Techno-Economic and GHG Mitigation Analyses Based on Regional and Seasonal Variations of Non-Concentrating Solar Thermal Collectors in Textile Sector of Pakistan

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Session 2018-20

Supervised by

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

I would like to wholeheartedly dedicate my thesis to my beloved parents, who have been a constant source of inspiration and strength and continuously provided their moral, spiritual, and emotional support.

Abstract

SDG implementation in the industrial sector of Pakistan is significant for its economic growth, sustainable industrialization, innovation, and sustainable production. Integration of solar thermal collectors in the textile industry will encompass sustainable development goals (SDG 7,9,12,13). Meeting these goals in the thermal sector of Pakistan is becoming increasingly challenging due to the limited resources and harmful emissions from conventional fuels. In this study, the technical feasibility of two non-concentrating collectors, Flat Plate Collector (FPC) and Evacuated Tube Collector (ETC) was investigated for the application of preheating of feedwater of boilers. Choosing the better performing collector, a comparative analysis of three fuels (coal, oil, and natural gas) has been carried out by using TRNSYS and RETScreen for economic analysis and GHG emission mitigation respectively for five different cities (Karachi, Quetta, Faisalabad, Islamabad, and Peshawar) of Pakistan. The output temperature of collectors against a setpoint of 80 ^{0}C, for these selected cities was compared to investigate the thermal performance of the system. The overall best results have been observed in Quetta. Replacement of coal has shown the highest GHG emission mitigation potential of 182,326 tonnes of CO_2 and the highest NPV for oil (1509.4 million PKR) for Quetta among the three fuels studied. Based on the results, it can be deduced that this work can be further extended to concentrating thermal technologies as well. Since real-time industrial data has been used, the insights will promote solar thermal technology in Pakistan.

Keywords: *Evacuated Tube Collector, Feasibility, GHG Mitigation, TRNSYS, RETScreen, Techno-economic analysis.*

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1. **Elia Nauroz Ali**, Rabia Liaquat*, Majid Ali, Adeel Waqas, Nadia Shahzad. "Techno-economic and GHG mitigation analyses based on regional and seasonal variations of non-concentrating solar thermal collectors in textile sector of Pakistan" *Renewable Energy Focus* (Published)

List of Abbreviations

INDC	Intended Nationally Determined Contribution
FPC	Flat Plate Collectors
ETC	Evacuated Tube Collectors
STC	Solar Thermal Collectors
GDP	Gross Domestic Product
GHGs	Greenhouse gases
GHI	Global Horizontal Irradiance
SHIP	Solar Heat for Industrial Process
LCOH	Levelized Cost of Heat
NPV	Net Present Value
IRR	Internal Rate of Return
ALCS	Annual Lifecycle Savings
LNG	Liquified Natural Gas

Chapter 1: Introduction

1.1 Overview of Research

The heavy usage of fossil fuels in the municipal and industrial sectors is causing fast increases in energy demand. Oil consumption may surpass 120 million barrels per day by 2025 as a result of increased demand [1]. This strong reliance on fossil fuels adds to air pollution, which leads to global warming [2]. Renewable energy technologies are environmentally benign and are also considered to be sustainable since they leave a smaller carbon footprint than the more commonly used fossil fuels. Solar energy may be used for both domestic and industrial applications. A multitude of factors influence the quantity of energy received from the sun, including geographical location, date, time, and, lastly, meteorological conditions. Depending on whether the sky is clear or overcast, solar radiation has different characteristics as it travels through the atmosphere [3].

Because of its potential to provide low-cost household and commercial heating, solar thermal systems have gotten a lot of interest. Because of these systems being more advanced technologically, larger set-ups tend to be more expensive, but this disadvantage is countered by improved efficiency and increased CO_2 reduction capability.

FPCs can use both direct and diffused irradiance and can be categorized as glazed and unglazed collectors depending on the application. ETCs can also use both direct and diffused irradiance. However, they are more complex in design. Heat is absorbed from the solar irradiance and changes the state of fluid to vapor and condenses back to liquid once it transfers its heat energy [4], [5]. Though FPCs have lesser efficiency, it has a simple structure, relatively cheaper and longer durability than ETC. On the other side, ETC higher efficiency and lower heat losses [4]–[6].

1.1.1 Energy Scenario in Pakistan

In Pakistan, coal consumption has quadrupled in the previous five years to 21.5 million tonnes per year to satisfy rising industrial demand and the launch of coal power production in 2018. In contrast, coal imports have surged fivefold in the previous five years, mostly for industrial reasons - around 73 percent, with the cement industry accounting for 65 percent of industrial coal usage. The relatively strong economic growth until 2018 resulted in a rise in cement manufacture, with cement output expected to climb 10-15% each year over the following decade. This equates to an extra output of 15-25 Million Tonnes (MT) per year by 2030. Coal generated 24 percent of electricity in FY21 and is predicted to climb to 31 percent by FY25 owing to contracted facilities, but then decline to 20.1 percent by FY30. According to predictions, the growth in coal usage by the power industry would be just 6 MT by 2030. Only lignite mining in Sindh Province produces financially feasible coal electricity [7].

In 2016–17, Pakistan's industrial sector accounted for about 35.77 percent of total final energy consumed, not accounting for the fuel spent in thermal power generation [8]. Several studies have found that Pakistan's industries are heavily reliant on traditional fuels to provide heat for industrial operations, resulting in greater energy costs. In spite of this, Pakistan has one of the highest annual worldwide sun radiation levels, with more than 1500 W/m2 in more than 90 percent of the country. Since then, Pakistan's economy has maintained its development pace, with a remarkable reversal of approximately 4% GDP growth rate witnessed. The vital future of is the biggest and most diverse growth in the industrial, agricultural, and service sectors. Agriculture and the industrial sector rose by 3.81 and 5.80 percent, respectively, in fiscal year 2017–18, while the service sector stayed flat at 6.43 percent. Notably, industrial sector growth increased by 5.80 percent compared to previous year's negative development.

Industrial, transportation, and building sectors in Pakistan are the most energy-consuming due to substantial energy losses, wastes in the supply lines, a lack of investment in updating outmoded technology, and overall degrading infrastructure. Low energy production not only adds to the energy crisis; it also has an impact on industrial competitiveness and the cost of doing business. In comparison to regional nations, Pakistan's industry consumes more energy (15 percent more energy than India and 25 percent more than the Philippines) per dollar of GDP. This shows that the industrial sector has a considerable potential for improving energy efficiency.

The industrial sector offers a lot of room for energy savings. As the world's greatest energy consumer, Pakistani exports may become more competitive in global markets. Only energy efficiency improvements in Pakistan's industrial sector provide about $4 billion in investment potential, with a median return of roughly 5 years.

Implementation of energy management systems, mandated energy audits conducted by professional energy auditors/managers, energy saving certificate schemes, and energy efficiency finance mechanisms are among the primary areas of intervention for energy efficiency in the industrial sector. The energy efficiency finance methods will provide impetus to the energy efficiency push while also contributing to increased exports by making export-oriented companies more productive.

According to Pakistan Energy Outlook Report 2020, final energy consumption of industries is 37%. [9]. Being an agriculture country, textile sector is one of its largest manufacturing industries and is 8th largest textile exporter in Asia. The textile industry (which consumes 27.6 percent of all industrial electricity and 40 percent of all-natural gas) has the greatest potential for efficiency gains, with a total energy saving potential of 2,150 GWh by enhancing the efficiency of compressors, heat transfer & recovery systems, lights, motors, power factor correction panels, process control, steam system optimization, and variable frequency drives ("VFDs") [10]. This sector contributes 3.4% to Pakistan’s GDP and provides 54.7% of the country’s total exports [11]. Comprising 46% of the total manufacturing sector, it accounts for 40% employment of the labour [12].

Local reserves for natural gas are under the threat of depletion and fluctuating prices of fossil fuels can lead toward energy insecurity. Rising inflation rate (9%) and need to reduce carbon foot prints to qualify for international trade, forces Pakistan’s textile industry sector to look for alternative energy sources that are reliable, sustainable and affordable [13].

Pakistan is located in southern Asia, between latitudes 23.8 and 36.78N and longitudes 61.1 and 75.88E. Pakistan has an area of around 803,940 km2, of which 97 percent is land and the remainder is surrounded by sea. Pakistan's coastline with the Arabian Sea stretches for nearly 990 kilometres [14]. Pakistan is one of the sunniest countries in the world, with significant potential for solar industrial process heating applications.

The Global Climate Risk Index report 2021 has placed Pakistan on the eighth position from fifth previously, in the list of countries most vulnerable to climate change [15]. Despite the measures taken, it still stands amongst top ten most vulnerable countries of the world. Pakistan is signatory member of The Paris Agreement [16], Pakistan has submitted the Intended Nationally Determined Contribution (INDC) which states that by 2030, 60 % of all energy produced in the country will be generated from renewable energy resources [7], [17].

1.2 Problem Statement

Pakistan regularly faces energy crisis, and the high demand of fuel from the industrial sector only aggravates it. Instead of relying completely on fossil fuels to meet their energy needs, the industry can adopt methods such as preheating water through alternate and sustainable sources such as solar. This will not only guarantee an uninterrupted supply in energy but will also help in cutting down the expenses.

In every textile industry, electricity and steam is required to carry out different process such as spinning, weaving, and processing at different temperature ranges [18] [10] [19]. It has been reported that around 70-80% of the consumption of the total energy in processing of fabric is thermal energy [21]. Many studies have been performed to analyse the potential of solar thermal energy in textile industries [22]–[25]. Solar thermal collectors can be integrated in textile industry for preheating of water for steam boiler. Preheating can be done using low temperature application solar thermal collectors which are non-concentrating such as Flat Plate Collectors (FPC) and Evacuated Tube Collectors (ETC) [26] [4], [5]. ETCs are more suitable choice for industrial use since they perform better.

1.3 Hypothesis

The techno-economic feasibility of the solar preheating system and its impact on GHG emission reduction and mitigation will be evaluated by using TRNSYS and RETScreen. The analysis has to be carried out with conventional fuels such as (natural gas, oil, and coal) with the focus on pre-heating the industrial water application. The best city will then be evaluated based on the output temperature of water against the target temperature of 80 °C from the solar thermal collector which should consequently results in higher NPV and lower payback time.

1.4 Objectives

The objectives of this study are:

1. To determine the solar thermal potential of different locations across Pakistan
2. To evaluate the collector output performance of FPC and ETC technically

3. To perform economic and GHG analyses on different fuel types against Solar Thermal Collectors (STCs)

1.5 Scope of Work

The data collected from the industry was used to determine the heat demand. Using the values of heat demand, integration of solar thermal was identified as the alternate means to mean that energy demand. The solar resource availability of the location was checked to determine preliminary feasibility. Thermal simulation was carried out using TRNSYS and economic and environmental evaluation was done using RETScreen on different fuel types such as coal, oil and natural gas.

1.6 Outline

- Introduction – Covers the current scenario of solar heating for industrial processed in the world, along with Pakistan's potential in terms of solar resources and industrial set up
- Literature Review – Reviews the current solar thermal technologies, textile industrial processes and solar resource potentials
- Methodology – Describes the thought process and investigation techniques used for this research
- Results and Discussion – Shares and elaborates on the findings of this study
- Conclusion and Future Recommendation – Outlines the key findings and possible policy changes that can be implemented in light of this study

Summary

Energy shortages and climate change are two of the key problems Pakistan is facing currently. This can be curtailed if solar thermal collectors are introduced into the existing industries in Pakistan. This will not only reduce the economic burden on the industry, it will also help the country reduce the load on it dwindling fuel supply and help in GHG mitigation.

The focus of this study is to evaluate the performance of FPC and ETC in different key locations in Pakistan. The collectors have been simulated in TRNSYS using textile industry as basis across Pakistan. Economic and GHG mitigation evaluations have been done using RETScreen.

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Chapter 2: Literature Review

2.1 Overview

Energy consumption is rapidly increasing, primarily to the heavy reliance on traditional fuels in the civic and industrial sectors. Because of rising demand, oil consumption might exceed 120 million barrels per day by 2025 [1]. This heavy reliance on fossil fuels contributes to air pollution and, as a result, global warming [2]. Renewable energy technologies are environmentally benign and are also considered to be sustainable since they leave a smaller carbon footprint than the more commonly used fossil fuels. Solar energy may be used for both domestic and industrial applications. A multitude of factors influence the quantity of energy received from the sun, including geographical location, date, time, and, lastly, meteorological conditions. When solar radiation flows through the atmosphere, its properties alter depending on whether the sky is clear or cloudy [3].

Solar thermal systems have received a lot of attention from the scientific community in recent decades because of their great efficiency and potential to provide affordable home and commercial heating [4]–[6]. Solar thermal systems are classified into small and large systems based on their size. Smaller systems can be utilized for home hot water, heating assistance, and process heat generation in residential areas or industrial activities. Larger systems are distinguished by more complicated technologies than their smaller counterparts, which are often delivered in the form of standardized packages. These systems are mostly utilized in single-family homes, with energy collected in the form of hot water in water storage tanks. Furthermore, large systems must be tailored to the consumption profile, requiring appropriate design and dimensioning. Large-scale systems are more expensive because to their greater technological level, however this drawback is offset by better efficiency and CO_2 reductions when compared to smaller systems.

The global proven coal reserves, natural gas reserves, and oil reserves all declined in 2015 considerably, but are still enough to fulfill 114 years, 52.8 years, and 50.7 years of global demand [7]. Every year, industry utilizes a considerable quantity of energy. The share of industrial energy usage varies among areas. As indicated in Fig. 2-1, the fraction of industrial energy consumption in total value exceeds 50% in areas such as Asia, Latin America, the Middle East, and OECD Asia Oceania, [8]. Process heat accounts for 50–70% of overall industrial energy consumption, with low- and medium-temperature heat accounting for 45 percent [9].

