# Techno Economic Analysis of a Hybrid System of Solar Thermal and Biomass for Preheating of Boiler to Reduce Fossil Fuel Usage in Industry

By

Sajida Zafar

(Registration No: 00000364256)

Department of Energy Systems Engineering

U.S. Pakistan Center for Advanced Studies in Energy (USPCAS-E)

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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A thesis submitted to the National University of Sciences and Technology, Islamabad,

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Supervisor: Dr. Rabia Liaquat

Co-Supervisor: Dr. Majid Ali

U.S. Pakistan Center for Advanced Studies in Energy (USPCAS-E)

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2025)

# THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by **Ms. Sajida Zafar, Registration No. 00000364256**, of United States Pakistan Center for Advanced Studies in Energy (USPCAS-E) at National University of Sciences & Technology (NUST), Islamabad has been vetted by undersigned, found complete in all respects as per NUST Statutes/ Regulations/ Masters Policy, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of Masters degree. It is further certified that necessary amendments as point out by GEC members and foreign/ local evaluators of the scholar have also been incorporated in the said thesis.

Signature: ____________

Name of Supervisor: Dr. Rabia Liaquat

Date: 04/01/2025

Signature (HoD): ____________

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**Examination Committee Members**

1. Name Dr. Mustafa Anwar Signature:

2. Name Dr. Abeera Ayaz Ansari Signature:

Co- Supervisor's Name Dr. Majid Ali Signature: Majid

Supervisor's name: Dr. Rabia Liaquat Signature:

Date: 03/01/2025

**Dr. Rabia Liaquat**
*Head of Department*

Signature

24/01/2025
Date

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Student Name: Sajida Zafar | Signature: ____________

Examination Committee:

a) GEC Member 1: Dr. Mustafa Anwar | Signature: ____________
(Assistant Professor, USPCAS-E NUST)

……………………………………………..

b) GEC Member 1: Dr. Abeera A. Ansari | Signature: ____________
(Assistant Professor, USPCAS-E NUST)

……………………………………………..

Supervisor: Dr. Rabia Liaquat | Signature: ____________

Co-Supervisor: Dr. Majid Ali | Signature: ____________

HOD: Dr. Rabia Liaquat | Signature: ____________

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I dedicate this work to my elder brother, **Qasim Iqbal**, whose constant support and dedication made this achievement possible and shaped my academic journey.

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**Nomenclature**

| | |
|---|---|
| ALCS | Annual Life Cycle Saving |
| CHP | Combined Heat and Power |
| CSP | Concentrating Solar Power |
| CV | Calorific Value |
| ETC | Evacuated Tube Collectors |
| GHG | Greenhouse Gases |
| GHI | Global Horizontal Irradiance |
| HSBS | Hybrid Solar Biomass System |
| HSBS | Hybrid Solar Biomass System |
| IRR | Internal Rate of Return |
| LCOE | Levelized Cost of energy |
| LCOE | Levelized Cost of Energy |
| LF | Linear Fresnel |
| MSW | Municipal Solid Waste |
| NPP | Net Primary Production |
| NPV | Net Present Value |
| PTC | Parabolic Trough Collectors |
| RES | Renewable Energy Resources |
| SPB | Simple Payback |

| | |
|---|---|
| Cp | specific heat of the water (J/kg K) |
| UL | collector overall heat loss coefficient (W/m$^2$ K) |
| FR | heat removal factor |
| (τα) | transmittance-absorptance product |
| α | absorptance |
| ST | Solar Tower |
| SF | Solar Fraction |

**Symbols**

| | |
|---|---|
| A | Area (m$^2$) |
| ∑ | Total Sum |
| N | North |
| E | East |
| ὴ | Efficiency |
| T | Temperature |

# ABSTRACT

Globally, industrial process heat represents over two-thirds of total energy consumption, with half of this demand requiring low to medium temperatures (<400°C). Fossil fuels are used to meet these requirements that can be integrated with renewable energy sources particularly with solar. The solar resource is available only during sunny hours and cannot work during non-sunny hours without a backup. Owing to the intermittency of solar, it needs to be hybridized with some other renewable energy source e.g. Biomass resource. In this way, the incorporation of hybrid renewable energy systems, such as solar-biomass combinations hybrids, offers a promising, efficient, and eco-friendly solution to meet the industrial process heat demands across various applications. This study primarily aims to present a novel Hybrid Solar-Biomass System (HSBS) specifically designed for pre-heating feedwater entering the boiler in process heat industries. This hybrid system includes evacuated tube solar collectors (ETC) and the biomass boiler, which is the facility proposed for low temperature applications (80°C in this case) in industries. Additionally, the initial simulation results of the hybrid solar-biomass system for pre-heating, evaluated through a case study using TRNSYS software, are presented. While, the financial analysis of the system is performed using RET Screen software. The values of economic indicators, obtained from economic analysis, shows the feasibility of the system e.g. positive NPV, IRR, B-C Ratio and short payback period indicate the system feasibility for any process heat industry operate for low to medium temperatures. The use of hybrid system as a new design to integrate to the conventional fuel boilers, that are widely used for heating demands in industries, is economical and sustainable as per the results of system evaluation on RET Screen software. The hybrid system saved 54.6% fuel with a substantial reduction of 44.3% in GHG emissions which is 670 tons of $CO_2$.

**Keywords:** Net Present Cost, Hybrid System, Renewable Energy Resources, Internal Rate of Return, TRNSYS, B-C Ratio, Payback Period.

# CHAPTER 1 : INTRODUCTION

In the following chapter, major key points are related to the need of a renewable energy resource to overcome the fossil fuel usage, integration of solar in process heat industry and the need of hybridization of solar with some other renewable energy resource due to its intermittent nature alongside the potential resource to be hybridized with solar. Moreover, the problem statement and the objectives of research work are highlighted, as well as, the challenges and advantages of usage of non-conventional resources in developing countries are discussed.

## 1.1 Background

The consumption of fossil fuels is not only affecting the environment but also a serious concern for energy security for the future generation as the fossil fuels are depleting. Over the years, global energy demand is increased, and it is expected by the year of 2050 it will rise up to 50% [2]. Particularly, Industrial sector consumes about 32 to 35% of the entire global energy [3]. The burning of fossil fuels for industrial processes like steam generation not only consumes large amount of electricity but also contribute to the greenhouse gas (GHG) emissions [4]. As far as Pakistan is concerned, the current energy mix of Pakistan comprises 59% from fossil fuels, 25% from hydroelectric power, 7% from renewables (solar, wind, and biomass), and 9% from nuclear energy as shown in figure 1.1 [5]. The industrial sector is the second highest energy consuming sector in Pakistan after household sector as shown in figure 1.2. [5]

According to climate transparency report 2020, industry related $CO_2$ emissions make up to 38% of the total GHG emissions in Pakistan. Cement, steel making and process heat industries are the most carbon intensive industries in Pakistan [6]. So, there is a need for time to make the transition from conventional energy sources to renewable energy sources. The development and utilization of renewable energy can assist in achieving 75% of the (SDGs) Sustainable Development Goals proposed by United Nations [6]. As stated by the International Renewable Energy Agency (IRENA), the proportion of renewable energy (solar, wind and other renewable energies) in power generation until 2050 will rise to 86% from 25%. Transformation in energy scenario is shown in a fig 1.1.

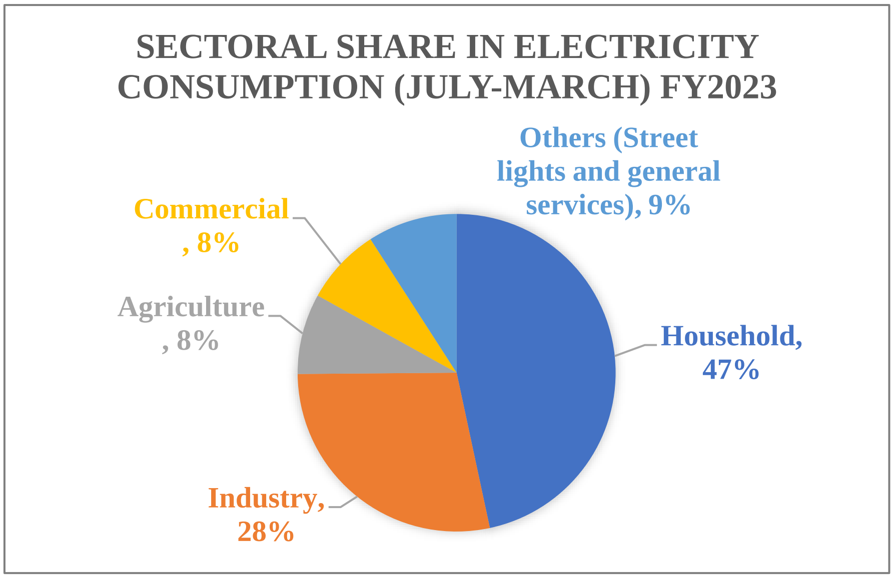



**Fig 1.1** Share in electricity consumption

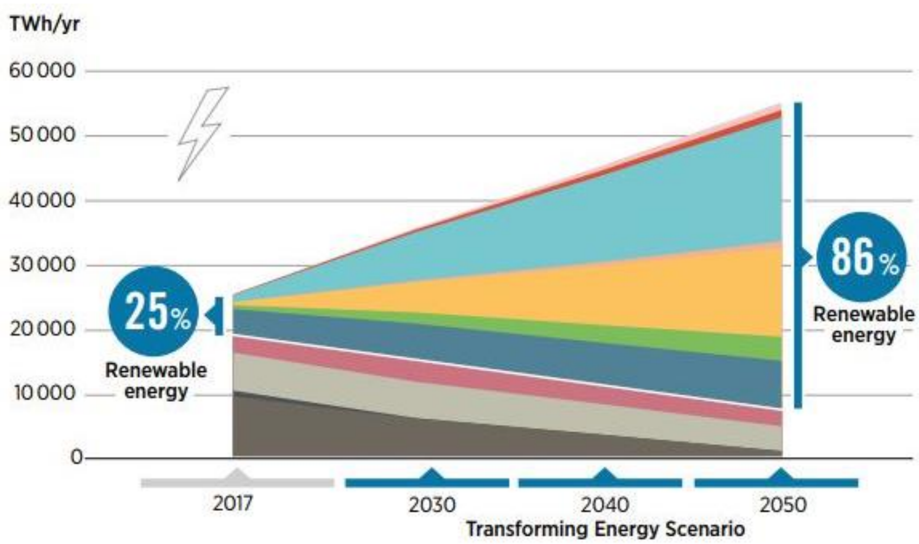



**Fig. 1.2** Renewable Power Generation until 2050 [7]

This scenario describes that the energy sector is focusing on environmentally friendly energy options, technological development, and the transition to strong, green energy economy. Adopting and supporting the sustainable development goals can help

Pakistan achieve its renewable energy targets and help the world combat climate change [8].

## 1.2 Problem Description

Process heating in industry, which accounts for a significant portion of global energy consumption, relies heavily on fossil fuels to fulfil the requirement for low- to medium-temperature applications (below 400°C). This dependency contributes to high operational costs, increased greenhouse gas emissions, and environmental degradation[9]. In countries like Pakistan, where industry is a critical economic sector, finding sustainable and economically viable solutions to reduce fossil fuel use has become imperative [10]. To address these challenges, Pakistan has set a target to produce carbon-free energy by increasing the share of renewable energy sources to 60% by 2030 [11].

Many researchers focused on the study of use of renewable energy specifically solar energy because it is the most abundant form of renewable energy and do their research on integrating solar thermal energy with industrial processes for instance, steam production through solar thermal collectors [12]. Approximately 630,000 TWh of solar energy reaches the Earth's surface in a year but unfortunately Solar energy contributes to less than 1% of the global energy supply [13],[14]. Many industrial processes like steam generation, desiccant pasteurization, sterilization, desalination etc. required low to medium temperature [15]. Therefore, this temperature can be achieved by renewable energy such as solar thermal energy. Solar energy is the intermittent renewable energy source and cannot provide thermal energy in a night or forecast conditions therefore it is necessary to integrate another system such as biomass energy system that can be used when solar energy is not available [16]. By combining these sources, a hybrid system can deliver a stable and efficient energy supply for industrial heating applications, especially for processes requiring preheating of boiler feedwater [17]. This model would provide a sustainable and cost-effective solution to fulfil the increasing energy demands of Pakistan's industrial sector while promoting environmental sustainability. Moreover, a comprehensive environmental and techno-economic feasibility study of Hybrid Solar-

Biomass System is needed to evaluate its potential benefits, cost-effectiveness, and environmental impact.

