Solar Energy for Process Heating: a Case Study of Select Indian Industries

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Abstract

The annual consumption of petroleum products in India was about 221 million metric tons in 2015. Of this, 84% was imported. The Indian industrial sector accounts for about 16%–20% of the total fuel consumption for thermal energy for different heating applications in the temperature range of 50°C–250°C. Solar collectors can meet these temperature requirements and offer the possibility to mitigate the consumption of oil. This study highlights the fact that conversion efficiency from solar energy is much higher for process heating than for electricity generation and that process heating applications constitute a significant share of industrial energy consumption. In this paper, a methodology has been developed to estimate the potential for integration of solar collectors for process heating. The methodology employs process operating temperatures to select the type of solar collectors. The size of the solar field is estimated taking into account the thermal heat loads, working fluid and temperatures of these processes, the efficiency of the chosen solar collectors, location-based solar irradiance and capacity utilization of the solar collectors. The proposed methodology has been validated with a software tool called System Advisor Model (SAM). The techno-economic analysis will indicate the viability of solar systems for integration in industries. Therefore, the consociated parameters on economic (capital cost, fuel oil savings, monetary benefits), financial (Payback periods, Rates of Returns) and environmental (Carbon savings) are estimated. Further, the methodology has been applied to select Indian industries to verify its potential quantitatively. The industries selected include Textile, Pulp & Paper, Dairy, Leather and Automobile. Process-wise energy demands are considered while estimating the potential as the fuel requirement offset by solar energy in terms of absolute fuel oil savings, monetary benefits and carbon savings. The other economic and financial parameters mentioned above were estimated to verify the capability and present the market position of solar systems. Further, sensitivity analyses have been performed with respect to solar energy penetration and fuel oil prices to address the viability of integration of solar energy for process heating.

Keywords: Solar Energy; Process Heating; Monetary Savings; Carbon Savings; Payback Period; Internal Rates of Return.

Nomenclature

Symbol	Variable Name	Units
A_c	Area of a solar collector	m^2
$A_{process}$	Solar collector area required for a process	m^2
C_f	Fuel oil equivalent carbon dioxide emission factor	kg/ton of fuel oil
C_p	Specific heat of working fluid	kJ/kg/K
I_{day}	Solar irradiance over the day	kWh/ m^2 /day
k_f	Fuel oil equivalent energy factor	GJ/ton
N_s	Number of sunshine days in a year	Days
P	Hot water/air requirement	Liters/ton of product
P_c	Solar collector system capacity	Liters per day
Q_c	Thermal energy collected by a solar collector over a day	kJ/ m^2 /day
$Q_{process}$	Thermal energy requirement of an industry	kJ/year
$Q_{thermal}$	Thermal energy supplied by a solar collector over a year	GJ/year
Q_{year}	Thermal energy collected by a solar collector over a year	kJ/ m^2 /year
T_a	Ambient temperature	$^{\circ}C$
T_{avg}	Average temperature of fluid in a process	$^{\circ}C$
T_{in}	Inlet temperature of fluid in a process	$^{\circ}C$
T_{out}	Outlet temperature of fluid in a process	$^{\circ}C$
$q_{process}$	Thermal energy requirement of a process	kJ/ton of product
t_f	Tilt factor	Constant
Y_p	Production capacity of the industry	Tons/year
DPP	Discounted payback period	Years
IRR	Internal Rate of Return	%
η	Efficiency of solar collectors	%
$\eta_{combustion}$	Combustion efficiency	%

Abbreviations: DNI, Direct Normal Irradiation; ETC, Evacuated Tube Collector; FPC, Flat-Plate Collector; GHI, Global Horizontal Irradiation; HTC, High-Temperature Collector; IEA, International Energy Agency; IREDA, Indian Renewable Energy Development Agency Ltd.; LTC, Low-Temperature Collector; MTC, Medium Temperature Collector; NDCs, Nationally Determined Contributions; NREL, National Renewable Energy Laboratory; RE, Renewable Energy; SAM, System Advisor Model.

1. Introduction

The socioeconomic growth of a country depends a lot on the availability of energy (Adams et al., 2016; Kanagawa and Nakata, 2007). The source of this energy is a critical parameter to be evaluated with respect to energy security, sustainability and its impact on the environment (Dawn et al., 2016). As an example, the total installed capacity of electricity in India is 306 GW, of which 70% is derived from fossil fuels, 15% from nuclear and hydro, and 15% from Renewable Energy (RE) sources (CEA, 2016), with a small contribution from clean energy sources. Further, 85% of the crude oil requirement in India is met through imports. According to International Energy Agency (IEA), these imports will increase to 91.6% by 2020 (Mauthner and Werner, 2014). India spent about US\$ 6711 million annually on oil imports from 1957 to 2016. The expenditure reached an all-time high of US\$ 45,281.9 million in May 2011, with an average of about US\$ 25,000 million per month only in the past decade (Trading Economics, 2016). At the same time, the Prime Minister of India recently announced the government's intention to reduce dependence on oil imports by 10% by 2022 and 50% by 2030 (Sudheer, 2015). India's emissions presently exceed 2.5 Gt of CO₂, which is 6.5% of the total world emissions (Liu, 2016). In an effort to check these emissions, the government has taken many initiatives to reduce the national carbon footprint as reflected in the National Action Plan on Climate Change, the Nationally Determined Contributions (NDCs), The International Solar Alliance and RE goals. These initiatives are mainly to mainstream alternate clean energy sources and increase the energy efficiency of existing technologies to address the rising demand for energy, issue of climate change, energy security, reduce oil import dependence, etc. India aims to achieve the following RE targets by 2022: 100 GW from solar, 60 GW from wind, 10 GW from biomass and 5 GW from small hydro. In addition, India's NDC goal is to achieve 40% of total installed power generation capacity from RE and reduce the emission intensity per GDP unit to 33%–35% below the 2005 levels by 2030 (Ashok, 2015). In this context, the present study has been conducted to develop a methodology for assessing the potential of solar energy for process heating in any industry. Further, a case study has been presented for select industries in India to assess the techno-economic potential quantitatively.