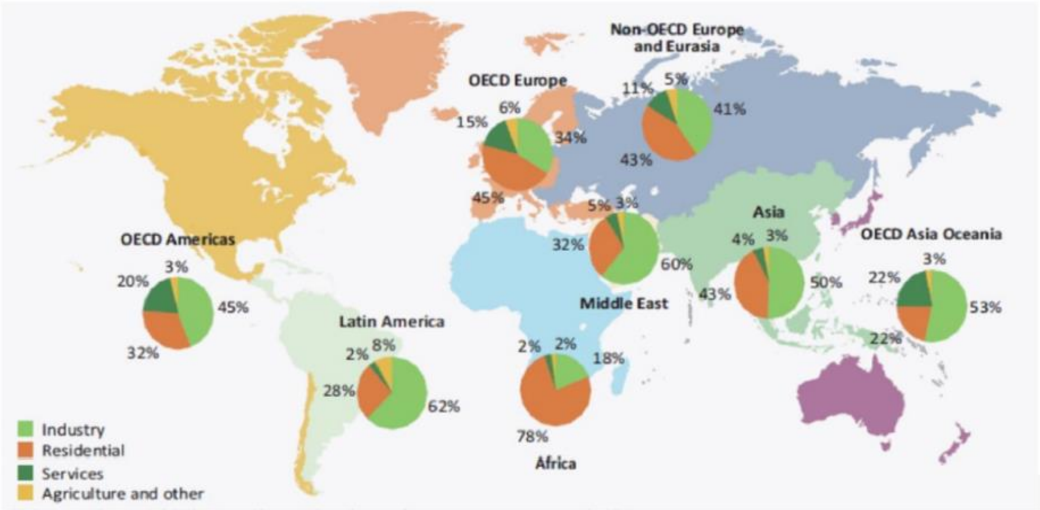

Figure 2-1 - Share of the total final energy consumption by region

By the beginning of 2015, a total installed capacity of 410.2 GWth has been reached. A total of 586.1 million square meters of collectors have been installed. In 2014, the total area of solar collectors was 6670m^2, and due to the steep reduction in worldwide crude oil prices, saw a 15.2 percent drop compared to 2013. China continued to account for the lion's share of newly installed capacity, accounting for 78.6 percent (see Fig. 2-2) [10].

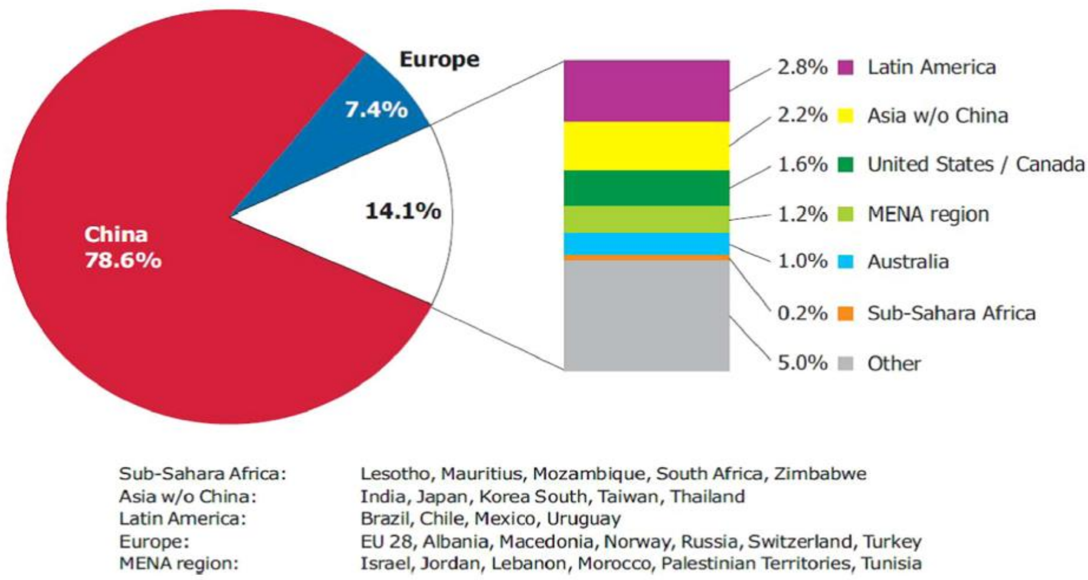

Figure 2-2 - Capacity of newly installed solar collectors in 2014

Global warming is an international challenge and needs ambitious interventions to curtail or at least limit its detrimental effects. Along with world leaders, Pakistan too, have come together to reduce GHG emissions in participating in the historic event of The Paris Agreement 2015- where the goal is to control global warming to below 2°C, compared to 1.5°C of pre-industrial levels [11]. However, in their latest document, The Emissions Gap Report 2021 of United Nations Environment Programme shows global temperature may rise to 2.7°C by the end of this century[12]. This means that in spite of our mitigation measures, we have surpassed the objective of The Paris Agreement leaving the world prone to more disastrous effects of climate change. The effect of global warming will vary for different locations, putting some countries more vulnerable and at higher risk than others.

The Global Climate Risk Index report 2021 has placed Pakistan on the eighth position from fifth previously, in the list of countries most vulnerable to climate change [13]. Despite the measures taken, it still stands amongst top ten most vulnerable countries of the world. As every signatory member of The Paris Agreement, Pakistan too has submitted its policies on how to reduce its GHG emissions in the Intended Nationally Determined Contribution (INDC). Way forward is to reduce emissions by proposing a higher percentage of renewable energy in the country´s energy mix. In the updated version of this document, Pakistan´s mitigation strategy states that by 2030, the country will ensure that the 60% of all energy it produces will be from renewable resources[14].

2.2 Solar Thermal Collectors

Solar collectors convert solar energy into thermal energy and can transmit it to either a storage vessel or directly to the application. The system can be classified as either natural or forced circulation. These systems are commonly used to provide hot water or space heating, but they may be utilized for a variety of other reasons [15]. The quantity of solar radiation that a solar thermal panel may intercept and absorb is the theoretical limit of energy efficiency. Table 2-1 includes the energy uses as well as the various types of solar collectors employed.

Solar thermal heating can be done using solar thermal collectors. The main categories of these types of collectors are presented in Table 2 below. Each of them has a specific application depending on the requirements of specific temperature ranges. As can be seen from Table 2, for our application solar thermal collectors such as flat plate collectors (FPC) and evacuated tube collector (ETC) can be used.

FPCs can use both direct and diffused irradiance and can be categorized as glazed and unglazed collectors depending on the application. In glazed type, incident solar irradiance passes through the clear cover and falls on absorber surface. It absorbs a significant amount of energy and then transfers to the fluid in the tubes. In unglazed collectors, glass layer is absent.[16]. ETCs can also use both direct and diffused irradiance. However, they are more complex in design. Heat is absorbed from the solar irradiance and changes the state of fluid to vapor and condenses back to liquid once it transfers its heat energy [17], [18]. Though FPCs have lesser efficiency, it has a simple structure, relatively cheaper and longer durability than ETC. On the other side, ETC higher efficiency and lower heat losses [17]–[19]. They are more suitable choice for industrial use since they perform better.

Table 2-1 - Solar thermal collectors used for different applications [21]

Application	Solar thermal collector type	Circulation
Solar Water Heating	• Flat-Plate Collector • Evacuated Tube Collector • Compound Parabolic Collector	Natural/Forced
Solar heating & cooling	• Flat-Plate Collector • Evacuated Tube Collector • Compound Parabolic Collector	Forced
Solar refrigeration	• Flat-Plate Collector • Evacuated Tube Collector • Compound Parabolic Collector	Forced
Industrial process heat	• Flat-Plate Collector • Evacuated Tube Collector • Compound Parabolic Collector • Parabolic Trough Collector • Linear Fresnel Collector	Forced
Solar desalination	• Flat-Plate Collector • Evacuated Tube Collector • Compound Parabolic Collector	Natural/Forced
Solar thermal power	• Parabolic Dish Collector • Heliostat Field Collector • Compound Parabolic Collector • Parabolic Trough Collector • Linear Fresnel Collector	Forced
Simultaneous generation of electricity & heat	• PV/T Collector	Forced

2.2.1 Flat-Plate Collectors

These collectors are the most extensively researched technique for producing household hot water [10]. Its principle consists of a dark surface being heated by solar radiation, converting energy to a warm or hot fluid for later use. A typical panel consists of the following components: a black surface capable of absorbing solar radiation (typically made of a conducting metal); a transparent cover capable of transmitting radiation to the absorber; internal channels containing the heat transfer fluid; a structure capable of protecting the components and holding them in place; and insulation capable of containing heat losses. To optimize solar radiation absorption, the absorber might be coated with a selective layer. Figure 2-3 depicts a schematic view.

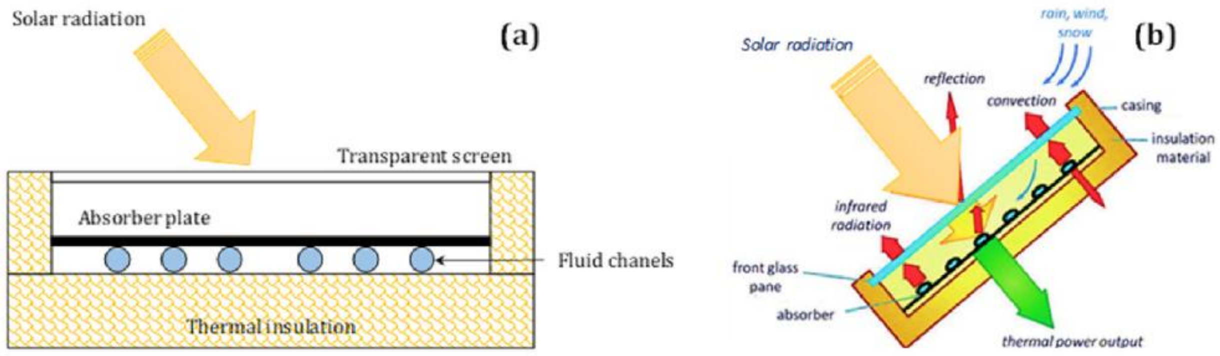

Figure 2-3 - Flat-plate thermal collector (a) Basic Schema, (b) Heat Transfer Phenomena [22]

2.2.2 Unglazed Collectors

These collectors have an absorber that is not covered by glass (see Fig. 2-4). Because they are uninsulated, these collectors are utilized where the desired temperature is less than 30 °C. Unglazed solar collectors are often composed of dark plastic that has been UV-stabilized. Because these collectors lack glass, a large portion of the solar light is absorbed. However, because these are uninsulated, a considerable portion of the collected heat is lost, especially in high winds and cold weather [21]. As a result, the efficiency of these collectors is lower. These collectors are commonly used for heating swimming pools.

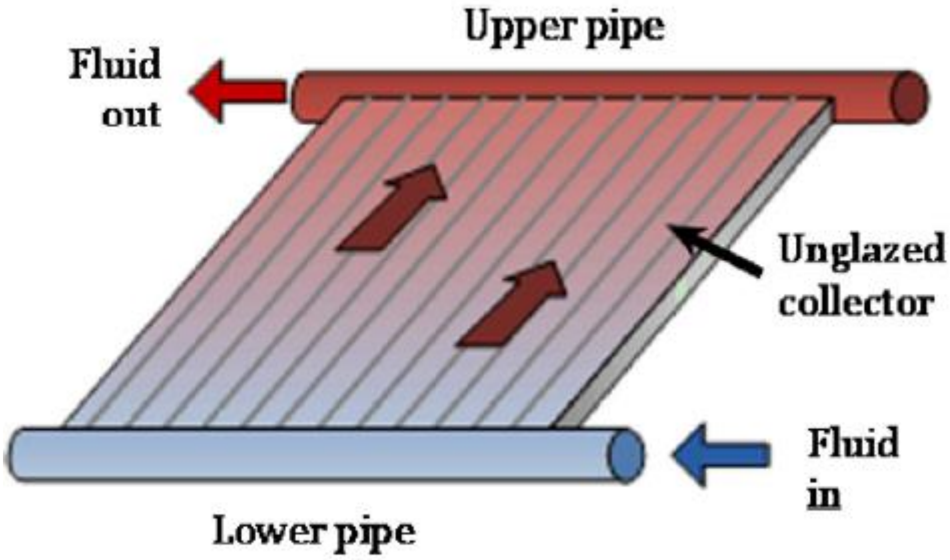

Figure 2-4 - Unglazed solar collector[23]

2.2.3 Evacuated Tube Collectors

Evacuated tube collectors are distinguished by a free-air space between the absorber and the clear cover. They are commonly employed for medium-temperature requirements ranging from 60 °C to 80 °C depending on the ambient temperature [24]. Every tube has a supplementary concentric tube that has been coated with a black selective paint that can absorb solar energy. Figure 2-5 shows a schematic illustration. There are three types of evacuated tube collectors [25], [26] (see Fig. 2-6):

1. **Water-in glass** collectors are made up of waterlogged tubes with a single end that are attached to a horizontal tank. The pipes are made up of two concentric glass tubes that are closed at one end by a vacuum in the annular space between the pipes and have a selective surface treatment on the exterior surface of the internal tube. The heat transmission mechanism is determined by the natural flow of water through the horizontal tank's single-ended entrance. Solar radiation warms the water, which gradually rises along the pipe's upper section. Warmer water is replaced with cooler water from the tank. Figure 2-6a shows a depiction.
2. In **U-Type collectors** the thermal fluid flows straight into the absorber, which is located within the tube vacuum. The plate is replaced with metal cylinders (e.g., copper), sometimes finned, and painted black on the surface; each of these tubes is put, in turn, into an outer glass tube. To achieve vacuum

conditions, air is sucked in between the two glass tubes during collector construction. As indicated in the simplified diagram of Fig. 2-6b, the various tubes are linked to one another.

3. **Heat-pipe collectors** can be outfitted with a heat-pipe system to recover heat from the absorber. Each glass tube has an extra copper pipe filled with an alcoholic solution that can evaporate at low temperatures. The alcoholic solution returns to the heat-pipe by heating up. The heat-carrying fluid that flows into the collector is then heated as it condenses. Figure 2-6c shows a schematic illustration.

