INDUSTRIAL OVEN POWERED WITH A PAIR OF SCHEFFLER SOLAR REFLECTORS

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Abstract.

Direct utilization of solar energy is the most promising option to deal with climate change and fossil fuel depletion. Innovating new technologies and exploring new applications for existing renewable technologies is the key to resolve this problem. Scheffler solar concentrators based steam generation systems are successfully deployed for community cooking applications in India. There is need to look beyond cooking and develop different commercial and industrial applications using Scheffler solar concentrator as a primary heat source. An Industrial Oven is developed by authors for catering mid temperature applications in Industries, which utilizes two Scheffler solar reflectors of 16 m² as a prime source, focusing concentrated solar radiation inside an oven. This innovation delivers 9 kWth, which is good enough heat for many industrial applications, in 100℃ to 200℃ range, replacing electricity or fossil fuels like LPG or LDO. The trials show excellent technical and financial viability of the new design of industrial oven. Depending on fuel to be replaced, payback period varies from 2 to 6 years. Paper discusses development process of the new oven and financial analysis for the same.

Keywords: *Solar energy, Scheffler solar reflector, concentrator, industrial oven*

Nomenclature

A_p Aperture area m^2	C_{ps} Specific heat of steel kJ/kg-K
I Solar radiation total watts/ m^2	I_b Solar beam radiation, watts/ m^2
I_d Solar radiation diffused, watts/ m^2	M Mass of steel in kg
Ta Ambient temperature °C	t Time sec
T_{s1} Start temperature of steel °C	T_{s2} End temperature of steel °C
ηb Efficiency with beam radiation %	ρ reflectance of mirror
τ transmittance of the toughened glass	

1. Introduction

Low temperature solar applications like solar water heaters, solar box cookers and solar dryers are established and time tested. All of these gadgets primarily work below 100°C. To expand solar energy utilization to mid temperature applications, up to 300°C, many designs of solar concentrators are available and also being developed. Dish concentrators, troughs and Liner-Fresnel are major solar technologies that are used for process heating in commercial and industrial applications. Scheffler concentrators are now stabilised in India, with major installations in community cooking and few projects in air conditioning (Pillai et al 2010, Gadhia 2009).

From 1998 to 2009 size of commercial Scheffler concentrators have grown from 7 m^2 at Mount Abu to 16 m^2 at Shirdi, which is world's biggest solar steam cooking kitchen. There have been many developments with respect to size of reflector, materials, mirror fixing, tracking and design of receivers over the past decade (Golo 2009, Scheffler & Solare 2006). Scheffler concentrator of 16 m^2 area delivers 3 to 6 kW of thermal output depending on load temperature, aperture and intensity of solar beam radiation.

Industrial ovens normally use electricity, LPG or LDO as primary energy source and operate from 60°C to 200°C. Industrial ovens used in food and pharmaceutical industry, require secondary heat exchanger to avoid contact of flue gas with the food or pharmaceutical product. Similarly painting ovens require clean air for quality reasons. Solar heating provides clean hot air and hence can be excellent alternative for such industrial applications. A new design of oven utilizing a Scheffler concentrator of 16 m^2 was developed and tested by the authors. This unit provided heat duty of around 4 kWth at 125°C operating temperature (Chandak et al 2009). Authors further developed an innovative design which puts foci of two Scheffler dishes of 16 m^2 each inside a single oven, with 9 kWth heat output, which is suitable for most of the mid temperature industrial applications. Financial analysis shows suitability of the unit with payback period between 2 to 6 years.

2. Scheffler Reflectors

Scheffler reflector is a partial lateral section of a much larger paraboloid as shown in Fig. 1. The inclined cut produces the typical elliptical shape of the Scheffler concentrator dish. The solar beam radiation that falls onto this section of the paraboloid is reflected sideways towards the focal point of paraboloid, located away from the reflector.

Scheffler reflectors are fixed focus concentrator and the reflector-frame is elastically deformed to obtain different paraboloidal geometries. This deformation of the dish has to be carried out every 3-4 days as per the seasonal adjustment. In winter the standing dish tends to be more vertical while in summer it tends to be flatter. Because of this seasonal change in shape of reflector and change in incident angle of radiation the aperture area of the dish varies over the year. The effective aperture for different months of the year is presented in figure 2. This aperture is for standing dish installed in northern hemisphere. Aperture area for sleeping dish is mirror image as that of standing dish.