Fossil fuels currently play a significant role in fulfilling the demand for process heating in industries for various applications. A majority of these processes operate in the temperature range of 50°C–250°C (Fuller, 2011; Kalogirou, 2003). In India, these processes generate oil consumption of about 40% (70 Million Metric Tons) of the total oil consumption of the country (EIA, 2013; MPNG, 2015; Rastogi, 2014). The use of solar collectors as an alternative for supplying this heat can reduce the usage of fossil fuels to some extent. At present, most of the solar collectors are used for domestic water heating. For use in industries for processes like sterilization, pasteurization, drying, evaporation, washing, cleaning, bleaching, cooking, pre-heating, etc. (ETSAP and IRENA, 2015), solar collectors will have to supply heat in the required temperature ranges for specific processes.

The integration of solar collectors in existing process cycles is, however, a challenging task. Also, some industrial processes operate round the clock and require constant energy continuously. Despite the potential of solar collectors in meeting the required heat demand, their smooth operation is a challenge owing to the intermittent nature of solar irradiance. Further, since sunlight is available for only one-third of a day, storage or hybridization would be required (Kulkarni et al., 2008). Though a system containing solar with storage and hybridization (with fuel source such as natural gas or fuel oil) is an option to avoid process intermittency, this would generate additional costs. The working fluid must be pressurized if required temperatures are above 100°C for heating applications to avoid boiling (in case of water) inside the solar collector system.

According to a report released by the IEA (Mekhilef et al., 2011), solar energy will be able to meet about 45% of the global energy demand by 2050. Many strategic programs are already underway across the globe to increase its adoption (ESTTP, 2008; MNRE, 2010; SERIUS, 2016).

A brief summary of the literature findings on solar energy for process heating is covered in this paragraph. (Carnevale et al., 2011) analyzed the impact of integration of parabolic trough solar systems in a Textile factory both technically and economically. They found that although integration leads to annual natural gas savings of 40%–50% (out of 47 Nm³), it is not sufficient to recover the capital investment. However, a decrease of 50% in the cost of solar components reduces the payback period to 6 years. (Fuller, 2011) reviewed the achievements of solar industrial process heating in Australia and found that solar-based systems are technically feasible but not viable financially (payback period is more than 17 years) due to high capital cost. (Silva et al., 2014) studied the thermo-economics of a solar plant for industrial process heating and found that solar energy will play a vital role if fossil fuel prices increase rapidly. (Koroneos and Nanaki, 2012) examined the life-cycle assessment of a solar water heater and found that a 4 m² flat-plate collector (FPC) can provide energy of 1,700 kWh/year and monetary life-cycle savings of US\$5,600 with a payback period of 5 years.

The available literature is not sufficient if one is interested to verify the possibility of integration of solar thermal collectors for process heating in industries and its potential at national level. Therefore, the current study proposes a methodology to estimate the potential of solar energy collectors for process heating in industries. Further, this methodology is applied to select Indian industries, as a case study, to understand the gross potential of solar thermal collectors. The unique feature of this paper is that it considers the process-wise energy demand in industries while estimating the potential at national level. The gross assessment is expressed in terms of economic and environmental benefits. Sensitivity analyses are performed to observe the impact of fuel oil price and solar energy penetration rate on key economic parameters. Details of the methodology and potential findings from select Indian industries are explained in the following sections.

2. Methodology

A methodology has been developed to estimate the potential of solar energy for process heating in industries. Initially, all processes in each industry that requires thermal energy are identified. The operating temperatures of these processes are considered for the selection criteria for solar collectors. Further, the total quantum of thermal energy required for each industry is estimated based on the production capacity of the industry at national level. This total thermal energy is used to estimate the size of the solar field required for each industry. The associated capital costs and payback periods for retrofitting solar collectors are then estimated. Benefits in terms of CO₂ reductions and monetary are also quantified with offsetting of base-fuel. These economic and environmental parameters are useful in addressing the sustainability aspects of this intervention. The method for integrating a solar thermal collector for process heating is shown in Fig. 1.

Fig. 1: Method for integrating a solar thermal collector for process heating

The sections below describe the detailed step-by-step methodology used to carry out the potential assessment.

2.1. Selection of Solar Collectors for Process Heating

Solar collectors can be primarily categorized as low- (LTCs), medium- (MTCs) and high-temperature collectors (HTCs) with operating temperatures of <80°C, 80°C–250°C, and >250°C, respectively (Tchanche, 2015). LTCs are mainly used for water heating and space heating applications. MTCs are used for generating hot water, steam and hot air in industrial process heating and cooling applications, whereas an HTC is mainly used for power generation and for supplying hot water/steam. Most of the LTCs and MTCs are stationary-type collectors and they do not track the sun, whereas HTCs are moving-type collectors and track the position of the sun over a day. An appropriate combination of these types can be used in different industries depending on the heat demand in different processes.