## 1.3 Potential of renewable sources in Pakistan

The potential of renewable sources of energy in Pakistan provides a ray of hope in achieving its energy security, environmental sustainability and socio-economic goals. By planning strategies, policies and partnerships, Pakistan can harness the power of renewable energy to create a better, cleaner and more sustainable energy future for its people. Pakistan has a vast potential to extract the sustainable and clean energy to achieve the national growing demand from renewable energy from many sources and handle energy related issues. Renewable energy resources such as solar, biomass, wind, hydro, and geothermal have enormous potential in Pakistan [18]. However, Solar, wind and biomass are the most efficient energy sources for $GH_2$ production in Pakistan [19], [20], [21].

### *1.3.1 Solar Resource Potential*

The world's energy needs can be fulfilled by harnessing solar energy [22]. Due to the geographic location of Pakistan, it has significant high potential for solar energy as it is fortunately receiving a maximum of solar radiation, mainly in its western and southern regions. Both solar thermal systems (STS) and Solar PV are useful for cooling and heating system for generating electricity and can be able to make huge contributions to the mix of renewable energy resources. Solar energy has become popular in recent years because it is available in different areas of the world that can be converted into heat and electricity. It is expected to finally replace coal by 2050. Therefore, solar energy may be best for the climate as it can deliver good results to meet the power needs of the future while creating jobs and increasing income for families, agriculture and small and medium-sized businesses. Green energy consumers tend to be ecologically conscious [23].

According to the GHI map of Pakistan shown below in fig. 1.3, average solar radiations in Pakistan ranges from 5 to 7 kWh/m2/day [23] [24].

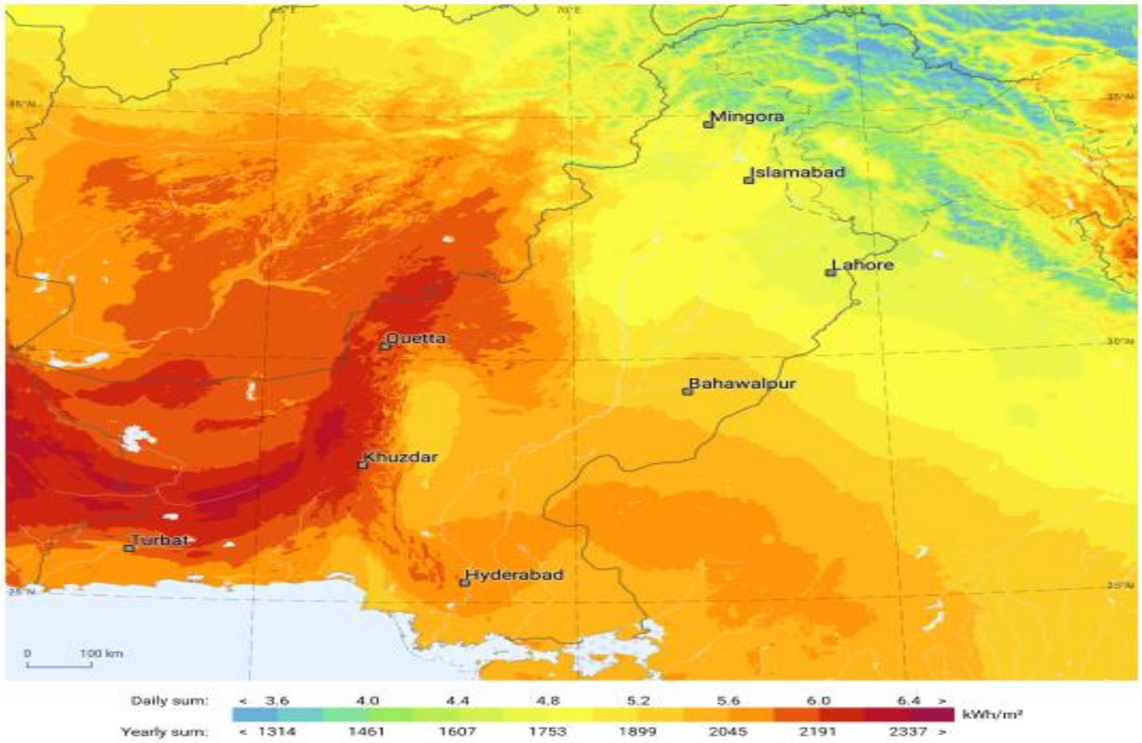



**Fig. 1.3** GHI map of Pakistan [23]

Solar energy, presents a promising opportunity for Pakistan to meet its increasing energy demands, especially given its current dependence on imported fossil fuels. The Alternative Energy Development Board (AEDB) and governmental initiatives have been actively working to increase solar power's contribution to the national energy grid, with an emphasis on sustainability, reduced greenhouse gas emissions, and energy security. Solar photovoltaic (PV) and solar thermal technologies can be deployed to harness this resource, potentially transforming the energy landscape by powering remote areas and various industries, which aligns with the government's goal of diversifying energy sources and promoting renewables.

### *1.3.2 Biomass Resource Potential*

Biomass is the third-largest renewable energy resource, after solar and wind, capable of sustainably providing bioenergy [25]. According to a recent report of IRENA, the average Net biomass primary production (NPP) of the world is 3-4 tonnes of carbon. While, NPP represents the annual amount of carbon captured by plants and stored as biomass. It is a fundamental measure of biomass productivity. The NPP of Pakistan compared to the global average is shown in the figure 1.4 below [26].


**Fig.1.4** Biomass potential: net primary production of Pakistan compared to the global average [26]

Pakistan has an untapped bioenergy potential of 44.5 MTOE/year from agricultural residues, a daily potential of 34 million $m^3$ of biogas from animal manure, and 449 MW of electricity or 0.56 million $m^3$/day of biogas from municipal solid waste (MSW) generated in 10 major cities. Despite this significant potential, bioenergy remains underutilized, and the country has faced severe energy crises for decades. Figure 1.5 below also represents the biomass resource potential in Pakistan.[27] Pakistan is a country with a high capacity for biomass generation with the total estimated biomass potential of 50,000 GW h/year encompassing sources such as forest residue, crop residues, animal waste, and municipal solid waste (MSW). Pakistan produces a huge number of agricultural residues including the residues of wheat, rice, cotton and sugar cane. Pakistan is placed as fourth largest country in sugarcane production with the sugarcane residue possessing the energy potential of 9475 GWh alongside the cotton residue containing the power potential of 614 GWh. Moreover, Pakistan is listed as the third largest wheat producing country among the world. While wheat is considered as a potential source to produce clean energy [28].

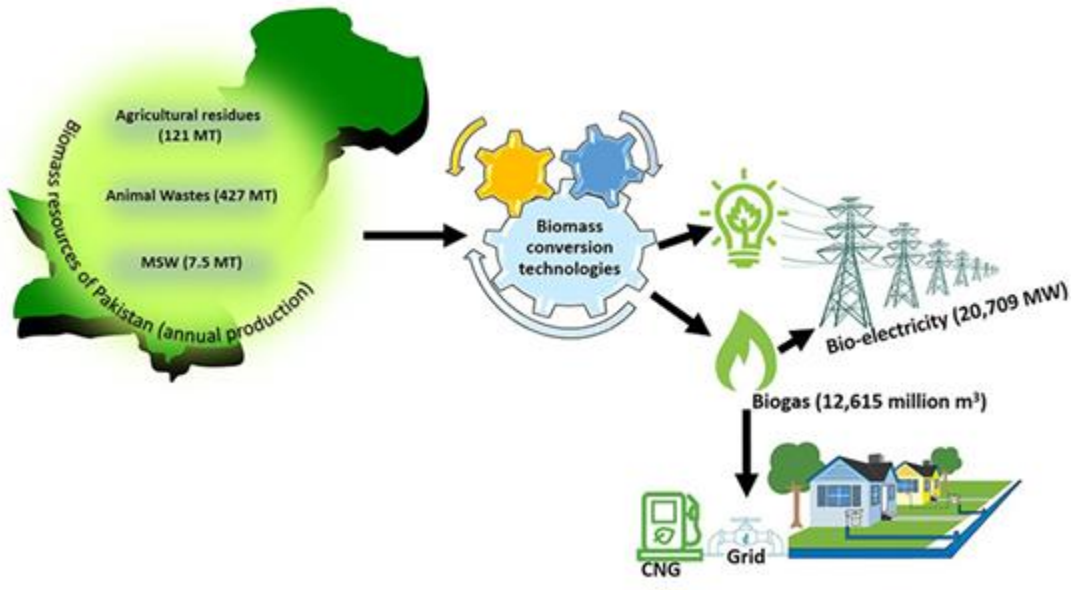



**Fig.1.5** Biomass potential: net primary production of Pakistan compared to the global average [27]

## 1.4 Motivation

As a developing country like Pakistan has worst energy transition scenario. There would be a need to shift usage of energy resources from traditional to renewable resources. By monetizing and maintaining a paradigm of optimized usage of renewable energy resources, the emission problem can be controlled in a most suitable way. Pakistan has huge resources of renewable energy, so it should be utilized in a most efficient way to reduce the emissions and energy demand supply can also be reduced.

## 1.5 Objectives

This research work's objectives are summarized below,

- To develop a hybrid Solar-Biomass model for water heating demands in industry.
- To integrate hybrid Solar-Biomass system in the process heat industries for low to medium temperature for heating requirements.

- To evaluate the economic performance parameter for integrated hybrid Solar-Biomass system.
- To overcome fossil fuel usage in industry, ultimately reducing GHG emissions.

## 1.6 Thesis Organization

Thesis work is divided into 5 chapters. **Chapter 1** presents the introduction of the research, problem definition, sustained energy, motivation and purpose. **Chapter 2** is related to theoretical review. **Chapter 3** presents the methodology of a whole proposed system. **Chapter 4** includes the simulation, results, discussion, and financial analysis. **Chapter 5** describes the research conducted.

# CHAPTER 2 : LITERATURE REVIEW

In the following chapter, background work of this study is highlighted. Integration of solar thermal and biomass in water heating set ups are discussed individually. Furthermore, hybrid system of Solar-Biomass for water heating, specifically in process heat industries, is also described. Lastly, the benefits and insights that this study will provide in future, are also taken into consideration.

## 2.1 Solar thermal integration in process heat industries

Integrating renewable energy sources, particularly solar energy, into industrial process heating is increasingly recognized as a promising solution for reducing carbon emissions and reliance on fossil fuels. Solar thermal systems, like flat-plate and evacuated-tube collectors, can effectively generate heat at low to moderate temperatures, suitable for many industrial processes, such as in the food, tobacco, and textile industries. However, solar energy's variability presents a significant challenge for applications that demand a continuous heat supply, particularly in industries requiring high-temperature processes, such as in steel and cement production. Here is a review of recent studies about the integration of solar thermal in process heat industry requirements. The study conducted in 2018, provided an overview of the significant role that district heating solar systems, combined with seasonal thermal energy storage, could play in reducing carbon emissions from heat demand in the UK. With buildings accounting for about 40% of energy consumption in higher latitude regions, the potential for solar thermal integration, as successfully demonstrated in countries like Denmark and Germany, is particularly relevant. The study employed a validated simulation model to assess the technical feasibility of such systems in the UK, revealing that while they can be implemented, their performance may be lower than expected compared to existing models like the Drake Landing Solar Community in Canada. Key insights included the necessity of balancing solar supply with heat demand and the critical importance of appropriately sizing long-term storage solutions. Additionally, the findings suggested that financial incentives and supportive policies are crucial for making solar thermal systems competitive against traditional heating technologies. Overall, this research not only highlighted the technical and economic challenges but also paved the way for tailored solar district heating solutions in the UK and other similar climates [29]. Other than that, the study proposed a methodology to assess the potential integration of solar collectors for industrial heating, considering factors like process temperature, solar irradiance, and collector efficiency. Validated using the (SAM) software, this approach evaluated economic and environmental metrics—such as capital cost, fuel savings, and carbon reduction—for sectors like textiles, dairy, and automotive. Additional sensitivity analyses on solar integration and fuel prices further validated the viability of solar thermal integration in industries[30].

