Islamic University of Technology
Organization of Islamic Cooperation

TECHNO-ECONOMIC AND ENVIRONMENTAL FEASIBILITY ANALYSIS OF SOLAR WATER HEATING SYSTEM FOR A TEXTILE INDUSTRY IN BANGLADESH

Thesis
B.Sc. in Mechanical Engineering

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Candidates' Declaration

We hereby declare that this thesis titled "*Techno-economic and environmental feasibility analysis of solar water heating system for a textile industry in Bangladesh*" is a genuine report of our study carried out as a requirement for the award of degree Bachelor of Science in Mechanical Engineering at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Sayedus Salehin and Dr. Md. Rezwanul Karim, MPE, IUT during January 2020 to February 2021. This thesis has never been submitted in whole or in part to any other university/college for the award of any other degree or diploma.

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The thesis titled '**Techno-economic and environmental feasibility analysis of solar water heating system for a textile industry in Bangladesh**' by Md. Ashiqur Rahman (160011078), Shoieb (160011032), and R.R.M. Salahuddin (160011015) has been accepted as satisfactory in partial fulfilment of the requirement for the Degree of Bachelor of Science in Mechanical Engineering on March 2021.

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Abstract

Considering the energy crisis and environmental concerns, green energy technologies are being focused to harness energy from every available source. Extraction of thermal energy using solar collector is one such technology that is very promising to be used in the industrial sector as it is one of the largest energy-consuming sectors which mainly consumes thermal energy. Textile industries are one of the most common industrial sectors in Bangladesh requiring a large amount of hot water in different processes. No existing literature is found exploring the potential of integrating solar thermal collectors in the textile industry of Bangladesh.

In this thesis, the feasibility of using solar thermal energy in the textile industries of Bangladesh is studied from thermal, economic and environmental perspectives. For this purpose, a review of solar collectors is carried out to select the appropriate solar collector analyzing different parameters e.g. weather condition, heat demand, and economical aspect.

Flat plate solar collector is selected for this work and the modeling of the collector is done extensively explaining the design parameters, assumptions and relevant calculations. MATLAB code is developed and validated with existing literature to analyze the thermal performance of the collector varying different parameters. Economic and environmental analyses are also conducted since the economic anal-

ysis is one of the most crucial parts of the feasibility study and environmental analysis helps to determine the environmental impact of installing solar thermal collector in the system.

From this study, it is found that integration of solar collector can save up to 14.7% energy in the summer and approximately 9% in the winter for the system studied in this work which leads to a payback period of 13.58 years. From the environmental analysis, it is found that the amount of CO_2 emission that can be reduced is around 2.8 tons per day in summer and 1.65 tons per day in winter indicating this to be environment-friendly solution from Bangladeshi context.

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Nomenclature

I_T	Total incident radiation
S	Absorbed radiation
η_o	Optical efficiency of the collector
Q_u	Useful energy output
A	Cross-sectional area of the tube
A_c	Collector area
$A_{c,\ total}$	Total collector area
U_L	Overall loss coefficient of collector
U_t	Top heat loss coefficient
U_b	Bottom heat loss coefficient
U_e	Edge heat loss coefficient
N	Number of glass covers
T_{pm}	Mean absorber plate temperature
T_a	Ambient temperature
T_e	Outlet fluid temperature
T_i	Inlet fluid temperature
β	Collector tilt
ε_g	Emittance of glass (**??**)

ε_p	Emittance of plate
h_w	Wind heat transfer coefficient (w/m^2 °c)
K_p	Thermal conductivity of collector plate
k_i	Thermal conductivity of insulation
L	Thickness of insulation
W	Distance between the tubes
D	Tube diameter
D_i	Inside tube diameter
δ	Sheet thickness
h_{fi}	Heat transfer coefficient between the fluid and the tube wall
C_b	Bond conductance
k_b	Bond thermal conductivity
γ	Bond thickness
b	Bond width
$\dot{m}$	Total collector flow rate
F	Standard fin efficiency for straight fins with rectangular profile
F′	Collector efficiency factor
F_R	Collector heat removal factor
C_{FPC}	Capital investment cost of the flat plate collector
C_A	Cost of flat plate collector for unit area
C_E	Operation and maintenance cost per unit area

φ_{FPC}	Maintenance factor
t_{FPC}	Annual operation time
t_{boiler}	annual operation time of the boiler
$C_{FPC,\ rate}$	Cost rate of the collector
CRF	Capital recovery factor
$C_{NG,rate}$	Cost rate of natural gas
$\dot{m}_{NG}$	Mass flow rate of natural gas
V_{NG}	Volume of consumed natural gas
Q_{boiler}	Heat required from the boiler
HHV_{NG}	Higher heating value of natural gas
η_{boilew}	Efficiency of the boiler
ν_{NG}	Specific volume of natural gas
EMI_{CO2}	Carbon dioxide emission rate
m_{CO2}	Mass of carbon dioxide

Chapter 1

Introduction

In the recent technological and industrial advancement, overall energy consumption is increasing around the world. The US energy administration projected the world energy usage will be increased by nearly 50% from 2018 to the year 2050. More than half of the projected total energy consumption increase occurs in Asian countries including China and India. The Organization for Economic Co-operation and Development (OECD) member countries' GDP growth is slightly lower than the non-OECD countries. With this rate the energy consumption varies. Figure 1.1 and Figure 1.2 show that economic growth and energy consumption are projected as very high in the non-OECD countries compared to the OECD countries. [1].

Bangladesh (a non-OECD country), with its recent GDP growth [2] also has a significant share of total energy usage in Asia. The primary energy consumption of Bangladesh has been increased from 6.43% in the year 2018 to 18.63% in 2019 [3]. The energy demand forecasting suggests a huge increase in the upcoming years. It will rise two times in the year 2050, with respect to the year 2010 [4].

The energy supply profile of 2018 has shown in Figure 1.3 [5], it shows that the

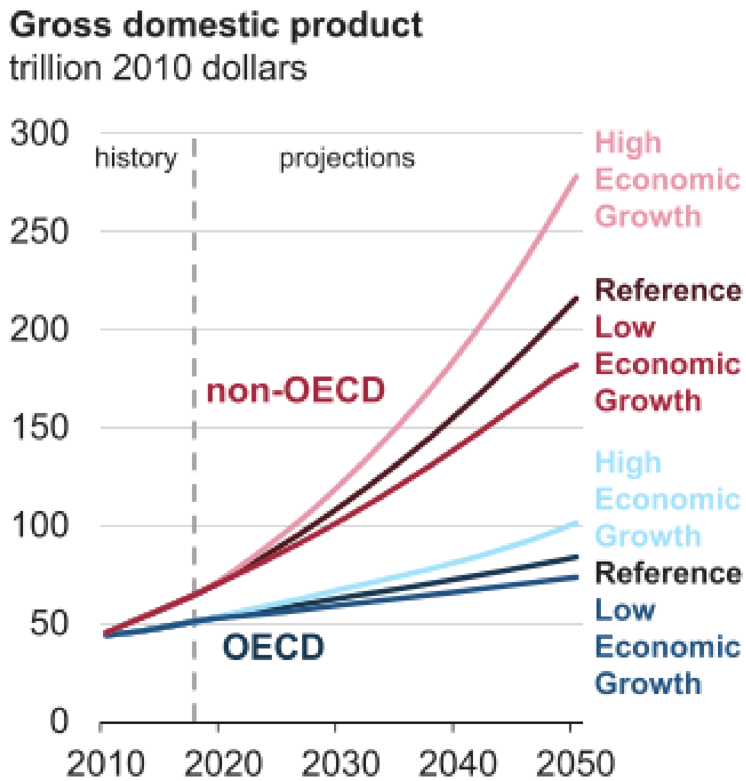

Figure 1.1: GDP of OECD and non-OECD countries [1]

total global energy supply of 2018 was 14282 mega tonnes of oil equivalent (Mtoe), among which more than 49% of energy comes from natural gas and coal.

Globally 40% of the total industrial energy is supplied by fossil fuels; for Bangladesh, almost 98% supply is from conventional energy sources. Table 1.1 [6] shows the primary energy projection of Bangladesh by source, where it is assumed that the production by natural gas and other fossil fuels are only going to rise.

The government is trying to meet the demand for natural gas by importing LNG [6]. The most energy usage is observed in the industrial sectors. Almost 35% of the world's total energy is used in the industrial sectors [7]. In Bangladesh, more than 30% of its total energy usage is in the industrial sectors. This industrial energy demand is only going to rise, it is estimated annual growth of 1.7% till 2030. [6], [8].

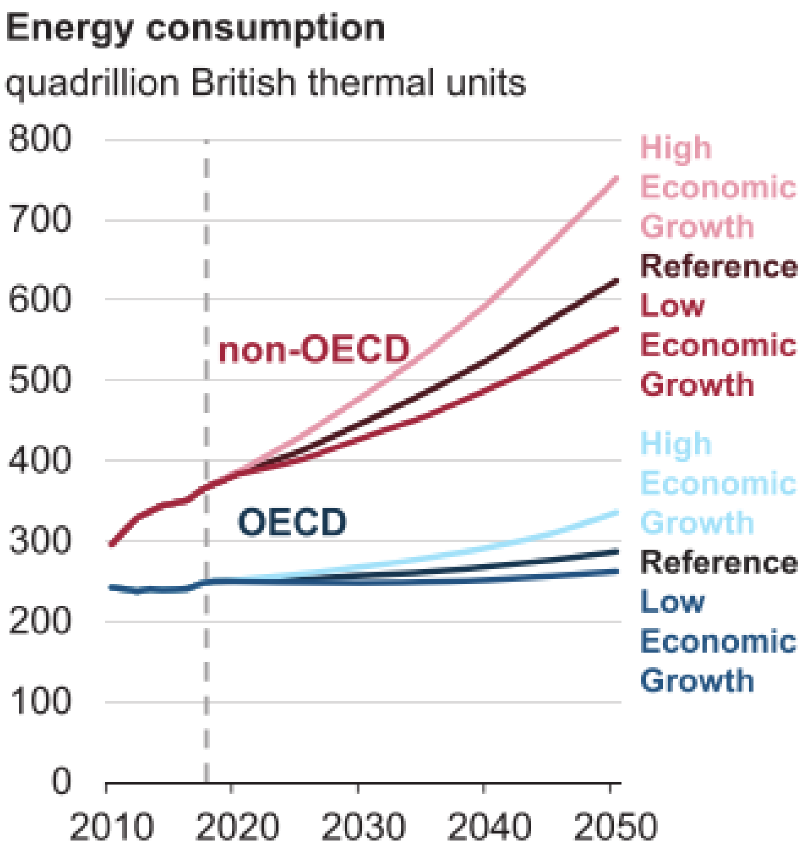

Figure 1.2: Energy consumption in the OECD and non-OECD countries [1]

Table 1.1: Primary energy projection of Bangladesh [6].

Energy Source	**2014**		**2041**	
	ktoe	**Share (%)**	**ktoe**	**Share (%)**
Natural Gas	20728	57	49783	38
Oil	6060	17	32162	25
Coal	1038	3	25401	20
Nuclear Power	-	-	12029	9
Renewable Sources	36	.1	199	.16
Biofuel and waste	8449	23	4089	3
Power(Export)	377	1	6027	5

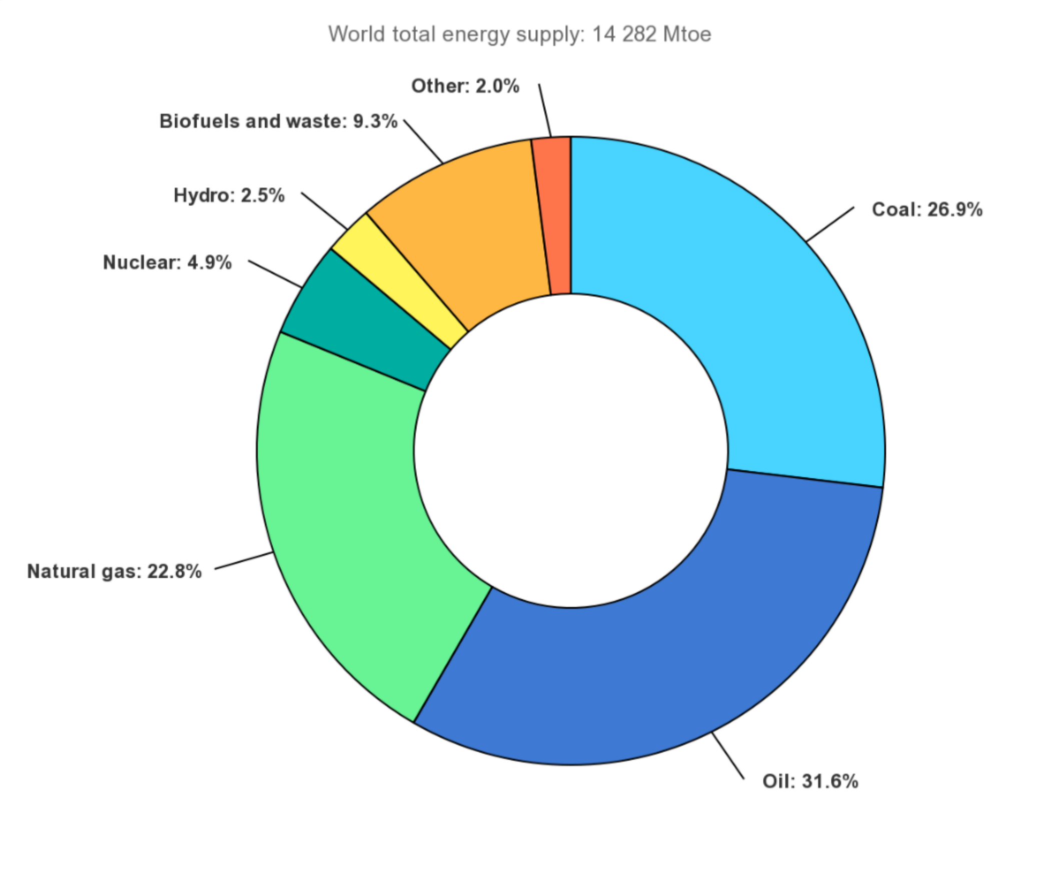

Figure 1.3: Global energy supply by source 2018 [5]

Bangladesh has a large amount of textile, pharmaceuticals, food and chemical industries, and along with these large-scale industries there are many other small to medium scale industries influencing the total energy consumption of Bangladesh. Ahaduzzaman et al. has shown that 25% of the total industries in Bangladesh are textile industries Figure 1.4 [9]; in which more than 30% of energy consumption occurs Figure 1.5 [10]. Other sectors like Brick manufacturing, rice mills, frozen foods, ceramics, sugar mills, paper mills, tannery, jute mills, sanitary and the tile merchants can be categorized as small to medium scale industrial sectors [11] and consumes 45.2% of the total share [7], [9].

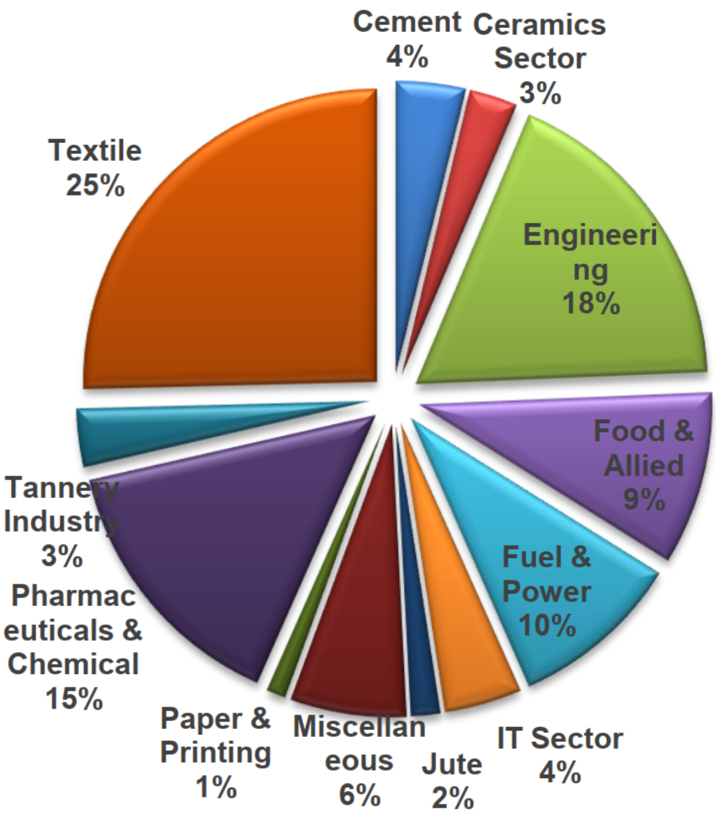

Figure 1.4: Percentage of Sector-wise industries in Bangladesh [9]

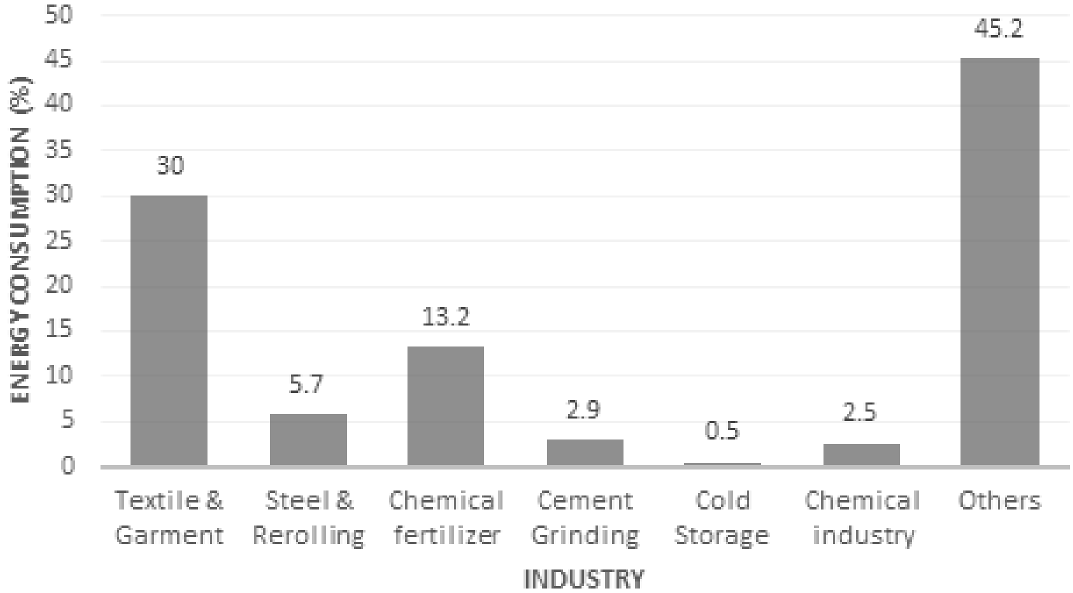

Figure 1.5: Energy consumption by different industries of Bangladesh [10]

More than 74% of industrial energy supply is used for process heating. This heat is supplied by the boiler using petroleum-based fuels [2], [12]. More than 97%

of the total energy of Bangladesh comes from fossil fuels, which is responsible for significant CO_2 emission every year [13]. In 2018 it was estimated, 81.97Mt which is 617.78% higher from 1990 [14]. Also, the industries, utilizing fossil-fuel based fuels for their energy requirement, play significant roles to increase the CO_2 emission every year; replacement of the existing energy sources with different renewable energy sources can reduce the total emission by up to 50% [15].