The selection of a solar collector depends on the operating temperatures of the processes. Most of the industrial processes require thermal heating at temperatures in the range of 40°C–250°C (Fernández-García et al., 2015; Kalogirou, 2003; Schnitzer et al., 2007). FPCs and Evacuated Tube Collectors (ETCs) are economical to generate heat up to 150°C for process heating (Kalogirou, 2004). HTCs can generate heat up to 400°C, but the interventions for process heating in industries are capital- and space-intensive. In addition, HTC technologies such as parabolic trough, linear Fresnel and Solar Tower are not suitable for industrial wastelands (Purohit et al., 2013). Therefore, dish collectors are considered among other HTC technologies for processes that can generate temperatures greater than 150°C. Water and air are appropriate working fluids in these collectors. Forced-circulation solar collectors are preferable for industrial purposes. ETCs are suitable for use in cold climate as they have no freezing issues. However, ETC-type collectors are made of glass and are fragile in nature, whereas FPCs contain metallic components and have longer lives. Dish collectors require high capital investment

compared with FPCs and ETCs, but they can generate higher temperatures. The general plant life for an FPC, an ETC and a Dish are 20, 15 and 25 years, respectively. Table 1 mentions the criteria for selecting the type of solar collector based on the average operating temperatures of industrial processes.

Table 1: Selection of Solar Collector based on the Operating Temperature of a Process

Operating temperature (T_{avg}), °C	Solar collector	Lifetime (years)
40–80	Flat-plate	20
80–150	Evacuated tube	15
>150	Dish	25 (glass based)

2.2. Input Parameters for the Methodology

The inputs for the techno-economic assessment of solar collectors are as follows:

- Solar irradiance, I_{day} (kWh/m²/day)
- Number of sunny days in a year, N_s
- Tilt factor of the solar collector, t_f
- Operation & Maintenance (O&M) of solar collectors
- Efficiency of solar collectors, η
- Ambient temperature, T_a

2.3. Estimation of Thermal Energy Requirement

The steps followed for estimating the thermal energy requirement in any industry are given below:

- Identify the number of processes required for thermal heating
- Calculate the average operating temperature for each process, T_{avg} (°C)
- Calculate the hot water/hot air requirement for each process, P , as liters/ton of product
- Estimate the thermal energy requirement (heat demand), $q_{process}$, as kJ/ton of product (MA Ramaswamy et al., 2012):

$$q_{process} = P \times C_p \times (T_{avg} - T_{in}), \quad (1)$$

where C_p is the specific heat of water or air (kJ/kg/K) and T_{in} is the fluid inlet temperature.

2.4. Estimation of the Energy and Solar Collector Area Requirements for a Specific Process

The solar collector area is estimated based on the thermal energy requirement of a specific industrial process. The steps followed to estimate the solar collector area are shown in the flowchart in Fig. 2. The tilt factor indicated in Fig. 2 is used to adjust the solar collector such that it receives maximum amount of solar energy over the year. Tilting up a collector by an angle equivalent to latitude from horizontal (facing south for locations in Northern hemisphere and facing north in Southern hemisphere) will increase the incident irradiance compared to that of a collector which is at horizontal. This adjustment factor is called the tilt factor. Tilt is not required for tracking systems (e.g., a dish).

Fig. 2: Flowchart to Estimate the Energy and Solar Collector Area Requirements for Process Heating

2.5. Estimation of Total Capital Cost

The steps followed for estimating the capital cost of solar collectors used for process heating in industries are as follows:

1. Identify the number of processes requiring thermal energy
2. Estimate the solar collector area required for each process as explained in Section 2.4
3. Estimate the capital cost of the solar collectors on a per m² basis.

2.6. Estimation of Benefits

The benefits of the implementation of solar collectors in terms of fuel savings, monetary savings and carbon emission savings in each industry are estimated as explained below.

2.6.1. Annual Fuel Oil Savings

Annual fuel savings are estimated based on the amount of thermal energy ($Q_{thermal}$ in GJ) supplied by solar collectors as follows (Karbuz, 2004):

$$Fuel\ oil\ savings\ (toe) = Q_{thermal} / (k_f \times \eta_{combustion}), \quad (2)$$

where $\eta_{combustion}$ is the combustion efficiency and k_f is the fuel equivalent energy factor in GJ per ton (e.g., k_f for fuel oil is 41.868 GJ).

2.6.2. Annual Net Monetary Savings

The annual net monetary savings from the solar collectors are estimated as follows:

$$Net\ monetary\ savings = (Price\ of\ fuel\ oil \times Fuel\ oil\ savings - Annual\ O\&M\ cost\ of\ solar\ collectors). \quad (3)$$

2.6.3. Discounted Payback Period

Discounted Payback Period (DPP) is defined as the length of time that elapses before the present value of the cumulative net cash flow first exceeds the initial cash outlay (Weil and Maher, 2005). This indicator is used to evaluate the time period required for solar collectors to recoup the capital investment and bring in profits post the payback period. DPP is estimated as follows (Weil and Maher, 2005):

$$\text{Discounted Payback Period} = A + B/C, \quad (4)$$

where A = Last time period in which the cumulated cash flow was negative, year

B = Absolute discounted cash flow corresponding to the year ' A '

C = Discounted cash flow corresponding the subsequent year (' $A+1$ ').

2.6.4. Internal Rate of Return

Internal Rate of Return (IRR) is a decision-making parameter that is used to calculate the rates of returns on an investment. This is estimated considering all discounted cash flows of the system over the lifetime of a project (in this case, solar collector system) using the in-built formula of Microsoft Excel, version 2013 (MA Ramaswamy et al., 2012):

$$\text{Internal Rate of Return} = \text{IRR (all cash flows over the lifetime)}. \quad (5)$$

2.6.5. Carbon Savings

Carbon dioxide savings due to reduction of fuel oil use for process heating are estimated as follows (Carbon Trust, 2016):

$$\text{Annual } CO_2 \text{ Savings (kgCO}_2\text{)} = C_f \times \text{Fuel oil savings (toe)}. \quad (6)$$

Here C_f is the fuel equivalent carbon dioxide emission factor in kg per ton of fuel [e.g., C_f for fuel oil is 3,232.7 kg of carbon dioxide (Mauthner and Werner, 2014)].