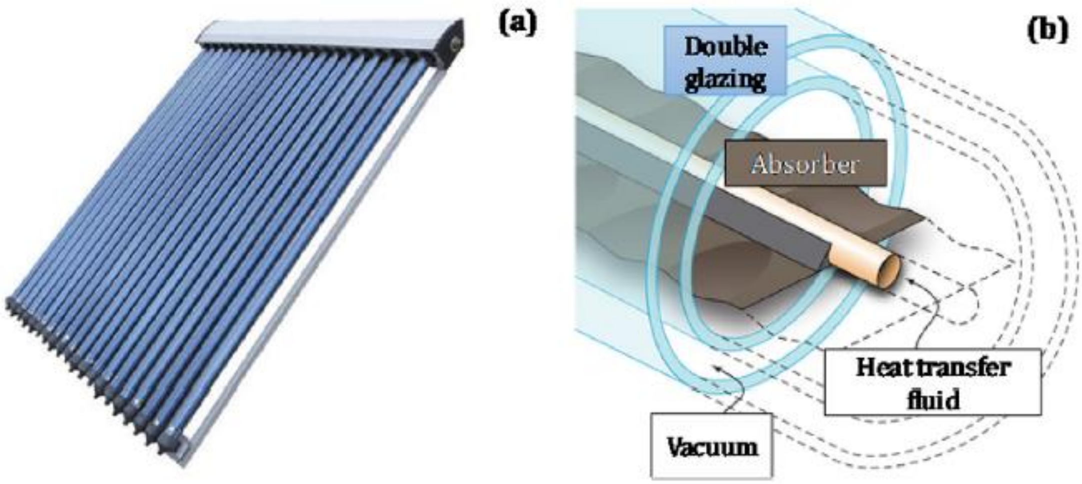

Figure 2-5 - (a) Evacuated tube collectors; (b) Schematic of a concentric tube

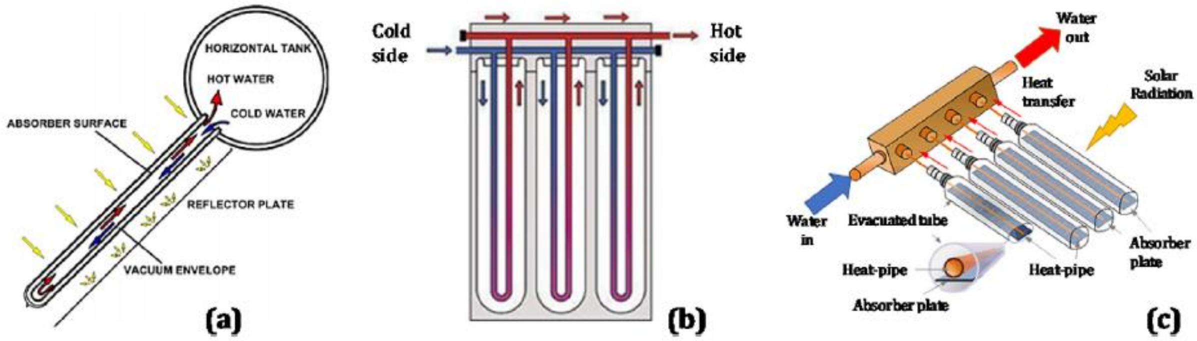

Figure 2-6 – Schematics of (a) a water-in glass collector [27], *(b) of a U-type collector and (c) of a heat-pipe collector*

2.3 Impact of Geographical Factors on Solar Thermal Performance

2.3.1 Altitude

Under a clear sky, the altitude effect is determined by wavelength, solar elevation, air turbidity, and terrain albedo. Because direct irradiance is partially altered by scattering, the global irradiance has a much less altitude impact than direct irradiance (diffuse irradiance). The effect of altitude on direct irradiance is significantly larger at smaller wavelengths than the altitude effect of global irradiance. Varied sun altitudes cause different route lengths through the layer between the two locations, resulting in varying scattering and absorption efficiency. The altitude impact is larger at low solar altitudes than at great solar elevations, resulting in a modest seasonal dependency of the altitude effect, with a greater altitude effect in winter than in summer. The altitude impact is substantially influenced by the number of aerosols and tropospheric ozone in the layer between the two locations, as well as the albedo of the topography at both sites. Because of the high natural fluctuation in the altitude effect, even in cloudless circumstances, it is required to identify the real air conditions and terrain albedo at measurement locations in order to understand the recorded altitude effect [28].

2.3.2 Humidity

Humidity is defined as the amount of moisture in the atmosphere. The scattering and absorption of solar radiation in the visible spectrum is caused in part by water vapor particles in the atmosphere. As a result, the amount of water vapor at a given place will necessarily impact the amount of solar irradiation received. It has been proven that the effect of humidity on solar irradiance is non-linear [29]. This is consistent with the non-uniform distribution and random size distribution of water vapor particles in the atmosphere. It also agrees with the non-linear fast dampening of electromagnetic radiation under water, requiring the use of Sonar signals in under-water communications.

2.3.3 Latitude

Seasonal temperatures at varying latitudes are affected by the angle of incoming solar energy. The incoming solar energy is more direct when the sun's rays strike the Earth's surface near the equator (almost perpendicular to or closer to a 90-degree angle). As a result, solar energy is concentrated across a smaller surface area, leading to greater temperatures. Higher latitudes have a narrower angle of solar radiation, causing energy to be scattered across a larger region of the surface and cooler temperatures. Because the angle of sunlight varies with latitude, average surface temperatures are greater at lower latitudes and lower at higher latitudes (even though higher latitudes have more hours of daylight during the summer months).

2.3.4 Wind Speed

Wind speed has a significant influence on the efficiency and heat dynamics of a solar thermal collector. Increased wind velocity enhances heat loss to the ambient environment, and glazing can considerably lessen its impacts. Wind velocity has a significant impact on pavement surface temperature and cumulative heat gain, and rising wind velocity causes these values to drop. The calculated correlation shows a roughly linear relationship between thermal performance and wind velocity. The thermal performance of the glazed state, however, decreases in a sharper gradient as compared to the unglazed condition [30].

2.4 Global Advancement in Solar Heat for Industrial Processes (SHIP)

Solar heat for industrial processes (SHIP) is currently a niche sector, but in recent years, a number of interesting initiatives ranging from small-scale demonstration plants to extremely large systems have been developed. Among solar heating and cooling applications, process heating has been identified as the most promising [31].

2.4.1 Solar Thermal in Different Industries

Temperatures in industrial processes range from low (100 °C) to medium (100 °C to 250 °C) to high (> 250 °C). Low- and medium-temperature operations account for a sizable portion of heat demand in the mining, food and beverage, tobacco, pulp and paper, machinery, and transportation equipment manufacturing industries. High-temperature applications account for a large portion of heat demand in the chemical, non-metallic minerals, and basic metals industries [32]. Almost all industries demand energy in some form or another. Many industrial processes, as illustrated in Table 2-3 [20], are appropriate for solar thermal technology. It suggests that solar heat has a wide range of uses in industrial operations at low and mid temperatures.

2.4.2 General Modes of SHIP

1. **Solar industrial hot water** systems require a temperature of more than 80 °C (in certain cases 100–250 °C) and dependable operation, as well as effective combination with industrial processes based on a suitable initial investment payback period.

2. **Solar industrial steam** is used mostly for cleaning, sterilization, and high-temperature dehumidification.
3. **Solar drying** can be accomplished in either a direct or indirect manner. in greenhouse-type, collector-type, and greenhouse-collector combination type drying systems.
4. **Solar seawater desalination** systems may work autonomously, without the need of steam or power, and in a clean manner without the use of fossil fuels.

2.4.3 SHIP across the World

Worldwide a number of solar heat for industrial processes (SHIP) have been implemented recently. In 2013, Chile installed a solar process heat application to provide 85% of heat energy for Gaby copper mine at a peak thermal output of 27.5 MW using FPCs covering area of 39,300 m^2 with 4000 m^3 of thermal energy storage. [33]. In 2012, USA commissioned FPCs covering area of 7804 m^2 with capacity of 5.5 MW in North Carolina for a turkey processing plant. [34].According to Jia et al, in Jinhao textile industrial park, ETCs were installed on rooftop of the factory to provide hot water where 2826t of CO_2 was reduced. In another industry in Jiangsu province, solar energy was provided to preheat cold water using ETCs over an area of 7460 $m^{2.}$ CO_2 emissions were reduced by 3100t with payback time of 6 years. [35].So far, by the April of 2016, globally only 188 SHIP applications were reported. However, according to Technology roadmap - solar heating and cooling, IEA, the potential capacity of installation of solar thermal heat processes are expected to increase worldwide by 2050 [31].

Where the world is predicted to move towards increased installations of solar thermal capacity, Pakistan, the country with abundant solar potential, higher than that of the current solar market leaders, like Germany, China, and Malaysia, have no significant studies carried out to evaluate the performance of solar thermal technology in Pakistan[36]. There is generally limited social awareness of potential of this technology, no insights into the financial assessments of system installations for both- the clients and the investors, non-existent regulatory policies, and lack of trained human capital. Though feasibility of the solar thermal collectors around the globe has been studied [37]–[42], no significant insight is available to address the lack of confidence of benefits of these collectors to the stakeholders of the textile industry in Pakistan. Therefore, essential for textile sector´s economic growth and increasingly challenging sustainability, this study has been conducted to assess the potential of harnessing solar energy through solar thermal technologies for process heating in major cities of Pakistan. Furthermore, its techno economic feasibility and its impact on GHG emission reduction and mitigation is evaluated. The analysis is carried out with conventional fuels such as (natural gas, oil, and coal) with the focus on pre heating the industrial water application. Also, LCOH is calculated for comparison among the 3 fuel types with that of solar thermal collector integrated model.

These countries with relatively lower irradiance, have significant studies carried out on solar thermal industrial applications [37]–[42], whereas Pakistan, has not pursued this technology since there is generally limited social awareness of its potential and no insights into the financial assessments of system installations which are needed for both the industries and the investors. The situation is further aggravated by non-existent regulatory policies and a lack of trained human capital in the country.

2.5 Energy Consumption in Pakistan

2.5.1 Energy Consumption in Textile Sector

Energy consumption of any sector is based on its processes. To calculate the amount of energy needed, the processes must be first briefly understood. Every industry follows some basic processes. For textile the main manufacturing processes include spinning, weaving, and processing shown in Fig. 2-16. In spinning process, yarn is converted from raw fibre using spinning mill where electricity is the major source of energy [43]. If the yarn needs to be dyed, then hot water is needed. For this process heat, thermal energy is required. Secondly, power looms or hand looms are used in weaving process where yarn is used to make fabric. Electricity is the source of energy if power looms are used. Finally, processing includes multiple processes that convert woven fabric into finished fabric or cloth. Thermal energy is used in large amounts for these processes. Typically, 80% of overall energy is used in these operations in composite mills. These processes also shown below in Table 2-5 require steam and hot water directly or indirectly are the main heat transfer media. More details on these processes are explained by Hasanbeigi et al. and Sharma et al [43], [44].

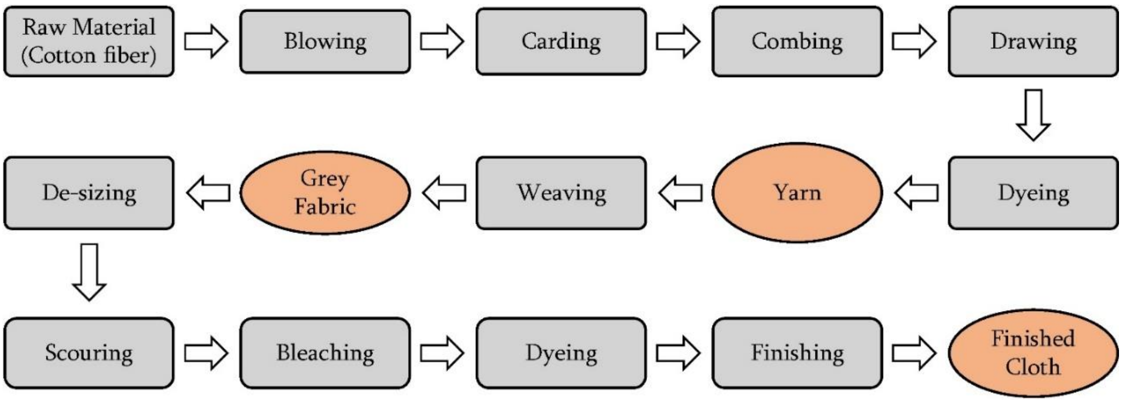

Figure 2-7 - Schematic of manufacturing process in textile industries

Table 2-2 - ***Details of installed systems in textile industries*** [45]

Process	Operating Temperature (°C)	Fuel sources used	Suitable solar collector
Sizing	60–90	Natural gas, oil, coal and other fuels	ETC
Scouring	90–110		ETC
Bleaching	90–95		ETC
Mercerizing	60–70		FPC
Dyeing	70–90		FPC
Finishing	40–100		ETC

Usually, temperature range for different processes varies in different sectors. Generally, low temperature range is below 100 °C, medium temperature ranges between 100°C - 250°C, while high temperature ranges above 250°C [35]. The process temperature ranges required for process heating are from low to intermediate range. A significant amount of energy demand in the textile industry is for process heating, most of which is required between 50-200°C [20]. According to Hasanbeigi et al., around 70-80% of the consumption of the total energy in processing of fabric is thermal energy. More details on the temperature ranges of different applications for process heating is provided in Table 1 [44]. Many studies have been performed to analyse to assess the potential of solar thermal energy in textile industries [37], [46]–[48]. As can be seen in Fig. 2-17a, integration of solar thermal collectors can be done by either direct connection of low energy requirements directly in parallel with the heating processes setup; or by using the solar thermal collectors as direct heating source for circulating fluids for example, feedwater or air preheating; or as an extra source for preheating the feedwater for steam boilers. For our study we will go for third option. i.e., feedwater solar preheating as depicted in Fig. 2-17b.