It is evident that with the increasing energy demand, fossil fuels are becoming insufficient in the manner of source, cost, and environmental safety. To meet the global energy requirements solar thermal energy can be utilized. Solar water heating for domestic purposes is common in cold climatic countries. Also, countries with higher solar radiation utilize thermal energy in different industrial processes. A number of countries, China, Turkey, India, Israel, Japan, Morocco, Australia, Spain, Germany, Greece, United States, Brazil, utilize solar heat for different domestic and industrial processes [16]. Industrial processes require a large range of temperature. The temperature requirements can be classified into three categories. Low-temperature heat classifies the temperature requirements under 150°C, intermediate-temperature process heat ranges between 150-400°C, high-temperature process heat is more than 400°C [17]. Recent findings of solar thermal collector technologies suggest that different collectors can achieve a temperature as high as 2000°C but the typical ones which are also considered to be cost-effective can achieve easily up to 250°C [7], [17].

Processes that require heat at less than 250°C temperature are suitable for solar heating integration. Drying and dehydration, pasteurization and sterilization, washing and cleaning, chemical reactions, surface treatment, space heating, the supply of hot water or steam are the suitable processes for solar heat integration. Industries containing such processes may include chemical industries, food and beverages, paper, fabricated metal, textiles, wood, rubber, plastics etc. Industries that may include solar process heating and the respective processes are shown detailed in Table 1.2 [12], [17].

Table 1.2: Industrial Processes where solar heat can be applied [17]

Industry	**Process**
Dairy	Pressurization, Sterilization, Drying
Tinned food	Sterilization, Pasteurization, Bleaching, Cooking
Paper	Cooking, Dying, Boiler feed water, Bleaching
Textile	Bleaching, Dyeing, Drying, Fixing, Pressing
Chemical	Soaps, Synthetic rubber, Processing heat
Meat	Washing, Sterilization, Cooking
Beverage	Washing, Sterilization, Pasteurization
Timber by-products	Thermo-diffusion beams, Drying, Pre-heating water
Plastics	Distillation, Separation, Extension, Drying

Flat plate collectors, parabolic trough collectors, and concentrated dish collectors can provide heat to meet the low and intermediate temperature requirements. Solar thermal integration has proven positive impact on the economy and environment [18].

Solar thermal applications can involve direct process heating or indirect solar water heating. The system also can be integrated as part of a large system or the source of heat for one process. Direct heating is largely used for domestic heating purposes. However, industries are likely to integrate with the existing system [7].

Concerning the yearly radiation profile of Bangladesh and the economic feasibility of solar thermal collectors, it is suggested to use for integrating in low to medium heat range [7], [19]–[21]. The processes in textile industries require low to medium heat shown in Table 1.3 [17].

Table 1.3: Processes in textile industry and their working conditions [17]

Industry	Process (es)	Temperature (^{0}C)	Medium
	Blanching - dying	60-90	Water
Textile	Drying, degreasing	100-130	Steam
	Pressing	120-140	Steam
	Fixing	160-180	Steam
	Printing	40-130	Water, Steam

Solar heat can be applied in the many different industries of Bangladesh. In contrast with the data of energy consumption of Bangladeshi industries (Figure 1.5), it may be stated that the textile industries is the most relevant sector of Bangladesh in terms of energy consumption as well as CO_2 emission. Also, it has many different processes where solar heat can be applied. So, it can be hypothesized that solar thermal heating application has a good future in the Bangladeshi textile industries.

However, the research and findings on this topic in Bangladesh are insignificant.

This study aims to find the potential of integrating solar thermal technologies in the textile industries of Bangladesh. Technical feasibility analysis was done in line with the specific textile industrial data in Bangladesh. Also, the economic and environmental analyses were shown using a systematic approach [22].

Chapter 2

Literature Review

Several studies have been done to explore the potential of solar process heating integration in industries for different climatic conditions around the world. Researchers focused on the temperature required to execute certain processes as well as the economic and environmental potentials [23]–[30].Different industrial sectors such as textile, food, paper, etc. have the potential to exploit solar thermal energy as supplementary or primary sources of heat (Table 1.2). The following sections will contain short reviews of the different studies have done around the world.

Schweiger et al. has investigated the potential of solar thermal application for the low to medium grade heat for the region of Spain and Portugal [23]. A total of 34 industries were analyzed for tracking the heat demand. A major share of the industries studied was of the food and beverage sectors, papers, textile, leather and also a motor vehicle industries. More than 60% of the total industries required temperature less than 160°C temperature. The paper industries require less heat (<60°C). They concluded that the solar thermal system can supplement 3.4% of total industrial heat in Spain and 4.4% in Portugal. The food and beverage sectors are the most viable option for Spain and Portugal's perspective. Textile industries are also suitable for solar thermal applications.

Kalogirou determined the potential of industrial process heat generation in Cyprus [24]. The author used parabolic trough collector for the study as this collector has a high heating capacity. The working fluid was water with a very high flow rate of 2000 kg/s, the temperature output was 85°C. It was concluded that the collector area needs to be increased if the load is increased. Also, the system is viable for large industries as they can subsidize the initial costings and with the increased load, the fuel savings is also increased. It can significantly reduce CO_2 emissions too. It was concluded that with good solar radiation of Cyprus, it has great potential to use solar thermal energy in the industries.

In following studies, Kalogirou has found the probability to integrate solar thermal systems in a set of different industries [25], [26]. Comparison of Flat plate collectors, compound parabolic collectors, and evacuated tube collectors was discussed in the following papers. He mentioned that the flat plate collectors are for the low-grade heat, concentrated collectors are suitable for the higher temperature requirements.

Fatouh et al. have shown that the solar thermal heat extraction for Egyptian industries [27]. They observed the operation using parabolic trough collector. They proposed some performance optimization by modifying the collector by adding different insulation materials and glass covers. The study suggests that for the temperature range of 80-150°C of temperature range this collector can be used in

Egyptian industries.

Vannoni et al. have determined the potential of solar industrial process heating in Greece, Belgium and some industrial sectors of Germany [28]. The authors found potential to produce hot water in some sectors (Food and beverages, Paper, Textile, Leather and transport equipment). For the condition of Germany's food and beverages, paper and textile industries were studied. They found promising results in paper recycling.

Muller et al. investigated the low to medium grade heat demand containing the demand for space heating and steam generation for various industries in Austria [28]. They focused on Chemicals, textile and prefabricated concrete components, rubber and plastics, food and beverages. They also recommended the solar collectors for the low to medium grade heat demand for the processes of cleaning, washing, and surface treatment of metals in all industries. The thermal system can complement up to 60 % of the industrial heat demand of Austria.

Mcleod et al. showed the viability of solar process heat for Australia [29]. For the state of Victoria, the industrial sectors occupied 53% of the total energy consumption. The authors selected the Chemical, Machinery and equipment, textile, papers, food and beverage industries as suitable for the application of solar thermal technology.

India has sunny weather conditions over the country most of the days of the year. Different authors have studied this sector to explore the potential of solar thermal energy in the industries of India. Sharma et al. have extensively studied the potential of exploiting solar energy in the perspective of meeting heat demand as well as the economic and environmental feasibility for paper and dairy industries in 8 different locations in India [31], [32]. The solar industrial process heat potential for paper and dairy industries is calculated 25PJ and 6.40PJ respectively. Uppal et al. have investigated automobile industries, which are responsible for a large amount of energy consumption for India [33]. Suresh et al. have worked with the performance optimization for the solar collector parameters to increase the solar radiation harnessing potential for the solar collectors as well as increasing the efficiency so the system becomes feasible [34].

Jia et al. have studied the solar industrial process heat integration from the perspective of China [35]. They have summarized 10 out of 26 industrial sectors of China. The suitable industries are dairy, tinned food, textile, paper, chemical, meat, beverages, flours and by-products, bricks and blocks, plastics. Integrating the system in the possible sectors, China can reduce 98.22millions of CO_2 emissions.

Lauterbach et al. have thoroughly investigated the solar industrial heat potential according to the perspective of German industries [36]. The author has found potential for different industries such as motor vehicle industries, machinery and equipment, printing and wood, textile, fabricated metal etc. The solar thermal collectors can provide 16 TWh heat per year.

Taibi et al. described solar thermal power has a global potential of 1555 TWh (5.6 EJ)/year by 2050 [30]. They found that globally the region with high solar radiation is more economically feasible for solar thermal applications than the lower solar radiation areas. A summary of the solar industrial process heat (SIPH) integration values for different industries across the world is stated in Table 2.1 [37].

Table 2.1: Summary of SIPH potential in different countries [37]

Country /Region (year)	**Industrial Sectors included for potential estimation**	**Temperature range selected (°C)**	**SIPH Potential (PJ/annum)**	**Collector area (million m^2)**
Portugal (2001)	Food products, wine and beverages, beer and malt, textile, chemicals, pulp and paper, tobacco products	up to 160	4.0	1.9–2.5

Spain (2001)	Food products, wine and beverages, beer and malt, textile, chemicals, pulp and paper, tobacco products.	up to 160	17.0	8–10
Netherland (2001)	Food products, wine and beverages, beer and malt, textile, leather, pulp and paper	up to 60	1.95	0.8–1
Austria (2004)	Food products, wine and beverages, beer and malt, textile, machinery and automobile	up to 250	5.4	4.3

Greece (2006)	Chemicals, Food and beverages, Tobacco, Paper, Textiles, Leather and Transport equipment	up to 100	0.21	0.015
Italy (2008)	Food products, wine and beverages, beer and malt, textile, leather, chemicals, machinery and automobile, pulp and paper, tobacco products	Up to 300	31.8	14.3

European Union 25 (2008	Food products, wine and beverages, beer and malt, textile, leather, chemicals, machinery and automobile, pulp and paper, tobacco products	Up to 250	260	143–180
India (2011)	Textile, paper, food processing, dairy, Automobile, Leather	50–250	24.75	

Germany (2012)	Food products, wine and beverages, textile, rubber and plastic chemicals, pulp and paper, manufacturing	up to 300	57.6	
Mexico (2014)	Food and textile	60–160	28.5	
Chile (2014)	Food, paper textiles, wood mining	Below 250	26	9
India (2015)	Paper	50–250	25	1.83
Morocco (2015)	Surface treatment, food, chemical, textile and leather	Below 100	6.1	2.3

Egypt (2015)	Chemical, food, textile and agriculture	Below 100	16.42	4.6
Pakistan (2015)	Textile, surface treatment, food, chemical and leather	Below 100	20.41	7.1
India (2017)	Dairy	Up to 200	6.40	1.11

Chapter 3

Overview of solar collectors

Solar collector analysis ensures effective use of solar radiation. Efficiency and techno-economic effectiveness depends on correct selection of solar collector. The optimum solar collector will give best possible output. This chapter broadly discusses all the different types of solar collector and their selection criteria.

3.1 Solar System and energy

The solar system is a gravitationally bound system of the sun and the object that orbit it. In solar system sun is the only star having potential to deliver energy to the whole system. The energy flows in a form of electromagnetic radiation called solar radiation. This is the primary energy source for the earth. Solar energy is considered as the cleanest form of energy. The sun uses nuclear fusion of hydrogen and helium for generating energy. The sun is a blackbody having temperature around 5800K created by mostly hydrogen and helium. The measured average diameter of sun is $1.39 \text{x} 10^9$ m and distance from the earth is $1.5 \text{x}\ 10^{11}$ m. The energy flux emitted by sun's surface is around 63×10^6 W·m^{--2} calculated by Stefan-Boltzmann equation [38]. Figure 3.1 shows the solar emission curve outside the earth atmosphere to the emission curve of a black body of 5800K located at sun's distance from the earth [39].

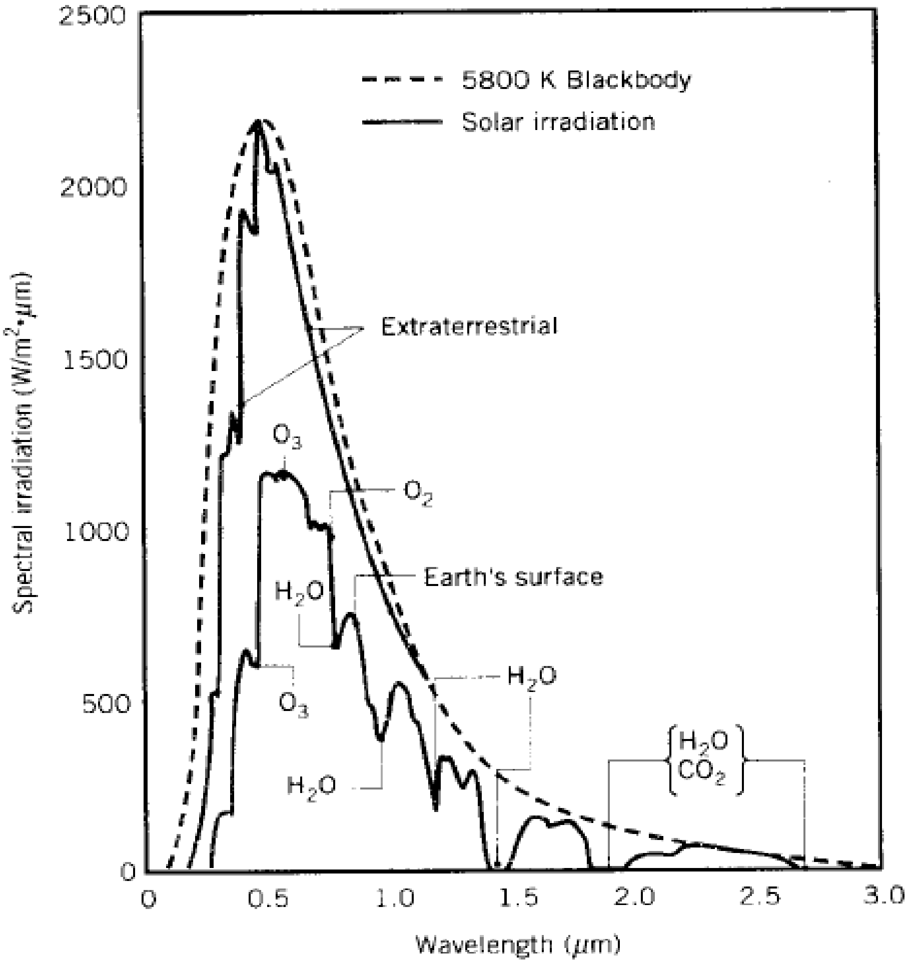

Figure 3.1: Spectral distribution of solar radiation [39]

3.2 History of Solar collector

World's first solar collector was built by Swiss scientist Horace de Saussure in 1767 [40]. Robert Stirling built an engine in his workshop which ran in Stirling cycle which is a solar thermal electric technology that concentrates the sun's thermal energy in order to produce power. He applied this patent on September 27, 1816 [41]. The solar cell technology started to develop during Industrial Revolution, in

1839, when French physicist Alexandre Edmond Becquerellar first demonstrated photovoltaic effect (convert sunlight to electricity using solar cell) [42]. First solar powered engines were constructed in 1860. August Mouchette and his assistant built and used this engine for decade [43]. In 1876 it was discovered that selenium produces electricity when exposed to light. Two Cambridge scientists, William Grylls Adams and his student Richard Evans Day wrote a paper on this[44]. In 1883, solar rooftop array was developed by Charles Fritts. Then panels were coated with selenium to produce electric current. But it was too weak and the process wasn't understandable [45]. In 1888, Edward Weston received two patents for solar cells [45].

In 1905, Albert Einstein wrote a paper over photovoltaic effect [46]. Later in 1908, a Carnegie Steel Company owner invents solar collector with coper coils [47]. In 1921, Albert Einstein won Nobel Prize for explaining photovoltaic effect. Later, Audobert and Stora discovered the photovoltaic effect in cadmium sulphide in 1932 [48].

Solar thermal process heating system was also started to be developed around 200 B.C.E. Roman republics used solar heat for their public baths so less coal and labour needed [49]. The process was forgotten for about 1500 years and later re-invented in 1891. World 1^{st} solar heater was invented by Clarence M. Kemp [50]. He used a black water tank inside an insulated box having one glass side to heat up the water. The system was quite largely used but there were freezing problem in the heating system during winter. Later antifreeze was used to get rid of this problem. In 1909, William Bailey separated the solar thermal collector for collecting solar radiation along with storage tank for storing the produced hot water. And thus introduced a new form of solar heating [51]. He also introduced thermosyphon principal for circulation of water in collector and storage tank [52]. Thermostatically controlled gas water heater hit the market around 1920s. California market was overtaken by primitive solar water heating designs. 1^{st} commercial SWH in Japan was developed in around 1950. It was inspired from a view of a large bath tub, filled with water that was kept outside in the sunshine for a longer period of time [53]. Until 1930, water heating was used only in domestic and space heating usage. SWH system was commercially started to be used after 1960 [54]. Major advancements in solar thermal energy are being made all over the world was introduced after 1980s. SWH was commercially started to be sold in USA, Spain, and Australia. In 2007, Spain constructed Europe's first fully commercial solar towers. It used the molten salt storage system to ensure 24 hour power usage [55]. With the demand of clean energy being increased, SWH system will continue to play a key role as it has done throughout history.

3.3 Solar collector

Sun is the most plentiful energy source in earth. Solar energy falls on the surface of the earth at a rate of 174 petawatts, (1 petawatt = 10^{15} watt) [56]. It is the cleanest form of energy. But it's hard to capture the solar energy in this form. It needs to be transformed into other forms for efficiency and effectiveness.