3. Case Study of Select Indian Industries

The methodology presented above (Section 2) is applied to a few energy-intensive industries in India to assess the economic and environmental parameters. These parameters give an idea of the sustainability of integrating solar thermal systems for process heating in industries.

3.1. Inputs for the Case Study

India-specific inputs and assumptions for the case study are presented in the following section.

3.1.1. Efficiency of Solar Collectors

The variation of the thermal efficiencies of FPCs, ETCs and Dish solar collectors with the operating temperature of the working fluid is shown in Fig. 3 (Kedare et al., 2012; Purohit et al., 2013). T_{op} and T_a represent the operating and ambient temperature, respectively. An increase in temperature causes more heat losses and, hence, a decrease in efficiency. The efficiencies of the collectors vary among systems according to design specifications (Kalogirou, 1999; Kedare et al., 2012). However, the variation of efficiency shown in Fig. 3 is employed for assessing solar collectors.

Fig. 3: Variation of a solar collector's efficiency with process operating temperatures

3.1.2. Assumptions

The assumptions for the techno-economic assessment of solar collectors are as follows:

- i. Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) for India vary from 4.5 to 6.5 kWh/m²/day (NREL, 2015). Therefore, an average value of 5.5 kWh/m²/day is taken as the reference solar irradiance.
- ii. The number of sunny days (N_s) in a year is 260 (Khare et al., 2013).
- iii. The tilt factor (t_f) of both FPCs and ETCs is taken as 1.1. See Section 2.4 for details.
- iv. Solar energy penetration can technically go up to 100% with additional storage. The solar collector area will increase proportionately with the storage capacity. However, industries may have the potential of 20%–40% solar energy penetration (The base case study considers 20% of thermal energy demand of a process by solar energy.) Reasons for this assumption are as follows: (a) sunlight will be available for only a maximum of 10–12 hours a day; (b) most industrial processes require energy round the clock—100% energy from solar without storage is not possible; and (c) industries have space constraints.
- v. O&M is taken as 2% of capital cost. Further, a 2% escalation is considered each year (UNDP, 2010).
- vi. The thermal energy needs of the industries are predominantly met with fuel oil compared with coal and electricity (Kalogirou, 1999; Thiruchelvam et al., 2003).
- vii. The efficiency of solar collectors depends on ambient temperatures. Based on the temperature variations across India, an average ambient temperature (T_a) of 25°C is considered for the analysis.
- viii. The percentage consumption of petroleum products in Industries is estimated based on 2012 levels.
- ix. The capital costs (in US \$/m²) of FPCs, ETCs and Dish collectors are 178, 163 and 331, respectively.
- x. The price of fuel oil over the past decade varied from US\$1.0 to US\$3.7 per gallon (Indexmundi, 2016). This range is considered in performing the economic analysis.

3.1.3. Validation of the methodology

The methodology presented in Section 2 has been validated with both simulation software and experimental data. System Advisor Model (SAM), a performance and financial tool developed by National Renewable Energy Laboratory (NREL), is used as simulation software for this validation. The input parameters considered and output parameters estimated are presented in Table 2. It can be seen that the annual thermal energy generated per m² of solar collector area matches well between the model and simulation software, with the error difference being 2.1%. With respect to experimental validation, we have used the data from the demonstration system installed by the company CONTANK in Barcelona, Spain. CONTANK's system uses 510 m² of FPC and it generated annual thermal energy of 429 MWh, equivalent to 841 kWh/m². Hence, the results obtained from the model are quite satisfactory to estimate the potential in process heating.

Table 2: Validation of the methodology with SAM

	Model	SAM
Input parameters		
System capacity (liters per day, LPD)	200	200
Ambient temperature T_a (°C)	25	25
Working fluid	Water	Water
Solar collector	FPC	FPC
Working fluid inlet temperature (T_{in} , °C)	25	25
Working fluid outlet temperature (T_{out} , °C)	60	60
Location	India (general)	Ahmedabad, India
Solar collector area	2.46	4
Solar irradiance (kWh/m ² /day)	5.5	5.45
Solar radiation availability (based on days in a year or hourly)	260	Hourly data
Output parameters		
Average collector efficiency	0.57	0.55
Annual thermal energy generated (kWh _t)	2116.2	3369.4
Annual thermal energy generated per unit collector area (kWh/m²/year)	842.4	860.2

3.1.4. Limitations and Implications

The present study has not included the following in its analysis:

- Operational issues
- Control and technical issues with resource intermittency
- Additional costs due to water quality and flow pressures

Considering the above limitations, the study can be used to make a gross assessment of the solar thermal collector potential for process heating in industries. Further, it is to be noted that the costs of the systems reduce exponentially with capacity.

3.2. Potential of select Indian Industries

The industries considered in the present analysis are Textile, Pulp & Paper, Dairy, Leather and Automobile. These industries consume 2,800 ktoe of fuel oil for process heating in the operating temperature range of 50°C–250°C. This corresponds to 6.3% of the total consumption by all industries. The methodology presented in Section 2 can be applied to any other industry in addition to these where process heating can be achieved with solar thermal collectors.

Details of assessment in each industry and findings are presented in the sections below.

3.2.1. Textile Industry

In India, the Textile industry contributes 14% to the total industrial production, 4% to the GDP and 11% to the country's export earnings. This is also an energy-intensive industry and is the second largest industry in the world in terms of fiber production and employment generation (IBEF, 2014; Palanichamy and Sundar, 2005). This sector has large process variants in terms of products, namely, man-made fiber, cotton, handloom, woolen, jute, and sericulture and silk. The operating temperatures of different processes, the conventional fuels for heat generation and the potential solar collectors to retrofit the existing conventional systems in this industry are given in Table 3 (Anjali, 2012; Kalogirou, 2004; Mekhilef et al., 2011; Tanapongpipat et al., 2008).