Another study explored the latest advancements and critical factors influencing the integration of solar thermal energy into industrial processes. It highlighted the operational challenges and benefits of using solar thermal systems, such as reducing reliance on fossil fuels and cutting greenhouse gas emissions. The article also examined specific industrial applications, including those requiring medium to high temperatures, and discusses innovations in solar collectors and heat storage solutions that have enhanced the feasibility of these systems [31]. Another article assessed the economic and technical feasibility of solar thermal integration in industrial processes across diverse climate zones. By modeling different climate and industrial scenarios, the authors provided insights into how local solar irradiance levels, temperature needs, and economic factors influence system performance and costs. The findings reveal that climates with consistent sunlight yield better economic outcomes for solar thermal installations and suggest specific improvements in system design to optimize integration in areas with less solar availability [32]. This study examined the energy performance and economic considerations of solar thermal systems in industrial applications. The authors discussed critical factors for system efficiency, such as local solar irradiance and thermal storage solutions, emphasizing how these systems can reduce dependency on fossil fuels in process heating [33]. This article focused on solar thermal technologies that can reach temperatures up to 400°C, which are suitable for many industrial applications. The authors analyzd the feasibility and economic advantages of integrating high-temperature solar thermal systems in various industries, providing a foundation for future research and development [34]. This article provided a comprehensive review of solar thermal integration in food processing industries, examining the unique temperature requirements and economic challenges in this sector. The authors discussed case studies and strategies to overcome barriers, making solar thermal energy more accessible and cost-effective for food processing [35]. This comprehensive research study focused on the recent technological advancements in designing and optimizing solar thermal systems for industrial uses. The article covered improvements in solar collector technologies, enhanced thermal storage designs, and advanced control strategies. It also presented case studies where solar thermal systems have been effectively optimized to meet the specific heat demands of industries, underlining how these developments contributed to improved energy efficiency and lower operational costs [36].

Mills et al. presented an environmental and economic analysis of solar thermal systems designed for low-temperature industrial applications. They highlighted the significant reductions in greenhouse gas emissions and energy costs achievable through solar thermal integration, providing a strong case for adoption in sectors with moderate heat requirements [37]. Meyer et al. explored the existing barriers that prevent wider adoption of solar thermal systems in industry, including cost issues, technological limitations, and a lack of supportive policy frameworks. They examined potential solutions, such as policy incentives, standardization, and research investments to foster solar thermal adoption. The paper also discussed how solar thermal systems can be designed to cater to industries with high-temperature requirements, which are typically the most challenging to decarbonize [38]. This article addressed the challenges and solutions for integrating solar thermal energy into high-temperature industrial processes, which require advanced thermal management solutions. The authors discussed the latest collector designs, high-performance materials, and storage technologies that make solar thermal viable at high temperatures. They also analyzed the economic feasibility of these systems and highlight industries where solar thermal integration has been most successful, offering a roadmap for future research to overcome the technical barriers [39]. This study addressed Pakistan's ongoing energy crisis, highlighting issues such as poor governance and a reliance on limited energy sources. The research proposed a solar thermal system designed to generate hot water at 75°C, emphasizing the potential of solar energy as a sustainable alternative. The system, capable of producing 80 tons of hot water daily over 16 hours, is based on simulations conducted using TRNSYS software, confirming the feasibility of achieving the desired temperature with a collector area of 600 $m^2$. This innovative solution presented a viable replacement for traditional, more costly energy sources like diesel and gas, which are commonly used in industries such as textiles. The findings indicated a practical application of solar technology in addressing energy shortages and reducing operational costs, contributing to environmental sustainability and economic resilience in the region [40]. This study presented a compelling case for using tankless solar heat for industrial processes (SHIP) systems, specifically employing flat-plate collectors (FPC) to meet the low-temperature heat requirements of the food and beverage sector, where over 40% of the heating demand is below 100°C. By utilizing a mathematical modeling approach validated through on-site experiments, the study highlighted the effectiveness of different temperature configurations for preheating water, demonstrating that these systems can operate efficiently with a mass flow rate of just 60 liters per hour. The findings suggested that integrating solar thermal systems into industrial processes is not only economically viable but also a promising strategy for reducing fossil fuel dependency [41].

### 2.2 Biomass resource integration in process heat industries

Integrating biomass into industrial process heat systems offers a renewable, carbon-neutral alternative to fossil fuels, particularly valuable for sectors with high-temperature heat needs, such as cement, steel, and pulp and paper production. Biomass is advantageous because it provides consistent energy output, independent of weather conditions, which makes it suitable for industries requiring continuous operation. Unlike solar energy, which depends on sunlight availability, biomass can deliver steady heat by combusting organic materials like crop residues, wood, or dedicated energy crops. A brief review of past studies is provided here regarding the biomass resource integration in process heat industries. Like, a study presented a critical examination of the potential for biomass to transform industrial process heat supply in the context of greenhouse gas emissions reduction, using Germany as a case study. It highlighted the need for a nuanced understanding of biomass utilization, especially at temperatures above 200°C, by analyzing various energy-intensive industrial sectors. The findings suggested a significant shift in biomass use from residential to industrial applications, particularly in cement and clinker production. However, the study emphasized the necessity for further research and development to solidify these conclusions and optimize biomass utilization strategies [42]. Another study effectively examined the critical role of biomass in reducing greenhouse gas emissions through the transformation of industrial process heat supply. It highlighted a focused analysis based on German examples and introduced a novel method for assessing biomass utilization at temperatures above 200°C across various industrial sectors. The emphasis on shifting biomass use from residential to industrial applications, particularly in cement and clinker production, suggested a significant opportunity for decarbonization. However, the call for further research and development underscores the complexities involved in fully realizing this potential [43]. Another research study effectively outlined the importance of integrating biomass-powered combined heat and power (BCHP) systems within district heating frameworks, particularly in conjunction with thermal energy storage. It emphasized the need for proper sizing of components to optimize performance while minimizing costs and environmental impacts. Additionally, the mention of future strategies for evaluating and integrating biomass energy systems highlighted the ongoing relevance of this research in addressing energy demands sustainably. Overall, the paper addresses critical factors necessary for advancing biomass integration into district heating systems [44].

Malico and colleagues reviewed biomass use across various European industries, particularly for steam generation in the wood and pulp sectors. The paper addressed regulatory frameworks that incentivize biomass integration, as well as challenges like technological limitations in achieving high combustion efficiency. The study also highlighted biomass's potential as a renewable resource to meet stringent emission standards in Europe [45]. This study pointed out that while biofuels offer environmental benefits, they must be paired with carbon capture and storage (CCS) technology to efficiently minimize carbon emissions, especially since a large portion of emissions in cement production stems from the limestone calcination process rather than energy generation alone [46]. The study emphasized the economic and environmental advantages of replacing heavy fuel oil with biomass and demonstrates successful implementations across different countries. The research also underscored the potential for adapting this technology in cement kilns and other high-heat industries [47]. The study identified practical applications in industries across Europe, with a focus on biomass-fueled boilers and combined heat and power (CHP) systems. It highlighted challenges such as feedstock availability, policy incentives, and the need for efficient technology integration in traditional process heating systems [48]. Dou's study analyzed the growing role of biomass in China's industrial energy mix, especially as the nation aims for carbon neutrality by 2060. It details how biomass is beginning to substitute coal and natural gas in industrial boilers and examined challenges like biomass supply chain constraints and technical adjustments needed for high-temperature processes. The analysis was particularly insightful for understanding biomass's role in small to medium-sized industrial applications within China [49].

## 2.3 The potential and need of hybridization

Solar thermal energy is often proposed for industrial applications for the fact that it's a green source of energy, yet studies indicate limitations in reliability and temperature control. According to Lüpfert et al., flat-plate and evacuated-tube collectors are effective for low-temperature applications but struggled to reach and maintain high temperatures (above 200°C) required by industrial processes, especially in regions with variable solar irradiance or during nighttime. This inconsistency makes solar alone insufficient for continuous industrial operation without an additional energy source backup. Concentrated solar power (CSP) systems, although able to reach higher temperatures, demand substantial space and optimal weather, limiting their applicability in many settings [50]. On the other hand, biomass presents a viable alternative, especially for industries demanding high-temperature heat, but its sole reliance introduces issues related to supply consistency and emissions. Koppejan and others highlighted that although biomass can effectively meet higher temperature needs, its supply chain is often inconsistent and can be costly, particularly when sourced from afar. Additionally, biomass combustion necessitates pollution control measures, especially in regulated areas, which can diminish its environmental advantages. This supply variability makes biomass alone less reliable for steady industrial heating demands [48]. However, studies on hybrid systems combining solar and biomass show improved operational stability and emissions reduction. Mari et al. demonstrated that hybrid solar-biomass systems effectively balance solar's cost-efficiency with biomass's temperature capabilities, offering a more reliable and flexible energy supply for industrial processes. This hybrid approach enables stable, sustainable heating by leveraging both sources' strengths and mitigating individual limitations, thus reducing fossil fuel reliance while maintaining consistent industrial productivity [51].

## 2.4 Biomass-a suitable resource for hybridization with solar

Mari et al. highlight that biomass not only enhances system reliability in a hybrid setup but also contributes to emission reductions and operational cost savings. Biomass acts as a renewable alternative to fossil fuels and allows for a cleaner energy profile in industrial applications, reducing overall carbon emissions. When combined with solar energy, hybrid systems are shown to require less biomass, thereby lowering both the fuel cost and the emissions compared to using biomass alone. This dual-benefit makes biomass-solar hybrid systems an economically and environmentally beneficial choice for industrial heating needs [52]. Research by Koppejan indicated that hybrid systems using solar and biomass improve system efficiency, particularly in high-temperature applications. While solar is efficient for low- to mid-range temperatures, biomass combustion can achieve the higher temperatures required in processes like cement and steel production. By integrating both, hybrid systems capitalize on the strengths of each source, using solar during lower demand periods and biomass during peak heating demands, which is particularly advantageous for energy-intensive industries. This synergistic setup maximizes efficiency and minimizes the operational gaps each energy source alone might leave [53]. Studies showed that biomass complements solar energy by providing a stable energy supply, especially when sunlight is not available. In hybrid systems, solar energy is typically used during peak sunlight hours, while biomass compensates during off-peak hours, such as at night or during cloudy periods. According to Dou et al., the combination helps mitigate the variability of solar power, creating a more reliable energy system for industrial applications. Biomass's high calorific value supports the higher temperature ranges needed for many industrial processes, making it an ideal candidate to work alongside solar to meet consistent demand [48].

## 2.5 Hybridization of solar and biomass resource

In recent times, Numerous studies have explored the integration of solar thermal energy with industrial processes for various applications. However, due to the intermittent nature of solar energy, hybridization techniques have gained prominence and are being actively researched as a solution to address this challenge. A brief review of recent work is presented here. [53] was among the first to introduce the practical application of electricity generation from hybrid Concentrating Solar Power (CSP) and biomass power plants. This study investigated the techno-economic benefits of hybrid CSP-biomass energy systems by analyzing alternative configurations for a 10 MWe hybrid CSP-biomass combustion power plant. Using the Solar Advisor Model (SAM), the study assessed the solar field's contribution under quasi-steady generation conditions and estimated the role of biomass and gas boilers based on year-round radiation availability. The economic analysis revealed that while the investment costs for hybrid CSP-biomass power plants were higher than standalone CSP or biomass combustion plants, the use of shared equipment significantly reduced costs, achieving a 24% savings compared to combining the standalone systems' costs. Furthermore, hybrid systems demonstrated significantly higher effective operating hours and energy generation—2.77 times greater than conventional CSP systems—without requiring an expensive heat storage system. Additionally, the lower biomass requirements of the hybrid system enabled larger capacities compared to standalone biomass combustion systems, resulting in higher energy efficiencies and reducing the risks associated with biomass supply. The institute conducting this research was developing this first commercial CSP-biomass power plant in collaboration with different private companies, and it was expected to start operating in 2012. [54] explored Various solar technologies and their suitability for hybridization with biomass for combined heat and power (CHP) generation in Europe have been studied, with both technical and economic aspects examined. Three solar-biomass hybrid configurations were analyzed: solar tower (ST)-biomass, parabolic trough (PT)-biomass, and linear Fresnel (LF)-biomass systems. Among these, only one operational solar-biomass hybrid power plant was identified, utilizing PT technology due to its higher heat and optical efficiency compared to LF and its easier installation process compared to ST