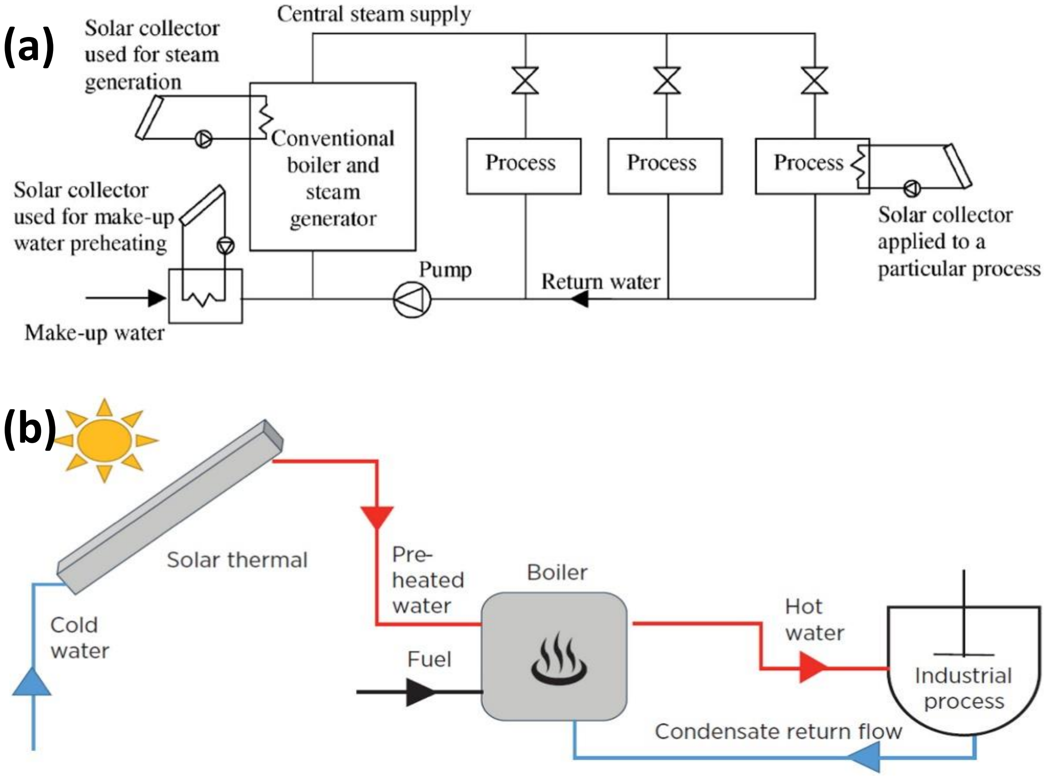

Figure 2-8 – ***(a) Possibility of combining solar system with existing heat supply, (b) Principle of solar preheating for boiler feed water*** [49]

2.5.2 System Integration with SHIP

SHIP systems are frequently classified as direct or indirect, and solar heat may also be utilized to create electricity, which in turn provides services to industrial operations [50]–[52]. Seven sample SHIP system designs are provided in IEA Task49 Integration Guideline [53], encompassing a great variety of industrial and commercial applications using liquid and gaseous (steam and air) media. Solar collectors must be integrated with traditional energy sources in a way that is consistent with the processes. SHIP systems can be connected in three methods:

1. Connecting the low temperature needs in conjunction with the existing heating operations [21]

2. As a direct heat source for a circulating fluid (e.g., feed-up water, closed-circuit return water, air preheating) [54]

3. As an extra source for pre-heating supply water for steam boilers, or as a direct integration of solar heating into fossil-fueled industrial steam boilers [54]

Furthermore, in order to allow the system to operate during periods of low irradiance and/or at night, solar heat storage, which is now extensively employed in solar systems, becomes the simplest approach to do this.

2.5.3 Solar Irradiance in Pakistan

Solar thermal collector technologies harness their energy from solar irradiance and its performance is dependent on various other parameters such as thermal load of the processes in the industry, weather conditions of the area, efficiencies of the collector technology, etc. [55]. Countries closer to equator have most of the sunlight falling on their lands hence have abundant solar resources [56]. Pakistan is one of the countries near to equator ranging yearly sum global horizontal irradiation from 1600 to 2200 kWh/m^2 and annual mean daily solar global horizontal irradiance of 5.67 kWh/m^2/day [57], as can be seen in Fig. 2-18. Land areas on the southern and western sides shows a yearly sum of direct normal irradiation above 2000 kWh/m$^{2.}$ [57].

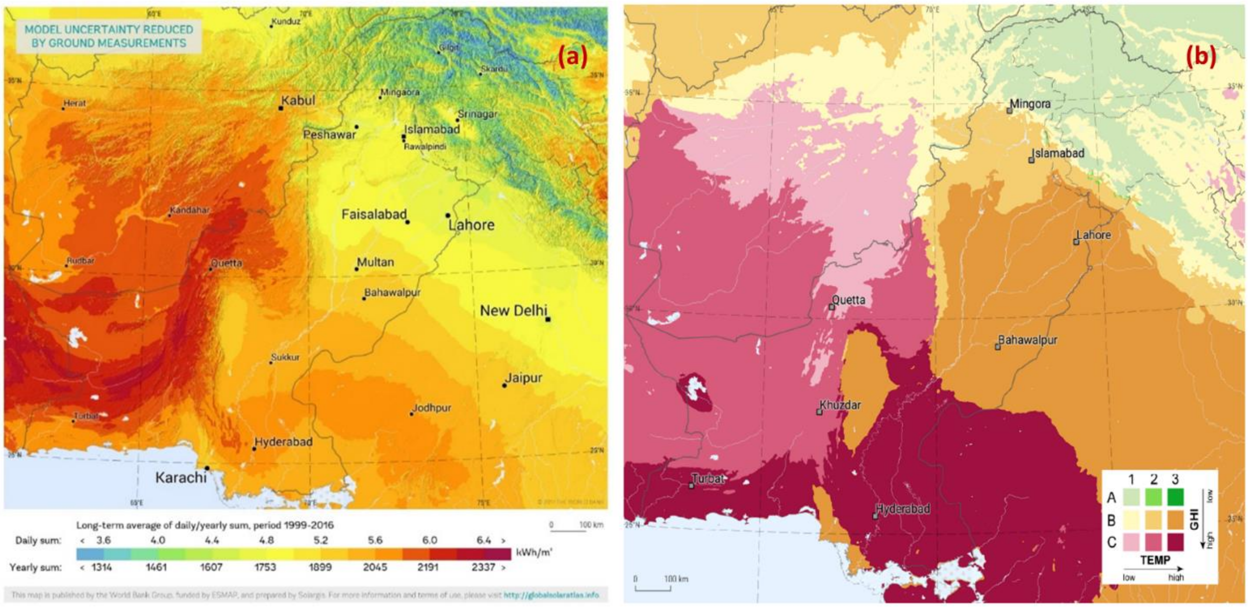

*Figure 2-9 - **(a) GHI map of Pakistan (b) Climatic zones of Pakistan based on GHI and temperature*** [57]

2.6 Simulation Tools

Because of the unpredictability of weather conditions, proper design of any thermal system requires complicated. As a result, modeling and simulation is a simple approach for simulating and forecasting the system under various weather circumstances. It may also be tuned to provide the desired results. The benefits of modeling and simulation of thermal systems are as follows [58]:

1. It eliminates the requirement for prototypes.

2. Aids in the optimization of system components. These strategies can also arrange a complicated thermal system into a simple and intelligible style.
3. Modeling and simulation approaches may also be used to estimate various parameters and analyze their sensitivity.

Modeling and simulation tools are critical for accurately describing the conduct of a given thermal system in an experiment. As a result, the initial stage in modeling any system is the construction of a structure that will be utilized to characterize it. It is necessary for the system's design and proper functioning, and it also helps in managing costs and saving energy. The proposed system, however, will differ from the actual system. There are a few downsides to these methodologies, such as a lack of control over assumptions and restricted design adaptability in the simplified analysis. If the system configuration under evaluation is non-standard, a complete computer simulation may be required.

Summary

This chapter presents the literature review of the study. It begins with the overview of the current energy scenario and the GHG impact globally. Types of solar thermal collectors are then discussed along with their working principles and their advantages & limitations. The solar heat for industrial processes is elaborated on and its importance is stressed upon. Pakistan’s energy consumption and solar resource are then explained before discussing some of the simulation tools used today for solar thermal simulation and feasibility studies.

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Chapter 3: Methodology

3.1 Selection of Textile Industry & Data Collection

The textile industry was chosen with the criteria to be based on a location with dense industrial setups. Since the technology is new in Pakistan, the results and analysis can be used for comparison to build insight into and deepen understanding of the advantages of using this technology to encourage surrounding industries to promote its adoption [1].

The textile industry selected for this was Master Textile located inside Sundar Textile Industrial. This consisted of a number of processes such as spinning, weaving, denim, drying, dyeing, finishing, and etc.

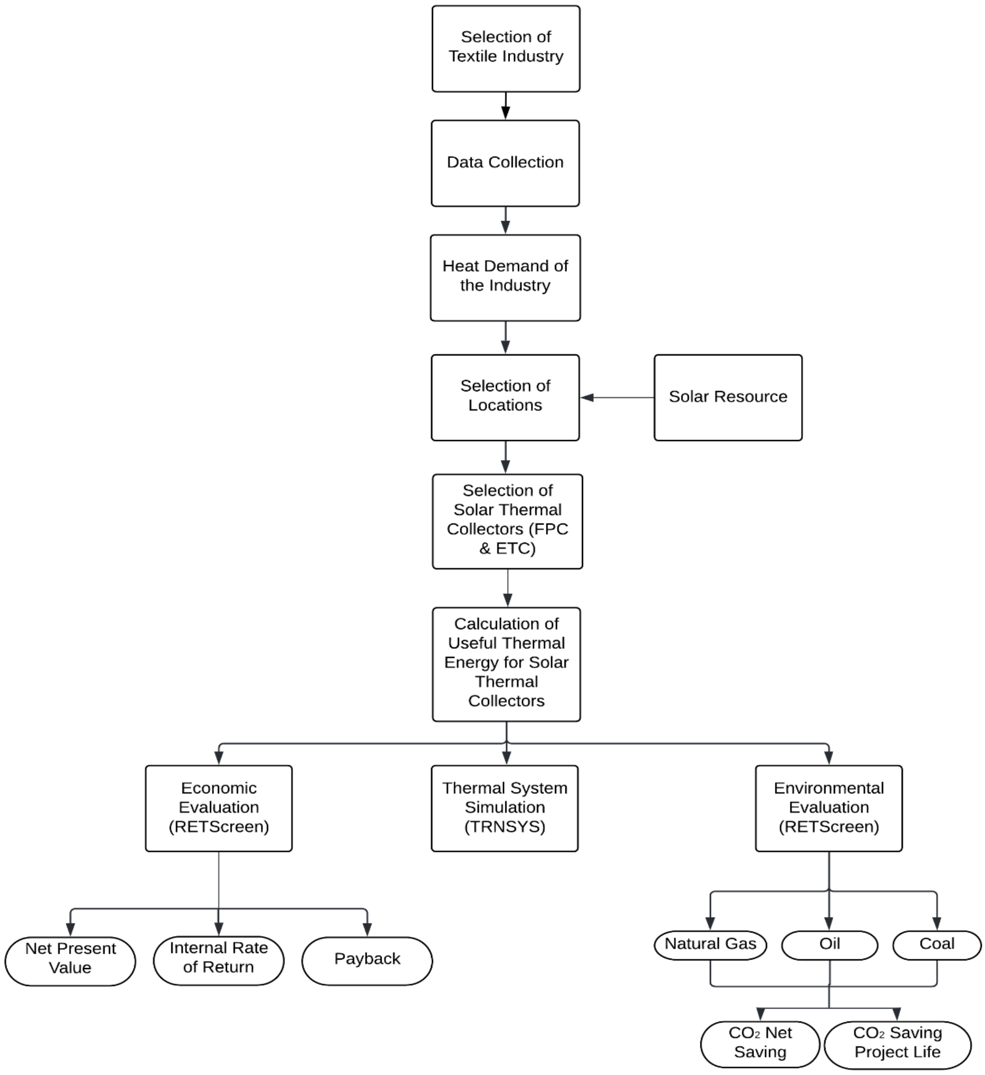

Figure 3-1 – Methodology framework of the potential of solar thermal integration in the textile industry in Pakistan

3.2 Heat Demand of the Industry

The data taken from the industry included, the daily water usage, temperature requirement of water/steam in the processes and the land area available for solar thermal collectors. This data was used to calculate the heat demand using the following equation[2]:

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

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

The production capacity was constant on an annual basis, as most of the products in the industries were exported internationally. Furthermore, the existing system in the industry consisted of a co-generation coal-fired boiler plant, where high-pressure steam was used to generate power and low-pressure steam was used for heating.

3.3 Selection of Locations

The locations were selected by keeping a few major factors in consideration. First, the cities with the highest and lowest irradiance were identified based on available data from weather stations. The cities chosen were from the south- the coast, north- the federal capital, westward and eastward, and one in between. These locations also accommodated other factors such as sea level as well as with high altitudes and in between. This could help in understanding the best and worst performance of collectors depending on the available solar radiation at the site. Fig. 3-2 shows the distribution of solar irradiance across Pakistan.

Secondly, locations selected either have industrial zones or are provincial capitals because these provincial capitals are industrial hubs. This was important because the areas near the chosen locations could also benefit from the results of the study, as the radiations falling on those areas would be similar. The insight would help the stakeholders make informed decisions to encourage them to pursue the technology.