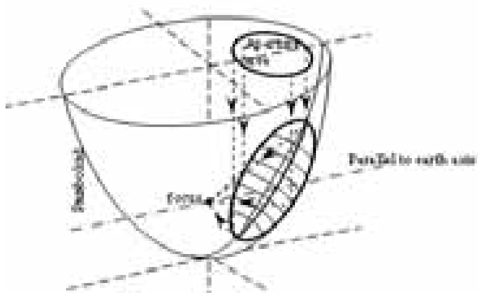


Figure 1 - Typical section of Scheffler from a large paraboloid

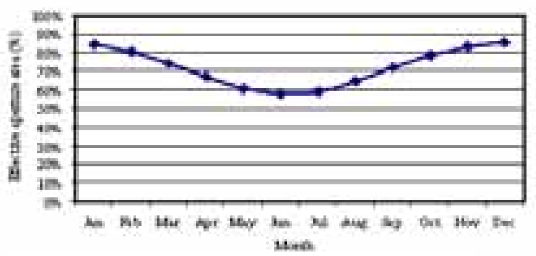
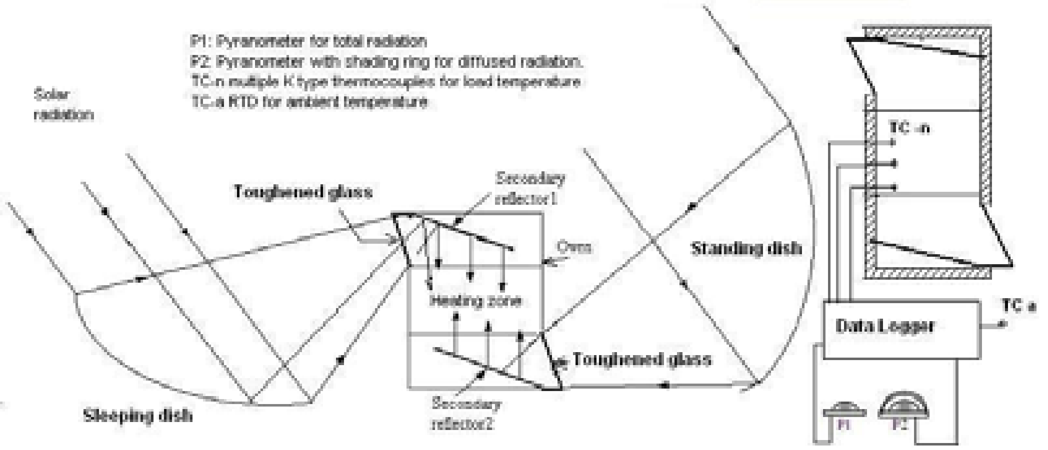


Figure 2 – Aperture area variation of a Scheffler standing dish

Scheffler concentrators are polar axis mounted and dish turns at 15° per hour in direction opposite to Sun, and gets locked to the Sun. Focus remains at receiver throughout the day (Scheffler 2009).

3. Development of Industrial Oven with a Pair of Scheffler Concentrators

3.1 The Innovation: Author[1] invented a unique combination which permits use of a pair of 16 m^2 Scheffler reflectors with axis of the reflectors are kept offset. Such combination results in two foci in single vertical plane at different heights. An oven is constructed around the foci in a manner that the heat trapped inside the oven can be used for industrial heating application. New design of oven permits entry of concentrated solar radiation from top and bottom of the oven and heating zone is designed in the middle of the oven, where load can be kept. Figure 3 shows schematic of such an arrangement along with instrumentation diagram that was used for testing. Solar radiation reflected from Scheffler concentrators enter the oven through the toughened glasses fixed at top and bottom of the oven. Toughened glasses are fixed at a latitude angle so as to receive solar radiation normal to the glasses. Secondary reflectors are mounted inside the oven which diverts this concentrated radiation towards central part of the oven where the load is kept. Bhirud & Tandele (2006) experimented with a pair of Scheffler concentrators of 9.3 m^2 each to establish the concept.



List of Instruments used:

S. No.	Instrument	Specifications Range	Least count
1	Pyranometer for direct radiation.	0 to 1100 W/m^2	5% of full range
2	Pyranometer for diffused radiation with shading ring.	0 to 1100 W/m^2	5% of full range
3	K type thermocuples.	0-900 ^{0}C	2 ^{0}C
4	RTD for ambient temperature measurement.	0-200 ^{0}C	1 ^{0}C
5	Data Logger Universal input	16 channel.	