[55]. Subsequently, a simulation model for Rankine cycle-based solar-biomass hybrid power plants was developed using ASPEN PLUS software [56]. In this model, solar parabolic collectors and biomass combustion were arranged in parallel to generate steam for power production. Thermal efficiency, fuel consumption rates, and $CO_2$ emissions were analyzed for 1 MW and 5 MW capacities. A financial analysis was also performed, calculating the Net Present Value (NPV) and Internal Rate of Return (IRR). Results showed that hybridization reduced biomass consumption by 18% and $CO_2$ emissions by 20% compared to a standalone biomass power plant of the same capacity. The IRR for an 80% debt financing scenario was calculated to be 15.64% [57]. presented thermodynamic modeling for sizing a solar-biomass hybrid power plant using steam Rankine cycle. The solar system used parabolic trough technology, and biomass system used fluidized bed combustion technology to generate steam for power generation. The paper discussed the significant role of biomass in the hybrid system during the solar intermittency period. Moreover, in a stand-alone mode, boiler can also generate power to meet the power demand during post sunshine hours. Furthermore, various techno economic factors were also analyzed in this research ultimately suggesting that hybridization could be a sustainable solution. [58] analyzed the different design stages for the implementation of the hybrid solar-biomass systems to identify the optimal solutions for the systems to be integrated into an existing district heating system. Therefore, with the help of a case study, a detailed description of the feasible technical solutions was provided. [59] introduced a hybrid solar-biomass system for space heating and hot water supply in public bathhouses in Morocco, replacing the traditional firewood furnaces that were commonly used for this purpose. The system consisted of small dimension parabolic trough solar collectors (PTC) and small-scale pellet boilers which was proposed for low temperature applications (less than 100°C). Simulation was performed using TRNSYS software and results showed a significant savings in firewood which would result in reduce of deforestation and $CO_2$ emissions as well. [60] introduced the integrating techniques of solar thermal technology at different locations in a coal fired power plant to increase the temperature of boiler feed water. Steam extracted from high pressure turbine was replaced by solar technology (parabolic trough collectors) to increase feed water temperature while considerably reducing the amount of heat input from the boiler. The innovative model for this was

developed in MATLAB which represent the actual PTC modules and are subsequently integrated into the coal-fired power plant. Therefore, economic and carbon emission analysis were also performed and the benefits of integrating solar thermal technology were also exposed through this work. [61] analyzed various parameters of hybrid solar-biomass system in order to assess the market profitability factor. [62] evaluated a technical and financial analysis of a hybrid system of solar thermal and biomass cogeneration cycle in corn ethanol distillery to meet the steam requirements for its operation in Phoenix (USA) and Barreiras (BRA). The annual savings of biomass in proposed cycle are 14% and 12% for Phoenix (USA) and Barreiras (BRA) respectively. For both locations, the hybrid solution was found to be technically feasible but economically it was not proved to be feasible due to negative Net Present Value. [63] assessed a solar-biomass on-grid HRES system for Hattar Industrial Zone phase-VII. The model was developed on HOMER software and the techno-economic and sensitivity analysis was carried out for the optimization of the system.

Hybrid systems that combine biomass with solar or the renewables that can enhance reliability and reduce emissions further, offering industries a pathway to more economical, sustainable and resilient energy models.

# CHAPTER 3 : METHODOLOGY

In this chapter, the site and load profile of selected area, the total water heating requirements, solar irradiance data and biomass potential data is analyzed. The methodology used in developing the proposed system on basis of technical and economic analysis is discussed. Components used in the modelling and simulation are described one by one. Finally, the various economic indicators and the formulas to calculate these indicators are also presented.

## 3.1 Site and Load Profile of study area

An integration of the HSBS system with in process heat industry for pre heating of boiler feedwater is developed for the targeted industry that is tobacco industry, located in Islamabad Pakistan, having site elevation at 508 m with 33.6°N, 73.1°E latitude and longitude above the mean sea level [64]. The monthly solar radiation weather profile is provided in the figure 3.1 below.

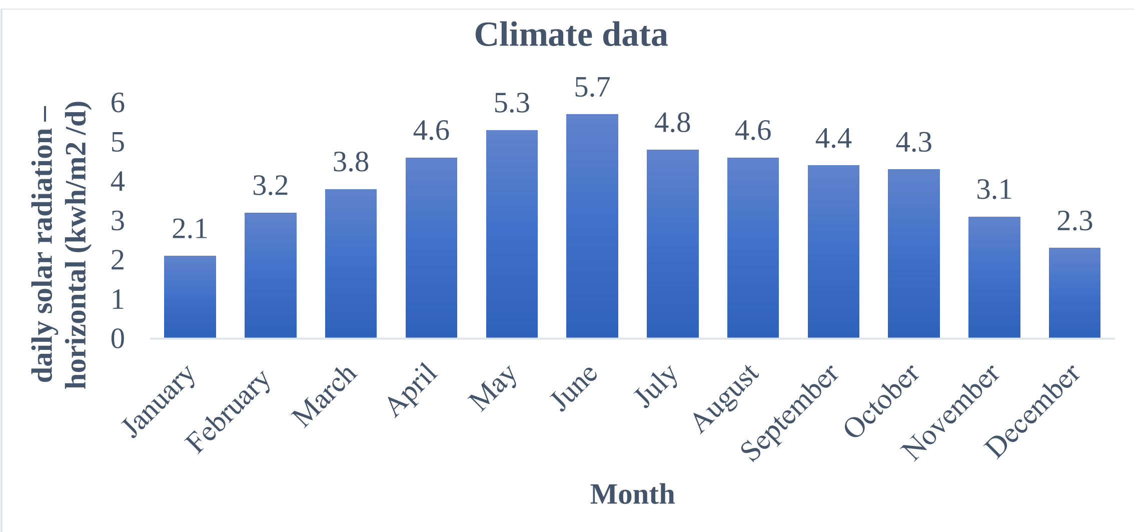



**Fig. 3.1** Monthly solar radiation weather profile. Source: RETScreen database

The annual weather data for Islamabad is also presented in the table below in the table 3.1 below.

**Table 3.1** Annual weather data of Islamabad-design condition parameters

| **Parameters** | **Values** |
|---|---|
| Elevation [m] | 508 |
| Longitude [E] | 73.1 |
| Latitude [N] | 33.6 |
| Wind speed [m/s] | 2.4 |
| Relative humidity [%] | 62.0 |
| Daily Solar Radiation Horizontal [kWh/m2 /d] | 4.02 |
| Air temperature [℃] | 21.6 |
| Atmospheric pressure [kPa] | 91.1 |
| Elevation [m] | 508 |

In Pakistan, sugarcane bagasse is a significant and underutilized biomass resource with considerable potential for meeting the process heat requirements of various industries. Pakistan is one of the top sugarcane producers globally, with approximately 83 sugar mills operating nationwide. These mills annually produce around 3.5 million metric tons of sugar, resulting in substantial quantities of bagasse as a byproduct as shown in table 3.2. During the sugarcane crushing season, which typically spans about four months, the available bagasse can generate up to 3,000 MW of energy through cogeneration processes. This biomass is primarily used to produce steam and electricity, which are integral to the operations of sugar mills and can be extended to other industrial applications requiring process heat [65].

The system is modelled for a tobacco industry that is currently using natural gas for production of steam for process heat requirements. The water consumption for steam generation is 50,000$m^3$ per year and the operation is throughout the year except on Sundays and scheduled holidays. The system operates in two different symmetries through the year e.g. from December to June it operates in two shifts from 6 am to 10 pm while from July to November, there is used to be a three-shift operation in 24 hours. Therefore, the water consumption for aforementioned symmetries is 195.6 and 130.4 cubic meter per day respectively with the flow rate of 180 and 120 cubic meter per day.

**Table 3.2** Bagasse-based biopower generation holds the highest capacity in Pakistan. [27].

| Power plant name | Location | Bagasse/rice husk production (tonne/yr) | Electricity generation (GWh/yr) | Power capacity (MW) |
|---|---|---|---|---|
| Al Noor Sugar Mills Ltd. | Shaheed Benazirabad | 387,978 | 112 | 13 |
| Almoiz Sugar Mills Ltd. | Dera Ismail Khan | 238,909 | 69 | 8 |
| Ashraf Sugar Mills Limited | Bahawalpur | 345,000 | 100 | 11 |
| Chashma Sugar Mills Limited Unit-I | Dera Ismail Khan | 242,406 | 70 | 8 |
| Colony Sugar Mills Limited-I, | Mandi Bahauddin | 252,000 | 73 | 8 |
| Etihad Sugar Mills Ltd. | Rahim Yar Khan | 420,302 | 122 | 13 |
| Faran Sugar Mills Limited | Tando Muhammad Khan | 274,488 | 80 | 9 |
| Fatima Sugar Mills Ltd. | Muzaffargarh | 326,940 | 95 | 10 |
| Habib Sugar Mills Ltd. | Shaheed Benazirabad | 334,966 | 97 | 11 |
| Hamza Sugar Mills Ltd. | Rahim Yar Khan | 1,127,487 | 327 | 37 |
| Haseeb Waqas Sugar Mills Limited | Nankana Sahib | 246,600 | 71 | 8 |
| J.D·W Sugar Mills Limited (Unit III) | Ghotki | 451,430 | 131 | 15 |
| J.D·W Sugar Mills Limited (Unit IV) | Ghotki | 477,284 | 138 | 16 |
| JDW Sugar Mills Limited (Unit II) | Rahim Yar Khan | 355,881 | 103 | 12 |
| JDW Sugar Mills Ltd. | Rahim Yar Khan | 859,989 | 249 | 28 |
| JDW Sugar Mills Ltd. | Rahim Yar Khan | 859,989 | 249 | 28 |
| Kamalia Sugar Mills Limited | Toba Tek Singh | 495,000 | 143 | 16 |

The operating temperature of industry is 170$^o$C which consumes a huge amount of natural gas to achieve this point. There are 8760 hours in the simulation year. Additionally, the thermal system analysis performed in this study requires running the simulation more than once. Therefore, the hourly demand for each month is represented by only 24 data points, so 96 set points including 4 seasons 1 day per month 24 hours per date are used for the simulation instead of 8760 data points [66]. Hence, the daily demand profile presented through 24 data points.

## 3.2 Hybrid System Components

### *3.2.1 Solar thermal collectors*

In solar thermal collectors, Evacuated Tube solar Collector (ETC) has been selected for the simulation owing to its high efficiency and the temperature range that lies between 50 to 200$^o$C which is the requirement of most industrial processes. Other parameters or specifications of ETCs are provided in the table 3.3 below.

**Table 3.3** Parameters of ETCs and their values

| Parameters | Values |
|---|---|
| solar collector area [gross] | 2.03 $m^2$ |
| solar collector area [aperture] | 1.84 $m^2$ |
| FR UL coefficient | 1.72 $W/m^2$ /°C |
| FR (ꞇα) coefficient | 0.63 |
| $a_0$ | 0.802 |
| $a_1$ | 5.4 $kJ/h/m^2/K$ |
| $a_2$ | 0.00576 $kJ/h/m^2/K$ |
| solar collector area [gross] | $2.03^2$ |

*3.2.1.1 Solar fraction*

The solar fraction (SF) is widely recognized as a key technical metric for assessing the effectiveness of solar heating or cooling systems. It represents the proportion of thermal energy generated by solar collectors relative to the system's total required energy input for heating or cooling [67]. This fraction, often abbreviated as SF, can be mathematically expressed by the following equation to determine its specific value within the system's operation [68].

$$SF = \frac{Q_{solar}}{Q_{solar} + Q_{aux}} \tag{3.1}$$

Here, $Q_{Solar}$ represents the thermal energy output in kW generated by the solar collectors, and $Q_{aux}$ denotes the thermal energy in kW supplied by the auxiliary heating system.

### *3.2.2 Biomass Boiler*

The selection of the combustion method for biomass conversion in this system is based on its ability to generate heat, electricity, or combined heat and power (CHP) from biomass through thermochemical conversion. Among the common techniques—Direct Combustion, Gasification, and Pyrolysis—combustion is chosen here. In this process, biomass reacts with air, resulting in ash and hot gases. The chemical energy within the biomass is converted into thermal energy, which is harnessed as hot flue gases. The amount of thermal energy generated depends on the calorific value of the biomass being burned. While various biomass types can be used in combustion, those with moisture content above 50% must undergo drying prior to furnace feeding for efficient combustion. The furnace houses the combustion process, and the thermal energy produced is then transferred to another medium in the boiler. Specifications of the boiler used in the simulation are provided in Table 3.3 [69].