Table 3: Suitable solar collectors in the Textile industry

Process	Operating Temperature (°C)	Fuel sources used	Suitable solar collector
Sizing	60–90	Electricity,	ETC
Scouring	90–110	petroleum,	ETC
Bleaching	90–95	coal and	ETC

Mercerizing	60–70	other fuels	FPC
Dyeing	70–90		FPC
Finishing	40–100		ETC

The Indian Textile industry has an annual fabric production capacity of about 9.6 million tons (Ministry of Textiles, 2014; The Textile Magazine, 2013). Of the total domestic production, 20% of the fabric production undergoes the processes mentioned in Table 3 via the organized sector. The thermal energy requirements of all these processes can be met through FPC and ETC solar collectors as their operating temperatures are less than 150°C.

The potential of solar energy penetration with FPCs and ETCs in the Textile industry for various processes at national level is estimated and is given in Table 4. It can be seen that the total thermal energy demand in the Textile industry is 8.3×10^7 GJ/year, which is similar to the observations of (Thiruchelvam et al., 2003). Of this, the solar component can supply 1.7×10^7 GJ/year. This requires a solar collector area of 6.2 million m², which requires a capital investment of US\$970 million. Details of higher solar energy penetration through thermal energy storage are presented in the sensitivity analysis in Section 4.

Table 4: Energy demands and the possibility of solar energy integration in the Textile industry

Process	Energy demand ($\times 10^6$ GJ/year)	Solar collector area (million m ²)	Capital cost to install solar (US\$ million)
Sizing	6.23	0.40	60
Scouring	12.1	0.87	128
Bleaching	6.85	0.45	67
Mercerizing	4.82	0.34	55
Dyeing	39.78	3.29	537
Finishing	13.02	0.82	122
Total	82.79	6.18	970

The overall annual benefits are presented in Table 5. It is found that Textile industries have the potential to make fuel oil savings of about 439 ktoe. This translates to annual net monetary savings of US\$123 million and annual CO₂ reductions of about 1,420 kt (0.06% of total Indian emissions) with the integration of solar collectors.

Table 5: Overall annual benefits of Textile industry with solar energy

Description	Value
Fuel oil demand (ktoe)	2,471
Fuel oil saved by solar energy (ktoe)	439
Net monetary benefits (US\$ million)	123
CO ₂ reductions (kt)	1,420

3.2.2. Pulp & Paper Industry

Pulp & Paper is another energy-intensive industry in India with a production capacity of more than 10 million tons. India accounts for only 2%–3% of the global paper and paperboard production (IREDA, 2010), but the energy requirement cost through fuel accounts for nearly 25% of the overall manufacturing cost. IREDA estimated that the total annual energy consumption of the Indian paper industry is about 52 million Gcal, which is equivalent to about US\$220 million.

Processes in this industry that have scopes for integration of solar technologies are debarking, pulp making, bleaching, stock preparation and paper making. These processes are highly energy-intensive and utilize heat mainly for cleaning, boiler feed water heating and drying (Edenhofer, 2012; Gemechu et al., 2012). The operating temperatures of these processes, the fuels used for heat generation and suitable solar technologies are given in Table 6 (Mekhilef et al., 2011; The Textile Magazine, 2013).

Table 6: Suitable solar collectors in the Pulp & Paper industry

Process	Temperature (°C)	Existing fuel source	Suitable solar
Cooking, drying	60–80	Fuel oil, pet	FPC
Boiler feed water	60–90	coke, rice husk	FPC
Bleaching	130–150	and coal	ETC

The solar energy potential estimation is done based on the gross production and thermal energy requirements (ComSolar, 2011; IPMA, 2014). Details are given in Table 7. It can be seen that the solar component can supply 2.5 PJ of energy. However, estimates made by (Sharma et al., 2016) indicate that the total process heating potential of the Pulp & Paper industry in India is 25.2 PJ/annum. This estimation has been arrived at based on the fact that the industry uses the parabolic trough technology, which supplies energy at high temperatures. However, the present paper production process considers FPCs and ETCs for preheating at 70°C. It can also be seen that the total solar collector area required is 0.9 million m² and the capital cost is US\$149 million.

Table 7: Energy demands and the possibility of solar energy integration in the Pulp & Paper industry

Description	Quantity	Units
Total production of paper and paperboard	10.11	Million tons/year
Hot water requirement for preheating @70°C	6.5	Tons/ton of paper
Energy required	12.38	PJ/year
Energy from solar collectors	2.48	PJ/year
Solar collector area required	0.91	Million m ²
Capital cost for solar collectors	149	US\$ million

Further, it can be seen from Table 8 that the total fuel oil required for all the processes is about 329 ktoe. However, the amount of fuel that can be saved through the solar component is 66 ktoe, with annual CO₂ reductions of about 213 kt. The net monetary savings due to replacement with the solar component is US\$18.3 million.

Table 8: Overall annual benefits in the Pulp & Paper industry with solar energy

Description	Quantity	Units
Fuel oil demand	329	ktoe
Fuel oil saved by solar energy	66	ktoe
Net monetary benefits	18.3	US\$ million
CO ₂ reductions	210	kt

3.2.3. Dairy Industry

The Dairy industry in India accounts for 13% of the global milk production. The annual growth rate in milk production was about 4% in 2002–12. In FY 2010–11, 122 million tons of milk were produced and it is expected that milk production will exceed 140 million tons in 2014 (Indiastat, 2014). In India, only 13% of the total milk production is processed by the organized sector. The shares of hot water and thermal energy consumption by various processes and their operating temperatures in the Dairy industry are given in Table 9 (ComSolar, 2011; Mekhilef et al., 2011; Müller et al., 2014).