3.3.1 Solar collector Technology

Solar energy can be harnessed by two ways:

a) Solar photovoltaic

b) solar thermal

Solar Photovoltaic technology

Photovoltaics can generate electricity directly [28], [31], [32]. The photovoltaics work when light radiation falls on solar cell and it directly converts it into DC electricity. The solar cells use semiconductor materials which knocks the electron loose and allows them to flow freely. A 250 µm thin wafer is sliced from a silicon doped p-type crystal and n-type impurity is diffused to form a p-n junction [57]. A photovoltaic system consists of PV modules, arrays, mounting structures, AC-DC inverters etc. Figure 3.2 shows a PV solar panel.

Figure 3.2: Photovoltaic Solar panel [58]

An individual PV cell is usually small, typically producing about 1 or 2 watts of power. The power output of PV cells is boosted by connecting together in chains to form larger units known as modules or panels. Modules can be used individually. By connecting several modules will create an array. One or more arrays is then connected to the electrical grid as part of a complete PV system. This modular structure helps to meet almost any electric power need, small or large. PV panels are around 15% efficient while some up to 20% [41].

Solar thermal technology

Solar thermal collectors are used in variety of purposes e.g. space heating/cooling, process heating, steam generation, electric power generation [59], [60]. It utilizes the sun's energy and convert it into heat. The heat is absorbed by a heating system utilizing a heat transfer fluid. The sources of this heat generation are through mounted solar collectors. This system is also used in conjunction with a boiler, collector or immersion heater.Solar water heater absorbs sunlight and converts it to usable heat. The collector is coated with black coated absorber as it helps to gain maximum sunlight incident on the panel. High quality absorber coatings are able to absorb up to 95% of the energy in sunlight throughout the full spectral range [41]. Figure 3.3 shows a solar thermal collector. Both Photovoltaic and Solar thermal collector can be used together for efficient energy generation.

Solar Thermal Photovoltaic Technology

Solar thermal and PV technology has their respective ground of operation and generation of electricity. PV produces less energy but thermal system but merging PV with Thermal system gives an optimized solar energy system. It can be used as a universal solar energy generation system [61]. Figure 3.4 shows solar thermal PV hybrid panel.

Figure 3.3: Solar Thermal Collector

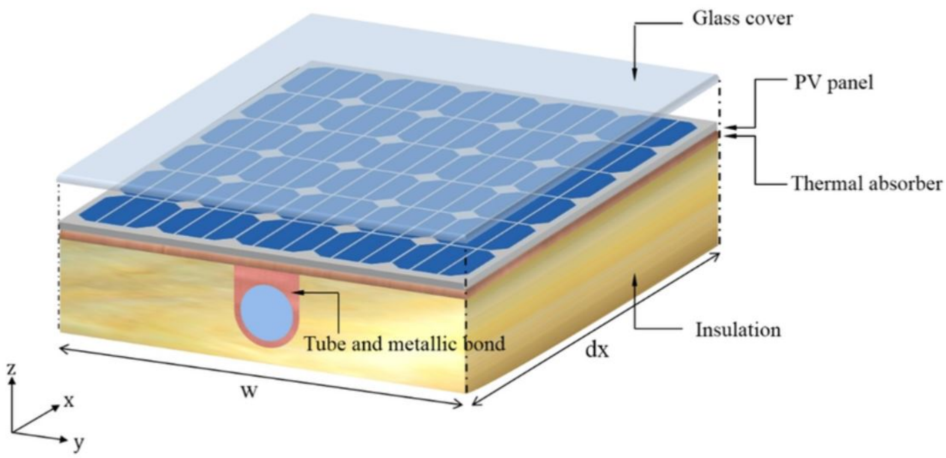

Figure 3.4: Solar Thermal PV hybrid panel [62]

3.3.2 Solar collector working principal

Solar collector is the main element of a solar energy conversion unit. Solar energy is captured by solar collector, then this collector converts this solar energy to heat energy. Heat can be absorbed by heat transfer fluids such as water, paraffin etc. This solar heat can be stored and later can be used for various purposes especially in cloudy days or nights.

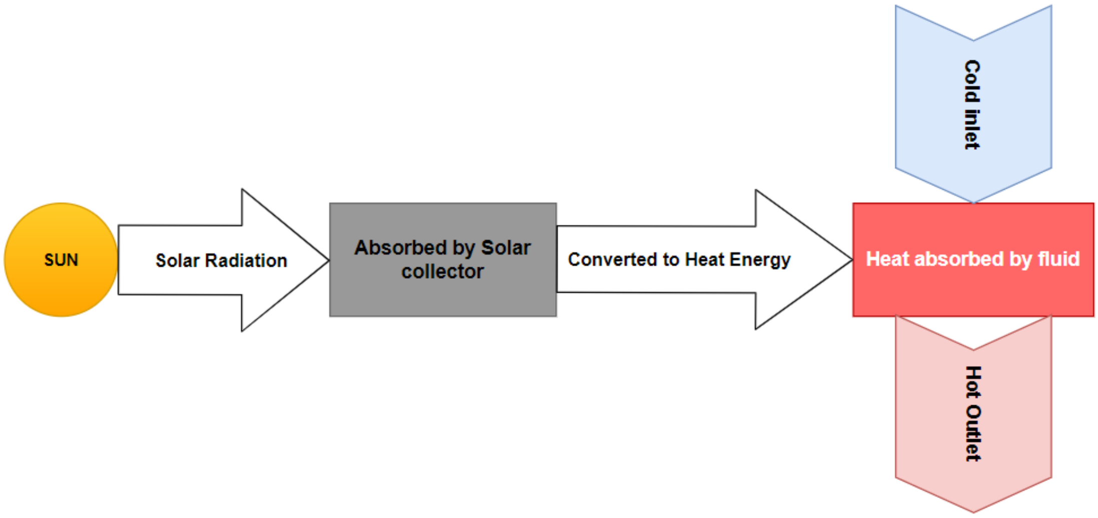

Figure 3.5: Solar collector working method

3.4 Solar collector types

Solar collectors can be categorized by motion and by operating temperature. Solar collectors are mainly two types.

a. Stationary

b. Tracking

Table 3.1: Different solar collectors and their properties

Collector Type	Absorber Type	Concentration Ratio	Temperature Range (^{o}C)
Flat plate collector (FPC)	Flat	1	30-80 [26]
Evacuated tube collector (ETC)	Flat	1	50-200 [26]
Evacuated Flat Plate Collector (EFPC)	Flat	1	40-60 [26]
Compound parabolic collector (CPC)	Tubular	1-5	60-240 [26]
Linear Fresnel reflector (LFR)	Tubular	10-40	60-250 [26]
Parabolic trough collector (PTC)	Tubular	15-45	60-300 [26]
Parabolic dish reflector (PDR)	Point	100-1000	100-500 [26]
Cylindrical trough collector (CTC)	Tubular	10-50	60-300 [26]
Heliostat field collector (HFC)	Point	100-1500	120-2000 [26]
Power Tower	Point	150-1500 [63]	300-2000 [63]
Central Receiver	Point	1300+	Upto 1000 [64]

3.4.1 Flat plate collector (FPC)

Flat plate collector is a type of heat exchanger. It is a cost-effective collector compared to other water heating collector types, due to its simple design and easier installation process. Also, it is capable of working on moderate temperature requirement in heating processes up to 80^{o}C. A typical Flat plate collector is shown in Figure 3.6 [65] from which we can identify the main components of FPC:

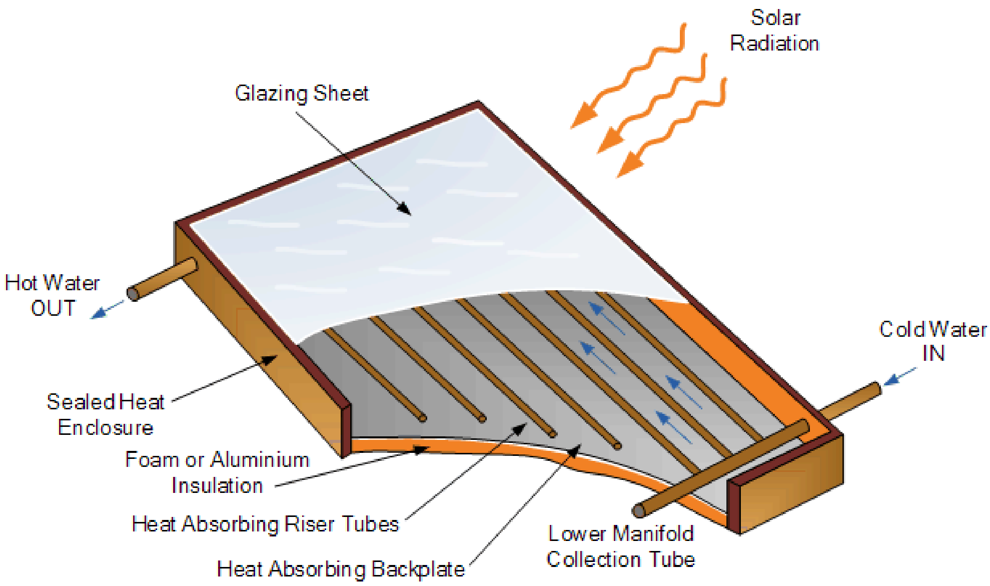

Figure 3.6: Flat Plate Collector [65]

1. **Cover:** Single or multiple glass sheets over the absorber plate. The cover is glazed mostly.

2. **Heat absorbing plate:** A large sheet of good conductors of heat like copper or aluminium which is painted black. The black absorbs as much solar radiation as possible for maximum efficiency.

3. **Riser Tubes:** With the heat absorber plate there are several parallel copper pipes called risers. This pipe contains heat transfer fluid, typically water. To

ensure maximum surface contact for efficient heat transfer the copper tubes are soldered directly to the absorber plate.

4. **Manifold:** For incoming and outgoing flow of fluid or water there is an admit and a discharge duct called manifold.

5. **Insulation:** The surface is insulated to minimize heat loss from the collector plates.

6. **Containers:** Protective container surrounds all the components and protects them from dust and moisture.

Advantages of the flat-plate collectors compared to other collectors are:

1. Easy to manufacture

2. Low cost

3. Collect both beam and diffuse radiation

4. Permanently fixed (no sophisticated positioning or tracking equipment is required)

5. Little maintenance

Solar Radiation fall on the absorbing surface and increases the temperature. The heat is passed through the tubes. The water or fluid gets heated and passed to the home or industry. Flat plate collectors have wide variety of design. Fluids like water, water plus antifreeze additive, or air are heated by FPC. Flat plate collectors can heat the fluid inside using either direct or indirect sunlight from a wide range of different angles. The major purpose is to collect maximum solar energy at the lowest possible cost. Solar flat plate collectors are cheap and easy to install. But the base problem is its flatness. It can only capture solar radiation when the plate is facing directly to the sun.

3.4.2 Evacuated tube collector (ETC)

Evacuated tube collectors use sun's ray perpendicular to the tubes for most of the day. This helps the collector to operate at a much high efficiency and temperature for a much longer period. From Figure 3.7 it is seen the collector consists of a heat pump inside a vacuum sealed tube. The class tubes are cylindrical in shape to capture the sunlight all day. In areas with cold, cloudy wintry weathers evacuated tube collectors are very useful. Each tube consists of a thick glass outer tube and a thinner glass inner tube. The tubes are manufactured with soda lime glass to make it strong, resistant to high temperatures and has a high transmittance for solar irradiation.

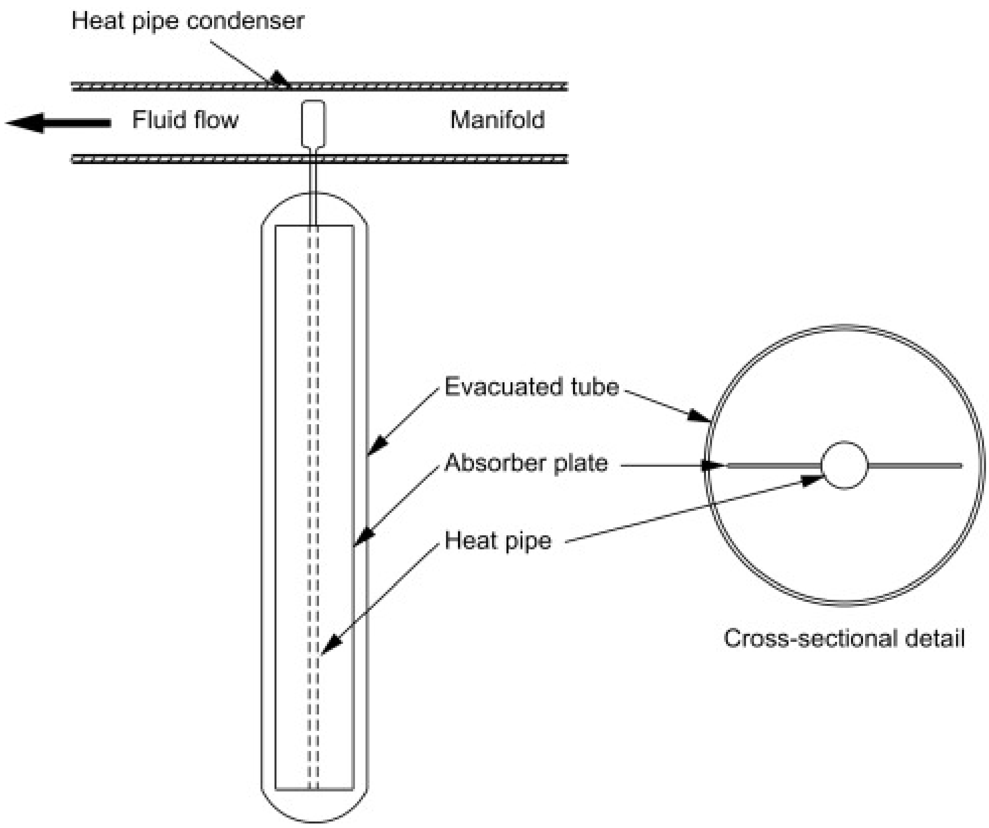

Figure 3.7: Schematic diagram of an evacuated tube collector [66]

Combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures and was demonstrated by ETC [67]. Air is removed or evacuated from the space between the two tubes, forming a vacuum. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than FPCs. ETC gives higher efficiency at low incidence angles. This gives ETCs an advantage over FPCs in terms of daylong performance. In each glass tube, an aluminum or copper fin is attached to a metal heat pipe. Figure 3.8 shows evacuated tube collector.

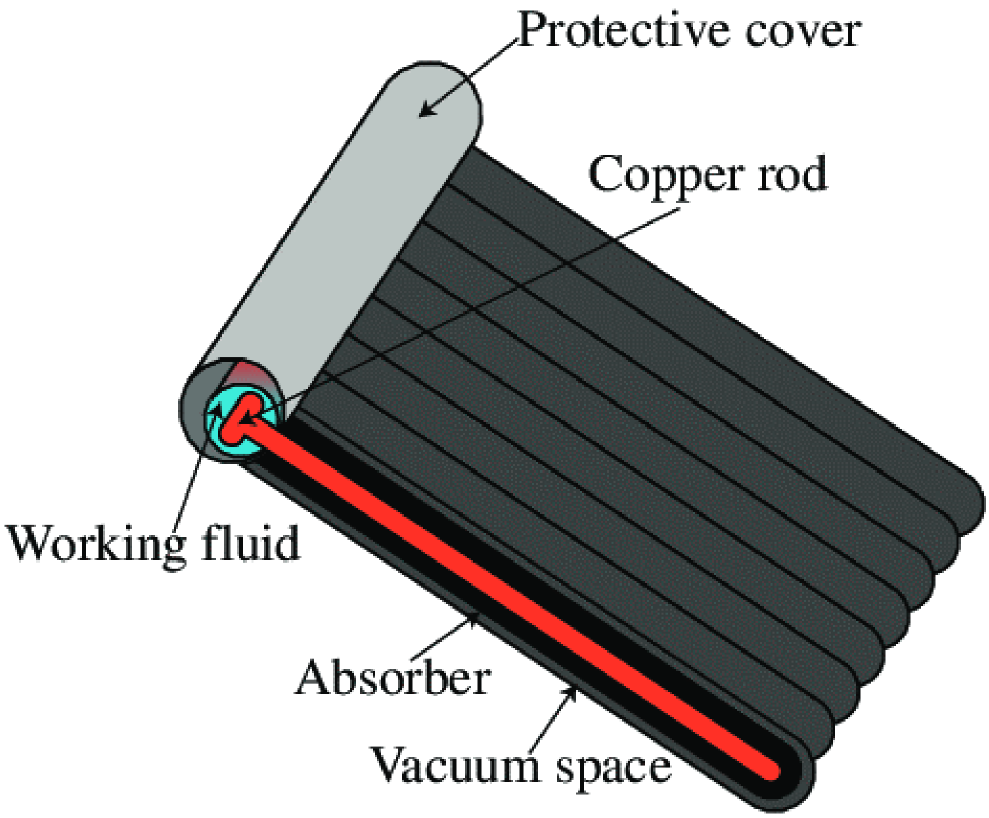

Figure 3.8: Evacuated Tube Collector [68]

The fin is covered with a selective coating that transfers heat to the fluid via convection method. Copper pipes are all connected to a common manifold which is then connected to a storage tank. Liquid–vapor phase change materials are used to transfer heat at high efficiency. A highly efficient thermal conductor placed inside a vacuum-sealed tube. The heat pipe contains a small amount of fluid (e.g., methanol) that undergoes an evaporating–condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapor travels to the heat sink region where it condenses and releases its latent heat.

The downside of using evacuated tubes is that the panel can be a lot more expensive compared to standard flat plate collectors. It is well suited to commercial and industrial hot water heating applications and can be an effective alternative to flat plate collectors for domestic space heating, especially in areas where it is often cloudy.

3.4.3 Evacuated Flat Plate Collector (EFPC)

As solar flat plate collector can only work up to 80^{o}C a new type of flat plate collector has been introduced. It is Evacuated Flat Plate Collector.

Evacuated Flat plate collector (EFPC) is a general flat plate collector but is designed to operate above 100^{o}C in large-scale deployments, with highly active flat surface and high-vacuum for best performance. It has moderate vacuum in the plate to reduce potential heat losses [69]. For long lasting high-vacuum operation a corrosion proof full-metal casing is used. Most importantly, it is fully recyclable. A prototype collector based on the commercially available flat plate collector was constructed by Benz and Beikircher [70]. The prototype was tasted and showed high efficiencies (more than 60% at 100^{o}C). Later it was tasted that the collector can reach up to 300^{o}C [71]. A solar powered pump maintained ultrahigh vacuum that made it possible to reach 300^{o}C. Later study shows that, while operating on 140^{o}C, EFPC got an around 60-65% improvement on efficiency while generic FPC got 25% of improvement in efficiency [72]. Most recent studies improvised the operating temperature 200^{o}C and the efficiency improvement raised up to 50% [73].