**Table 3.4** Specifications of biomass boiler

| **Parameters** | **Value** | **Unit** |
|---|---|---|
| Rated capacity | 520 | tons |
| Fluid specific heat | 4.19080.25 | kJ/kg.K- |
| Minimum turn-down ratio | 0.70 | - |
| Boiler efficiency | 0.85 | - |
| Combustion efficiency | | - |

The net energy content of biomass primarily hinges on its moisture content. In this study, bagasse was chosen as the biomass feedstock, with a moisture content of approximately 4% [70], [71]. The chemical composition of biomass significantly influences its combustion performance. Key factors impacting combustion include the ash, carbon, hydrogen, nitrogen, sulfur, oxygen, and chloride content [72]. Higher carbon and hydrogen content contribute to a higher heating value, while elevated oxygen content enhances reactivity at normal combustion temperatures, leading to faster combustion rates. The selected biomass has negligible nitrogen and sulfur content, resulting in minimal NOx and no SOx emissions post-combustion. Table 3.5 illustrates the energy potential of major crop residues.

**Table 3.5** Major crops residue and their energy potential [72].

| Crop | Crop Production (tons) | Residues (tons) | Power Potential (GWh) |
|---|---|---|---|
| Cotton | 200,000 | 5,898,771 | 614 |
| Sugar cane | 63,920,000 | 5,752,800 | 9,475 |

The physio-chemical properties of selected biomass are listed below in table 3.6.

**Table 3.6** Physico-chemical characteristics of biomass feedstock [72].

| Physico-chemical properties | Values |
|---|---|
| Volatile matter (%) | 72.3 |
| Moisture (%) | 4.6 |
| Hydrogen (%) | 6.26 |
| Carbon (%) | 46.52 |
| Nitrogen (%) | 0.18 |
| Oxygen (%) | 46.49 |
| Ash content (%) | 6.2 |
| Sulfur (%) | 0.06 |
| Calorific Value (MJ/kg) | 18.6 |

## 3.3 Architecture of the designed system

A hybrid Solar-Biomass System (HSBS) for preheating 50,000 $m^3$ water per year is developed TRNSYS. The system comprises of solar collector and biomass boiler linked with a water storage tank having a heat exchanger inside it. The cold water from the tank is pumped to the solar collector, through the pump. Therefore, the heated water returns from solar collector to the storage tank where it exchanges heat with cold water with the help of heat exchanger present inside the storage tank. The storage tank is set to deliver the heated water at 80$^{o}$C temperature to the facility (conventional boiler where the water will be heated up further till 180$^{o}$C and generate steam that will be transferred further, to be used in process heating needs). However, if the required temperature is not achieved through solar collector and temperature of water that tank delivers, remains below 80 degrees, then the water will be sent to the biomass boiler from the bypass valve where the biomass boiler will heat up the water and will deliver it to the facility at the required temperature. System architect of the proposed model is shown in the figure 3.2 below.

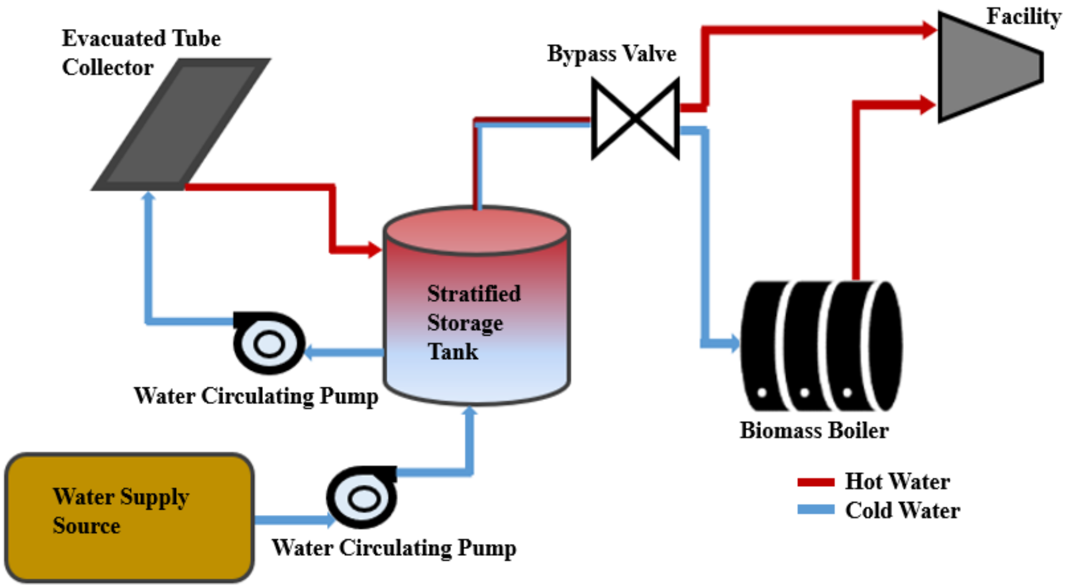



**Fig 3.2** System architect of a proposed model

### 3.4 Economic analysis

The economic feasibility of the project was assessed using RET Screen software, focusing on NPV, IRR, and payback period. A positive NPV, a quick payback period, and a high IRR demonstrate the system's economic feasibility [73]. A summary of all the economic parameters is presented in Table 3.7.

**Table 3.7** Input parameters for RET Screen economic assessment

| Parameters | Value |
|---|---|
| Natural gas fuel rate | PKR 3000 per MMBtu |
| Inflation rate | 20% |
| Discount rate | 10% |
| ETC cost | $ 370 |
| Project life | 20 |
| Biomass boiler cost | $24000 |

The important economic indicators are given below.

### *3.4.1 Net Present Value (NPV)*

The model computes the project's Net Present Value (NPV) represents the value of all future cash flows, discounted to today's currency using the discount rate. NPV is closely tied to the Internal Rate of Return (IRR) and is calculated at time 0, marking the shift from the end of year 0 to the beginning of year 1. It reflects the present value of the project's annual after-tax cash flows. A positive NPV suggests that the savings from reduced electricity bills exceed the system costs over the analysis period, whereas a negative NPV indicates that the project incurs higher costs than savings. The payback period is influenced by net savings: projects with greater savings will have shorter payback periods compared to those with lower savings. Generally, assuming a certain discount rate, a positive NPV shows an economically viable project, while a negative NPV points to an economically infeasible one.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1-d_{nominal})^n} \quad (3.2)$$

The NPV represents the current value of after-tax cash flows, adjusted to reflect year one with respect to the nominal discount rate.

Where,

N= analysis period in years

Cn= after-tax cash flow in Year n and

dnominal = discount rate (nominal)[74]

### *3.4.2 IRR*

IRR is traditionally calculated by setting NPV to zero. For this investment, this gives the following[74]:

$$0 = \sum_{n=0}^{N} \frac{C_n}{(1-d_{nominal})^n} \qquad (3.3)$$

### *3.4.3 Payback period*

The model determines the simple payback period (SPB), which indicates the time required for a proposed facility to recover its initial costs through the revenue or savings it generates. The fundamental idea behind the simple payback method is that a quicker recovery of investment costs makes the investment more appealing. For instance, in an energy project, a negative payback period suggests that the annual expenses exceed the annual savings.

The Simple Payback period can be defined as the first point in time when:

$$\sum_n \Delta I_n \leq \sum_n \Delta S_n \qquad (3.4)$$

Where

SPB = The minimum number of years needed for the total value of annual cash flows, without discounting, to equal or surpass the total undiscounted investment costs.

$\Delta I$ = The total investment costs that are not discounted, including any additional finance charges, represent the incremental investment expenses.

$\Delta S$ = The total value of the annual cash flows, excluding any discounts, represents the net annual costs [75].

### *3.4.4 Benefit-Cost Ratio (B-C Ratio)*

The Benefit-Cost Ratio (B-C Ratio) is a key financial indicator that assesses the economic feasibility of a project by comparing the present value of its expected benefits to the present value of its costs. It is calculated as follows:

$$B - C\ Ratio = \frac{Present\ Value\ of\ Benefits}{Present\ Value\ of\ Costs} \tag{3.5}$$

This ratio highlights the cost-effectiveness of a project: A B-C Ratio above 1 suggests that benefits exceed costs, indicating a financially attractive project. A ratio of 1 reflects a break-even scenario, while a ratio below 1 implies that costs outweigh benefits, making the project less financially viable [76].

# CHAPTER 4 : RESULTS AND DISCUSSION

In this chapter, the results of the simulations performed using TRNSYS software are presented. The financial calculation carried out using RETScreen software are also presented. The daily average temperature output of solar thermal and biomass obtained using TRNSYS software, as well as, the solar fraction achieved is also provided. Additionally, the output of HSBS is provided based on annual results as well as for the summer and winter seasons and the results are compared for both the seasons. The simulation runtime for one year is 8760 hours and for the summer and winter peak days is 24 hours.

The simulation is done according to the annual temperature output by solar thermal and biomass individually and then the average monthly temperature profile of the hybrid system in a day. Moreover, average contribution of solar and biomass resource used in this proposed case is calculated by using RETScreen software. Average seasonal data is calculated by taking peak days of summer and winter which has almost more sun irradiance data is taken for evaluation using TRNSYS software.

### 4.1 TRNSYS software model

A hybrid system of solar thermal and biomass, operating to preheat 50000 $m^3$ water per year in a tobacco industry is developed in TRNSYS as shown in figure 4.1.

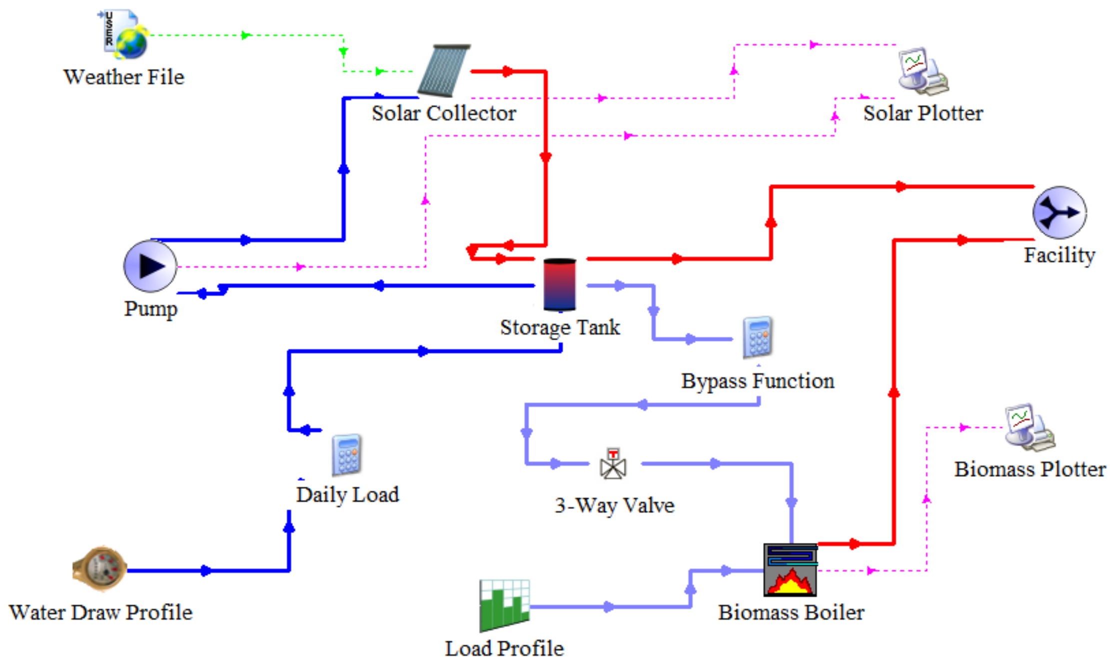



**Fig. 4.1** TRNSYS model of HSBS for preheating of boiler in industry

### 4.2 Technical Assessment

#### *4.2.1 Temperature profile*

The annual output temperature that can be achieved through the Hybrid Solar-Biomass System (HSBS) is illustrated in Figure 4.2, based on simulated data obtained from TRNSYS 18. During the Summer, ST resource achieves a maximum of 170ºC while in Winter it achieves a maximum of 110ºC. Furthermore, the output temperatures of the solar collectors consistently exceeded 80ºC throughout the year, indicating that evacuated tube collectors (ETCs) are well-suited for the application in this study. It is important to note that these temperatures refer to the fluid at the outlet of the collector, which will be stored in a storage tank before being sent to the boiler [77]. However, the simulations do not account for system losses, like those occurring in the storage tank, biomass boiler, and various collector field losses, including end losses. These factors are significant and should be considered for a more accurate representation of system performance [78].