Table 9: Suitable solar collectors in Dairy industry

Process	Water consumption (%)	Energy consumption (%)	Temperature (°C)	Suitable solar collector
Cleaning	18	5	40–60	FPC
Pasteurization, Sterilization and Evaporation (PSE)	18	36	70–120	ETC
Pre-heating	12	3	35–45	FPC
Incorporated into products	40	36	-	
Other purposes	12	20	-	

As per national norms, 0.034 kWh of electricity, 5 ml of fuel oil and 2 liters of water are required to process 1 liter of milk (ComSolar, 2011; Xu and Flapper, 2009). This is equivalent to about 0.33 MJ of energy. The thermal energy requirements for the processes mentioned above and the potential for solar energy penetration with FPCs and ETCs in the Dairy industry are given in Table 10. It can be seen that the solar component can supply 0.49 PJ of thermal energy. The total solar collector area required to supply this energy is about 0.16 million m² with an associated capital cost of US\$25 million.

Table 10: Energy requirements and potential in the Dairy Industry

Process	Thermal Energy (PJ)	Thermal energy from solar (PJ)	Collector area (Million m ²)	Capital cost (US\$ million)
Cleaning	0.58	0.12	0.035	2.8
PSE	1.62	0.32	0.12	17.2
Pre-heating processes	0.23	0.05	0.013	2.1

Details of fuel oil and monetary savings with integration of solar collectors in this industry are given in Table 11. The Dairy industry requires about 64.6 ktOE of fuel oil for process heating. Installation of solar components can bring in fuel oil savings of 12.9 ktOE and annual CO₂ reductions of about 41 kt.

Table 11: Overall annual benefits in the Dairy industry with solar energy

Parameter	Value
Fuel oil demand (ktOE)	64.6
Fuel oil saved by solar (ktOE)	12.9
CO ₂ reductions (kt)	41
Net monetary benefits (US\$ million)	3.7

3.2.4. Leather Industry

The Indian Leather industry occupies a prominent position on account of considerable export earnings, employment generation and various consumer products. Of the total production, the organized sector accounts for 56.4% and the un-organized sector accounts for 43.6%. Table 12 shows the operating temperatures and fuels used for heat generation in the tanning sector of the Leather industry (ComSolar, 2011).

Table 12: Suitable solar collectors in the Leather industry

Process	Temperature (°C)	Fuel being used	Suitable solar
Pre-tanning	40–60	Fuel oil, rice	FPC
Tanning	60–80	husk, firewood,	FPC
Post-tanning	70–100	coal	ETC

Tanning operations (soaking, liming, pickling, splitting, dyeing, etc.) consume most of the thermal energy in terms of heating water to a temperature of 40°C–80°C and air to a temperature of 70°C–100°C. This accounts for 40% of the total thermal energy consumption in the Leather industry (Buddhadeb, 2010). The total capacity of Indian tanning units is around 2 billion sq. ft. of hide/skin (annual production of about 0.7 million tons), with about 1,600 kcal of thermal energy required to process 1 kg of hide/skin. Leather industry consumes about 21 billion liters of water annually. The solar energy potential in the Leather industry is estimated and presented in Table 13 (ComSolar, 2011; Council for Leather Exports, 2014).

It can be seen that the hot water accounts for 8.4 billion liters, requiring thermal energy of 4.4 PJ per annum (31% for hot water and 63% for hot air). The industry has potential of about 0.27 million m² for ETC solar collectors to supply thermal energy, which requires an investment of US\$40 million.

Table 13: Process requirements and solar energy potential in the Leather industry

Parameter	Value
Hot water requirement (billion liters/annum)	8.4
Energy requirement for hot water (PJ/annum)	1.47
Energy requirement for drying (PJ/annum)	2.93
Energy for hot water from solar collectors (PJ/annum)	0.29
Energy for drying from solar collectors (PJ/annum)	0.59
Solar collector area required (million m ²)	0.27
Capital cost for solar collectors (US\$ million)	40

Further, it can be seen from Table 14 that 23 ktoe of oil savings translate to net monetary savings of US\$6.7 million and 75 kt of CO₂ reduction.

Table 14: Overall annual benefits in the Leather industry with solar energy

Parameter	Value
Fuel oil demand (ktoe)	116
Fuel oil savings due to solar energy (ktoe)	23
Annual CO ₂ reductions (kt)	75
Net annual monetary savings (US\$ million)	6.7

3.2.5. Automobile Industry

The Indian Automobile industry is one of the largest markets in the world. In FY 2012–13, the industry manufactured about 16 million vehicles (IBEF, 2014), and growth is expected to be more than 13% per annum in 2012–2021 (Kulkarni et al., 2014). The consumption of fossil fuels for the heat requirements in this industry is significant and is of the order of 1,000 ktoe/annum.

Most of the processes in the Automobile industry are mechanical and are driven by electricity. However, a few processes require considerable amount of thermal energy for drying and cleaning. Generally, drying is done by blowing hot air and cleaning by using hot water. The operating temperatures of these processes, the fuels used for heat generation and suitable solar technologies are given in Table 15. The energy consumption of the processes is analyzed considering an equivalent passenger vehicle. Therefore, for every vehicle, a weight factor is assigned with respect to the energy consumption of an equivalent passenger vehicle. The equivalent weight factors for two- and three-wheelers, small commercial vehicles, construction vehicles and heavy commercial vehicles are 0.5, 2, 3.7, and 4, respectively. The thermal energy requirement for air heating at 200°C is about 1,000 kcal/Eq. vehicle and is about 1,000 liter/car for heating water at 95°C (ACMA, 2009; ComSolar, 2011).