A EFPC is shown in the Figure 3.9. Though it has higher thermal output, these collectors have the advantage of longer lifetime compared to non-evacuated collectors. As evacuated, no humidity and condensation problems occur within the casing. Interior pressure is maintained economically between 1 and 10 kPa. It means that although convection losses are suppressed, gas heat conduction remains fully developed.

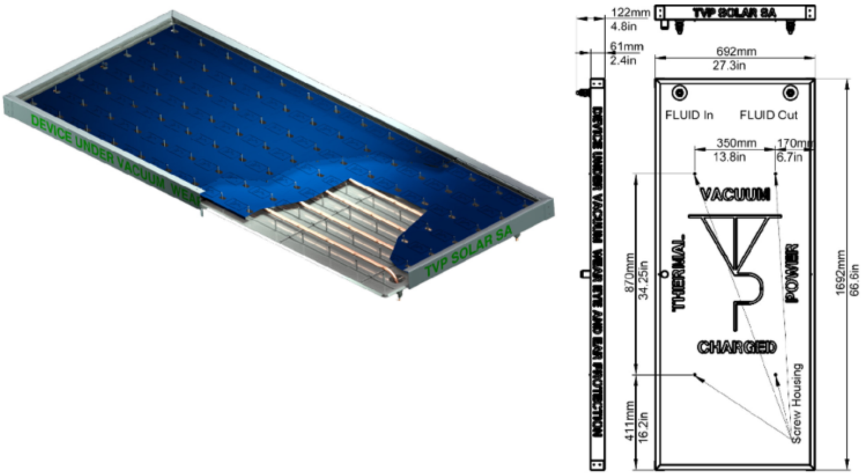

Figure 3.9: Evacuated Flat Plate Collector[74]

3.4.4 Compound parabolic collector (CPC)

Compound Parabolic Concentrators (CPCs) are designed to efficiently collect and concentrate distant light sources. It's fabricated in the shape of two meeting parabolas. This is a non-imaging concentrator but do have highest possible concentrating ratio.

The collector concept was originated back in late 1950s. Concept of the free-tracking concentrating static concentrator was proposed by Tabor [75]. Winston et al. [76] initiated research on non-imaging concentrators in the late 1960s. The naming of these concentrators as compound parabolic concentrators (CPCs) was done in 1974 when the U.S. Argonne National Laboratory established research on non-imaging concentrators [49], [50].

The concentration ratio that can be achieved by non-tracking mode is up to 10 which eventually reduces the cost. This collector has the highest possible concentration permissible by thermodynamic limit for a given acceptance angle. Its large acceptance angle results in intermittent tracking towards the sun. Figure 3.10 shows a geometric design of CPC. It has two parabola section A and B.

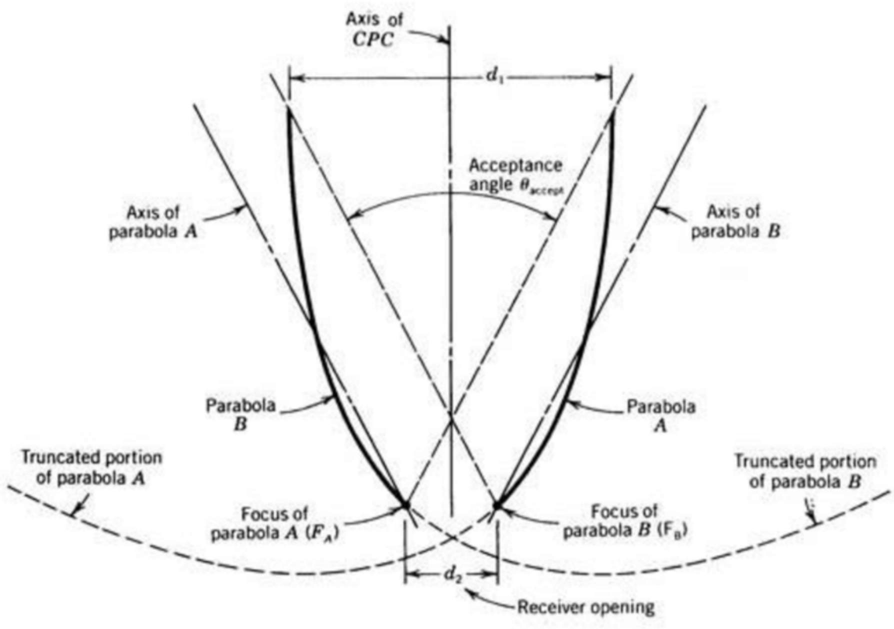

Figure 3.10: Compound Parabolic Collector [77]

d_1 is the width of aperture area and d_2 is width of absorber area. The axis is oriented in such a way that F_B is the focus of parabola 1 and F_A is the focus of parabola 2. The tangents of parabola A and B with the axis determines the height of the parabola. The acceptance angle is shown by θ_{accept}. The acceptance angle is also generally kept large so that tracking may be required intermittent only. The concentration ration is determined by $\frac{d_1}{d_2}$. Optical efficiency is around 65% which is 8% more than parabolic trough collector. A theoretical and experimental investigation on modifications of the optical and thermal performance of external concentrating tubular absorber CPCs was performed [78] Figure 3.11 shows a CPC with baffle. Their research showed that by setting a baffle inside the CPC, internal convection can be reduced, thereby reducing heat loss [79].

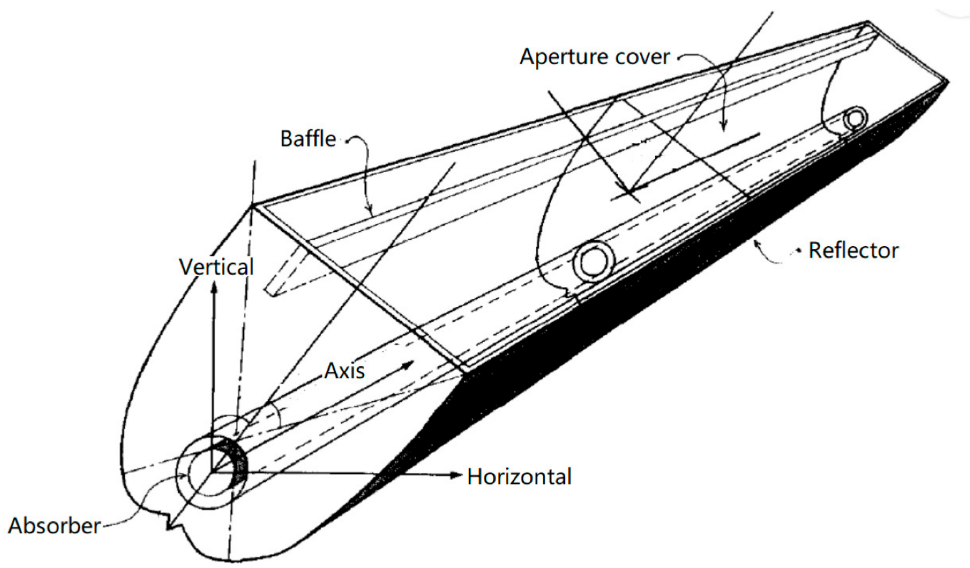

Figure 3.11: External concentrating tubular absorber CPC with baffle [79]

3.4.5 Linear Fresnel reflector (LFR)

Linear solar powered system has recently focused on bulk electricity production. This collector works by capturing sun's energy with large mirrors which then reflect and focus the sunlight onto a linear receiver tube. Flat mirrors are used instead of parabolic mirrors. The flat mirror collects solar power and utilizes to generate steam and then used to heat a traditional power cycle that spins a turbine driving a generator to produce electricity. Alternatively, steam can be generated directly in the solar field and that will eliminate the need for costly heat exchangers. The collector works on Fresnel lens effect which was first developed by French physicist Augustin-Jean Fresnel [80]. Fresnel collectors have two variations: the Fresnel lens collector (FLC) and the linear Fresnel reflector (LFR).

In Figure 3.12 we can see a reciever tube which collects the heat and passes it to the fluid to create steam. A conventional lens design depends on its mass and volume of the material. But linear fresnel design helps the construction of lenses of large aperture and short focal length without the mass and volume of material.

The main advantages of LFR is that flat mirrors are used which are cheaper and that more reflectors can be placed in the same amount of space, this allows more efficient utilization of the sunshine available. Also, Linear Fresnel Reflectors generally produce steam directly and have the requirement of expensive heat exchangers and it has no toxic materials.

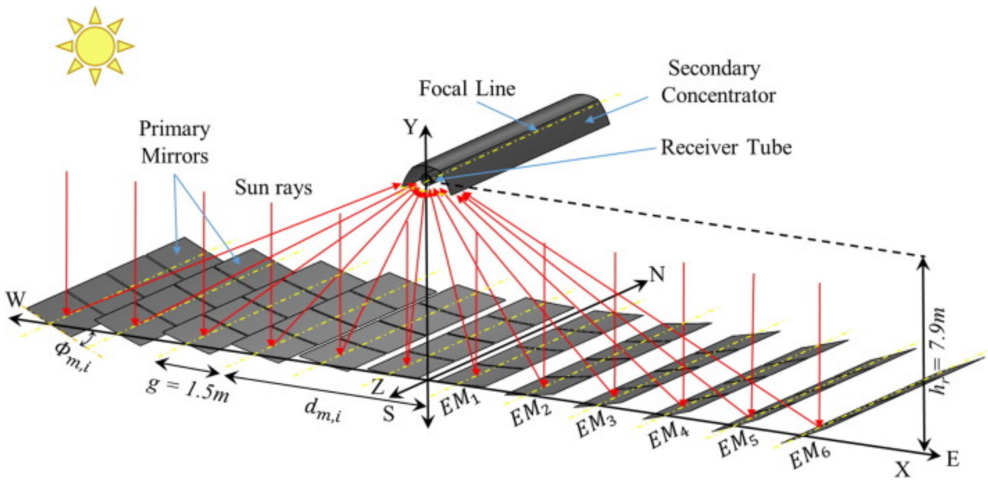

Figure 3.12: Linear Fresnel Reflector geometry (Simple) [81]

To avoid shading, mirrors need to be spaced in a greater area which requires more land and thus increases costs. Also, Very high temperatures are not produced as compared to a parabolic trough or a sterling dish and therefore the efficiency is less.

3.4.6 Parabolic trough collector (PTC)

Parabolic trough is a device in a parabolic shape, having small focal length. It's a concentrating, high performance, solar tracking collector. It can deliver high performance output in high temperature maintaining good efficiency. Figure 3.13 shows the geometry of a parabolic through collector. The major components are the solar absorber, the glass envelope, the positioning system, the support structure, and the reflector surface. There is a copper tube placed at a focal point of parabolic trough collector. Parabolic trough collector concentrates solar radiation on that tube. We can see the path of radiation and schematic of Parabolic trough collector from Figure 3.14 and 3.15.

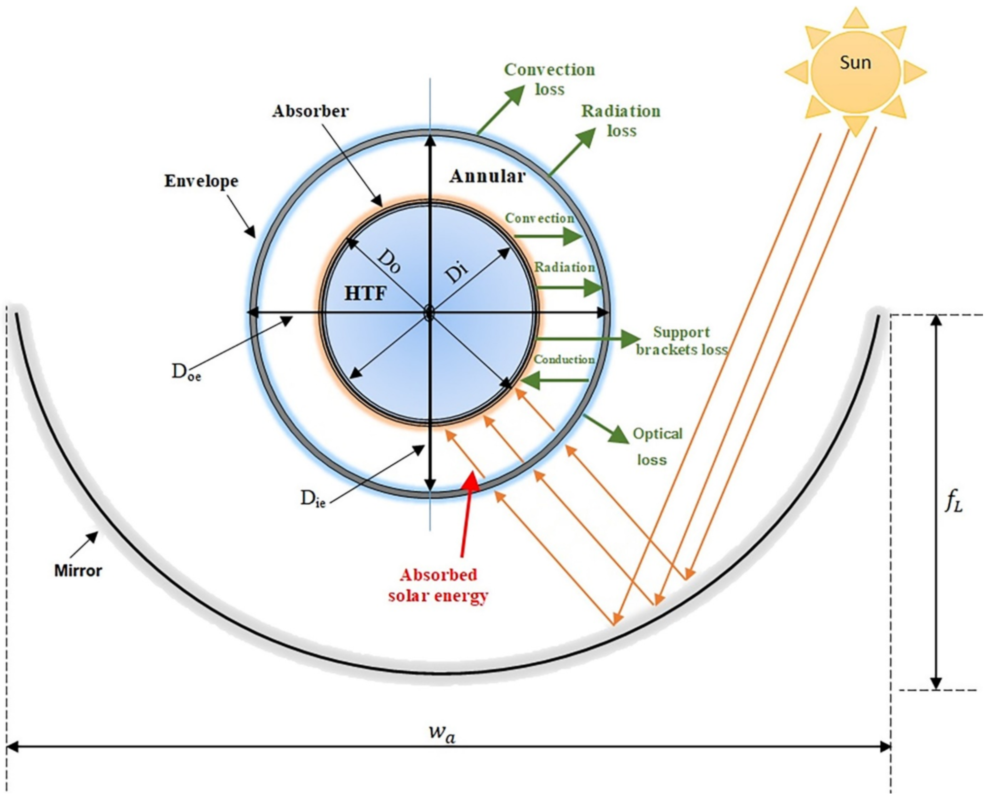

Figure 3.13: Geometry of Parabolic trough collector [82]

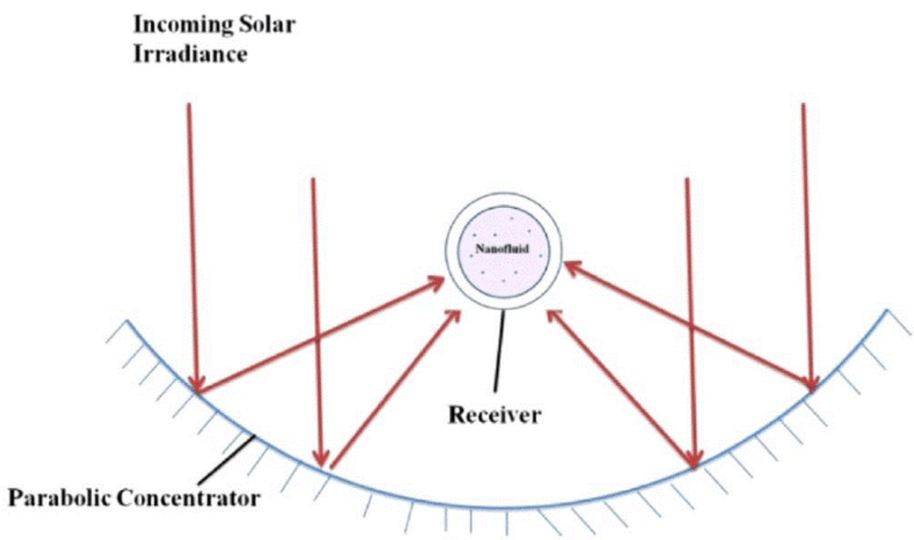

Figure 3.14: Path of Radiation [74]

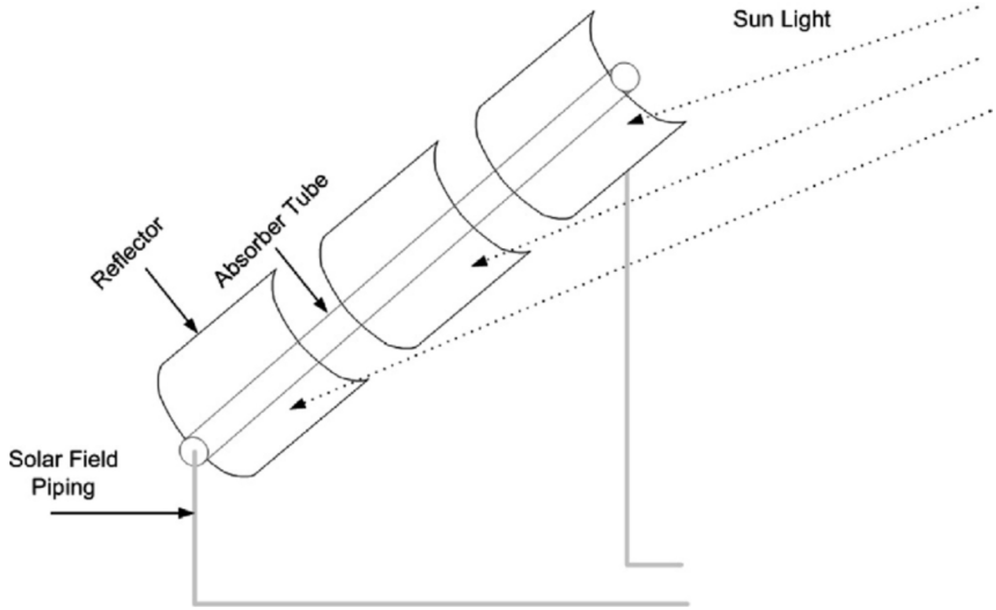

Figure 3.15: Geometry of Parabolic trough collector [82]

The collectors helps when sun rises, the solar radiation from the low-lying sun in the east is almost vertically incident on the parabolic opening. The parallel rays' incident on the reflector and are reflected onto the receiver tube, when the parabola is pointed toward the sun. The tube heats the fluid circulating inside. The solar radiation transforms into useful heat. Among some important characteristics of PTC are: Its highly concentrated, it can track the sun (tracking the sun from north to south, or in east to west), higher process temperature and greater efficiency, solar direct steam generation.

More than 95% of the commercially operated solar thermal power plants are parabolic trough systems. Because of considerable experience with the systems and the development of a small commercial industry to produce and market these systems, parabolic trough technology is the most advanced of the solar thermal technologies.

3.4.7 Parabolic dish reflector (PDR)

A parabolic dish collector is a concentrating solar collector that is similar in appearance to a large satellite dish. It tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. It optically reflects and focuses the suns incident solar radiation onto a small receiving area using mirrors or lenses. Each mirror and lens act as a single sun, shining directly at the same focal point on the dish. Because of this the intensity of the receiving solar energy is magnified by many times. The dish structure is designed track the sun to fully and also reflect the beam into the thermal receiver. For this purpose, double axis sun tracking is introduced in this collector. These highly polished mirrors can reflect more than 90% of the sunlight that is incident on them increasing the efficiency of the dish by more than 20% compared to the parabolic trough collector.