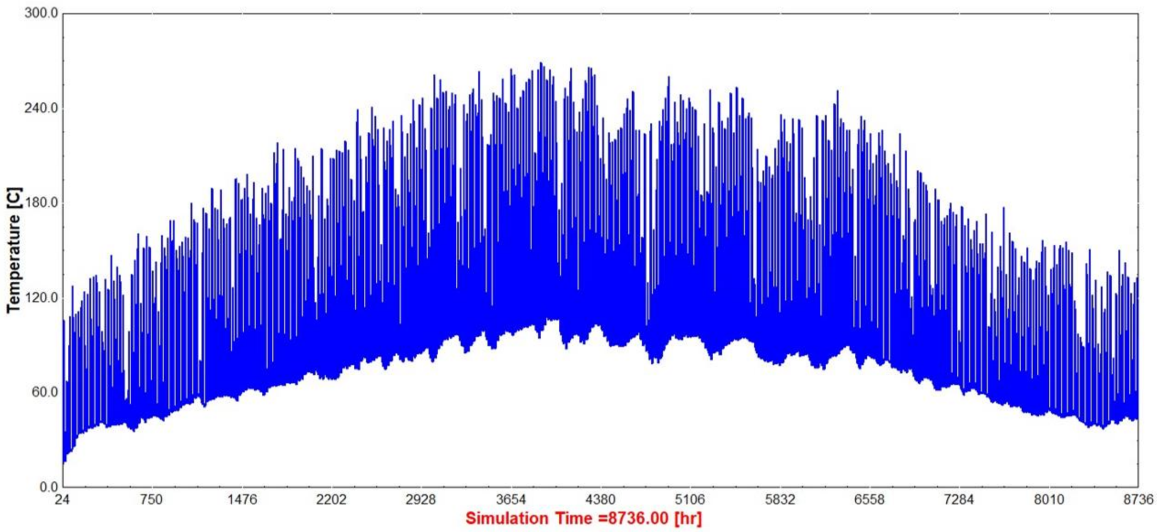



**Fig. 4.2** Output temperature of solar collectors for a year

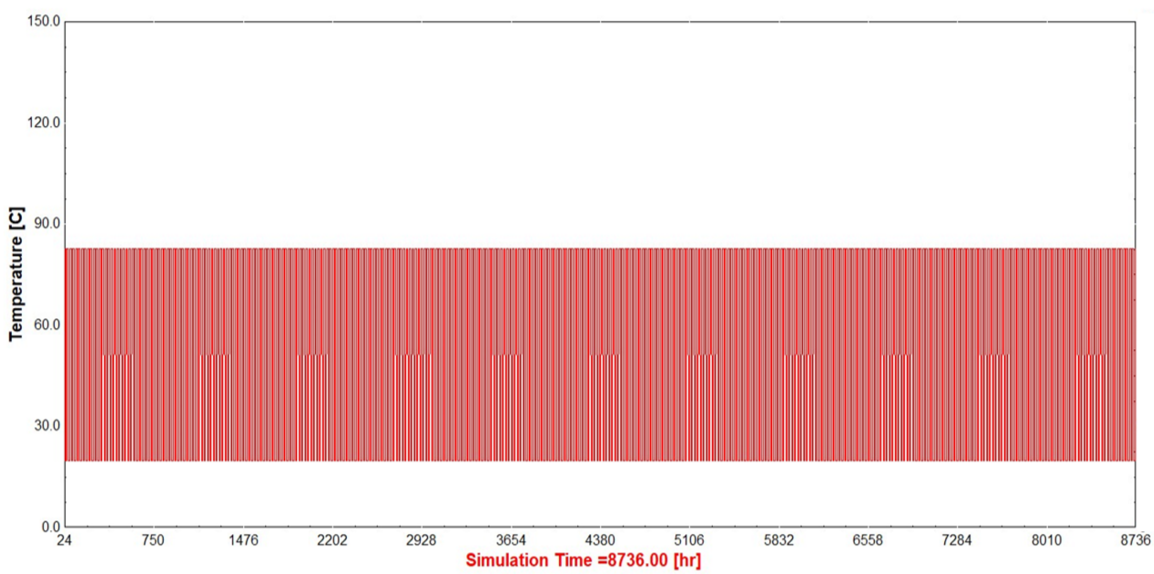



**Fig. 4.3** Output temperature of biomass resource for a year

However, biomass resource showed the constant output at 80ºC temperature as shown in figure 4.3 below, which indicates that during the period of solar intermittency, when temperature will drop below 80ºC in the storage tank, water flow will be diverted towards biomass resource and it will start meeting the temperature needs.

### *4.2.2 Temperature profile for summer and winter seasons*

The one-day performance of the solar thermal collectors (STCs) on the longest day (June 21st) and the shortest day (December 21st) is illustrated in the figures below. The purpose of examining the collector's performance on these two days is to showcase the hourly temperature output, helping industries make informed decisions about scheduling their auxiliary sources for hybridization. On June 21st, the longest day of the year and a summer day in Pakistan, the collector starts heating after 7 A.M., reaching its peak temperature around 2 P.M. The performance then gradually decreases until 6 P.M., and by 8 P.M., the collector's output temperature drops to zero.

#### *4.2.2.1 Summer season*

The output results can be seen for a summer day in Fig 4.4 where STCs perform efficiently and goes up to 170 ºC.

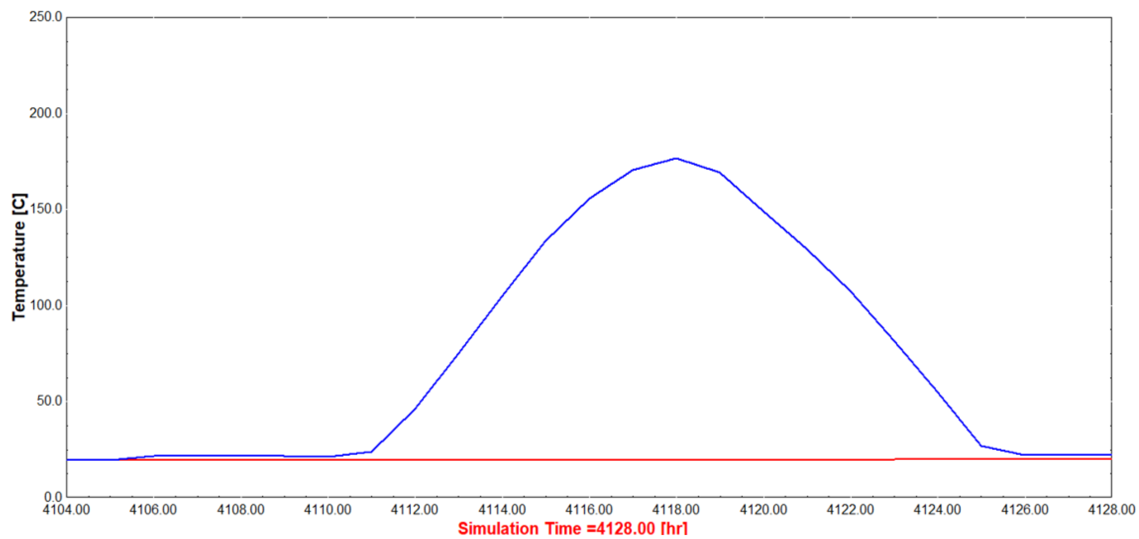



**Fig. 4.4** Performance of TRNSYS model for ST on 21st June

Meanwhile, biomass resource showed the output at 80ºC temperature during non-sunny hours as shown in figure 4.5 below.

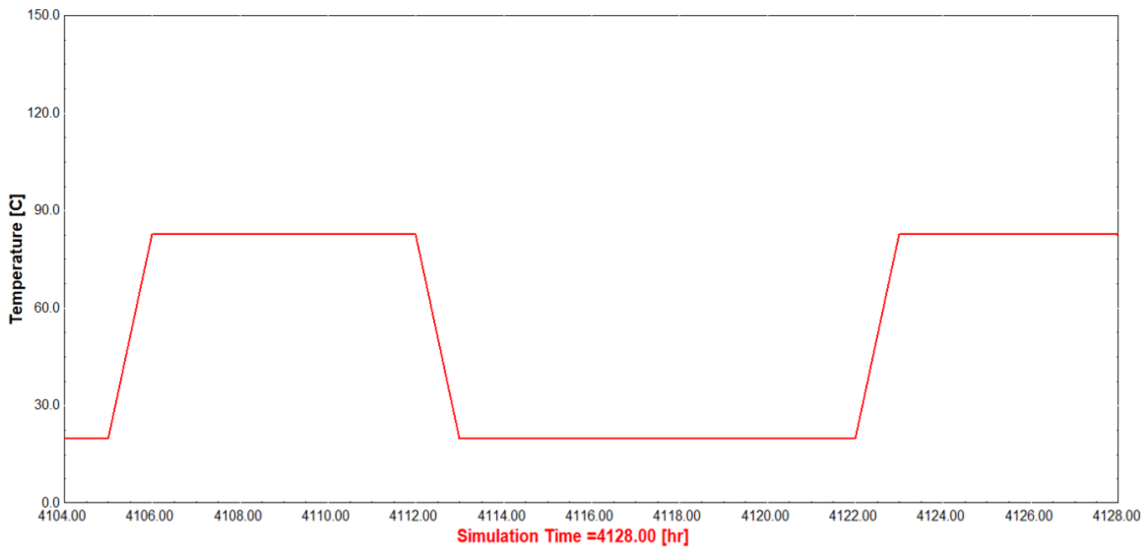



**Fig. 4.5** TRNSYS model performance of for biomass resource on 21st June

*4.2.2.2 Winter season*

On the other hand, the average temperature profile of winter season is observed by choosing the 21st December and the output temperature observed shows that temperature goes up to 120 ºC. the TRNSYS model performance for ST on 21st December is shown in figure 4.6 below.

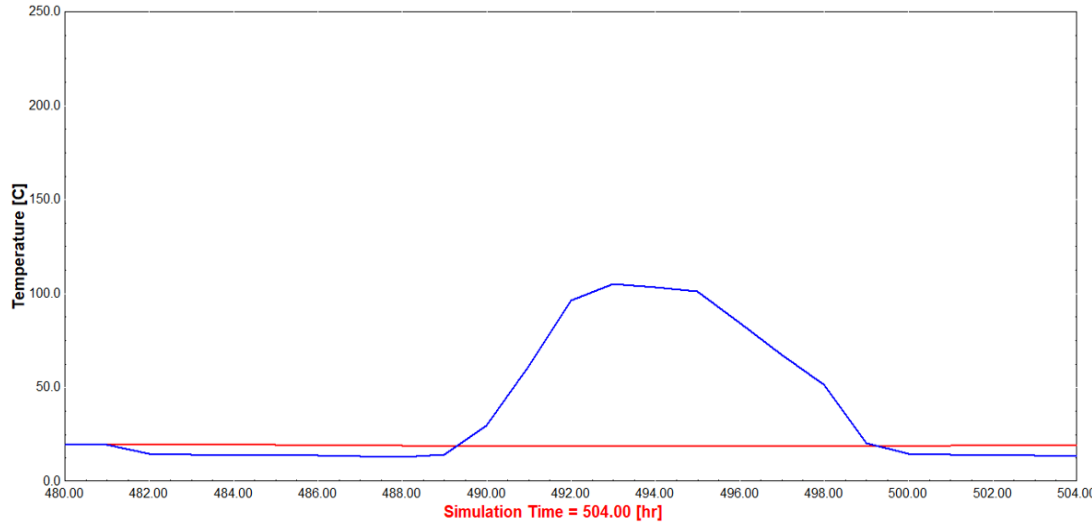



**Fig. 4.6** TRNSYS model performance for ST on 21st December

Simultaneously, the biomass resource output temperature is observed by choosing a day 21st December for winter season. It is found that, during intermittency period, biomass provide the backup by giving 80 °C output. The output results of biomass resource in the winter are shown in the figure 4.7 below.