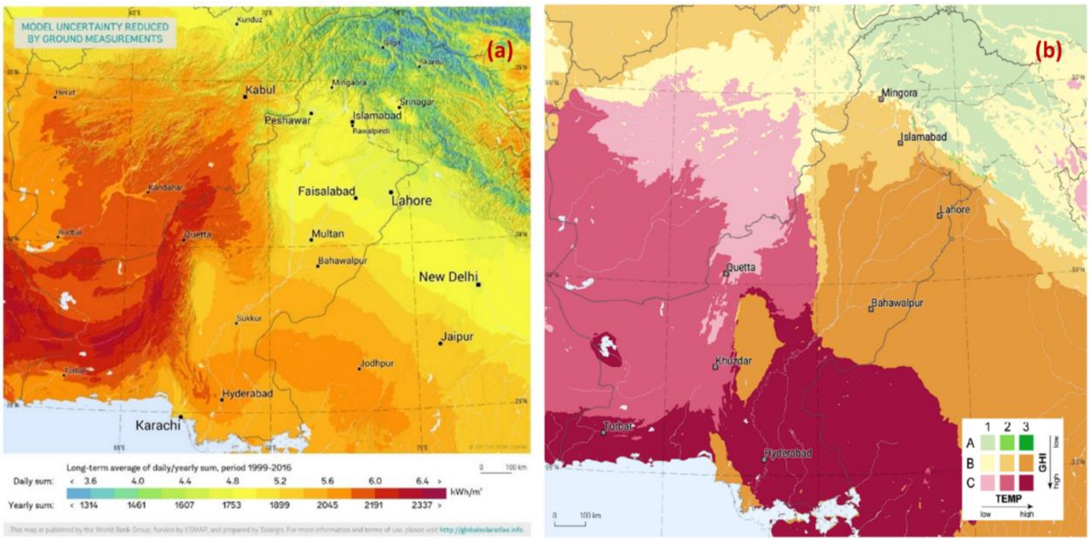

Figure 3-2 - (a) GHI map of Pakistan (b) Climatic zones of Pakistan based on GHI and temperature[3]

For our study, monthly annual solar irradiance data for Pakistan was taken from RETScreen for the selected cities. The plot in Fig. 3-3 shows the trends for available solar irradiance. It can be observed that annually the highest radiations are received in June and the lowest in December. Maximum solar irradiance for each city is available in the month of June and lowest in December [3]. For Pakistan, it was observed that solar irradiance is highest in the southern regions which are near the equator. Gradually moving towards the north, the intensity of the irradiance decreases comparatively. Balochistan which is in the southwest region receives the highest solar radiation. Quetta, which is its provincial capital, receives maximum solar irradiance of the annual average of 5.46 kWh/m^2/day. On the other side, the southeast region is Sindh province where Karachi receives high annual average irradiance of 5.34 kWh/m^2/day. On the northeast side of Punjab province, irradiance overall decreases with Faisalabad receiving high irradiance of 5.03 kWh/m^2/day and Peshawar in the northwest in Khyber Pakhtunkhwa province receiving 5.16 kWh/m^2/day of solar irradiance. Finally, the lowest irradiance is observed as we go further towards the central north where the federal capital Islamabad is situated receiving solar irradiance of 4.02 kWh/m^2/day.

These 5 major cities (Fig. 3-4) are chosen based on their positions in the north, south, east, and west as well as the highest and lowest irradiance in their regions (see

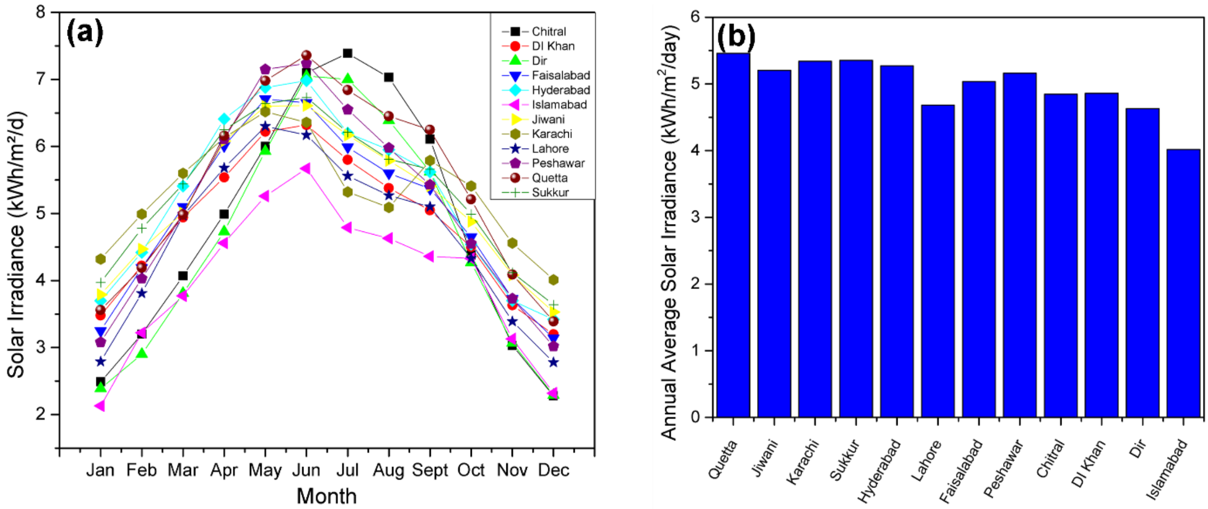

*Figure 3-3 - - **(a) Monthly solar irradiance, (b) Annual average solar irradiance***

Table 3-1) and the presence of significant industrial setups. The cities in the extreme north above Islamabad have lower irradiance and no major textile industrial setups.

Figure 3-4 - Chosen locations

3.3.1 Solar Resource

The solar resource and weather conditions used for TRNSYS were taken from the Climate One Building database, which provides hourly weather data files for selected locations. Climate One Building database contained all of the locations considered in this study and the same has been used in the simulated models [4].

The weather conditions used in the RETScreen models for the selected locations were taken from the RETScreen database itself. The annual weather data for the locations contained in the database have been tabulated in Table 3-1 [5].

Table 3-1 - Annual weather data for locations

Location	Latitude (˚N)	Longitude (˚E)	Elevation (m)	Air temperature (°C)	Relative humidity (%)	Daily solar radiation – horizontal ($kWh/m^2/d$)	Wind speed (m/s)
Chitral	36.0	71.8	4,115	-1.2	61.0	4.85	5.4
DI Khan	31.8	70.9	378	21.5	38.0	4.86	4.1
Dir	35.2	71.9	3,061	5.1	52.9	4.63	5.2
Faisalabad	31.4	73.1	186	23.8	45.0	5.03	3.3
Hyderabad	25.4	68.4	26	26.5	43.4	5.27	3.5
Islamabad	33.6	73.1	508	21.6	62.0	4.02	2.4
Jiwani	25.1	61.8	59	25.5	51.4	5.20	4.1
Karachi	24.9	67.1	22	26.1	60.8	5.34	3.5
Lahore	31.5	74.4	217	24.4	61.6	4.68	2.1
Peshawar	34.0	71.5	331	22.7	44.3	5.16	5.0
Quetta	30.3	66.9	1,621	18.0	33.7	5.46	4.5
Sukkur	27.7	68.9	51	26.2	34.3	5.35	3.9

3.4 Selection of Solar Thermal Collectors

Two types of non-concentrating collectors- ETC and FPC have been chosen since their temperature output lies in the 50-200 °C range which is required by most industrial processes[6].

Solar fraction is the percentage of total thermal load provided by solar energy. It is the ratio between the energy provided by the solar thermal collectors and the total energy required by the system. The greater the value, the more solar thermal energy can be extracted through the technologies used. However, this value varies for different technology types due to varying efficiencies.

To calculate the solar fraction and determine whether ETC or FPC will perform better in the chosen locations, the monthly percentage for January was set at 100% and the value for the rest of the month were taken to be 0% in RETScreen. This was repeated for each month, where one month's percentage of use was set at 100% and the rest were set to 0%. This was done for each city twice, once using FPC and then ETC. Once all the values for each city, technology and month were compiled, graphs were plotted to compare the performance of ETC and FPC for each city.

For ETC, Beijing Sunda Solar Energy Technology Model No. Seido 2-8 was selected for solar thermal analysis considering its better efficiency for preheating the water in the textile industry as well as its availability in Pakistan. The parameters for the chosen ETC have been listed in Table 3-2.

Table 3-2 - Values of parameters for the evacuated tube collector

Parameter	Value	Unit
Gross area per solar collector	2.03	m^2
Aperture area per solar collector	1.84	m^2
F_R (τα) coefficient	0.63	
F_R U_L coefficient	1.72	$(W/m^2)/°C$

3.4.1 Calculation of Useful Energy from Solar Thermal Collectors

Different solar thermal technologies have different efficiency due to different heat absorption capacities. The fluid inlet temperatures (T_{in}) and outlet temperature (T_{out}) of the collector are used to calculate useful thermal energy produced q_c [2].

$$q_c = P \times C_p \times (T_{out} - T_{in}) \tag{2}$$

where C_p is the specific heat of water or air (kJ/kg-K), and P is the amount of fluid.

The efficiency, η, was calculated using the process described by Suresh et al. [2]. Then thermal energy collected was estimated using:

$$Q_c = I \times t_f \times \eta \tag{3}$$

Where I is the solar irradiance per day, t_f is the tilt factor taken to be 1.1, and η is the efficiency of the collector. Solar collector area (A_c)was calculated by:

$$A_c = q_c / Q_c \tag{4}$$

3.5 Thermal System Simulation

In this study, the design and modelling of integrated solar thermal systems in existing textile industries was performed on TRNSYS. A validated TRNSYS model [7], [14] with a forced circulation water heating system depicted in Fig. 3-5 was used to run the thermal simulation on TRNSYS 17 software for a textile-based industry's preheating system at a specified site with values specified in Table 3-3. The value of 80°C as desired outlet temperature has been selected based on preheating requirements in the industry of supply water for steam boilers[15]. The collector efficiencies were calculated based on the method described by Suresh et al. [2].

Table 3-3 - Input parameters for RETScreen and TRNSYS

Parameter	Value		Unit
	RETScreen	TRNSYS	
Fluid inlet temperature	25	25	°C
Outlet temperature required at STC	80	80	°C
Working fluid	Water	Water	-
Amount of water/steam to be heated	427,060	427,060	kg/day
Specific heat capacity of water	4.18	4.18	kJ/kg C
Efficiency of FPC	N/A	0.44	-
Efficiency of ETC	-	0.55	-

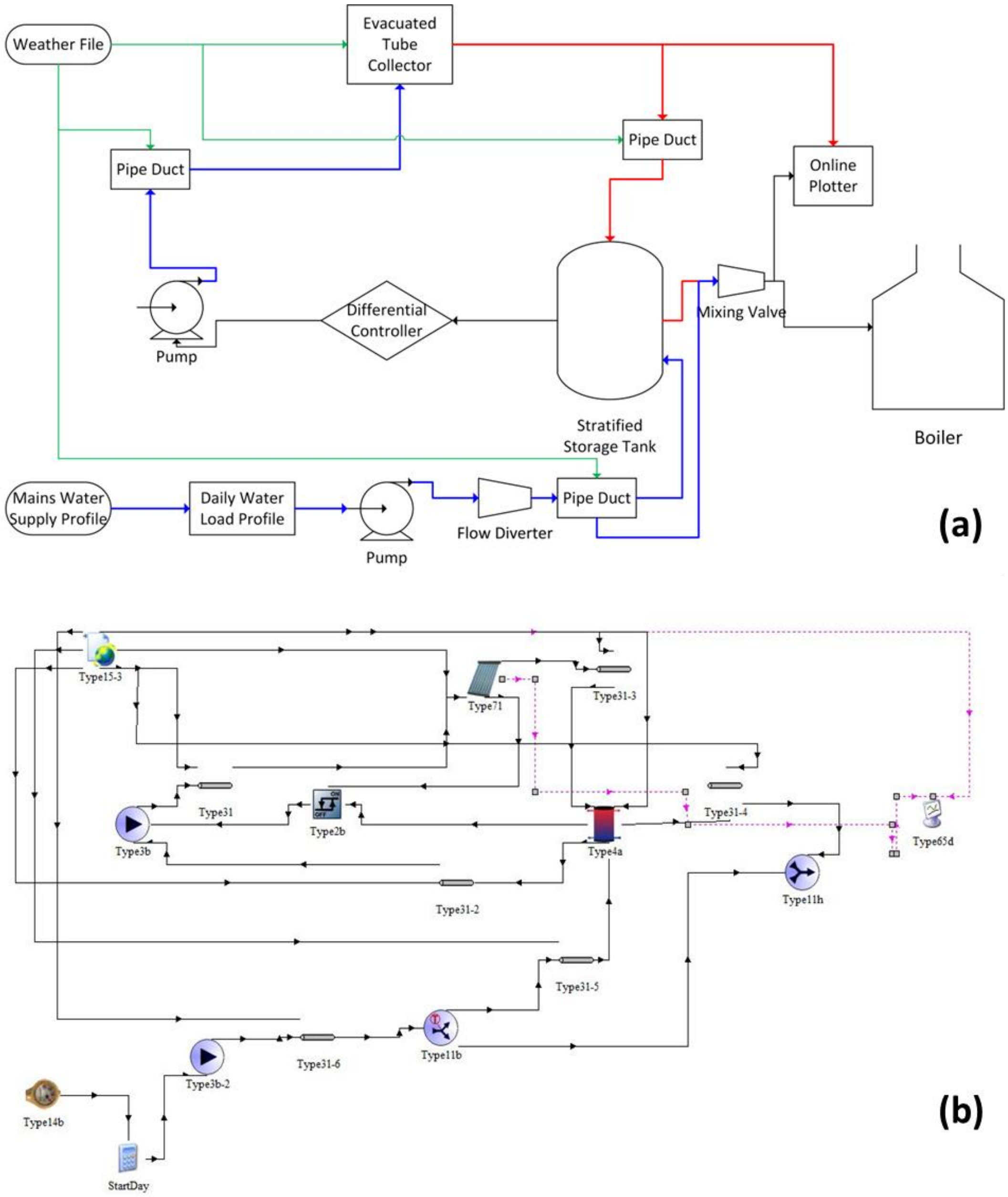

Figure 3-5 – (a)TRNSYS information flowchart of solar thermal preheating model for the textile industry (b)TRNSYS solar thermal preheating model for the textile industry

The functions of components used in the TRNSYS model are as follows [16]:

- **Type 15-3** – The weather file was used to test the model under the location's weather conditions. The data was taken from National Renewable Energy Laboratory (NREL).
- **Type 3b** – Pumps were used for the circulation of water.
- **Type 31** – Heat pipes were used to simulate weather conditions for the fluid being circulated through pipelines.
- **Type 4a** – Stratified storage tank was used for the storage of water.
- **Type 2b** – A differential controller was used to control the solar water heating process based on the water temperature in the tank and the setpoint.
- **Type 71** – Evacuated Tube Collectors was used to simulate the heat collected through an ETC module.
- **Type 11h** – Flow mixer was used to mix two different air streams to be fed into other components.
- **Type 11b** – Flow diverter was used to separate a single stream to be fed into two different components.