Table 15: Suitable solar collectors in the Automobile industry

Process	Temperature (°C)	Fuel being used	Suitable solar
Hot water	85-95	Fuel oil,	ETC
Drying (hot air)	~200	Electricity	Dish

The thermal energy requirements and solar energy potential in the Automobile industry are estimated and presented in Table 16. It can be noted that a dish collector is used for drying at 200°C and an ETC is used for generating hot water at 95°C. This industry has a potential of 0.29 million m² for solar collectors.

Table 16: Energy demands and the possibility of solar energy integration in the Automobile industry

Parameter	Value	
	Dish (drying)	ETC (water heating)
Total thermal energy per annum (PJ/annum)	0.07	4.34
Thermal energy from solar (PJ/annum)	0.013	0.87
Collector area (million m ²)	0.005	0.29
Capital cost (US\$ million)	1.57	43.4

Table 17 provides the overall benefits due to penetration of solar energy in the Automobile industry. It can be seen that annual net monetary savings of US\$18.15 million and total annual CO₂ reductions of about 76 kt can be achieved by using solar collectors.

Table 17: Overall annual benefits in the Automobile industry with solar energy

Parameter	Value	
	Dish	ETC
Fuel oil demand (ktoe)	1.8	115
Fuel oil savings (ktoe)	0.36	23
Net monetary savings (US\$ million)	0.1	6.5
CO ₂ reductions (kt)	1.2	75

4. Summary of Solar Energy Potential in the selected Industries

The overall potential of solar energy and the benefits for process heating in the Indian Textile, Pulp & Paper, Dairy, Leather and Automobile industries are given in Table 18. These industries have potential for fuel oil savings of anywhere between 565 ktoe and 2,827 ktoe using solar energy integration for process heating. With 20% solar energy integration, these industries require about 7.8 million m² of solar collector area with an investment of US\$1200 million. This will have annual net monetary benefits of US\$158 million, with 1.8 Mt of CO₂ load reduction to the environment.

Table 18: Overall potential of solar energy in the selected industries

Industry type	Fuel oil demand (ktoe)	Fuel oil savings by solar energy (ktoe)	Solar collector area (million m ²)	Capital cost to install solar collectors (US\$ million)	Net monetary savings (US\$ million)	CO ₂ emission reduction (Mt CO ₂ /year)
Textile	2,197	439	6.2	970	123	1.42
Pulp & Paper	329	66	0.9	149	18.3	0.22
Dairy	65	13	0.16	25	3.7	0.05
Leather	117	23	0.27	40	6.7	0.08
Automobile	117	23	0.30	45	6.6	0.08
Total	2,827	565	7.8	1,229	158	1.8

5. Sensitivity Analysis

A parametric study has been performed in this section with respect to key sensitive parameters. This analysis helps in making decisions on the implementation of these systems. The study identified capital cost, fuel oil savings, IRR, DPP, and carbon savings to be the major output parameters. The analysis that follows investigates the effect of key input parameters on these outputs.

5.1. Effect of Solar Energy Penetration

Fig. 4 shows the variation of capital cost and solar collector area for various penetration scenarios. The thermal energy storage cost is also accounted for the capital cost for higher solar energy penetration. It may be noted that the capital cost for 20%–100% solar penetration varies from US\$1200 to US\$6100 million with a solar collector area of 7.8–40 million m². The corresponding supply of thermal energy is 21–106 PJ. The actual

capital costs of solar collectors depend on the scale of the particular installation, which further depends on the scale of the actual industrial unit/plant. This has not been considered in this study and could be further examined depending on the scale of the system. The capital cost may decrease exponentially for systems of higher size. However, the present study is useful to assess the scale of costs and savings through installation of solar collectors.

Fig. 4: Variation of Capital Cost and Collector Area with Solar Energy Penetration

Fig. 5 shows the variation of fuel oil and carbon emission savings with solar energy penetration. It is important to note that fuel oil and carbon emission savings increase proportionately with solar energy penetration. With 20%–100% solar energy penetration, these savings amount to 565–2827 ktoe and 1.68–9.0 Mt CO₂, respectively. 100% solar penetration (equivalent to 2,827 ktoe) in these industries could reduce the total oil consumption in all industries by 6.5%. As indicated in Section 2.6, the savings of fuel oil will be proportional to the energy supplied by the solar collectors. Therefore, the fuel oil savings and carbon savings will be in linear proportion with the energy savings through solar energy.

Fig. 5: Variation of Fuel oil and CO₂ emission savings with Solar Energy Penetration

5.2. Effect of Fuel Oil Price

The influence of fuel oil price on the DPP and the IRR is investigated in this section. Fig. 6 shows the variation of fuel oil price from 2006 to 2016 (Indexmundi, 2016).

Fig. 6: Trend of Fuel Oil Price for India in the Past Decade

Fig. 6 shows that the price of fuel oil varied continuously over the past decade. It is important to note that the price of fuel oil was increasing during the period 2009–12, over which many initiatives were launched by the Government of India to increase the penetration of solar energy. Further, subsidies on both the capital cost for captive installation and the purchase cost of energy from solar were also offered to promote solar energy for various applications. Since 2013, the price of fuel oil started falling. Fig. 7 and Fig. 8 show the effects of this fall on the DPP and IRR of low-temperature solar collectors (FPC and ETC) and high-temperature collectors (Dish), respectively. It is to be noted that subsidies on solar thermal collectors were discontinued in 2014. The DPP and IRR are arrived at by considering 10% discount rate for LTCs and 5% for HTC, 2% of capital cost for O&M, and a 2% escalation in O&M for every year.

Fig. 7: Variation of DPP and IRR with Fuel oil price for LTCs

As can be seen from Fig. 7, both DPP and IRR of solar thermal collectors are sensitive to changes in fuel oil price. With increase in fuel oil price, DPP decreases exponentially whereas IRR increases proportionately. At a fuel price of US\$1.19 per gallon (present oil price), the DPP of solar collectors is over 20 years (exceeds the life of LTCs) and the IRR is 9.8%. In this condition, solar collectors are strictly not a viable option. However, DPP decreases to 4.5 years and IRR increases to 29% when the fuel oil price exceeds US\$2.5 per gallon (similar to the rates in the period between 2010 and 2014).