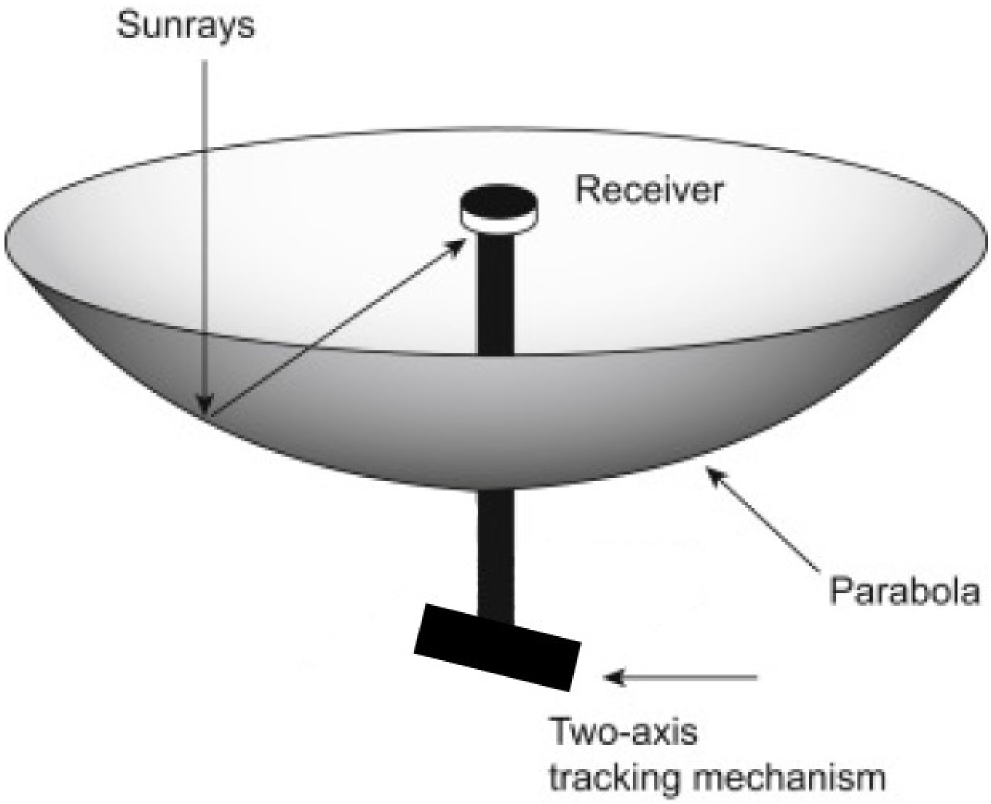

Figure 3.16: Parabolic dish reflector [83]

Figure 3.16 shows a parabolic dish reflector design. It is formed from thin sheet metal or thin aluminum coated mylar. The dish can be a few feet to several meters in diameter. The parabolic dish collects the incoming solar energy directly from the sun and concentrates it on a small focal point area positioned in front of the dish. Due to the very high temperatures at the focal point, a thermal oil type fluid is generally used instead of water inside the receiver, which transfers the intense heat created by focusing the sunlight on the receiver.

3.4.8 Heliostat field collector (HFC)

Heliostats collector systems can provide energy for domestic heating, electricity, and lighting. Altazimuth mounts are used to reflect the incident direct solar radiation onto a common target which can be source of extreme high inputs of radiant energy, multiplicity of flat mirrors, or heliostats. Heliostats can use slightly concave mirror segments; it helps in large amounts of thermal energy to be directed into the cavity of a steam generator to produce steam at high temperature and pressure.

Figure 3.17 shows a heliostat field collector. There are three general configurations of the collector and receiver. Firstly, heliostats completely surround the receiver tower, and the receiver, which is cylindrical, has an exterior heat transfer surface. Secondly, the heliostats are located north of the receiver tower (in the Northern Hemisphere), and the receiver has an enclosed heat transfer surface. Thirdly, the heliostats are located north of the receiver tower, and the receiver, which is a vertical plane, has a north-facing heat transfer surface.

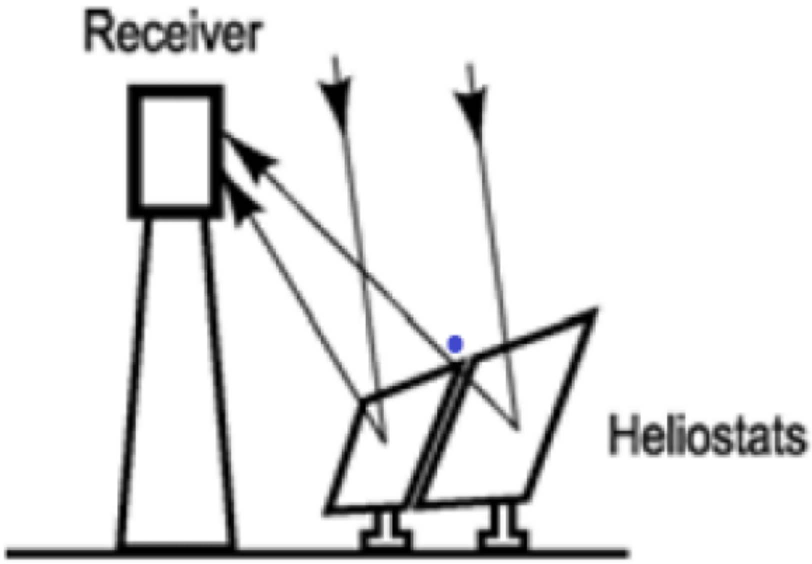

Figure 3.17: Basic Heliostat field collector design [62]

The concentrated heat energy absorbed by the receiver is transferred to a circulating fluid that can be stored and later used to produce power. Central receivers have several advantages [84]

1. Optically collecting solar energy and transferring to single receiver, thus minimizing thermal energy transport requirements.
2. Efficient in both collecting energy and converting it to electricity.
3. Concentration ratios of 300 to 1500.
4. Can conveniently store thermal energy.

The reflective surface is 50 to 150 m^2 with four mirrors installed on a common pillar for economy. The heliostats collect and concentrate sunlight onto the receiver, which absorbs the concentrated sunlight, transferring its energy to a heat transfer fluid. A thermal storage system typically stores the collected energy as sensible heat. The heat is later delivered to the power conversion system. The power conversion system consists of a steam generator, turbine generator, and support equipment, which convert the thermal energy into electricity and supply it to the utility grid. Energy is transferred to a working thermal fluid by concentration of the energy flux towards radiative-convective heat exchangers. the conversion of thermal energy to electricity is quite similar to the conventional fossil-fueled thermal power plants [85].

3.5 Selection of the solar collector

The selection is mostly depending on some factors like collector area, storage tank volume, life cycle savings, solar contribution and economic benefits. More collector area gives more energy output but it will drastically increase cost too. According to Kalogirou et al., the combination of collector area and storage volume, which gives the highest value of life cycle savings [25]. The research also indicates 3 major graphs [3.18, 3.19, 3.20] showing optimum collector area, life cycle savings and solar contribution.

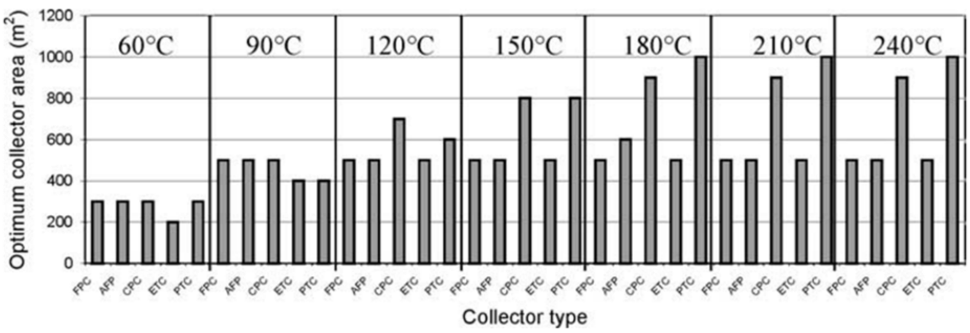

Figure 3.18: Optimum collector area for the various collector types and demand temperature [25]

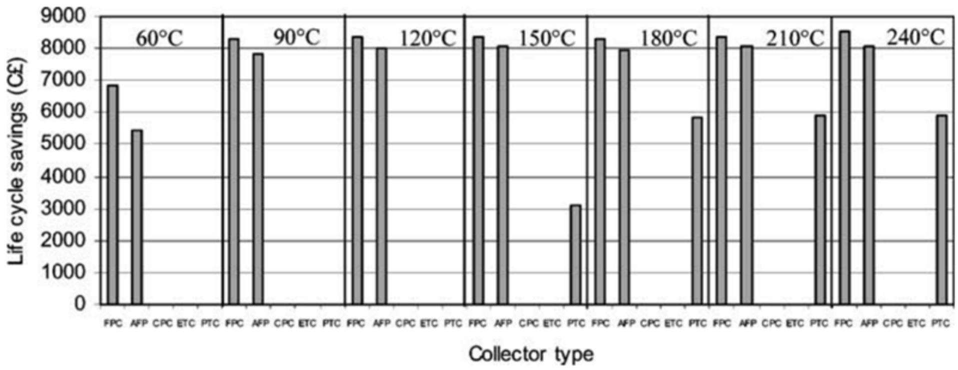

Figure 3.19: LCS for the various collector types and demand temperatures for subsidized fuel price [25]

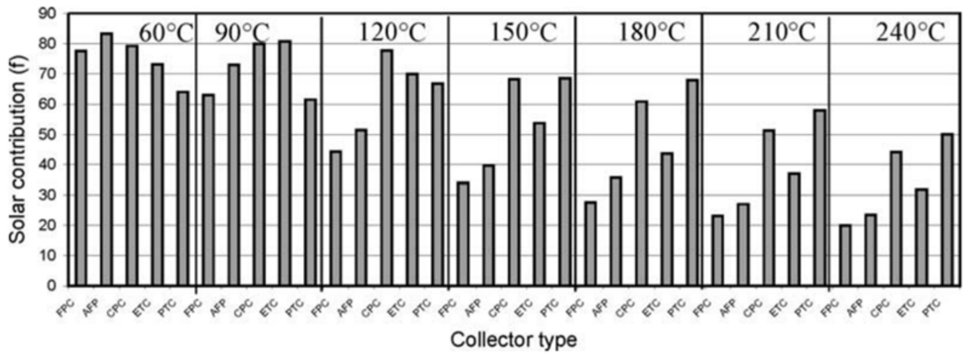

Figure 3.20: Solar contribution of the various collector types and demand temperature [25]

Flat plate has an effective temperature range of 30 to 80 degree that is lower than other collectors. Other collectors have the benefit of working in higher temperature range. But flat plate collector is cheaper than any other collector. Also, the life cycle savings and solar contribution is quite similar to the other collectors. So, the economic benefit and optimum solar contribution surpasses the low temperature range issue. Among all types of collector, flat plate collector is optimum one and thus selected for for this experiment.

Chapter 4

System design and methodology

4.1 System Design

The system design considered for this work is shown in Figure 4.1. Water from the ground water tank enters the flat plate collector and the temperature rises by absorbing thermal energy from the sun. The hot water from the outlet of the collector goes to the boiler feed water tank and from there it enters the boiler. The flat plate collector works as a preheater of the boiler feed water in this system. Then the water is heated to the required temperature in the boiler and sent to the processes.

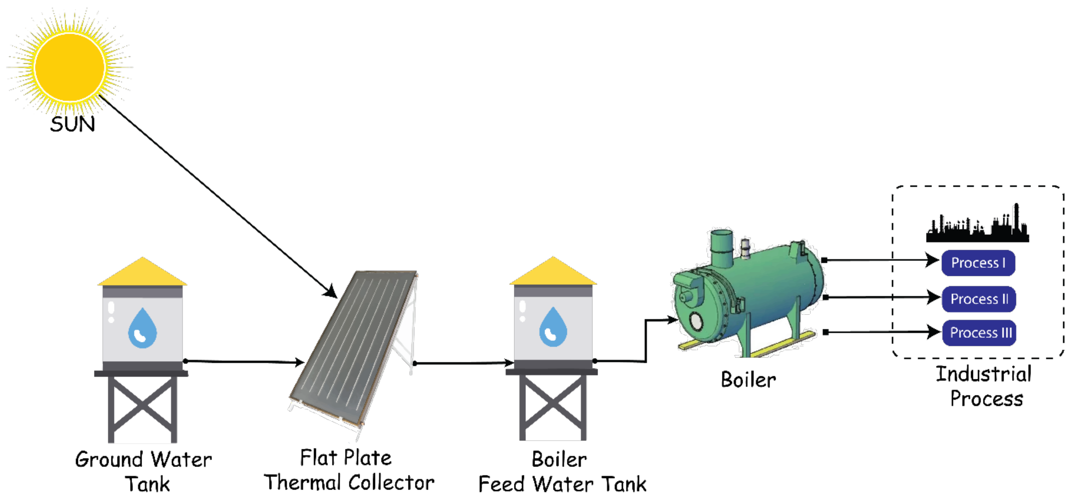

Figure 4.1: System design

4.2 Mathematical Modeling of the System:

As discussed by Duffie and Beckman [86], the useful energy output Q_u of a flat plate collector of area A_c in steady-state can be expressed by equation 4.1.

$$Q_u = A_c[S - U_L(T_{pm} - T_a)] \tag{4.1}$$

Where S, U_L, T_{pm}, and T_a represent absorbed solar radiation, overall loss coefficient of collector, mean absorber plate temperature, and ambient temperature respectively. Duffie and Beckman [86] stated that the mean absorber plate temperature is a complex term to be calculated or measured. However, according to Seco-Nicolás et al. [87] for flat plate collectors, it can be calculated simply by the arithmetic mean of the inlet and outlet temperatures of the collector fluid which causes about 5% error only. The calculation in the present work has done considering this relation for simplicity. Mathematically it can be expressed by equation 4.2.

$$T_{pm} = \frac{T_e + T_i}{2} \tag{4.2}$$

Absorbed solar radiation can be calculated as the product of the optical efficiency of the collector, $\eta_{o,}$ and total incident radiation, I_T which can be expressed by equation 4.3 [88].

$$S = \eta_o I_T \tag{4.3}$$

Heat loss occurs through the top, bottom, and edges of the collector and they are expressed as U_t, U_b, U_e respectively. Overall heat loss coefficient U_L is the sum of these three terms. It can be calculated by equation 4.4 [86].

$$U_L = U_t + U_b + U_e \tag{4.4}$$

The top loss coefficient U_t can be calculated by the empirical equation 4.5 which is an empirical equation developed by Klein in 1979 as mentioned by Duffie and Beckman [86].

$$U_t = \left[\frac{N}{\frac{C}{T_{pm}}\left(\frac{T_{pm}-T_a}{N+F}\right)^e} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma(T_{pm}-T_a)(T_{pm}{}^2+T_a{}^2)}{\frac{1}{\varepsilon_p + 0.00591 N h_w} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N} \tag{4.5}$$

Where f, C and e can be calculated by equations 4.6, 4.7 and 4.8 respectively.

$$f = (1 + 0.089 h_w - 0.1166 h_w \varepsilon_p)(1 + 0.07866N) \tag{4.6}$$

$$C = 520\left(1 - 0.000051\beta^2\right) \quad \text{For } 0° < \beta < 70° \tag{4.7}$$

$$e = 0.43\left(1 - \frac{100}{T_{pm}}\right) \tag{4.8}$$

Here, N represents the number of glass covers, β is collector tilt in degree, ε_g and ε_p are emittances of glass and absorber plate respectively, and h_w is the heat transfer coefficient of wind.

Bottom or back loss coefficient U_b can be calculated by equation 4.9 [86].

$$U_b = \frac{k_i}{L} \tag{4.9}$$

Where k_i is the thermal conductivity of insulation and L is the thickness of insulation. The edge loss coefficient is negligible for a well-built collector and it is considered as 1% of total heat loss as suggested by Duffie and Beckman [86].

For a collector with sheet thickness δ as shown in Figure 4.2 where the tubes of diameter D are at W distance, standard fin efficiency, F for straight fins with a rectangular profile can be calculated by equation 4.10 [86].

$$F = \frac{\tanh\left[\frac{m(W-D)}{2}\right]}{\frac{m(W-D)}{2}} \tag{4.10}$$

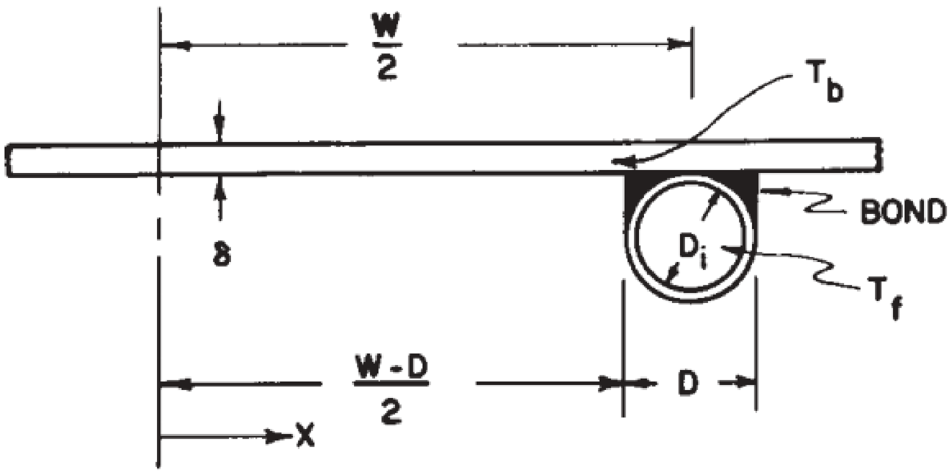

Figure 4.2: Sheet and tube dimensions of a collector [86]

Where m is defined by equation 4.11.

$$m = \sqrt{\frac{U_L}{k_p \delta}} \tag{4.11}$$

To evaluate temperature distribution, collector efficiency factor, F′ needs to be calculated which can be expressed by equation 4.12 [86].

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L[D+(W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]} \tag{4.12}$$

In this equation, C_b is bond conductance which is found by dividing the product of thermal conductivity and width of the bond by its thickness. Mathematically it can be expressed by equation 4.13.

$$C_b = \frac{k_b b}{\gamma} \tag{4.13}$$

However, in this work this term is ignored as Kalogirou [89] stated that if the tubes are centered in the plane of the plate and are integral to the plate structure, the bond conductance term, $1/C_b$, is eliminated from equation 4.12.

For a collector with a length of L in the flow direction, the temperature distribution can be expressed by equation 4.14 [86].

$$\frac{T_e - T_a - S/U_L}{T_i - T_a - S/U_L} = exp(-\frac{U_L A_c F^{'}}{\dot{m} C_p}) \tag{4.14}$$

Here, $\dot{m}$ is the mass flow rate of the fluid that is flowing through the collector tube and C_p is the specific heat capacity of that fluid.