The main component of the TRNSYS model is the evacuated tube solar collector (Type 71). The input for ETC comes in from the weather data file of the cities. The stratified storage tank (Type 4a), is the storage vessel that is used to store water as a buffer for the ETC. Stratified storage tanks (shown in Fig. 3-7) are most commonly employed when multiple system temperatures are used within a heating system, as is the case in many homes that use a low-temperature floor heating system and a high-temperature radiator system, as well as when solar thermal systems are used. During loading and discharging, the temperature stratification in the tank is maintained by a mechanism that permits the input of warm water at strata of varying densities and temperatures, such as plates incorporated into the tank. Another technique is to employ many internal heat exchanger coils at the temperature strata level. A third way involves externally filling the strata via a filling mechanism, allowing the stratification levels to be filled or emptied using valves. [18] The differential temperature controller (Type 2b), was used to monitor the temperature of water in the storage tank, and it was programmed to switch on the inlet pump of the ETC if the temperature drops below the setpoint temperature of 80 °C. The heat pipes

(Type 31) were used in the model to simulate realistic weather conditions across the solar water heating system.

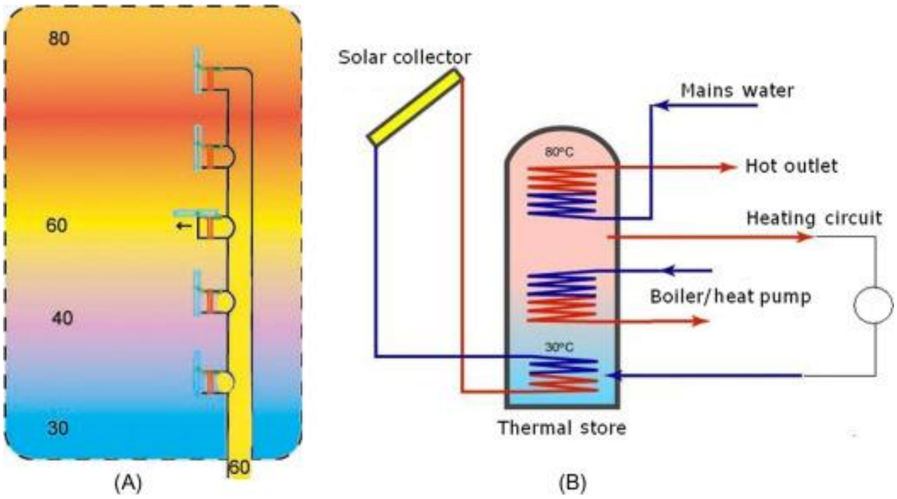

Figure 3-6 - Stratif store with valves (A) and with heat exchanger coils, solar thermal collector and boiler (B).

3.5.1 Validation of Model

This model was first discussed by Kalogirou in 2003 [11] and was then validated by Ayompe et al. in 2011 [8]. It was later adopted in a study by Shrivastava et al. in 2017 where the same model was used [12]. Furthermore, Mehmood et al. has also used this model and combined it with an auxiliary heater in their study in 2019 [7].

However, in this study, the emphasis was not on the model but on the unique results it discovered that were not explored earlier. Firstly, the validated model was used, to have an accepted model to explore the installation of solar thermal systems to study the techno-economic feasibility, which is the first step towards a nationwide acceptance and integration of this system otherwise the system may be so costly that the application in industries in multiple cities would not be practical. Secondly, we have used this validated model for the application of pre-heating of feedwater for textile industries and the results provide an insight into the comparative analysis of 3 fuel types in 5 major industrial cities of Pakistan. This was important to identify how each fuel type would affect the cost which is a significant concern for investors.

3.6 Economic Evaluation

The economic feasibility of the project was investigated in terms of NPV, IRR, and Payback period by using RETScreen software. Positive NPV value, short payback time, and high IRR indicate the economic viability of any system [5]. All the economic assumptions are summarized in Table 3-4 below.

Table 3-4 - Economic input parameters for RETScreen

Parameter	Value
Fuel rate coal	PKR 33,997 per tonne [13]
Fuel rate natural gas	PKR 1054 per MMBtu[14]
Fuel rate oil	PKR 83.64 per liter [15]
Inflation rate	9%[16]
Discount rate	10%[17]
Project life	20[17]
Cost of ETC	$ 460 [17]

3.7 Environmental Evaluation

Using RETScreen, net GHG reduction in tCO_2 per year and for the project life of the collectors is estimated as a function of:

a) Natural Gas
b) Coal
c) Oil

Summary

The methodology of the study has been discussed in detail in this chapter. The parameters and calculations used in TRNSYS and RETScreen has been shown. Types of collectors i.e., ETC and FPC, their performance comparison has also been discussed. Furthermore, the chosen locations, their solar resource potentials and their industrial importance has been discussed to justify their selections.

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Chapter 4: Results and Discussion

4.1 Thermal System Evaluation

To identify which technology type shall perform better between FPC, and ETC, the annual solar fraction has been determined and plotted. Monthly annual useful energy harnessed in the industry using ETC has been plotted for chosen cities, which is depicted in Fig. 4-1 (f). According to a previous study, the useful thermal energy delivered from the solar collector is the function of the solar fraction of the system [1]. Each city´s useful energy harnessed shown in Fig. 4-1 (f) shows the solar fraction trends in Fig 4-1 (a-e).

The solar fraction ranges from 40-70 % in all the cities except for Islamabad where the range is from 20-60 % since it receives the lowest solar irradiance. In each plot, ETC performs better than FPC because of its higher efficiency and lower convective and radiative losses [2]. According to the performance of both the collectors is affected by the ambient condition and solar irradiance but the yearly energy gain in ETC is 30% higher and 41% better than FPC[3]. Based on our results and numerous previous studies ETC was selected as suggested in those studies for thermal applications [2], [4]–[7].

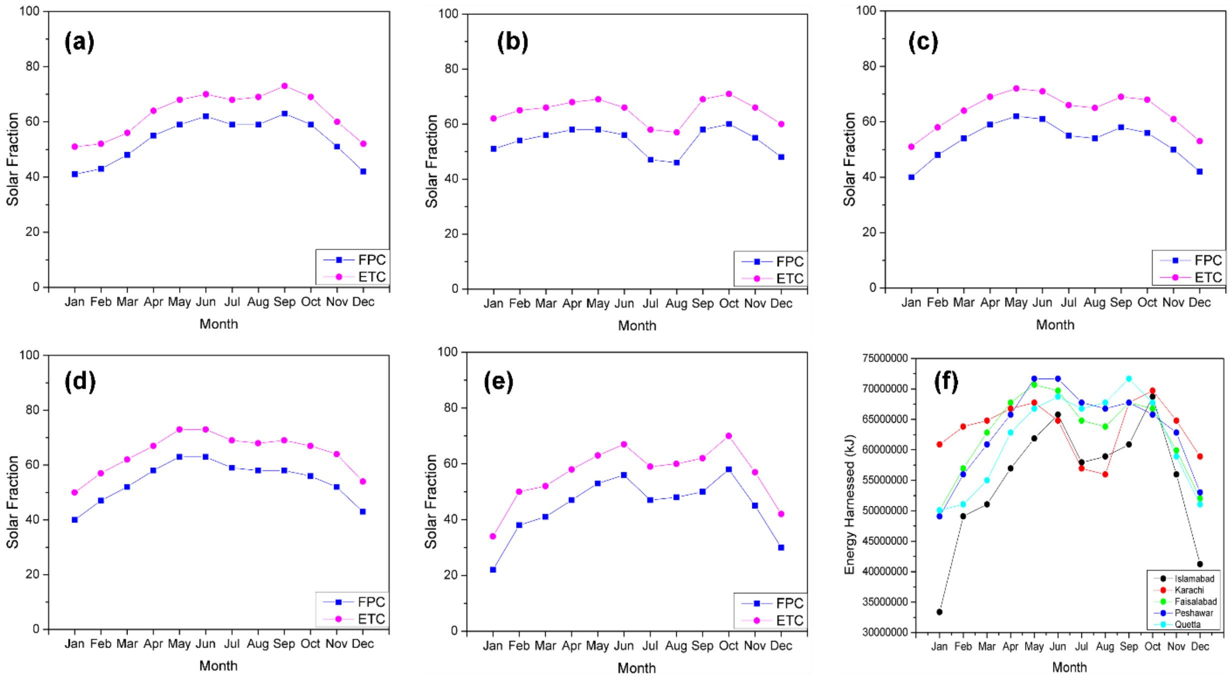

Figure 4-1 - Monthly solar fractions (a) Quetta (b) Karachi (c) Faisalabad (d) Peshawar (e) Islamabad (f) Energy harnessed annually from ETC

The output temperature that can be obtained by using ETC for a whole year of all the chosen cities has been presented in Fig. 4-3 (a-e) from the simulated data taken from TRNSYS 17. It can be observed from the figure that the annual output temperature of the collector in Quetta shows the best overall performance. The temperature range lies approximately between 175-200 °C. This is because it is at the highest elevation of 1621m in comparison with the other four cities, hence receiving the most radiation [8] (see Table 1). Moreover, this location has a relatively lower air temperature of 18°C and a higher wind speed of 4.5 m/s causing continuous cooling of collectors which leads to collector's better performance. The percentage of humidity shows the presence of water vapor in the atmosphere. Water vapor absorbs solar radiation reaching the collector. Lower the humidity percentage, better the performance of collectors [9], [10]. Quetta has the lowest relative humidity of 33.7%. As a result, more radiations reach the collector's surface. All these conditions make this city the best performing location for the installation of solar thermal collectors, hence yielding the best results (see Fig. 4-2).

Karachi is a coastal region with a moderate temperature range of 175-200 °C throughout the year. Extreme temperature differences between summer and winter are not observed here due to the presence of a large water body- the Arabian sea. Hence, unlike other cities in comparison, the collector in Karachi performs better during the winter months as well. But its performance drops significantly during the monsoon months i.e., July-August because of heavy rainfall and lesser solar radiations reaching the collectors [11]. This city still receives high solar radiation since it is closest to the equator as compared to other cities [12].

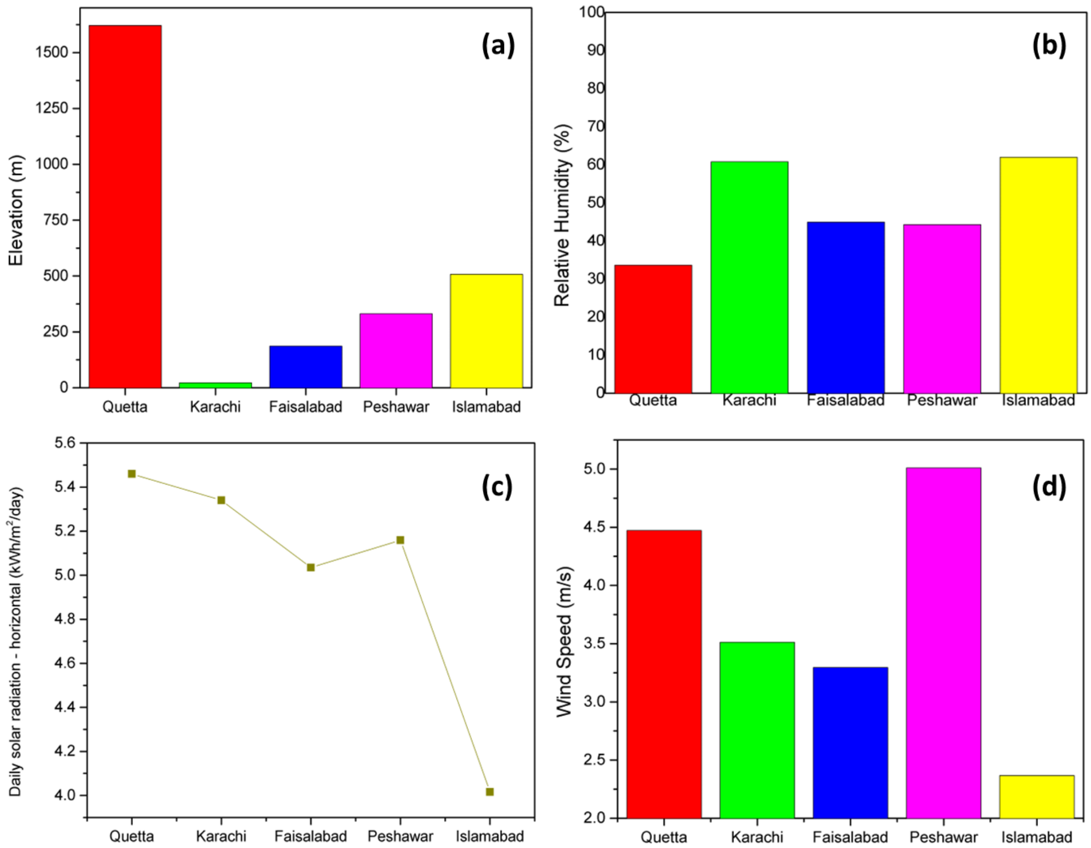

Figure 4-2 - Geographical parameters of chosen locations (a) Elevation (b) Relative Humidity (c) Daily solar radiation (d) Wind speed

The trends in collector output temperature patterns in Peshawar, Islamabad, and Faisalabad follow almost the same pattern with lower temperature outputs in winter months (Dec-Jan) months and higher temperature ranges in summer months (May-Jun). Faisalabad and Peshawar have approximately similar external conditions in air temperature and relative humidity. The differences are in their windspeeds and elevation levels. Where Faisalabad has a lower windspeed of 3.3m/s and a lower elevation level of 186m, Peshawar has a higher wind speed value of 5.0 m/s and a higher elevation level of 331m.