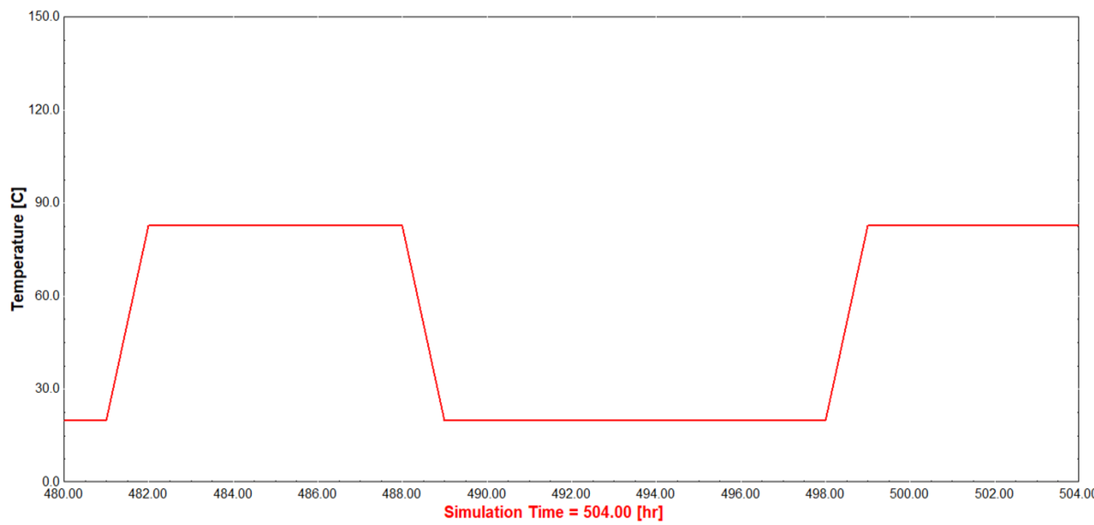
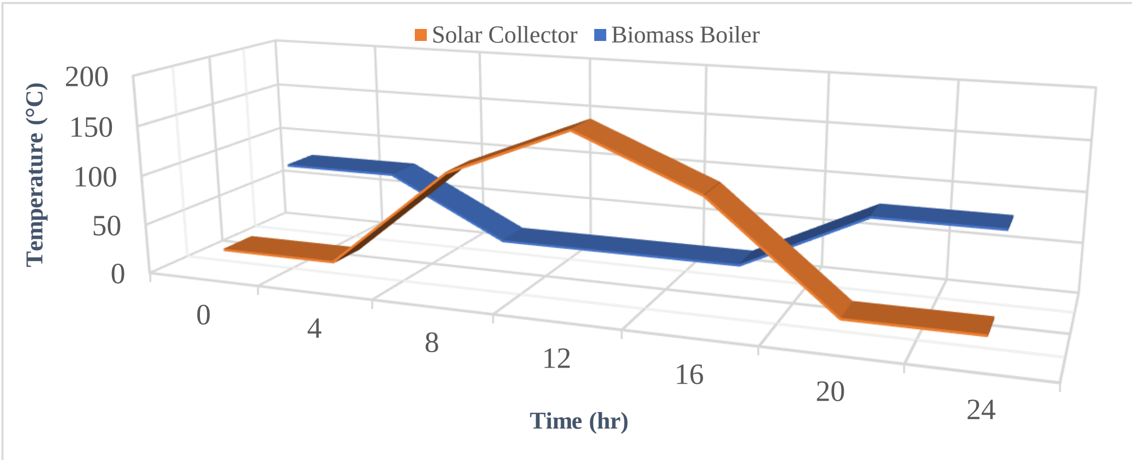
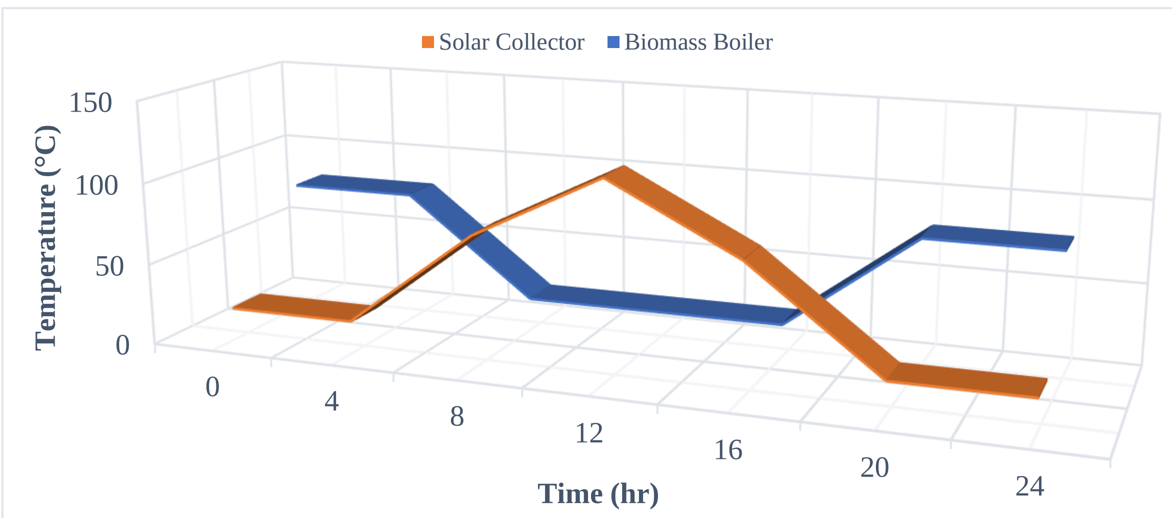



**Fig. 4.7** TRNSYS model performance for biomass resource on 21st December

The results presented above are the outputs obtained directly from TRNSYS software. However, in order to make the results of hybrid system more comprehensive, the results are plotted on excel and the output of HSBS is shown this way in the figure 4.8 (a) and figure4.8 (b) below.




(a)




**(b)**

**Fig. 4.8** TRNSYS model performance for ST and biomass on (a) 21$^{st}$ June and (b) 21$^{st}$ December

Figure 4.8 (b) illustrates 21$^{st}$ December, representing the shortest day of the year in Pakistan. The graph shows that the solar collector begins heating after 9 A.M., reaching its peak performance at 2 P.M., and then gradually decreases, with temperatures fully dropping after 6 P.M. This analysis suggests that more fuel savings are achievable during summer than in winter.

Optimizing the system is crucial, given the high installation costs, as selecting a design that maximizes savings with minimal expense is essential from an investor's perspective [79]. For solar thermal systems, optimization involved adjusting the area of solar thermal (ST) collectors and analyzing its impact on the Annual Life Cycle Savings (ALCS) over the project's 20-year lifespan. The optimal system size was identified as the point on the curve with the steepest slope, representing the best balance of savings and cost [80,81]. For the boiler, optimization was achieved by adjusting the turn-down ratio, typically ranging from 30% to 120% [82]. This design feature is instrumental in managing the intermittency of solar thermal systems and supports reliable operations [83].

### 4.3 Economic evaluation

An economic analysis has been performed based on the optimized design, focusing on indicators such as IRR, NPV, and payback period using RETScreen. The positive IRR, B-C ratio and short payback indicate the feasibility of this system. Moreover, positive NPV is another indicator of the system feasibility. The fuel saved due to integration of this hybrid system is 54.6%. therefore, annual life cycle savings along with net yearly cash flow and other important financial parameters are also presented in the table 8 below. The NPV of the system is $14.35 M. While the Annual life cycle savings are $1.92 M/yr and the Net yearly cash flow is $335526.44 for year 1.

### 4.4 Cumulative cashflow

The cumulative cash flow over a project lifetime for 20 years is illustrated in figure 4.9 This figure illustrate that it will help stakeholders to invest more and more in adapting renewable energy resources in near future for better solution to reduce fossil fuel usage. If a project is based on reduction of the carbon footprint, then there will be increment in providing more funds for developing the Renewable energy resources-based projects.

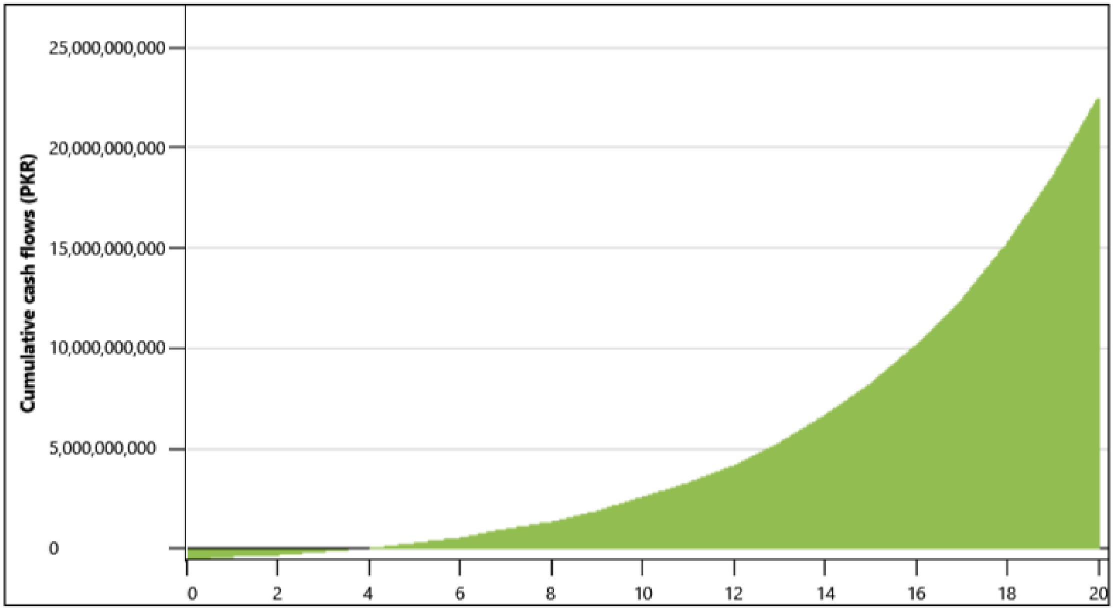



**Fig. 4.9** Cumulative cash flow of the HSBS for 20-year life cycle

### 4.5 Annual cash flow

The annual cash flow generated from RER is obtained using RETScreen software. The total contribution of each source in feedwater preheating per year is represented using figure 4.10, and is calculated using RETScreen software.

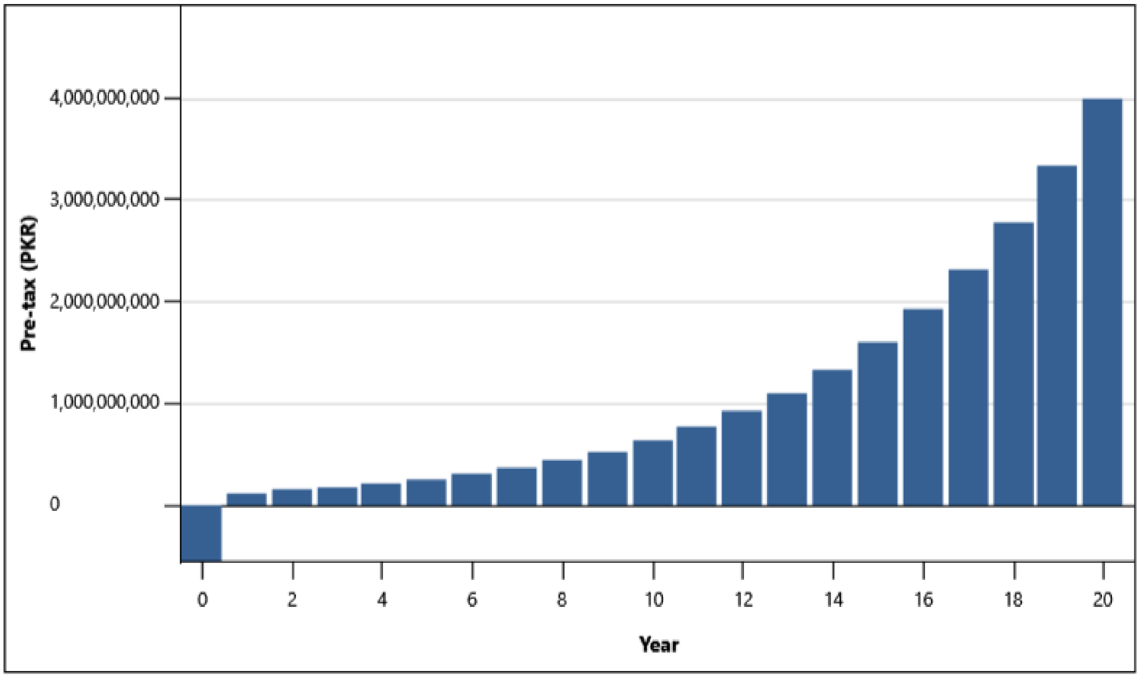



**Fig. 4.10** Annual cash flow of the HSBS for 20-year life cycle

Furthermore, the financial viability indicators that indicates the feasibility of the hybrid system are listed below in the table 4.1. The values of these indicators are obtained from RETScreen software analysis.