When the entire surface of the collector is at the inlet fluid temperature, heat losses from the collector to the surroundings are then at a minimum and the useful heat gain from the solar collector is maximum. Collector heat removal factor, F_R is required to be calculated in order to relate the actual useful heat gain from the collector to the maximum useful heat gain. It is equivalent to the effectiveness of a conventional heat exchanger and can be expressed by the equation 4.15 [86].

$$F_R = \frac{\dot{m} C_p (T_e - T_i)}{A_c [S - U_L (T_i - T_a)]}) \tag{4.15}$$

Considering the heat removal factor, the maximum useful heat gain from the collector can be calculated by equation 4.16 [86].

$$Q_{u,\ max} = A_c F_R [S - U_L (T_i - T_a)] \tag{4.16}$$

4.3 Economic Analysis

To perform the economic analysis, the capital investment, annual operating cost, rate of return, payback period life time, and energy cost needs to be calculated [5–7].

As studied by Haghghi et al. [23], the capital investment cost of the flat plate collector can be obtained by equation 4.17.

$$C_{FPC}=(C_A+C_E)*A_{c,total} \tag{4.17}$$

Where C_A is the cost of flat plate collector for unit area, C_E is the operation and maintenance cost per unit area, and $A_{c,total}$ is the total collector area. Piping, valves and all the additional equipment cost can be considered as the 20 % of the capital investment as stated by Bolognese et al. [90] Considering this, the equation of total capital investment cost can be expressed by equation 4.18.

$$C_{FPC,total}=C_{FPC}+20\%*C_{FPC} \tag{4.18}$$

To calculate the cost rate of the collector, maintenance factor, $\varphi_{Fpc,}$ and annual operation time, t_{FPC} needs to be evaluated. Then the cost rate can be calculated using equation 4.19 [23].

$$C_{FPC,rate}=\frac{C_{FPC,total}*CRF*\varphi_{FPC}}{t_{FPC}} \quad \text{7cm1pt3pt} \tag{4.19}$$

Here CRF is the capital recovery factor which can be calculated by equation 4.20 [23]:

$$CRF=\frac{i_r*(1+i_r)^m}{(1+i_r)^m-1} \tag{4.20}$$

Where m and i_r represents lifetime and annual interest rate respectively.

Electric, diesel or gas boiler is used in industries to supply hot water [91]. The selected textile factory for this work (discussed in section 4.4) utilizes natural gas fired boiler. The payback period of the system can be calculated by equation 4.21 [23].

$$Payback\ period = \frac{C_{FPC,rate}}{C_{NG,rate}} \tag{4.21}$$

Here $C_{NG,rate}$ is the cost rate of natural gas. To calculate this, mass flow rate of natural gas, $\dot{m}_{NG}$ and volume of consumed natural gas, V_{NG} are needed to evaluated equation 4.22 and 4.23 respectively [23].

$$\dot{m}_{NG} = \frac{Q_{boiler}}{HHV_{NG} * \eta_{boiler}} \tag{4.22}$$

$$V_{NG} = v_{NG} * \dot{m}_{NG} * t_{boiler} \tag{4.23}$$

Where Q_{boiler} represents the heat required from the boiler, HHV_{NG} is the higher heating value of natural gas, η_{boilew} is the efficiency of the boiler, v_{NG} is the specific volume of natural gas, $\dot{m}_{NG}$ is the mass flow rate of natural gas, and t_{boiler} is the annual operation time of the boiler.

Then, the cost rate of natural gas can be calculated using equation 4.24 [23].

$$C_{NG,rate} = \frac{V_{NG} * C_{NG}}{t_{boiler}} \tag{4.24}$$

Finally, the percentage of energy saved in the system for using solar collector can be calculated by the simple equation 4.25 [92].

$$\%\ of\ saved\ energy = \frac{Q_{u,\ max}}{Q_{boiler}} \tag{4.25}$$

4.4 Environmental Analysis

Burning fossil fuel to run boiler releases a huge amount of carbon dioxide which has an adverse effect on the environment. As discussed earlier, for present work, natural gas fired boiler is considered. Assuming natural gas as pure methane, the combustion equation can be expressed as [23]:

$CH_4 + 2O_2 + 3.76N_2 = CO_2 + 2H_2O + 3.76N_2$

Then carbon dioxide emission rate can be evaluated by equation 4.26.

$$EMI_{CO_2} = \frac{m_{CO_2}}{Q_{boiler}} \tag{4.26}$$

Here, m_{CO2} is the mass of carbon dioxide which can be computed by equation 4.27.

$$m_{CO_2} = \frac{\dot{m}_{NG} * 44}{16} \tag{4.27}$$

Where 44 and 16 are molecular weight of carbon dioxide and methane, respectively.

4.5 Selection of Location and Solar Collector:

In this present work, Square Fashion Ltd. at Valuka, Mymensingh (24°17’40.9”N, 90°23’17.3”E) is selected as a model textile factory and an industrial visit was done to collect required data from the factory which is presented in tabulated form in Table 4.1.

Table 4.1: Data from Square Fashion Ltd

Data	**Value**
Flue Gas Temperature at Economiser Inlet (Boiler exhaust)	210-220°C
Flue Gas Temperature at Economiser Outlet	90°C
Water Temperature at Economiser Inlet	50-65°C
Water Temperature at Economiser outlet	90-95°C
Steam pressure at boiler outlet	7.2 bar
Steam Temperature at boiler outlet	165-170°C
Steam Requirement	500 ton/day
Usable Space on Roof	6150 m^2
Tin Shaded Roof	32500 m^2
Mass Flowrate of Gas Flow	900 m^3/hr

G series solar collector of Thermo Dynamics Ltd. [93] is used as a model collector. It is a liquid collector of single glazed, low-iron tempered glass. The absorber plate is an arrangement of parallel riser fins which connects the top and bottom headers. The fins are made of aluminum with integrated copper riser tubes. The riser tubes are joined together metallurgically and joined to the headers by soldering. The back and sides of the collector are insulated with compressed fiberglass layer to reduce the heat loss from the collector.

The schematic diagram and cross-sectional view of the collector are presented respectively in Figure 4.3 and Figure 4.4 [93].

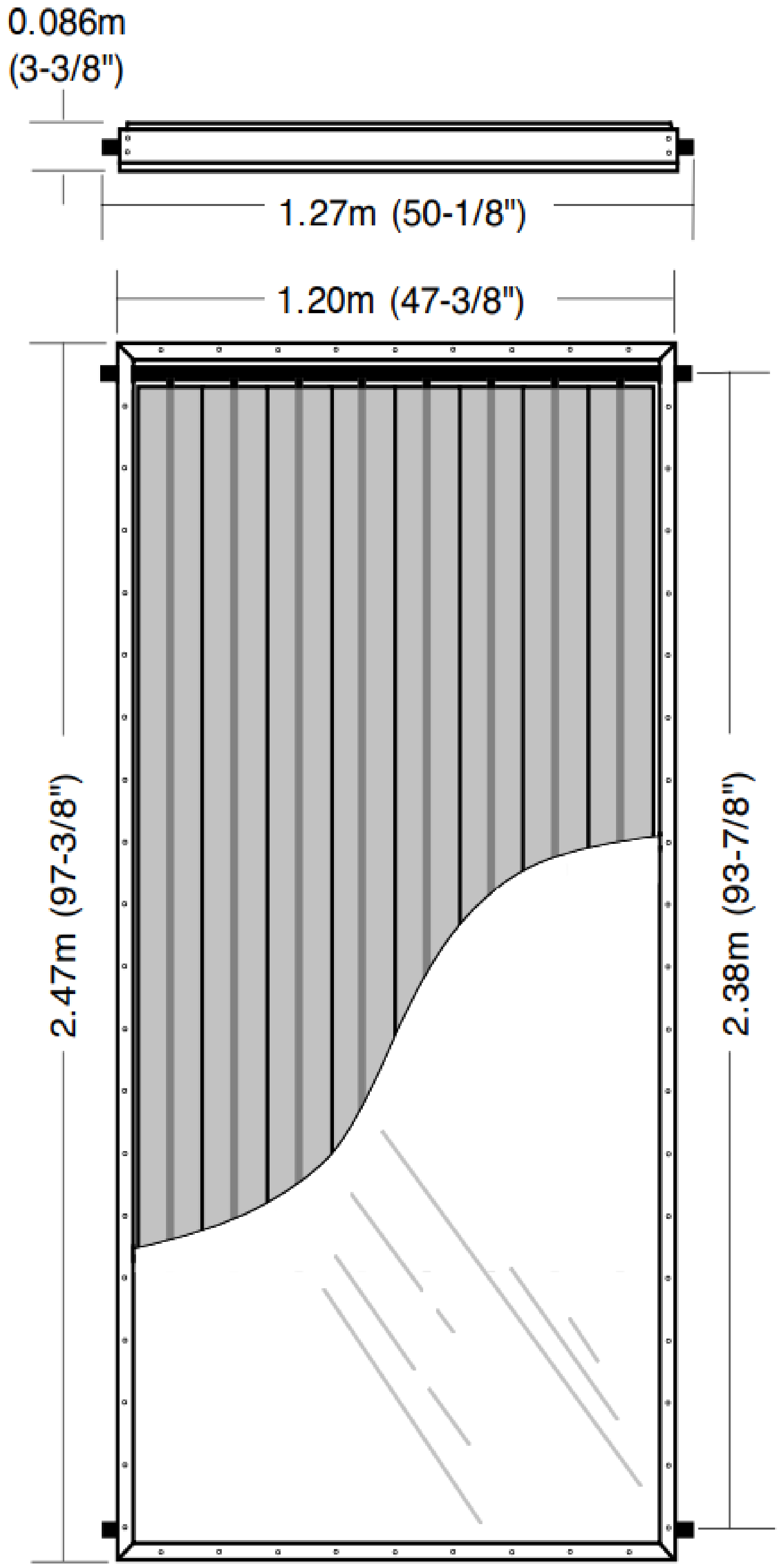

Figure 4.3: Schematic diagram of G series solar collector [93]

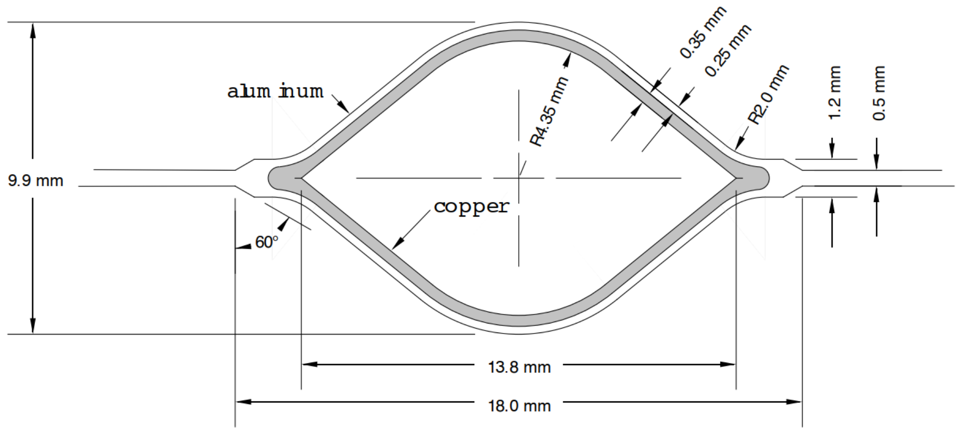

Figure 4.4: Cross-sectional view of G series solar collector [93]

4.6 Data used to run MATLAB code:

The water temperature at the outlet depends on several variable factors like ambient temperature, fluid inlet temperature, mass flow rate, etc. According to data from Square Fashion Ltd. at Valuka (24°17'40.9"N, 90°23'17.3"E), steam requirement per day is around 500 tons per day which is equal to around 5.25 kg per second. The area available at that factory is sufficient to house 1500 solar collectors of the specified model considered in this work. Hence, the required mass flow rate through each collector is 0.0035 kg/s.

Collector dimensions and other required data of the collector are taken from the technical specification of the selected collector. Parameters related to weather condition like the optimum tilt of collector and total solar irradiance is taken from Global Solar Atlas [94] and Renewables.ninja [95]. Some other parameters are calculated considering respective conditions and the details are explained following.

4.6.1 Equivalent tube diameter

The equivalent inside tube diameter is defined as four times the cross-sectional area of the tube divided by the wetted perimeter. Mathematically it can be expressed by equation 4.28.

$$D_i = D_{equivalent} = \frac{4A}{P} \tag{4.28}$$

In this case, the cross-sectional area of the tube, A is 120 mm^2 which is found from collector specification. As the cross-sectional area is of rhombic shape, the perimeter, P is calculated to be 14.71 mm using equation 4.29.

$$P = 2\sqrt{x^2+y^2} \tag{4.29}$$

Where x and y are diagonal of rhombic shaped cross-section. Finally, equivalent inside tube diameter is calculated 14.71 mm. The equivalent outside tube diameter is calculated adding the thickness of two outer layers, as seen in Figure 4.3, with equivalent inside tube diameter which is obtained as15.91 mm.

4.6.2 Wind heat transfer coefficient

Wind heat transfer coefficient, h_w is a function of wind speed and characteristic length. To determine it accurately for this particular case, there is no alternative of experimental approach. However, many researchers worked on this topic and provided empirical relation which can be used to determine the wind heat transfer coefficient considering a certain level of inaccuracy. Kumar and Mullick [96] reviewed previous work on wind heat transfer coefficient and mentioned that analytical equations provided by Sartori [97] considered plate length. Equation 4.30, 4.31, 4.32 are provided by Sartori [97].

$h_w = 3.83V^{0.5}L^{-0.5}$ (laminar flow) (4.30)

$h_w = 5.74V^{0.8}L^{-0.2}$ (fully turbulent flow) (4.31)

$h_w = 5.74V^{0.8}L^{-0.2} - 16.46L^{-1}$ (mixed flow) (4.32)

where V is the wind velocity and L is the length of the plate. Wind speed for the present work is calculated 4.3357 m/s as the average of wind speed obtained from renewable ninja [95] for 2019 in the location of Square Fashion Ltd. Under normal condition, the wind is considered to be in fully laminar zone. So, equation 4.29 is used to calculate the wind heat transfer coefficient by which wind heat transfer coefficient is obtained 5.17 W/m^2K.

4.6.3 Heat transfer coefficient between fluid and tube wall

Heat transfer coefficient between fluid and tube wall, h_{fi} is calculated following the process described by Kalogirou [89]. For the calculation, at first, the velocity of water is determined 0.291 mm/s from the mass flow rate and then Reynolds number is calculated 1568.14 using this velocity. As the Reynolds number is less than 2000, the flow of water is laminar flow and so, Nusselt number is a fixed value of 4.364 for this case therefore h_{fi} is calculated 195.64 W/m^2 °C from this.

Data used to run MATLAB code are summarized in Table 4.2.

Table 4.2: Data used to run MATLAB code

Parameter	**Value**	**Source/Remarks**
For Flat Plate Collector		
Number of glass cover, N	1	Collector Specification [93]
Emittance of glass, ε_g	0.88	Collector Specification [93]
Emittance of plate, ε_p	0.25	Collector Specification [93]
Thermal conductivity of the insulation, k_i	0.036 W/m °C	Collector Specification [93]
Thickness of insulation, L	0.025 m	Collector Specification [93]
Cross-sectional area of the tube, A	120 mm^2	Collector Specification [93]
Collector area, A_c	2.870 m^2	Collector Specification [93]
Distance between the tubes, W	0.143 m	Collector Specification [93]
Optical efficiency of the collector, η_o	0.7	Collector Specification [93]
Sheet thickness, δ	0.0005 m	Collector Specification [93]

Plate thermal conductivity, k_p	385 W/m °C	Collector Specification [93]
Optimum tilt of collector, β	24°	Global Solar Atlas [94]
Total solar irradiance, I_t	Hourly Data	Renewables.ninja [95]
Equivalent inside tube diameter, D_i	0.0147 m	Calculated according to collector specification
Equivalent outside tube diameter, D	0.0159 m	
Wind heat transfer coefficient, h_w	5.17 W/m^2 °C	Calculated according to average wind speed and characteristic length
Heat transfer coefficient between fluid and tube wall, h_{fi}	195.64 W/m^2 °C	Calculated
For Economic Analysis		
Total collector area, $A_{c,total}$	4305 m^2	Calculated
Cost of flat plate collector for unit area, C_A	USD 235 /m^2	Haghghi et al. [22]
Operation and Maintenance Cost, C_E	USD 30/m^2	Haghghi et al. [22]

Maintenance Factor, φ_{Fpc}	1.1	Haghghi et al. [22]
Lifetime, m	20 years	Haghghi et al. [22]
Interest rate, i_r	12%	
High heating value of natural gas, HHV_{NG}	50 MJ/kg	
Specific Volume of Natural Gas, v_{NG}	.068	
Price of natural gas for unit volume, C_{NG}	0.2 USD/ m^3	
Annual Operating time collector, t_{FPC}	4380 hours	Considering 12 hours daylight on average
Annual Operating time of boiler, t_{boiler}	8760 hours	Selected textile industry run 24 hours a day

4.7 Validation:

MATLAB code is developed using the mathematical model discussed in section 4.2. The model of the system is validated with Jafarkazemi and Ahmadifard [88] and the code of economic analysis is validated with Haghghi et al. [22]. The validated plots are shown in Figure 4.5 to Figure 4.9. The summary of the validation with error percentage is presented in Table 4.2. It can be observed from the graphs and summarized table that the shape of the graphs of this study are similar to the respective graphs of the papers with some error. Although it is done cautiously, possibly some error was generated while reproducing the graphs from the mentioned papers because of the limitation of the reproducing tool. Also, the equations are solved numerically in MATLAB which might also cause some error. The percentage of error is below 5% except for the graph of validation of economic analysis. Hence, the modeling methodology is validated and has been used for analyzing the proposed system.