A similar exercise for a Dish collector is presented in Fig. 8. The DPP and IRR figures indicate that Dish collectors for process heating are not viable with the preset capital costs of solar collectors and fuel oil prices. However, when the fuel price is above US\$2.5 per gallon, DPP is around 14 years and IRR is 13%, which is slightly viable. Further, it is to be noted that dish collectors can offer higher temperatures (150°C–400°C) and a longer lifetime (25–30 years).

These parameters can be optimized, but that depends on system costs, scale of the systems, solar irradiance and fuel oil prices. It is obvious that any investor will expect high returns and lower payback periods. At the present state, suitable solutions are largely dependent on fuel oil price. A possible solution could be when fuel oil price is >1.8 \$/gallon, at which the DPP is <7 years and IRR is >20% for the LTCs. And, for the dish collectors, the fuel oil price has to be >2.5 \$/gallon, at which the DPP is <15 years and IRR is >13%.

Overall, the viability of solar collectors will highly depend on the price of fuel oil unless the capital cost of solar collectors falls or subsidies are offered.

Fig. 8: Variation of DPP and IRR with Fuel Oil Price for Dish Collectors

6. Policy Recommendations

India has installed about 40,000 m² of solar collector area for process heating so far. However, the penetration of solar energy for process heating has to be increased substantially if the government is to meet its set NDCs. In this regard, the study proposes the following policy recommendations to meet the NDC targets:

- A mandate to for energy audits assess the true energy demands and space availability of all industries for solar integration
- Mandate for a focus on process heating (and electricity generation) through solar route in all industries, given that conversion efficiency is far greater in process heating applications
- Regulations on fossil fuel use and emission rates in industries
- Mandate of renewable energy mix for all existing and upcoming industries
- Fiscal benefits for industries which use solar energy for process heating
- Dissemination of information and advantages of solar systems for process heating
- Research & Development for robust solar systems with reduced cost

7. Conclusion

In this study, a generalized methodology is developed to estimate the potential of solar thermal collectors for industrial process heating. This methodology has been applied to verify the potential of select Indian industries that have scope for integration of solar collectors. In the selected industries, namely, Textile, Pulp & Paper, Dairy, Leather and Automobiles, the majority of the processes need thermal energy with an operating temperature range of 50°C–250°C. FPCs, ETCs and Dish collectors are considered for operating temperatures up to 80°C, 80°C–150°C and >150°C, respectively.

The selected industries have a total annual thermal energy demand of 106 PJ, which is equivalent to 2,800 ktoe. The sensitivity of the capital cost, DPP and IRR was analyzed with respect to solar energy penetration and fuel oil price. The study found that 20% solar energy penetration to meet the energy demand in the selected industries would translate to fuel oil savings of 565 ktoe and carbon savings of 1.8 Mt CO₂. However, this requires a capital investment of US\$1,200 million to set up 7.8 million m² of solar collector area. The corresponding annual net monetary savings after accounting for O&M is US\$158 million. For 100% solar energy penetration with thermal energy storage, the fuel oil and carbon savings are 2,800 ktoe and 9.1 Mt CO₂, respectively. This requires a capital investment of US\$6,000 million to set up 39 million m² of solar collector area. The net monetary savings per annum with 100% solar energy penetration is US\$800 million. The selected industries have the potential to reduce India's carbon emissions by 0.1%–0.4%. Further, they have the potential to reduce the fuel oil consumption by 6.3% (equivalent to 1.5% oil imports) of the total industries in India.

Though the above figures look promising, further investigation has been performed on DPP and IRR through sensitivity analysis. The percentage of solar energy penetration has little impact on DPP and IRR. In contrast, fuel oil price and discount rates (the former has a higher impact) greatly affect DPP and IRR.

The DPPs of the system for fuel oil prices of US\$1 per gallon and US\$3 per gallon are 20 years and 3.5 years, respectively. The corresponding IRRs for the same fuel prices are 9.8% and 35%, respectively. The option of integrating solar collectors is not viable considering the present fuel oil prices. However, it is viable if the fuel price exceeds US\$2/gallon (IRR–23% and DPP–6 years for LTC; IRR–13% and DPP–15 years for Dish). Therefore, unless the capital cost of solar collectors decrease or subsidies are offered, their viability will highly depend on the price of fuel oil.

The actual capital costs of solar collectors and the monetary savings depend on the scale of the particular installation, which further depends on the scale of the actual industrial unit/plant. This has not been considered in this study and could be further examined depending on the scale of the system. However, the present study is useful to assess the scale of costs and savings through installation of solar collectors.

The study highlights the fact that the conversion efficiency for solar energy is much higher for process heating applications as compared to electricity generation and provides compelling engineering economic analyses for specific industrial sectors. This study suggests several policy recommendations that could be considered to encourage industries to take up solar based process heating in an intensive manner.

Acknowledgements

This work is supported by the US–India Partnership to Advance Clean Energy-Research (PACE-R) for the Solar Energy Research Institute for India and the United States (SERIUS), funded jointly by the U.S. Department of Energy and the Government of India, through the Department of Science and Technology under Subcontract IUSSTF/JCERDC-SERIUS/2012. The authors are grateful to Dr. Anshu Bharadwaj and Dr. Jai Asundi for encouragement, support and guidance. The authors are also thankful to Dr. S.S. Krishnan, Dr. Mridula Bharadwaj, Thirumalai N C and Sahil Ali for critical reviews and Abhijit Chakraborty for editing inputs on the manuscript.

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