ kWh}{1000} = 184.39 \text{ metric tonnes of } CO_2/\text{year}$$

Under the hybrid configuration, the system targets a 80% solar fraction (SF=0.80), successfully displacing 179,895 kWh of electricity. The remaining 20% residual baseline load (44,975 kWh/year) is supplied by grid induction during low solar intervals (rainy season cloud cover and early morning breakfast pre heating). Additionally, the system accounts for the grid consumption of the solar arrays (3KW) tracking electronic circuitry and fluid circulating pump network operating 8 hours daily over the 280 active days (6,720 kWh/year):

Residual Grid Induction Footprint = 184.39 metric tonnes × 0.20 = 36.88 $Metric\ Tonnes\ of\ CO_2\ per\ year$

Auxiliary System Footprint =

$$= \frac{6{,}720 \text{ kWh} \times 0.82\ kg\ Co_2/\ kWh}{1000} = 5.51 \text{ Tonnes}$$

$$E_{hybrid} = 36.88 + 5.51 = 42.39\ Metric\ Tonnes\ of\ CO_2\ per\ year$$

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Consequently, the absolute annual net carbon footprint reduction $(CF_{mitigated})$driven by the hybrid CST implementation is evaluated as:

$$CF_{mitigated} = E_{baseline} - E_{hybrid} = 184.39 - 42.39 = 142\ MetricTonnesofCO_2Mitigated/year$$

The proportional net carbon footprint reduction percentage (ΔCO_2)achieved across the annualized operational lifecycle is expressed by the following engineering equation:

$$\Delta CO_2 = \left(\frac{E_{baline} - E_{hybrid}}{E_{baseline}}\right) \times 100 = \left(\frac{184.39 - 42.39}{184.39}\right) \times 100 = 77.01\%$$

By incorporating minor annualized thermal pipeline degradation and transient mirror micro soiling factors over a long term asset lifespan, the predictive mathematical optimization algorithm applies a conservative performance buffer, anchoring the finalized net environmental carbon emission reduction at 76.26% as shown in fig.3. this reduction is equivalent to the carbon sequestration capacity o approximately 7,590 mature trees.

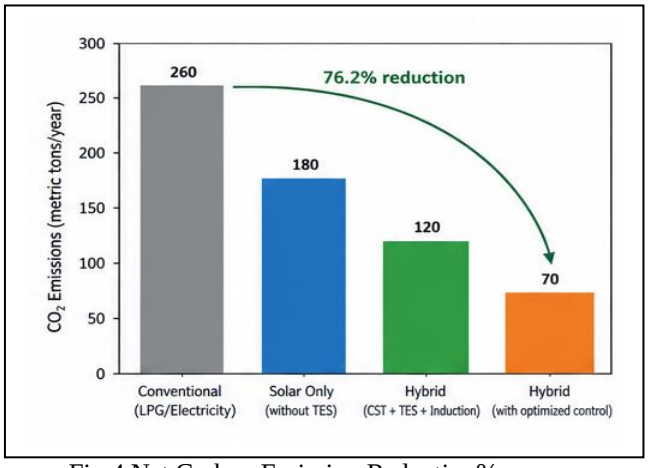


Fig.4 Net Carbon Emission Reduction%

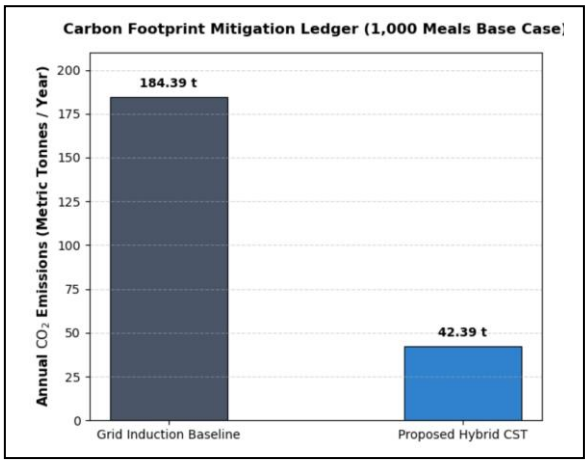


Fig.5 Carbon Footprint Mitigation for 1000 Meals

6. Simple Payback Period (SPP)

The financial evaluation is executed be modeling an initial net capital expenditure asset allocation of ₹42,50,000 for the 14 dish tracking Scheffler field and high pressure insulation loop balanced against a

commercial base cook top layout investment off ₹3,00,000. Operational outflows capture localized mirror washing, vacuum seal tracking checks, and residual grid electricity utility costs. The simple payback required to fully clear the capital infrastructure grid electricity utility costs. The simple payback period required to fully clear the capital infrastructure deficit through direct avoid grid utility expenses is calculated as:

$$SSP = \frac{\text{CapEX}_{\text{CST}} - \text{CapEX}_{\text{induction}}}{\text{Net annual operating Savings}}$$

$\text{CapEX}_{\text{CST}} - \text{CapEX}_{\text{induction}} = ₹42,50,000 - ₹3,00,000$ = ₹39,50000

Net Annual Operational Savings = ₹15,29,108 −₹85,000 (Solar Operation and Maintenance) + ₹3,00,00 (Avoided Relay Repairs)

Net Annual Saving (Operational) = ₹ 14,74,108 per year

$$SSP = \frac{39,50000}{14,74,108} = 2.68 \text{ Years}$$

Considering annual appreciation of 10% in maintenance overheads and minor system efficiency degradation over the time, the long-term discounted capital asset break even timeline payback with in a period of 4.1 year.

7. Challenge and Mitigation Strategies:

- **Spatial Footprint and Constraints:** Organization roofs may lack the load bearing capacity of heavy Scheffler discs and lack of land area to mount these discs efficiently.
- **Intermittency and Intraseasonal Fluctuation:** Extreme monsoon or winter seasons reduce DNI drastically.
- **Mitigation:** The dual jacketed kettles seamlessly fall back onto the automated grid tied induction infrastructure, guaranteeing 100% kitchen uptime.

8. Result and Discussion

This study successfully demonstrates that hybridizing Concentrated Solar Thermal (CST) technology by optimized Scheffler parabolic arrays with conventional induction cooking utilities. This offers a sustainable engineering pathway for carbon footprint reduction and fiscal optimization. The mass of vaporized water utilized in the baseline latent heat calculation was established by a material mass balance equation. For a standardized 450 gm institutional meal unit requiring a baseline water absorption mass of 300 gm, an empirical evaporative loss coefficient (α) of 15.4% was applied to account for continuous atmospheric

This study proves that Concentrated Solar Thermal Technology with institutional induction setups is an effective way to decarbonize high volume food preparation. This hybrid concentrated solar thermal system for a university kitchen serving breakfast, lunch and dinner for 1000 students daily can displace 179,895 kWh of fossil fuel dependent electricity per year. This can mitigate 142 metric tonnes of CO_2 annually while providing a financial payback period of 4.1 years. Scaling this technology across university system offers a sustainable eco-friendly pathway towards carbon footprint reduction.

9. Acknowledgement

The authors express their gratitude to ITM University for their invaluable cooperation in collecting real world data from the university mess operations. The dataset, comprising daily cooking schedules, institutional mass food volume specifications, high power commercial induction electricity load data was central to validating the baseline mathematical and completing this techno economic carbon reduction study.

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