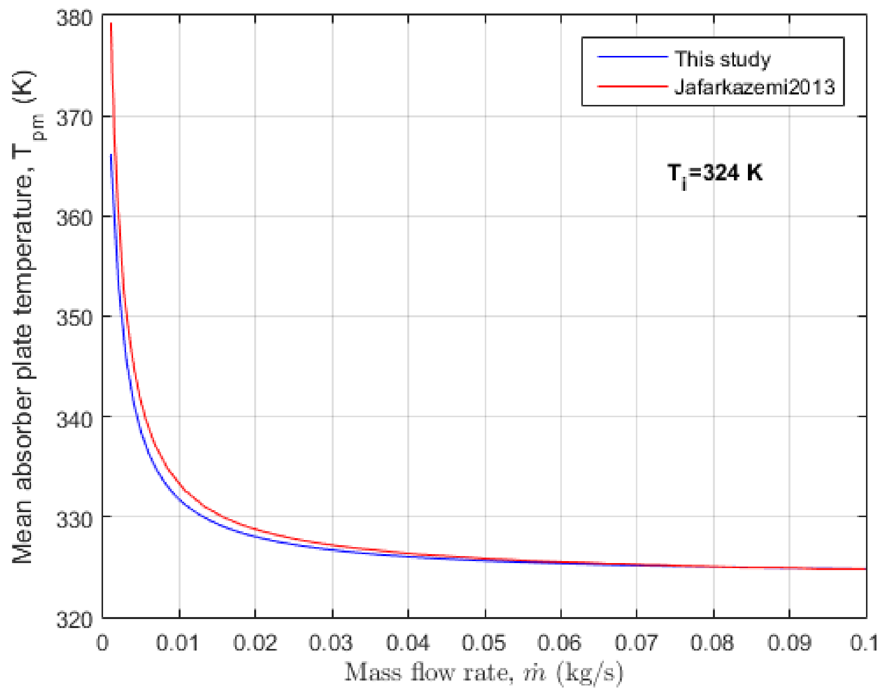

Figure 4.5: Validation of the model; mean absorber plate temperature (T_{pm}) versus collector mass flow rate ($\dot{m}$)

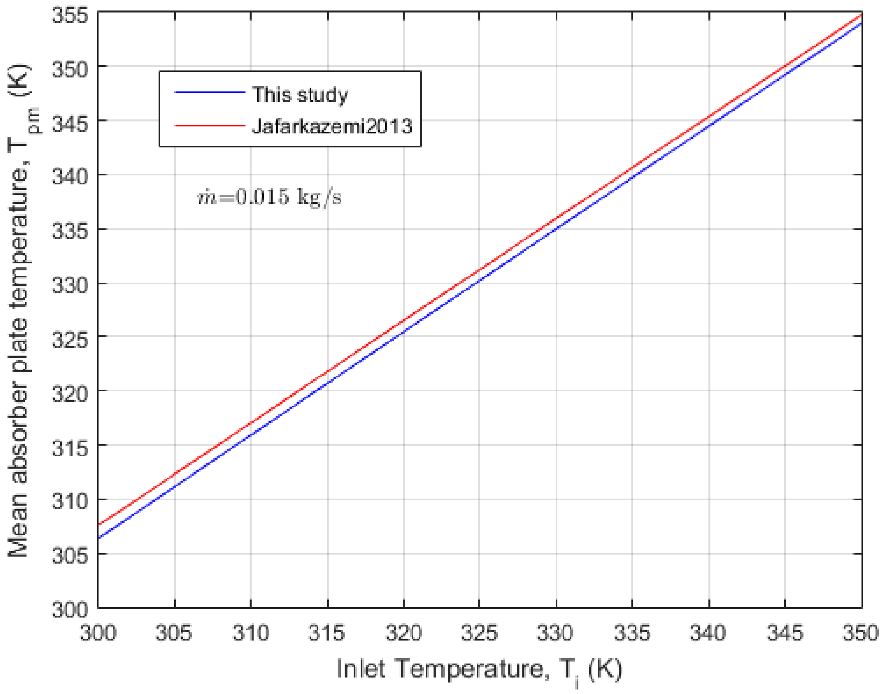

Figure 4.6: Validation of the model; overall heat loss coefficient (U_L) versus water inlet temperature (T_i)

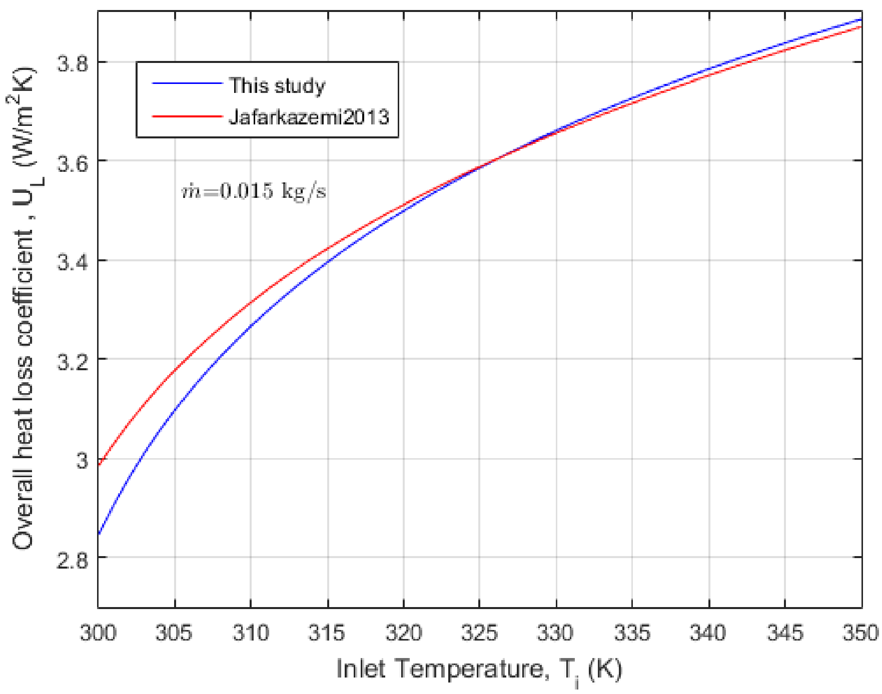

Figure 4.7: Validation of the model; mean absorber plate temperature (T_{pm}) versus collector mass flow rate ($\dot{m}$)

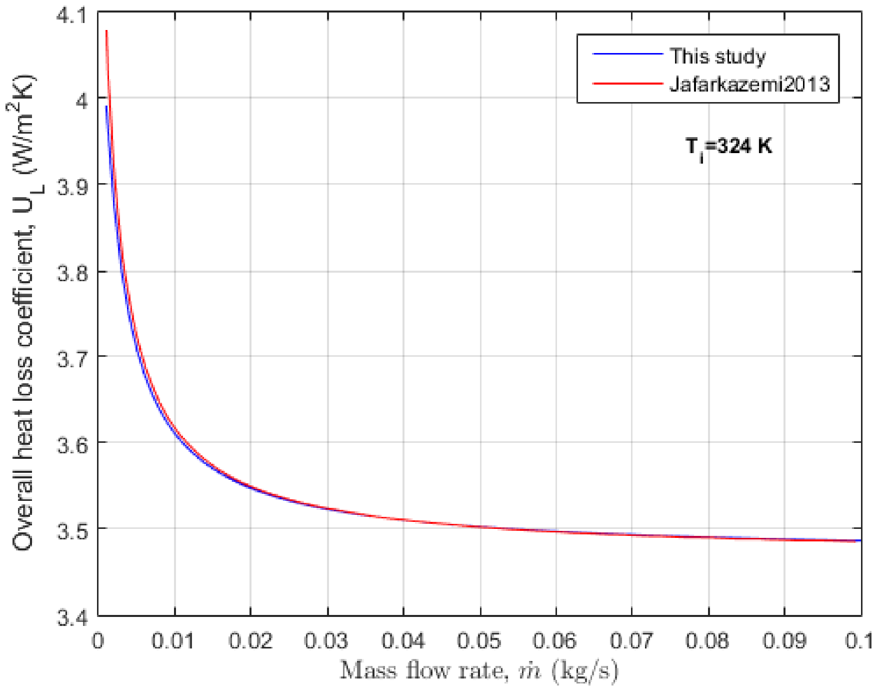

Figure 4.8: Validation of the model; overall heat loss coefficient (U_L) versus collector mass flow rate ($\dot{m}$)

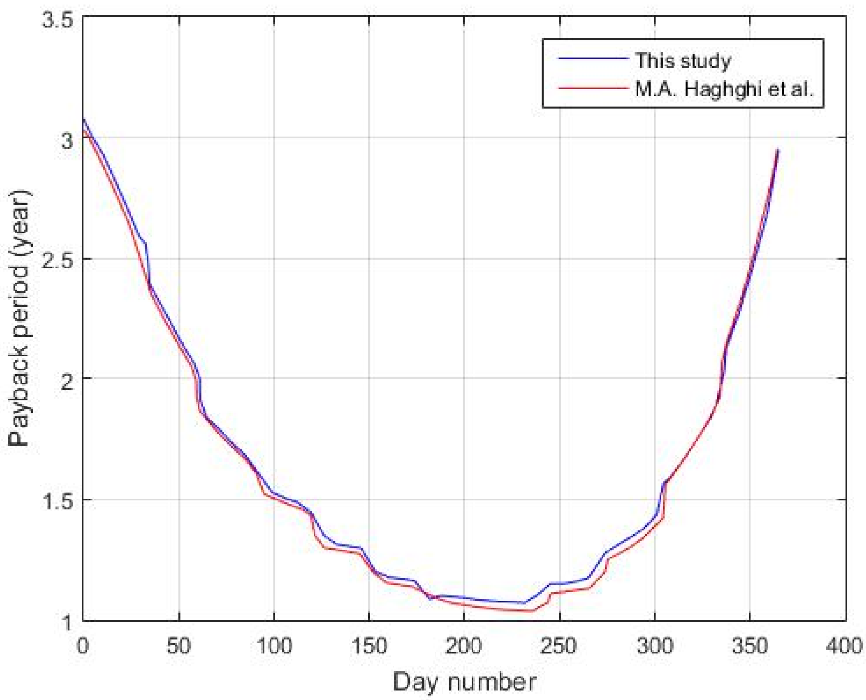

Figure 4.9: Validation of economic analysis; Payback period versus Day Number

Table 4.3: Summary of the validation study

Figures	**Maximum error occurs at**	**Corresponding value**		**Error Percentage**
		This Study	**From Jafarkazemi and Ahmadifard [88]**	
T_{pm} vs $\dot{m}$	$\dot{m}$ = 0.001 kg/s	T_{pm} = 366.15 K	T_{pm} = 379.3 K	3.47%
T_{pm} vs T_i	T_i = 300 K	T_{pm} = 306.4 K	T_{pm} = 307.6 K	0.39%
U_L vs T_i	T_i = 300 K	U_L = 2.8465 W/m^{2}K	U_L = 2.9855 W/m^{2}K	4.65%
U_L vs $\dot{m}$	$\dot{m}$ = 0.001 kg/s	U_L = 3.99 W/m^{2}K	U_L = 4.08 W/m^{2}K	2.21%
Payback period vs Day	Day number = 240	Payback period = 1.11625	Payback period = 1.0574	5.57%

Chapter 5

Result and Discussion

5.1 Radiation in selected location

Hourly radiation data of the selected place (Square Fashion Ltd. at Valuka, Mymensingh; 24°17’40.9”N, 90°23’17.3”E) is collected from Renewables.ninja [95]. The data is then converted to daily radiation at the optimum tilt of the collector (24° for this location) and presented graphically in Figure 5.1.

Absorbed radiation depends on the optical efficiency of the collector which is 0.7 for the solar collector selected for this work. Daily absorbed radiation is calculated by equation 4.3 and presented graphically in Figure 5.2.

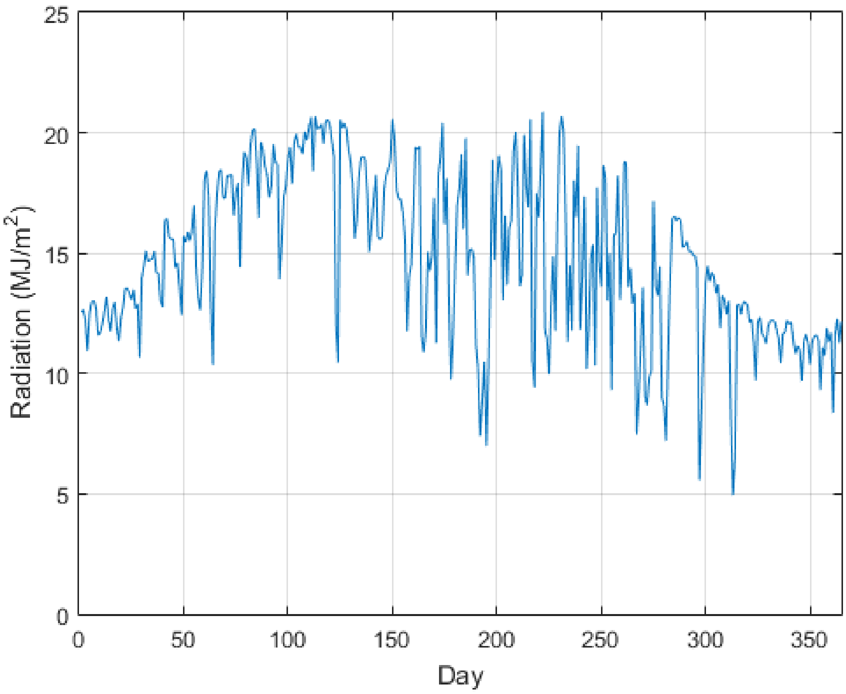

Figure 5.1: Daily radiation in the study location

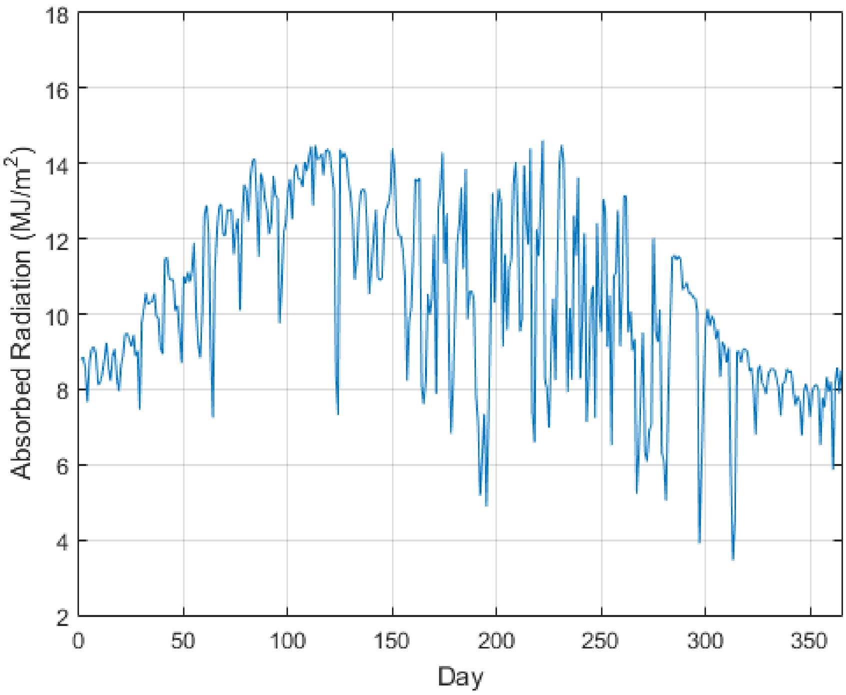

Figure 5.2: Daily absorbed radiation in the study location

5.2 Effect of collector mass flow rate ($\dot{m}$)

Figure 5.3 and Figure 5.4 are the graphical representation of the complex equation 4.14 which expresses the relation between exit temperature (T_e), overall heat loss coefficient (U_L) and collector mass flow rate ($\dot{m}$). In this equation inlet temperature (T_i), ambient temperature (T_a), cross-section area (A_c) and specific heat of fluid (C_p) are constant. Absorbed solar radiation (S) depends on location and time. Collector efficiency factor (F′) itself is a function of overall heat loss coefficient (U_L) expressed in equation 4.12.

From Figure 5.3 it can be seen that with the increase of mass flow rate up to 0.01 kg/s, exit temperature decrease rapidly. With the further increase of mass flow rate, plate temperature decreases slowly up to 0.022 kg/s and after that, plate temperature remains fixed at 303 K.

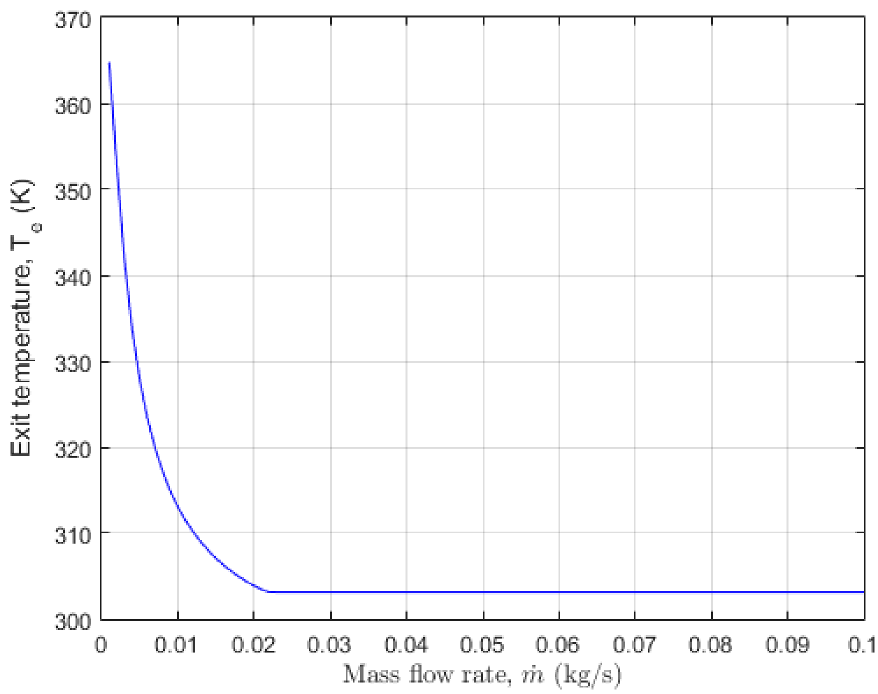

Figure 5.3: Exit temperature (T_e) versus collector mass flow rate ($\dot{m}$)

Figure 5.4 shows the relationship between overall heat loss coefficient (U_L) and collector mass flow rate ($\dot{m}$). From this figure it is observed that the overall heat loss coefficient (U_L) decreases rapidly with the increase of collector mass flow rate ($\dot{m}$) up to a certain limit. Then the overall heat loss coefficient (U_L) becomes almost constant.