Islamabad relatively shows overall poor performance. It has the lowest wind speed of 2.4 m/s, receives the lowest daily solar radiation of 4.02 kWh/m²/d, and has the highest relative humidity of 62 %. All these conditions explain its relatively poor performance in the output temperature of the collectors.

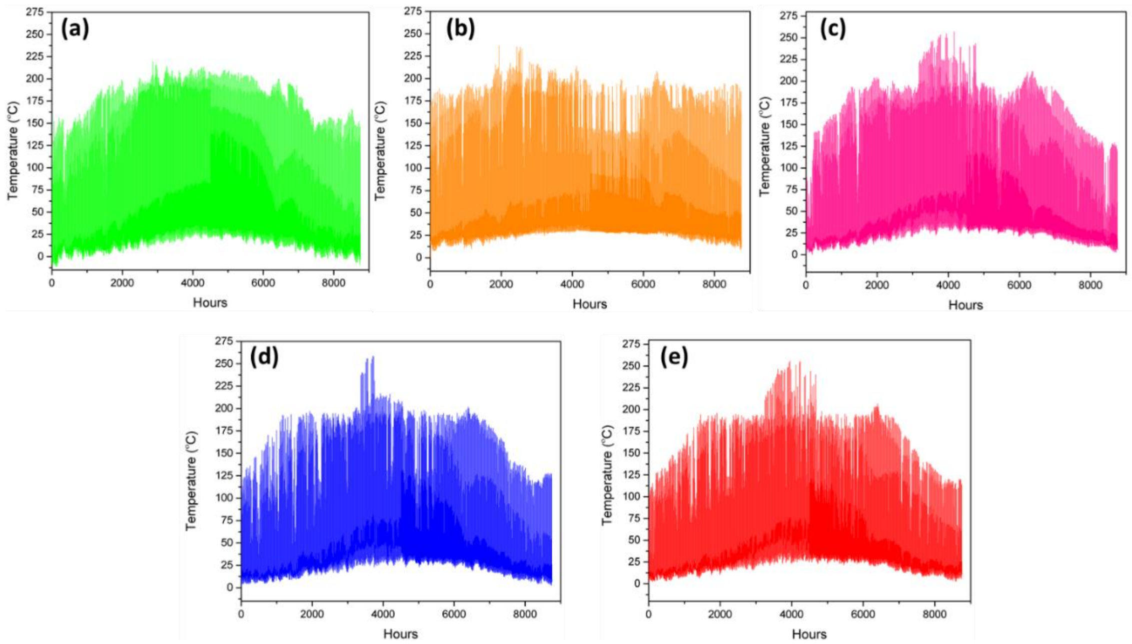

Figure 4-3 – Collector Output Temperatures for (a)Quetta, (b) Karachi, (c) Faisalabad, (d) Peshawar, (e) Islamabad

One-day performance of the of ETCs in the 5 chosen cities on the longest day (June 21st) and shortest day (Dec 21st) is shown in Fig. 4-4. The objective of studying the performance of the collector on these two days is to show the hourly collector temperature output in all the chosen cities. This will assist the industries to make an informed decision on the scheduling of the time of their auxiliary sources needed.

June 21st is the longest day of the year and a summer day in Pakistan, it was observed that in all the cities, the collector starts heating up after 7 A.M., reaching the highest temperature at around 2 P.M. The performance gradually starts dropping till 6 P.M. and by 8 P.M., the collector output temperature completely drops. Islamabad yields the highest output temperature, followed closely by Faisalabad, Karachi, Quetta, and lastly Peshawar with a peak output of 130 °C. The output results can be seen for a summer day in Fig. 4-4 (a) where ETCs perform efficiently irrespective of the location.

December 21st is the shortest day of the year and a winter day in Pakistan is shown in Fig. 4-4 (b). The plot shows that in all the cities, the collector starts heating up after 9 A.M. The peak is at 2 P.M. and after 4 P.M. the temperature completely drops after 6 P.M. Karachi outperforms the rest of the locations by significant margins with the peak output of 190 °C, followed by Quetta at 160 °C, then Peshawar, Islamabad, and Faisalabad.

From the analysis above, it is shown that in Pakistan, the collector can perform for longer hours in summers as compared to winters. More fuel can be saved during summers than in winters. However, the output temperature of collectors exceeds the 80°C margins for both winters and summers making ETCs good for our application in this study. However, these are temperatures of the fluid at the collector outlet which will be stored in the storage tank before going to the boiler [13]. It must be noted that system losses such as in the storage tank, etc., and collector field losses such as collector end losses, etc. are neglected in the simulations which are very important to be considered [14].

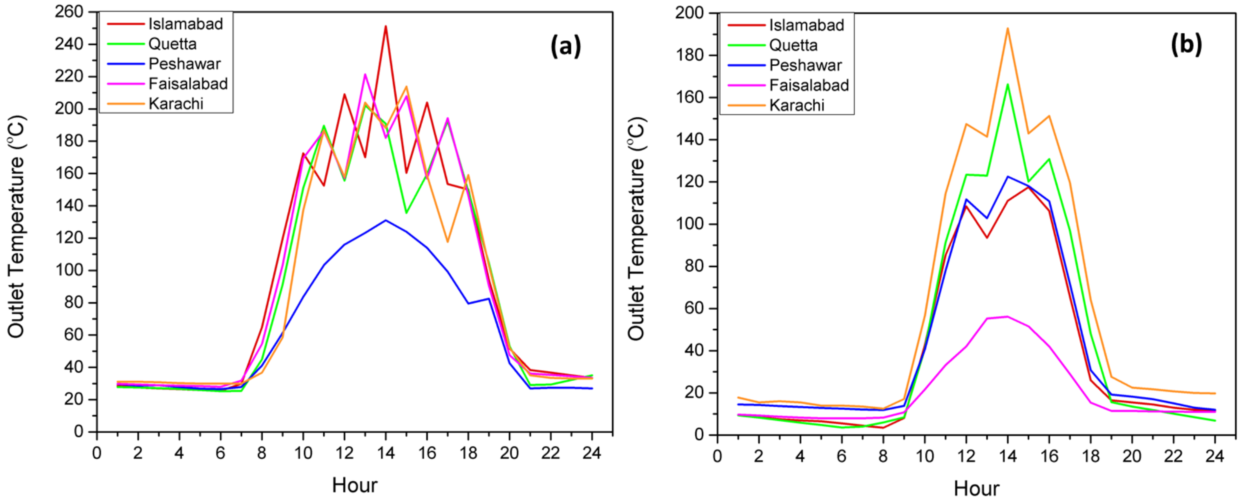

Figure 4-4 - Performance of TRNSYS model for ETC on (a) 21st June (b) 21st December

4.2 System Optimization

Since useful energy harnessed from the solar thermal collector for the same load varies with each location due to the different solar irradiance received, each location will have its optimal design for the system. Optimization is also very important because installation of the system is very costly and choosing the design with the highest savings in minimum cost is necessary from the investors' perspectives [14]. This was carried out by varying the area of the solar thermal collectors and by observing its effects on the Annual Life Cycle Saving (ALCS) for the duration of the project life i.e., 20 years, and the system size with a suitable point around the highest slope on the curve was taken as the optimized system size for further calculations[15], [16]. For the optimized systems, solar fractions of each location against fuel type are listed in Table 4-1.

Table 4-1 - Optimized solar fractions of each location against fuel type

City	Oil	Gas	Coal
Quetta	92%	30%	79%
Islamabad	63%	8%	53%
Faisalabad	88%	11%	73%
Karachi	83%	22%	78%
Peshawar	86%	21%	75%

For each location, all 3 types of fuels were considered. Fig. 4-5 shows the optimization curves for all 5 selected locations for a solar thermal system that has been integrated with oil, coal, or natural gas as the backup fuel. The optimized values of solar thermal collector area and its subsequent ALCS in million PKR are tabulated in Table 4-2.

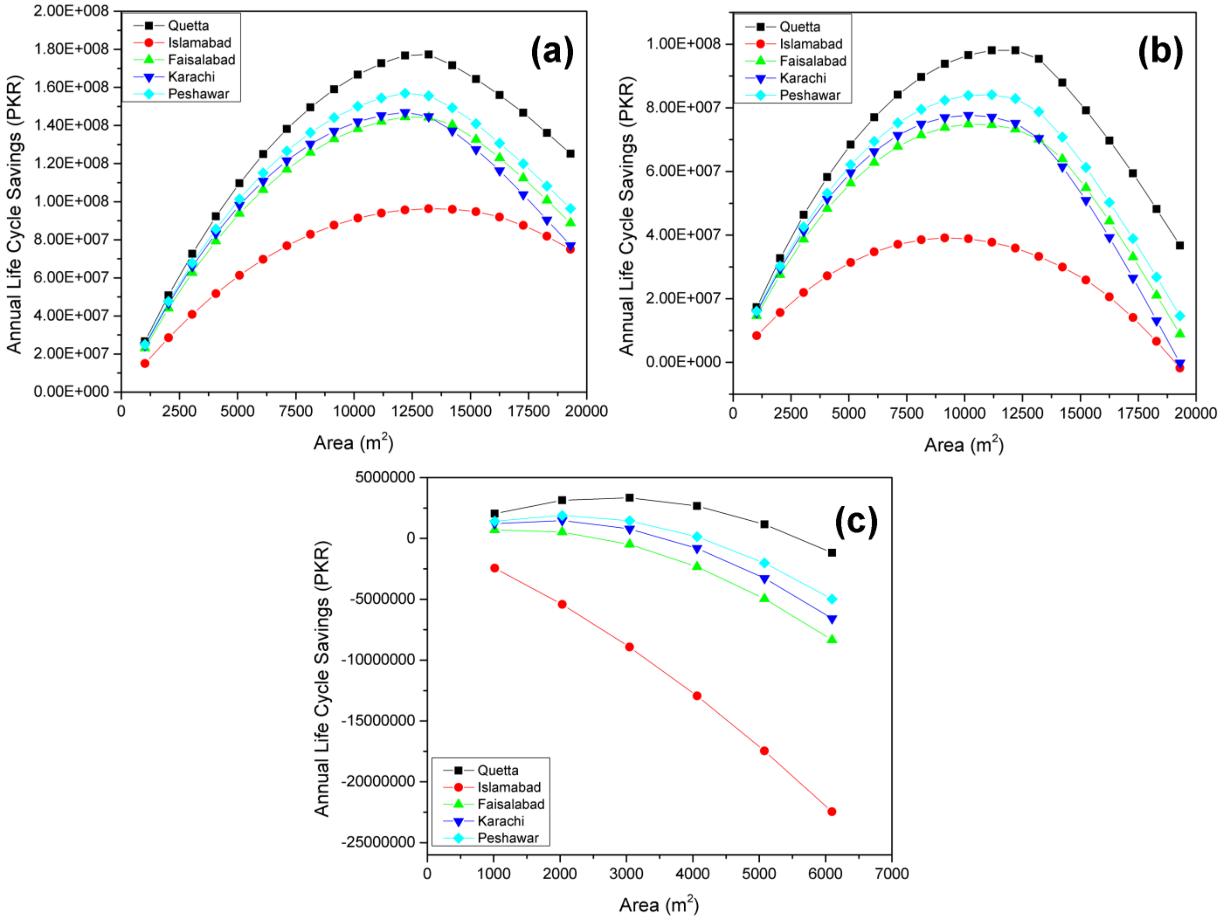

Figure 4-5 - Optimization for XYZ industry using ETC for (a) Oil (b) Coal (c) Natural Gas

Oil is the most expensive fuel out of the three fuels, resulting in the largest collector areas and the highest ALCS. This is followed by coal which too results in moderate life cycle savings. The advantage of integrating solar thermal collectors with this fuel type is its highest impact on GHG emission mitigation reduction. Lastly, natural gas is the least expensive fuel and from the optimized values of the area, it can be inferred that replacing it with solar thermal collectors may not be feasible in most cases. However, natural gas depletion is forecasted for Pakistan due to which switching to alternative energy options will be necessary. Though opting for solar thermal collectors may not be feasible with the current prices of natural gas, it may not be the case in the future [17]. In such a case, integrating solar thermal collectors can become a viable solution to the thermal energy shortages in the industry.