Figure 3: Schematic of Industrial Solar Oven with Instrumentation diagram.

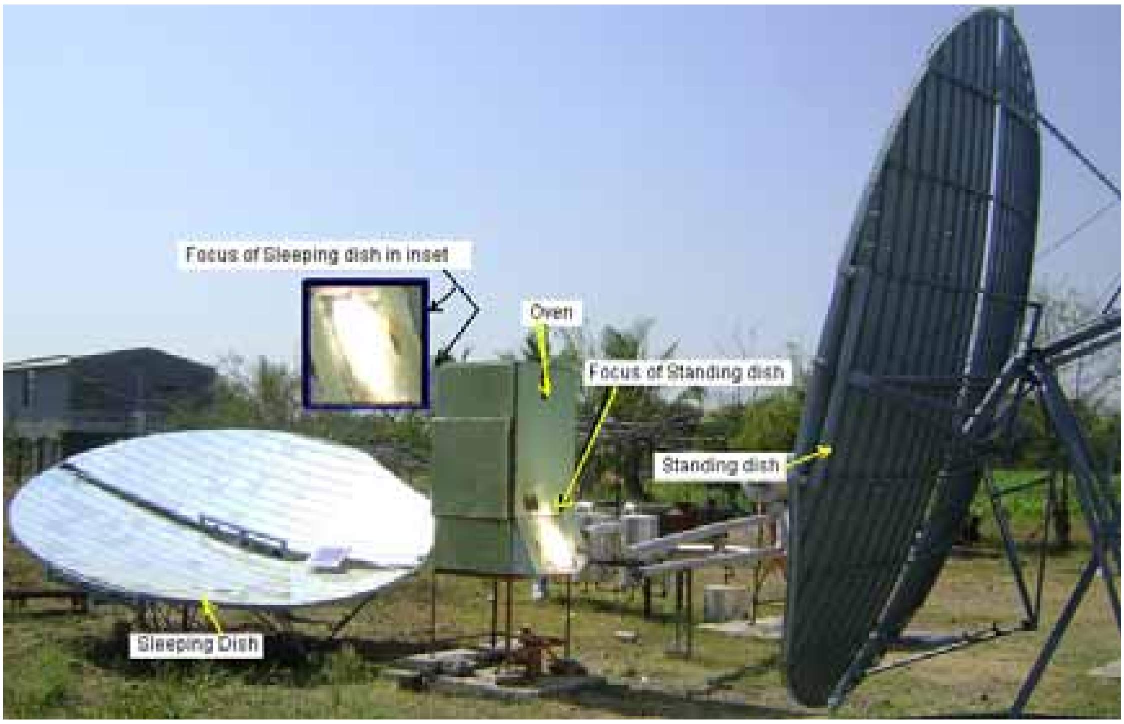


Figure 4: Photograph of test set up with pair of Scheffler Reflectors and Industrial oven.

3.2 Test setup : Experimentation were carried out on full scale commercial version of an industrial oven with a pair of Scheffler reflectors of 16 m^2 each, one in sleeping dish mode and other in standing dish mode as shown in photograph in Fig. 4. Field trials were conducted with mild steel slab and sections as heat load.

3.2.1 System specifications

Following are specifications for Scheffler solar reflectors and industrial oven.

3.2.1.1 Specifications of pair of Scheffler reflectors:

- Nominal size: 16 m^2 with elliptical shape. One standing dish facing south and other sleeping dish facing north with 22.50 m^2 aperture areas combined for sleeping and standing dish.
- Primary reflectors: Glass mirrors of 80% reflectivity and 2 mm thickness are fixed in special aluminum holding track on the dish.
- Secondary reflectors: Alanod make 0.4 mm thick polished, hardened, anodized aluminum reflectors with 0.25 m^2 area each. One reflector is at the top of the oven and other at the bottom.
- Daily tracking: Automatic Timer based with gearbox and chain mechanism.
- Seasonal tracking: Telescopic clamp arrangement operated manually once in 4-5 days.