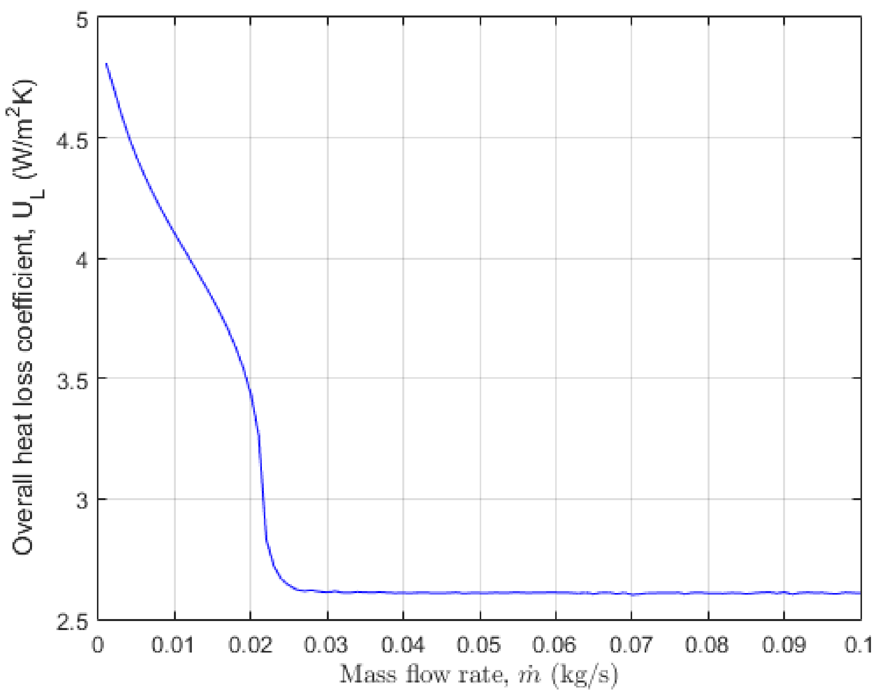

Figure 5.4: Overall heat loss coefficient (U_L) versus collector mass flow rate ($\dot{m}$)

Effect of collector mass flow rate ($\dot{m}$) on mean absorber plate temperature (T_{pm}) and overall heat loss coefficient (U_L) was also studied by Jafarkazemi and Ahmadifard [88] and the shape of the graphs that are shown in their study is almost identical with this study. In their study, higher temperature was obtained because it was conducted in Iran where solar irradiance is much higher than in Bangladesh.

5.3 Effect of inlet temperature (T_i)

Exit temperature (T_e) and inlet temperature (T_i) are proportional to each other as it is seen from Figure 5.5. With the increase of and inlet temperature (T_i), the exit temperature (T_e) increases linearly.

From Figure 5.6 it is seen that relation between overall heat loss coefficient (U_L) and inlet temperature (T_i) is also proportional but unlike the relation between exit temperature (T_e) and inlet temperature (T_i), they are not linearly dependent.

The same decision was concluded by Jafarkazemi and Ahmadifard [2] after studying the effect of inlet temperature (T_i) on mean absorber plate temperature (T_{pm}) and overall heat loss coefficient (U_L).

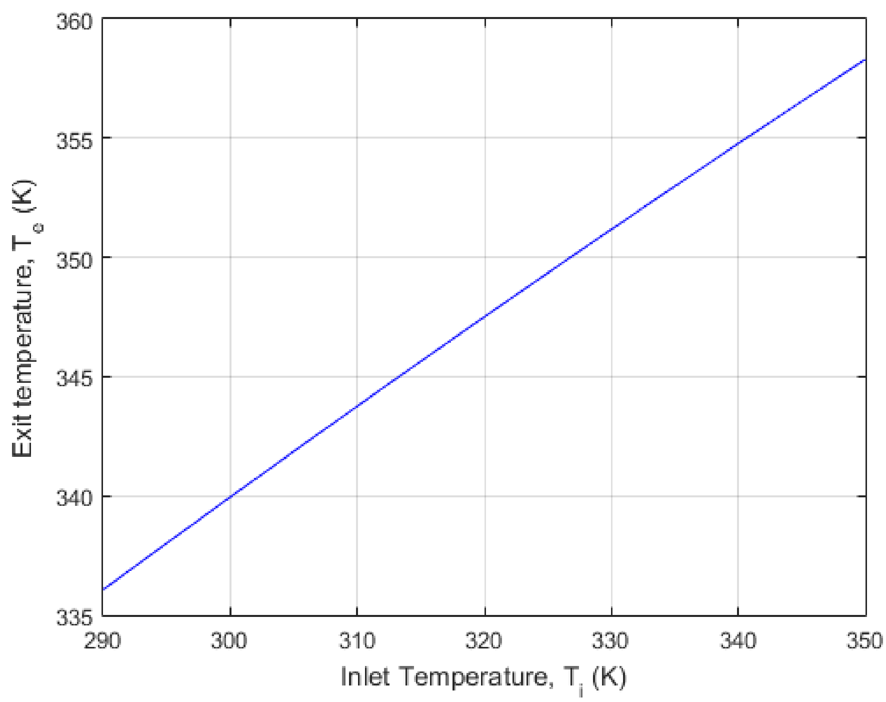

Figure 5.5: Exit temperature (T_e) versus Inlet temperature (T_i)

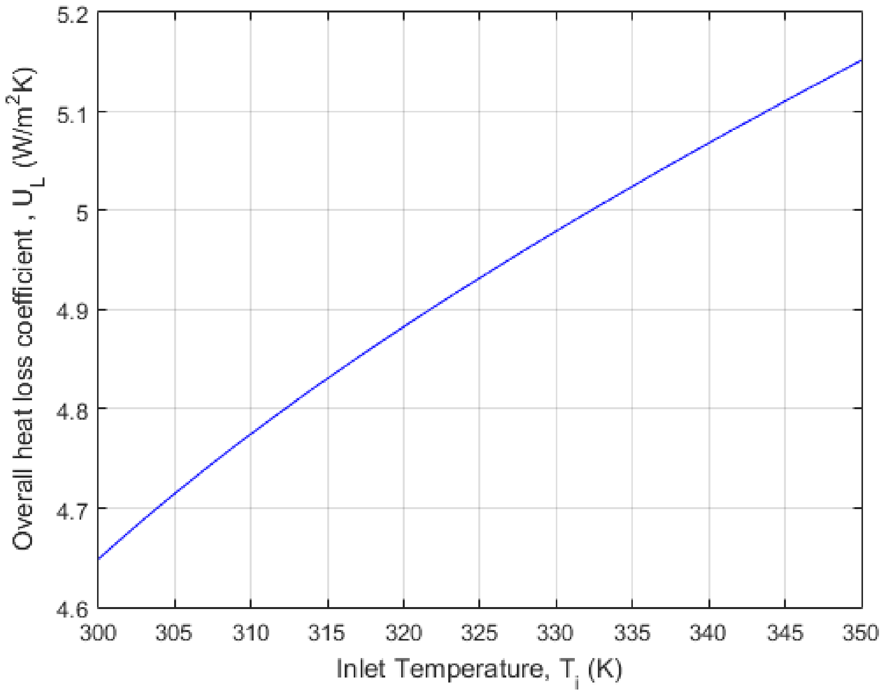

Figure 5.6: Overall heat loss coefficient (U_L) versus Inlet temperature (T_i)

5.4 Economical effect of integrating solar collector in the system

In Square Fashion Ltd. daily total required heat is calculated 285.12 GJ/day (to supply 500 tons hot water of 170°C). After integrating solar thermal collector in the system, some heat is supplied in the system from the collector and the rest is supplied by the boiler. Figure 5.7 represents the daily required heat from the boiler which is obtained by subtracting the useful heat gain of the collector from the total required heat of the industry. From Figure 5.7 it is seen that during the winter season, the required heat is around 260 to 255 GJ/day which is much higher than the required heat (around 250 GJ/day) in the middle of the year during the summer season.

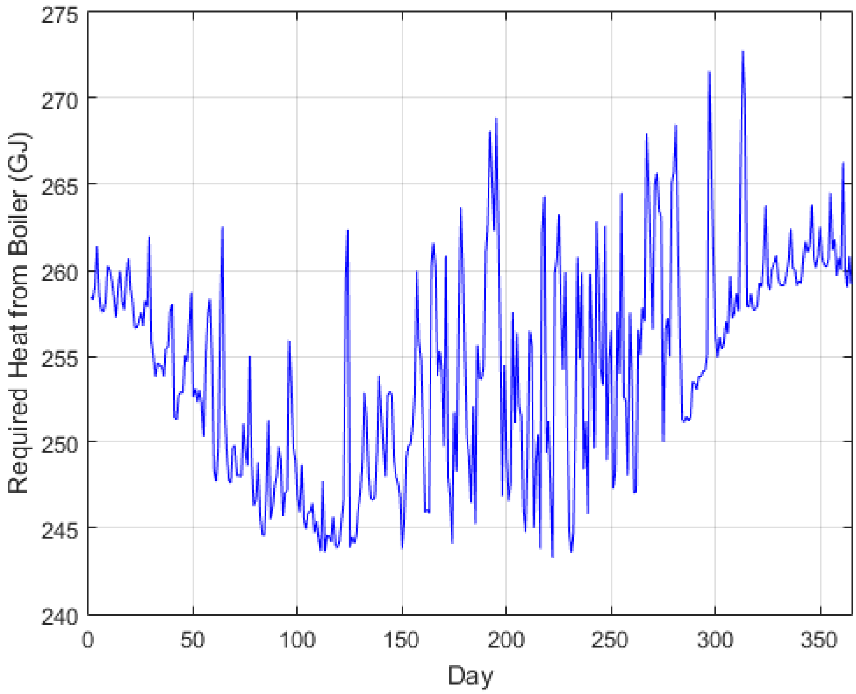

Figure 5.7: Daily required heat from boiler after integrating collector

Fig 5.8 expresses the percentage of energy saved after integrating solar collector in the system. Similar to Figure 5.7, the percentage of energy saved is much higher in the summer, up to 14.7% than the percentage of energy saved in the winter season approximately 9%.

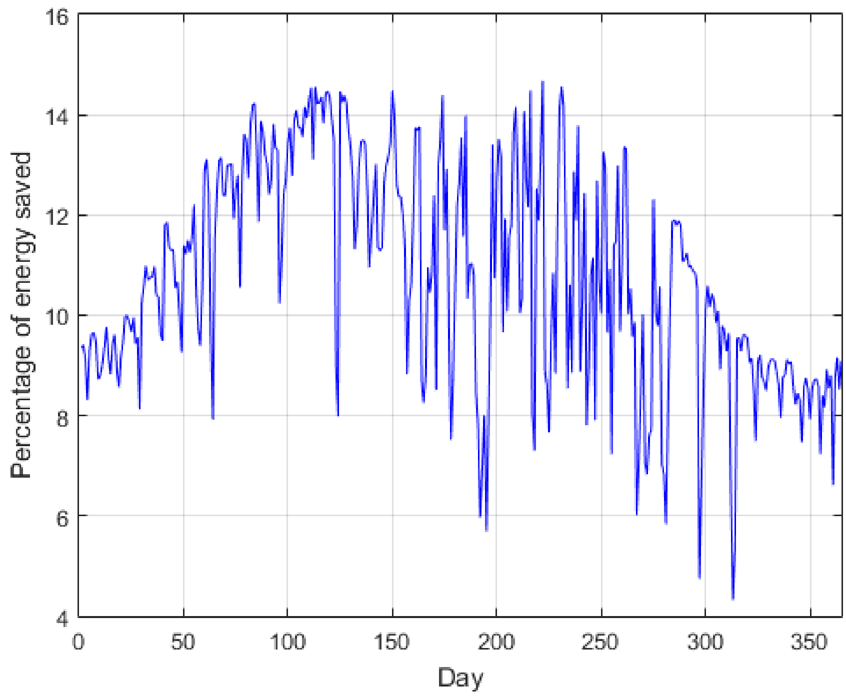

Figure 5.8: Percentage of energy saved daily after integrating collector

Natural gas is used as the fuel of the boiler. Figure 5.9 expresses the cost required per day for running the boiler considering 0.2 USD per m^3 of natural gas. During the winter season, the boiler supplies the greater portion of the required heat and thus cost for natural gas is much more (around 83 USD per day) than in summer (around 79 USD per day).

Payback period for this study has been calculated as 13.58 years. Chow et. al. [98] reported payback period of solar water heating system as 9.2 years and Hang et. al. [99] reported 4-13 years. The selected industry heats water to around 170°C but from Figure 5.5 it is observed that the exit temperature of the water supplied by solar collector is only 64°C when the inlet temperature is 20°C. Thus, most of the heat is required to be supplied by the boiler reducing the percentage of energy saved and eventually prolonging the payback period.

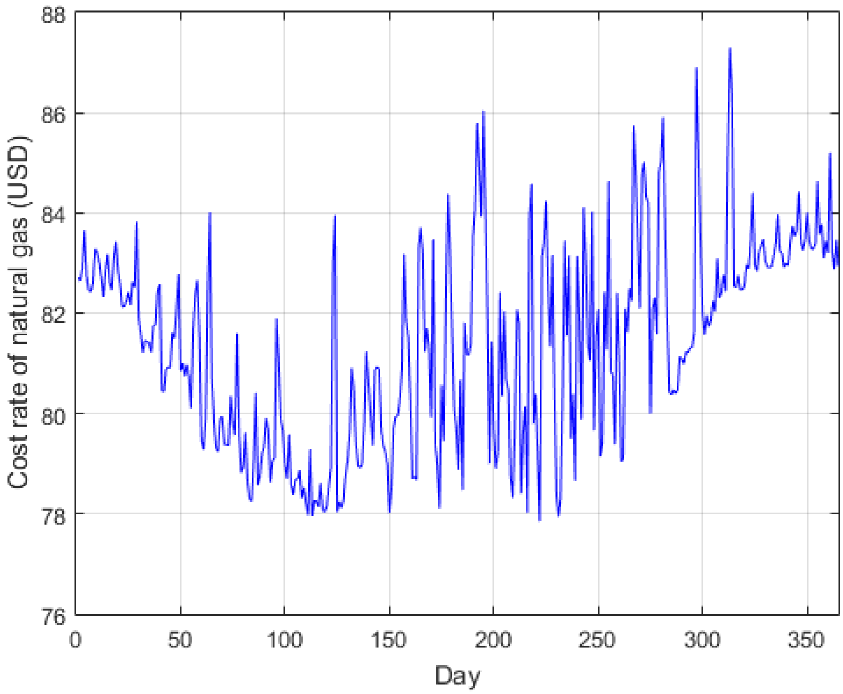

Figure 5.9: Cost rate of natural gas

5.5 Environmental impact of integrating solar collector in the system

Figure 5.10 represents the comparison of daily CO_2 emission rate with and without solar collector. Without solar collector, when the system is run by only boiler, the CO_2 emission rate is a constant value of 18.45 ton per day while integrating solar collector in the system, CO_2 emission rate reduces to the least value of 15.65 ton per day in the summer and around 16.8 ton per day in the winter.

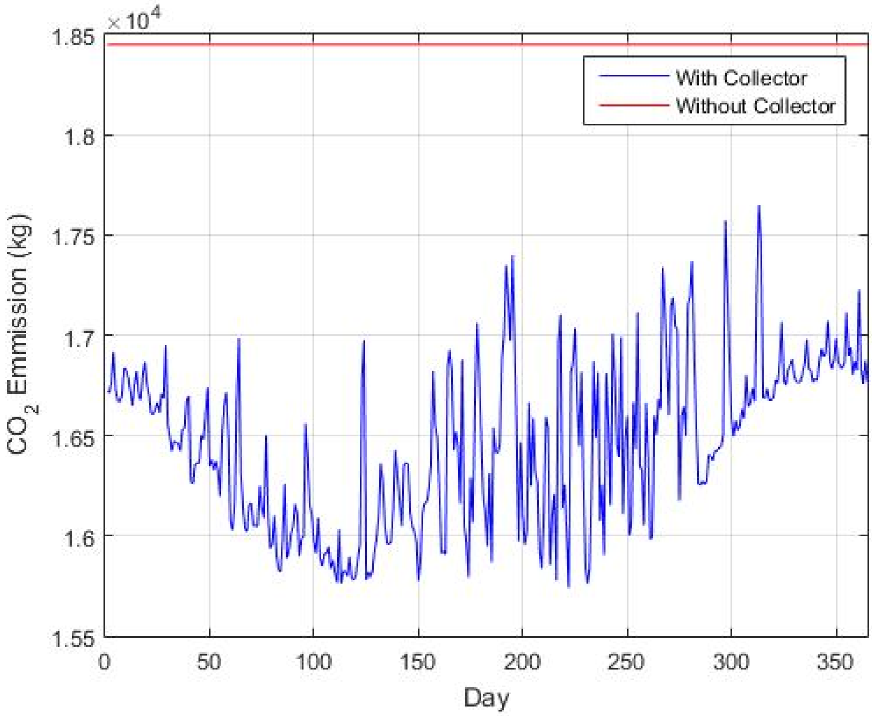

Figure 5.10: Comparison of daily CO_2 emission rate with and without solar collector

Chapter 6

Conclusion

In this study, the techno-economic and environmental feasibility of solar industrial water heating system in Bangladesh was analyzed.

In thermal analysis, the effect of collector mass flow rate and inlet temperature on exit temperature and overall heat loss coefficient was studied and following results are obtained:

• With the increase of mass flow rate up to 0.01 kg/s, exit temperature decrease rapidly. With the further increase of mass flow rate, plate temperature decreases slowly up to 0.022 kg/s and after that, plate temperature remains fixed at 303 K.

• The overall heat loss coefficient decreases rapidly with the increase of collector mass flow rate up to a certain limit. Then the overall heat loss coefficient becomes almost constant.

• Exit temperature and inlet temperature are proportional to each other.

• The relation between overall heat loss coefficient and inlet temperature is also proportional but unlike the relation between exit temperature and inlet temperature, they are not linearly dependent.

In economic analysis, the percentage of energy that is possible to save by incorporating solar water heating system was analyzed and the payback period was calculated. The results obtained are following:

• It is found that incorporating solar water heating system in selected factory can save energy up to 14.7% in the summer and approximately 9% in average in the winter which leads to reduction of cost of fuel.

• The payback period has been calculated as 13.58 years for this study. The higher mass flow rate and operating condition of the selected factory is responsible for higher payback period.

From environmental analysis it is found that Carbon dioxide emission rate can be reduced up to 14.5%.

The potential of SIPH for an industry has been explored here. The findings of this research work can help the industry leaders to make their decision towards integrating solar water heating systems in the textile industries around that location. However, this study is not sufficient to identify the solar thermal potential in Bangladesh.

Furthermore, there is a vast scope for similar studies in Bangladesh. This study only focused on flat plate thermal collectors and textile industry. Future researchers may find the potential of SIPH for different collectors and industry for different locations in Bangladesh.

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