**Table 4.1** Financial viability indicators

| **Parameters** | **Unit** | **Value** |
|---|---|---|
| IRR pre-tax - assets | % | 39.6 |
| IRR pre-tax - equity | % | 39.6 |
| Equity payback period | yr | 3.8 |
| Simple payback period | yr | 6.2 |
| Net yearly cash flow - Year 1 | $ | 335526.44 |
| Net Present Value (NPV) | $ | 14.35 M |
| Benefit-Cost (B-C) ratio | - | 7.9 |
| Annual life cycle savings (ALCS) | $/yr | 1.92 M |
| GHG reduction cost | $/ $tCO_2$ | -2868.12 |

## 4.6 Greenhouse gas emissions

An assessment of greenhouse gas emissions reduction, measured in terms of $CO_2$ tons mitigated, is illustrated in Figure 11 below. Therefore, the gross annual GHG emission reduction is 44.3% which is 670tons reduction in $CO_2$ emissions.

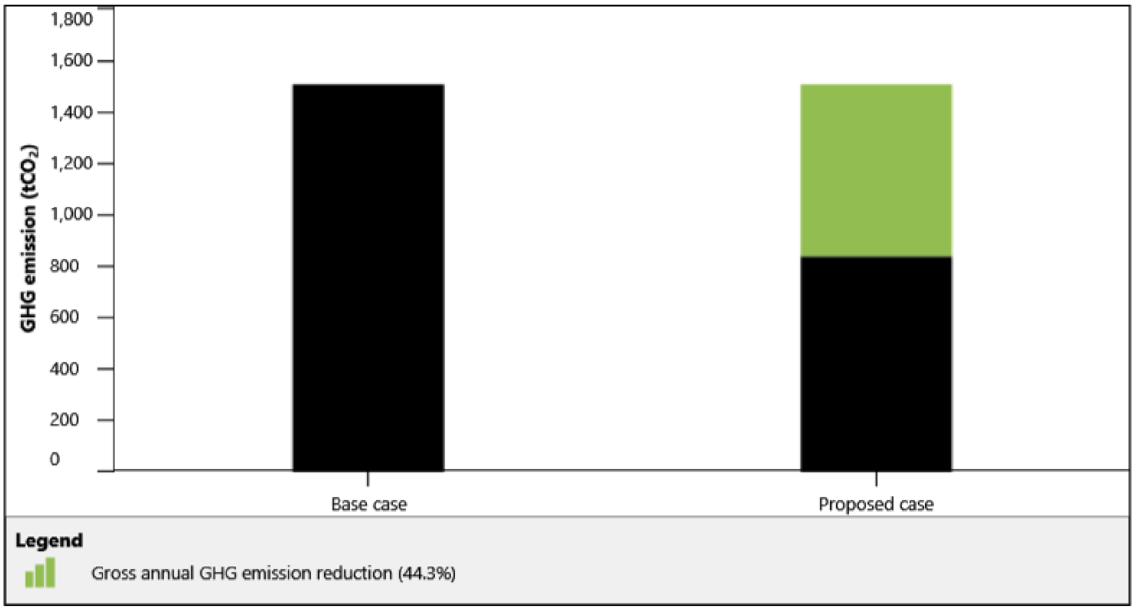



**Fig. 4.11** Gross annual GHG reduction of the HSBS

SUMMARY

As Pakistan is experiencing some serious energy issues, and the situation is getting worse now-a-days. Industrial process heating, which accounts for a significant portion of global energy consumption, relies heavily on conventional fuels to fulfil the requirement for low- to medium-temperature applications (below 400°C). This dependency contributes to high operational costs, increased greenhouse gas emissions, and environmental degradation. In countries like Pakistan, where industry is a critical economic sector, finding sustainable and economically viable solutions to reduce fossil fuel use has become imperative. To address these challenges, Pakistan has set a target to produce carbon-free energy by increasing the share of renewable energy sources to 60% by 2030. So, there is a need for time to make the transition from conventional energy sources to renewable energy sources. The development and utilization of renewable energy can assist in achieving 75% of the (SDGs) Sustainable Development Goals proposed by United Nations. By keeping in view of Pakistan’s large potential for non-conventional energy resources as a second option, hybrid renewable energy systems are better ideal for integration in process heat industries. The main focus of this presented project is to provide an economical, efficient, and reliable energy source to be integrated in industrial process heat requirements for sustainable growth while reducing fossil fuel usage.

The depletion of fossil fuels and world energy demand is still rapidly increasing. Many traditional energy resources are still facing the environmental issues. According to the literature review, many authors suggested non-conventional source of energy should be used to fulfill the energy demand of industrial process heat to replace or overcome the usage of these conventional fuels. Numerous research papers on hybrid mode of renewable energy systems have published in literature, and various tools and methodology for the analysis and design of hybrid systems for integration of RER to industries. have been offered. Some studies discussed hybrid systems electric energy management and control systems, while others discussed the techno-economic and environmental impact of renewable hybrid systems in developing countries. Similar studies for Pakistan's various are also reported in the literature. These literature reviews demonstrate relevant information and background for the proposed research project.

This study summarizes the economic analysis or technique used to perform this research. Initially, the water heating requirement data, as well as the potential and profiles of non-conventional sources of the country and of concerned region, are collected for the designing of hybrid solar-biomass system (HSBS). The methodology of the system presented the load requirement data, as well as the various daily, monthly, and seasonal heating load profiles. The collected average solar radiation and biomass resource per month is also observed and evaluated. The TRNSYS software is used to simulate the system. Different input variables were required for the simulation. The input variables include efficiency, cost etc. of different the major components. Costs of the components are determined by market study.

All simulation results and discussions are included. Economical and technical analysis of hybrid solar-biomass system is analyzed. The techno-economic analyses of the solar system hybridized with biomass resource is performed using both TRNSYS and RETScreen software.

# CHAPTER 5 : CONCLUSIONS AND FUTURE RECOMMENDATION

In this chapter the conclusions drawn by integrating HSBS to a process heat industry for pre heating of boiler feedwater, is discussed and future innovative possibilities are also mentioned.

## 5.1 Conclusions

The objective of the HSBS project is to model, evaluate, and optimize a novel hybrid solar thermal and biomass system designed to pre-heat feedwater to 80°C for a tobacco industry, considering the climate conditions of Islamabad, Pakistan. The above results indicate that the designed system is feasible and will be helpful for investors to invest in such renewable hybrid systems that are not prevalent so far in Pakistan. Therefore, the feasibility of this system is presented in a few points

- The results indicated that integrating the new hybrid solar-biomass system could effectively meet the temperature requirements of any industry that operates on process heating for low and medium temperatures.
- The analysis showed that the system saved 54.6% which makes this system economical and sustainable.
- The economic indicators NPV is $14.35 M.
- Another economic indicators IRR is also positive (39.6%) and simple payback period is 6.2 while, equity payback 3.8 yr.
- The Benefit-Cost ratio is 7.9 which is greater than 1 that indicates the system’s feasibility
- The results consistently indicate that implementing the HSBS would achieve a greenhouse gas mitigation of approximately 44.3%, equivalent to reducing 670 tons of $CO_2$.

## 5.2 Future Recommendation

The work on this proposed system can be extended in future by integrating other types of biomass feedstock or other Renewable energy resources with ST to sustainably tackle the issue of intermittency. Furthermore, the operation hours can also be extended. Based on the findings of this study, the following are some recommendations for the future.

- Future research should focus on implementing pilot studies of the hybrid system in various industries beyond tobacco, particularly those with similar low-to-medium process heating requirements, such as food processing, textile, and chemical manufacturing. This will provide insights into system adaptability and performance across different industrial needs.
- Since solar energy availability is intermittent, future work could explore the integration of advanced thermal energy storage technologies with the hybrid system. This could help ensure a more consistent heat supply, especially during low solar periods, improving system reliability and efficiency.
- To enhance the system's economic and environmental benefits, future research could investigate the utilization of various local biomass sources. Assessing the availability, sustainability, and cost-effectiveness of different biomass feedstocks will provide a better understanding of how the system can be optimized based on regional biomass resources.
- Further studies should analyze the potential for optimizing the individual components of the hybrid system. For instance, examining different solar collector types and materials could enhance thermal efficiency, while exploring efficient biomass boiler configurations could reduce operational costs and emissions.
- Given the positive economic indicators of NPV, IRR, and payback period shown in this study, future work should consider evaluating how government policy, subsidies, or financial incentives could further accelerate the adoption of hybrid renewable energy systems in Pakistan.
- Research could also examine how integrating digital monitoring tools, IoT, or automated control systems could enhance the performance and ease of operation of

the hybrid system. This would allow industries to monitor energy savings and $CO_2$ emissions in real-time, making the system more efficient and manageable.

- Lastly, further studies should explore the cost-benefit ratio of scaling up this hybrid system for larger industrial plants or regional applications. This would provide a clearer picture of scalability and how larger systems might impact both economic returns and environmental benefits on a broader scale.
- These recommendations aim to expand the application, enhance system efficiency, and strengthen the economic and environmental factors for hybrid solar-biomass systems in industrial energy usage.

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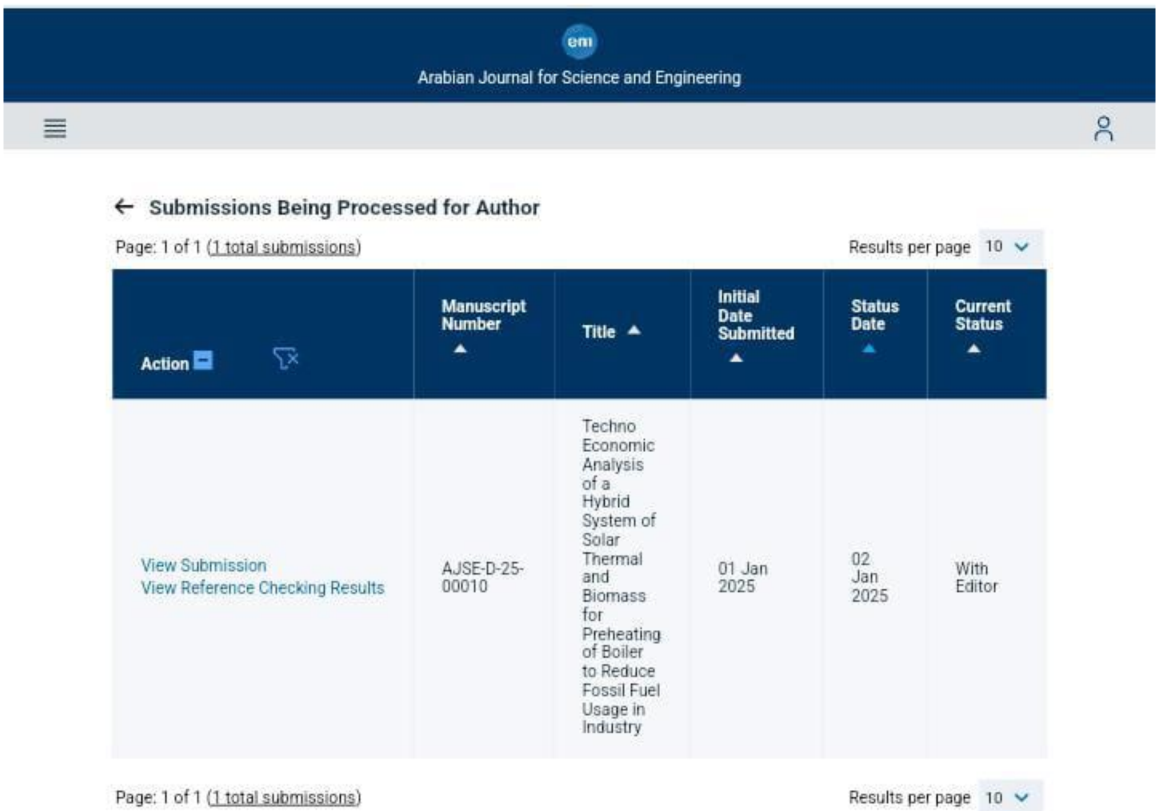

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