3.2.1.2 Specifications of oven

- Material for the oven walls = Mild steel powder coated sheets of 1.5 mm thickness.
- Insulation: Rockwool blankets of thickness 60 mm on sides and top and bottom of the oven.
- Outside Dimensions of oven: 900 mm X 900 mm X 1800 mm
- Weight of loading frame and inside sheet combined: 35 kg.
- Size of iron free toughened glasses: 500 mm X 500 mm, 2 nos. one each at top and bottom are installed at latitude angle, which is 21° in Dhule.

3.3 Test Procedure

Test protocols developed by Paul A. Funk (2000), by Mullick S.C. et al (1991) and Draft test procedure (2006) use water as heat load and sensible heat gain by water as useful heat gain. As proposed industrial ovens are to be operated above 100°C, i.e. boiling point of water, it is not practicable to use water as heat load. Mild steel slabs and sections were used for heat load. Heat gain, efficiency and heat losses from the oven are the parameters of interest. Tests were conducted during February-March 2009 for a single Scheffler reflector and heat rate of 4 kWth was recorded and reported for operating temperature of 125°C (Chandak et al 2009). For double reflector oven, trials were conducted during the period of 6^{th} February 2010 to 15^{th} April 2010.

Two combinations of tests were performed, variable load with constant temperature and constant load with variable temperature. For variable load batches of 100 kg, 150 kg and 200 kg were allowed to reach to temperature of 125°C and performance was recorded. For constant load test 200 kg of steel was loaded and time to reach temperatures of 125°C, 150°C, 175°C and 200°C were recorded. Two Apogee solar sensors were used, one for total radiation I and other for diffused radiation I_d. Total radiation, I, was measured in a plane at right angle to the beam radiation while pyranometer with shading ring was used for diffused radiation measurement. K type of thermocouples five nos. were placed at different heights in the oven connected to the mild steel load to record load temperatures. Average temperatures of these thermocouples were used for calculations. One RTD was used for recording ambient temperature T_a. All temperature sensors and solar sensors were connected to Sunpro data logger which has 16 channel universal inputs and data with frequency of 1 minute was recorded.

3.4 Calculations and Results

Average heat duty over the operating range was calculated using formula

$$HeatDuty = M \times C_{ps} \times \frac{T_{s_2} - T_{s_1}}{t} \qquad \text{(eq. 1)}$$

$$\text{System efficiency, } \eta_b = \frac{\text{Heat duty}}{\frac{I_b \times Ap}{1000}} \qquad \text{(eq. 2)}$$

Heat loss from the oven was calculated by using logic as below.

Heat loss from oven = Optical gain at oven – heat duty (Heat gain by the load)

Optical gain at oven = I_b *x Ap x* ρ x τ x *solidity factor x intercept factor* (eq. 3)

Where ρ is 0.80 and τ is 0.85. Solidity factor for Scheffler dish is 1, while intercept factor is taken as 0.95.

Sample observation along with results of system efficiency, heat gain and losses are shown in Table 1. Trends of results are shown in graphical form in Fig. 5 and Fig. 6

Table 1 Sample observation and results of Industrial oven with pair of Scheffler reflectors of 16 m^2 each

Parameter	With constant load variable temp.					With variable load constant temp.			
Mass of steel blocks M	200	200	200	200		100	150	200	250
Beam Radiation I_b	790	780	775	775		790	765	790	730
Start temp of steel T_{s1}	35	35	35	35		34	34	35	33
End temp of steel T_{s2}	127	153	177	202		132	121	127	124
Time interval 't'	870	1255	1615	2005		485	650	870	1160
System efficiency η_b %	**54.73**	**49.29**	**46.39**	**43.94**		**52.29**	**53.66**	**54.73**	**54.93**
Heat gain in kWth	**9.7**	**8.8**	**8.2**	**7.8**		**9.3**	**9.2**	**9.7**	**9.0**
Losses from oven kWth	**1.75**	**2.69**	**3.18**	**3.6**		**2.19**	**1.88**	**1.75**	**1.59**