Table 4-2 - Optimized area for each city using each fuel type against ALCS

Fuel	City	Area (m^2)	Annual Life Cycle Savings (Million PKR)
Oil	Quetta	13208	177.29
	Islamabad	10160	91.35
	Faisalabad	12192	144.48
	Karachi	10160	142.06
	Peshawar	11176	154.49
Coal	Quetta	10160	96.59
	Islamabad	8120	38.52
	Faisalabad	9144	73.81
	Karachi	9144	77.01
	Peshawar	9144	82.40
Natural Gas	Quetta	3048	3.34
	Islamabad	0	0.00
	Faisalabad	1016	0.70
	Karachi	2032	1.48
	Peshawar	2032	1.89

4.3 Economic Evaluation

Based on the above-optimized design, economic analysis has been carried out on indicators IRR, NPV, and payback using RETScreen. In the case of replacement of oil, coal, and gas-fired boilers with solar thermal (ETC), the earliest payback was observed in the case of oil-fired boilers followed by coal-fired and then natural gas-fired. The payback of around 6 years is observed in oil and 7 years for coal for Quetta, Peshawar, Karachi, and Faisalabad. However, Islamabad takes longer, i.e.,9 years and 8.7 years for oil and coal respectively. The use of natural gas gives payback of around 10 years and longer for all cities making it unfeasible for integrating solar thermal collector technologies. NPV is positive overall for all cases except for Islamabad with natural gas. Islamabad has the lowest solar irradiance receiving which makes the use of solar thermal collector technologies least viable economically. The results are shown below in Table 4-3 and Fig. 4-6. Hence oil overall can be seen to be the most economically feasible fuel to be replaced by solar thermal (ETC), followed by coal. Natural gas may not be economically feasible to be replaced due to its low costs and higher efficiencies. Therefore, NPV for natural gas for Islamabad can be seen to be negative, proving that replacing it with solar thermal in this location is not feasible now. However, as per the trend forecasted for depleting natural gas in Pakistan's Energy Outlook 2020 by the Petroleum Institute of Pakistan, the natural gas reserves in the country are rapidly dwindling. In the future, the supplies will be covered through either unconventional domestic resources or imported LNG. Either of which will be much more expensive than the currently available natural gas [17].

Table 4-3 - IRR, Equity Payback, and NPV results for the selected cities against 3 fuel types

City	Fuel	IRR (%)	Payback (years)	Net Present Value (PKR)
Quetta	Oil	19.9%	6.3	1,509,387,555
	Gas	11.0%	10.3	28,444,938
	Coal	17.4%	7.2	822,326,765
Peshawar	Oil	20.2%	6.3	1,315,284,319
	Gas	10.8%	10.4	16,083,436
	Coal	17.1%	7.3	701,511,557
Karachi	Oil	20.3%	6.2	1,209,457,518
	Gas	10.7%	10.5	12,578,934
	Coal	16.7%	7.5	655,602,597
Islamabad	Oil	13.3%	9.0	335,674,385
	Gas	7.6%	12.6	-20,783,538
	Coal	14.0%	8.7	327,929,222
Faisalabad	Oil	18.9%	6.7	1,230,072,646
	Gas	10.6%	10.5	5,993,578
	Coal	16.4%	7.6	628,354,620

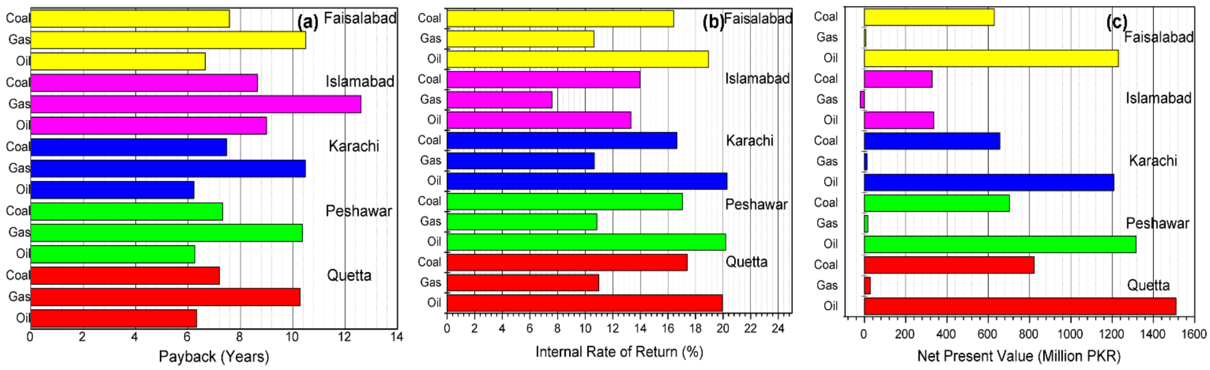

Figure 4-6 - (a) Payback (b) Internal rate of return (c) Net present value

4.4 GHG Mitigation

An analysis of GHG emissions mitigation in terms of tonnes of CO_2 reduced has been conducted. Analysis for both annual as well as throughout the lifetime of the project is shown in Fig. 4-7. Among fuel types used, coal has the highest mitigation potential while natural gas has the lowest potential. For coal, in the case of lifetime reduction potential, Quetta shows the highest reduction potential of 182,326 tonnes of CO_2 while Islamabad shows the lowest potential of 115, 172 tonnes of CO_2. However, replacing oil also yields a significant decrease in the CO_2 emissions from the industry. Emission reduction potential follows the same pattern of Quetta showing the highest potential of 111,995 tonnes of CO_2 and Islamabad's lowest reduction potential of 55,219 tonnes of CO_2. Natural gas is the most efficient fuel out of the three shown to be the least polluting. 18,405 tonnes of CO_2 of reduction potential for Quetta and 4629 tonnes of CO_2 reduction potential for Islamabad can be seen. The net GHG reduction of CO_2 in tonnes has been summarized in Table 4-4 for all cases.

Table 4-4 - GHG reduction

City	Fuel	Net Annual GHG reduction (tonnes of CO_2)	Net GHG reduction - 20 years (tonnes of CO_2)
Quetta	Oil	5,600	111,995
	Gas	920	18,405
	Coal	9,116	182,326
Peshawar	Oil	4,810	96,193
	Gas	606	12,126
	Coal	8,025	160,505
Karachi	Oil	4,398	87,964
	Gas	598	11,952
	Coal	7,812	156,234
Islamabad	Oil	2,761	55,219
	Gas	231	4,629
	Coal	5,759	115,172
Faisalabad	Oil	4,863	97,264
	Gas	298	5,961
	Coal	7,685	153,700

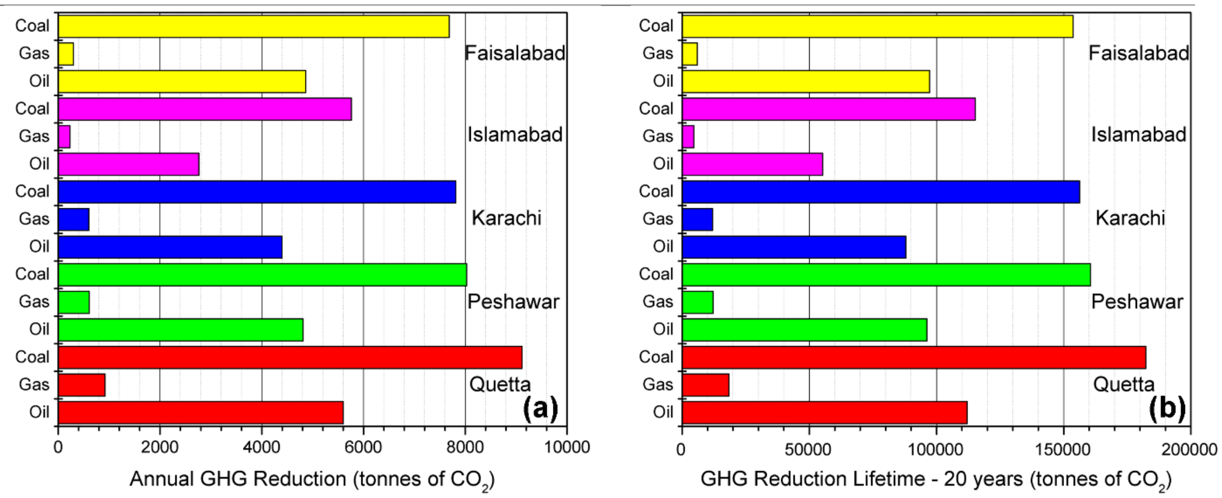

Figure 4-7 - GHG Reduction in tonnes of CO_2 (a) Annual (b) Project life

Summary

In this chapter the results of this study have been discussed in detail. Starting from thermal system simulations for selected cities in TRNSYS and their respective performances with evacuated tube collectors. This was then expanded on by determining their economic feasibilities against 3 different fuel types. Finally, the GHG mitigation feasibility for the 5 selected cities against 3 fuel types was also discussed.

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Chapter 5: Conclusion and Recommendations

5.1 Conclusions

The textile industry is a major contributor to Pakistan's export and the largest user of energy having immense potential for GHG as Karachi and Quetta are the most efficient, with daily average solar irradiance on the horizontal of 5.34 kWh/day/m^2 and 5.46 kWh/day/m^2 respectively as compared to cities furthest away such as Islamabad, with daily average solar irradiance on the horizontal of 4.02 kWh/day/m^2, least efficient due to lower irradiance.

The conclusions derived from this study are as follows:

1. Among technologies, the use of ETC was more productive than FPC for all the 5 selected locations, as proven against the solar fraction observed for a whole year.
2. The results of TRNSYS show that the collector output temperature exceeds our target of 80°C making our choice suitable for the application year-round.
3. An overall trend was observed where the collector performance was best in southern regions of Pakistan in comparison with northern regions due to decreasing solar irradiance from south to north.
4. Quetta demonstrates the best overall performance, given its highest elevation, lowest relative humidity, high daily solar irradiance and high wind speeds
5. More fuel can be saved in summers than in winters since collectors perform for longer hours during the summer months in Pakistan
6. As per the results of this study in the current situation, the average payback is of around 6 years for oil, 7 years for coal, and 10 years for natural gas making its use least feasible for most cities.
7. Whereas replacing coal and oil with solar thermal is already feasible, the situation for natural gas would evolve with time. As mentioned earlier, Pakistan's textile industry is heavily reliant on natural gas due to it being cheap and locally available. However, according to the fuel trends predicted the future price of natural gas will soar making the payback period relatively shorter and possibly making it feasible.

8. GHG emission reduction potential is highest with the use of coal and lowest with the use of natural gas.

Pakistan has aimed to achieve 30% off in the energy mix through the use of renewable energy by 2030 in its latest Alternate & Renewable Energy Policy [58]. Though the policy mentions the promotion of the use of solar thermal technologies, there is very limited insight as to how to achieve it and what will be the outcome. This study provides insight into the potential of the use of this technology for the application of preheating of feedwater with which one can make an informed decision to invest in sustainable energy use in their premises fulfilling their industrial thermal energy needs.

5.2 Recommendations

Pakistan is new regarding the implementation and use of solar thermal technology. This research will shed some light on the importance and potential of introducing solar thermal into the Pakistani market. However, following are some of the recommendations for future studies:

1. This study covers non-concentrating collectors, however, insights on the use of concentrating collectors, such as Linear Fresnel or Parabolic Troughs are yet to be investigated. Concentrating collectors also caters to the limitation of land cover.
2. The application covered in this research was on the preheating of boiler feedwater. Further studies can be conducted on other applications in the textile industry such as, bleaching, drying, washing, etc., in which steam or hot water can be used directly.
3. This research was based on validated TRNSYS models, while experimental research can be carried out to determine the actual performance of the set-up.

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Appendix A - Publication

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Techno-economic and GHG mitigation analyses based on regional and seasonal variations of non-concentrating solar thermal collectors in textile sector of Pakistan

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ABSTRACT

SDG implementation in the industrial sector of Pakistan is significant for its economic growth, sustainable industrialization, innovation, and sustainable production. Integration of solar thermal collectors in the textile industry will encompass sustainable development goals (SDG 7,9,12,13). Meeting these goals in the thermal sector of Pakistan is becoming increasingly challenging due to the limited resources and harmful emissions from conventional fuels. In this study, the technical feasibility of two non-concentrating collectors, Flat Plate Collector (FPC) and Evacuated Tube Collector (ETC) was investigated for the application of preheating of feedwater of boilers. Choosing the better performing collector for a range of regional and climatic variations across Pakistan, a comparative analysis of three fuels (coal, oil, and natural gas) has been carried out by using TRNSYS and RETScreen for economic analysis and GHG emission mitigation, respectively. The overall best results have been observed in Quetta. For this city replacement of coal has shown the highest GHG emission mitigation potential of 182,326 tonnes of CO_2 and the highest NPV for oil (1509.4 million PKR) among the three fuels studied. Based on the results, it can be deduced that this work can be further extended to concentrating thermal technologies as well. Since real-time industrial data has been used, the insights will promote solar thermal technology in Pakistan.

Introduction

The Global Climate Risk Index report 2021 has placed Pakistan in the eighth position on the list of most vulnerable countries due to climate change [1]. Despite the measures taken, it still stands among the top ten most vulnerable countries in the world. Pakistan is a signatory member of The Paris Agreement [2] and has submitted the Intended Nationally Determined Contribution (INDC) which states that 60 % of overall energy produced will be generated from renewable energy resources by 2030 [3 4].

According to Pakistan Energy Outlook Report 2020, the primary energy supply of the country comes from fossil fuels where about 85% of the total energy consumption is met through oil, coal, and gas. The top major consumers include industrial sector gas and industrial sector coal among others. The final energy consumption of the entire industrial sector is 37%. [5]. Being an agriculture country, the textile sector is one of Pakistan's largest manufacturing industries and is the eighth largest textile exporter in Asia [6]. The textile sector contributes 3.4% to Pakistan's GDP and provides 54.7% of the country's total exports [7]. Comprising 46% of the total manufacturing sector, textile accounts for 40% of the employment of the labor [6]. Currently, the textile industry is meeting 40% of its energy demand using cheap natural gas [8] but the situation will change as these reserves are depleting [5]. This along with the fluctuating prices of fossil fuels may lead the country towards energy insecurity. The rising inflation rate (9%) of the country makes the fuel more costly and the need to reduce carbon footprints to qualify for international trade has driven Pakistan's textile sector to look for alternative energy sources that are reliable, sustainable, and affordable [9].

In every textile industry, electricity and steam are required to carry out different processes such as spinning, weaving, and processing at different temperature ranges [10]. A significant amount of energy in the textile industry is used for process heating, most of which is required between 50-200 °C [11]. Hasanbeigi et al. reported that around 70-80% of the consumption of the total energy in the processing of the fabric is thermal energy [12]. Many studies have been performed to analyse the potential of solar thermal energy in textile industries [13–16].

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