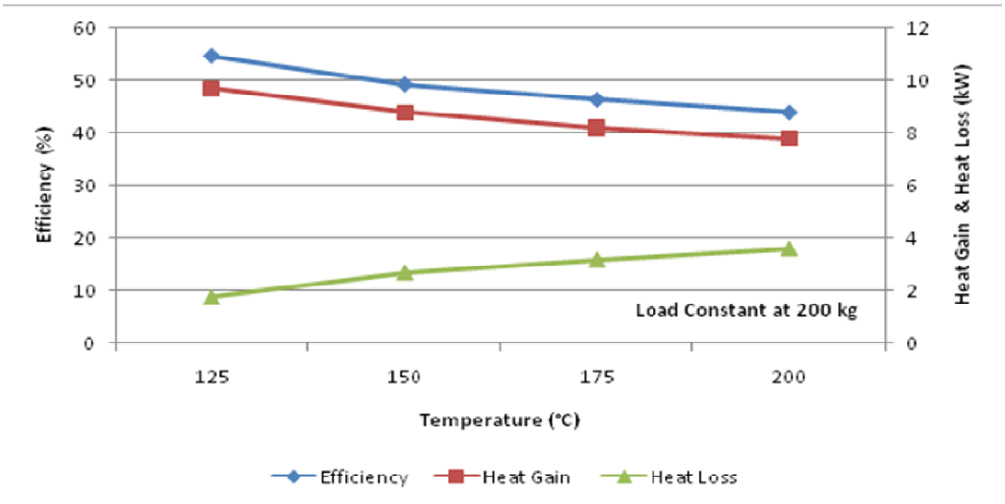


Fig. 5 Graphical representation of Temperature Vs Efficiency/Heat Gain/Heat Loss

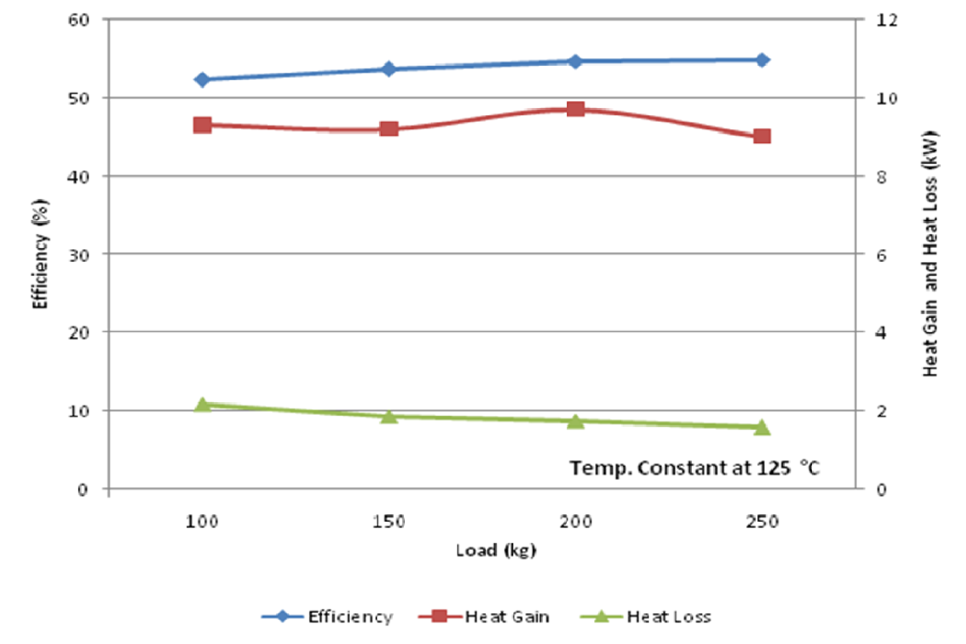


Fig. 6 Graphical representation of Load Vs Efficiency/Heat Gain/Heat Loss

It is evident from the results that the losses from the oven increase as operating temperature increases. However for constant temperature and variable load the losses reduce marginally when load is increased. It is possible to operate oven above 40% efficiency with operating temperatures up to 200°C. With better and thicker insulation it is possible to further reduce the heat losses and improve useful heat gains.

4.0 Financial Analysis

Most of the renewable energy applications are capital intensive with high paybacks, which is a reason for slow adoption of ‘Green technologies’ in industries. Typical Indian industry demands payback period of less than 3 years for adopting new projects. Government of India provides few incentives to the manufacturers in the form of tax waivers and to the end users by way of subsidies. These include 30% subsidy on the capital cost (JNNSM 2010) or special subsidy on Scheffler concentrators at ₹ 5600 per m^2 and 80% accelerated depreciation for all renewable energy projects in first year. 80% depreciation in the first year equates to 28% cash inflow by way of tax savings. Depreciation benefit can be claimed simultaneously along with subsidies. Additional revenues are possible by way of carbon credits and renewable energy certificates, for the projects of sizeable magnitudes. Financial analysis presented herewith considers all the scenarios, with and without financial incentives. Financial analysis is carried out for replacement of electricity as well as for replacement of LPG and LDO, which are very common fuels used in industrial ovens. Comparison is also done for LPG and LDO use with secondary heat exchanger which are commonly used in the food, paint and pharmaceutical industries. LPG, LDO heating systems normally delivers around 60% efficiencies in direct heating mode while the efficiency drops to 50% in indirect heating mode.

4.1 Capital Cost of the System: System comprises of two Scheffler reflectors of 16 m^2 each, costing ₹ 200000 each and one industrial oven box costing ₹ 100000. So total capital cost will be ₹ 500000. Considering the subsidies and other financial benefits net capital costs are calculated for different combinations and are shown in second column of table 2. For backup to the system, existing diesel or LPG burners can be installed in the same oven and hence this cost is not added to the system cost.

4.2 Cost Saving Calculations

Cost basis adopted: Electricity ₹ 7 per kWh, LDO ₹ 52 per kg and LPG ₹ 55 per kg.

4.2.1 Cost Saving for Electricity

Average thermal output of oven per day of solar system (8hrs) = 72 kWh thermal

Equivalent electrical input (Useful heat 9 kWth plus losses 3 kWth) = 12 kWth.

Electricity saved in 8 hrs = 8 X 12 kWth = 96 kWth

At ₹ 7 per kWh saving will be ₹ 672 per day or annual saving for 250 days will be = ₹ 168000.

4.2.2 Cost Saving for LPG and LDO

Average thermal output of oven per day (8hrs) expressed in kCal = 62000 kCal/day

Efficiency of LDO or LPG heated oven is @ 60% incorporating oven losses as well as losses in combustion system. Efficiency will reduce to 50% in case of indirect firing.

Calorific Value of LDO/LPG = 10000 kCal/kg.

LDO/LPG required per day = 12.4 kg with direct firing and 15.5 kg for indirect firing.

LDO cost per day = ₹ 635 per day with direct firing and ₹ 762 with indirect firing.

LPG cost per day = ₹ 672 per day with direct firing and ₹ 806 with indirect firing.

Payback periods are calculated for all combinations of capital cost as well as fuel replacement options and are tabulated in Table 2.

Table 2 Net capital investment and payback calculations for electricity and power saving options.

	Net Capital investment in ₹	Payback period in years with replacement of				
		Electricity	LDO		LPG	
			Direct firing	Indirect firing	Direct firing	Indirect firing
All capital investment by owner	500000	3.0	3.1	2.6	3.0	2.5
30% subsidy availed.	350000	2.1	2.2	1.8	2.1	1.7
80% accelerated depreciation benefit availed.	380000	2.3	2.4	2.0	2.3	1.9
30% subsidy and 80% depreciation, both benefits availed.	230000	1.4	1.4	1.2	1.4	1.1
Special subsidy for Solar concentrators at ₹ 5400 per m^2	327200	1.9	2.1	1.7	1.9	1.6
Special subsidy and 80% depreciation, both benefits availed.	207200	1.2	1.3	1.1	1.2	1.0

It is evident that new design of solar oven with twin reflectors will have payback period varying from 1.1 years to 3.1 years depending on the financial benefits availed. Payback less than 3 years is definitely attractive and can be accepted by the industry.

5.0 Conclusions:

Innovative design of focusing one sleeping and one standing Scheffler dish reflectors of 16 m^2 each inside a single oven permits utilizing high heat rates in small space. Performance characteristics and loss characteristics established herewith can be used for system sizing and predicting performance of solar oven for any commercial or industrial application. Industrial oven utilizing a pair of Scheffler concentrators of 16 m^2 each delivers more than 9 kWth at 125 °C, which is good enough for many industrial applications. These ovens can find applications in food processing, especially roasting and baking applications. Quality improvement in food processed product will be another value addition. Paint curing, baking, drying applications are other industrial application areas most suited for deployment of this innovative solar oven.

Depending on financial incentives availed and fuel or power to be saved the system can payback in 1 to 3.1 years which is attractive by any standards.

Designing heat storage system and use of absorber plates in place of secondary reflectors can also be tried out for improving utilization of existing system. These development projects will be taken up in coming years.

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