CHAPTER 1

INTRODUCTION

1.1 Motivation

A country's economic development heavily relies on the availability of abundant and diverse energy sources. The literature highlights the significance of energy sources in shaping a nation's economic structure, demonstrating a strong correlation between financial crises and energy demand (Hong et al., 2013). The world's energy demand is primarily fulfilled through two sources: Non-renewable energy sources (NRES) and Renewable energy sources (RES). The NRESs have been widely used due to their simplicity in energy generation. However, their extensive use has led to environmental challenges like acid rain, ozone depletion, and climate change, urging an urgent shift towards renewable options (Dincer, 1998). The shift towards RES like solar, wind, hydro, and geothermal power, provides a sustainable solution. According to statistics, 13% of correctly used RESs could fulfil all of the energy needed today and in countries like India, this number stands at approximately 4.5% (Grodsky & Hernandez, 2020). However, the move towards RES isn't solely about meeting energy demands but it's also about safeguarding our planet for future generations. Addressing this concern, India has now started to invest in research and development in the filed of RES and in the utilization of it. This becomes imperative for long-term economic growth, energy security, and environmental sustainability (J. Li & Just, 2018).

Among the availbe all RES, solar energy stands out due to its widespread availability, sustainability, and environmental benefits. Yet, the shift of solar energy and other RES to practical applications faces a significant challenge due to limitations in current technologies of harnessing and effective utilisation of RES. Traditional methods of harnessing the RES to commercial applications often yield relatively low energy outputs in comparison to the costs incurred. The motivation behind utilizing solar energy extensively lies not just in its abundance but also in its potential to meet the ever-growing energy demands of our society. For instance, statistics reveal that in country like India, the average solar energy available per square meter is estimated to be 400 W/m^2 (Fossa et al., 2021). Howevere the normal peak energy demand in the country is 262 W/m^2, it becomes evident that solar energy has the capacity to substantially contribute to fulfilling this energy demand. The key lies in the design and optimization of the technology to efficiently harness this abundant solar energy for various commercial and industrial applications. By developing more effective and affordable solar technologies, the posibility to boost energy production, reduce dependence on NRES and foster a more sustainable future (Memme & Fossa, 2022).

Besides, solar thermal technology is notably more efficient at converting solar radiation into thermal energy than solar photovoltaic systems. Recent study indicates that despite its usefulness, solar thermal energy haven't made significant breakthroughs and observed that the average individual cannot afford to use the expensive technology that is currently available (Jignesh et al., 2018). This high cost barried suggest that in order to overcome several challenges, there is a critical need for further development in this field to enhance its capabilities. In general, Solar thermal systems (STS) are categorized into two types: a) those with solar collectors and b) those with solar reflectors.

In genreal, managing the Solar collector system (SCS) is more challenging than handling the solar reflecting system, as it allows for separate operation of the solar thermal system and the reflector. Solar reflecting systems are further classified based on the type of reflectors used: Curved type reflectors (CTR) or Flat plate type reflectors (FPTR). However, the CTR system is highly effective but demands critical attention for optimal performance (J. Patel & Singh, 2015). In contrast, FPTR require less attention but are suitable for non-concentrated use. Additionally, it offers advantages with minor advancements in the tracking system, as well as in the development of flat plate augmented solar reflecting systems, leading to cost-effective methods of harnessing solar radiation energy.

The design and optimization of such systems can be achieved by analyzing the impact of a single beam ray on the receiver plate of the STS. This analysis helps in optimizing the reflective surfaces and enhancing energy capture efficiency. By examining the trajectory of rays after reflection, researchers can gain insights into improving the reflective capabilities of these systems, contributing to more efficient solar energy utilization. Finally, these advancements contribute to the continual enhancement of STS, driving progress towards more efficient and impactful utilization of solar energy in various applications. The pursuit of such innovations is essential for a sustainable and cleaner energy future.

1.2 Background

India has more than 230 days of solar radiation that is reached to the ground through the year and the average received Solar intensity (I_{avg}) is about 5 to 7 KWh/m^2 per day recorded on the ground (Himanshu, 2009). India enjoys a tropical environment due to its proximity to the equator. Near the equator, there are more days with considerable solar radiation because they receive more direct sunshine throughout the year. India has been determined to be among the nations in the world that utilises the most days of solar radiation in a single year (Chaithra et al., 2023). Hence a better development of solar system really helps in the critical energy need of the country. From literature it is observed that there has been substantial work carried out in harnessing and utilizing solar radiation energy across various commercial and industrial applications. The total volume of solar energy used for commercial and industrial applications worldwide in 2022 increased by approximately 13.4%, particularly due to the incorporation of solar photovoltaic and solar thermal technologies (Panchal et al., 2021). This trend is expected to continue in the days ahead. There is also a claim that all the global energy need may be met with just 23% of the gross solar radiation received on Earth ("India Energy Outlook," 2021).

The STS converts solar radiation to thermal energy mainly with use of (a) SCS and (b) solar reflecting system (Priyanshu et al., 2018). In which SCS are further divided in to two more category, concentrating type collector and flat plate type of collector. Literature demonstrate the various application of concentrating type collector by investigators for different thermal applications considering various positions of sun were discussed in details (Pranesh et al., 2019). Since, concentrating type collector and flat plate type collector typically designed to carry the entire weight of the system while tracking. This simultaneous act of carrying load and tracking the sun is extremely challenging and expensive. Opposite to this, solar reflecting system receive the solar radiation and reflect this to target, leading to a smooth and hassle free operation of the system. Furthermore, it lowers the self-consumption of power by the operating system because the system need less weight to carry while tracking the sun.

The solar reflting system is further divided into two main types: CTR and FPTR. The FPTR is then classified into heliostate reflectors (which is capable to follow the sum) and simple plane mirror type reflectors (which is remain stationary). The dual-axis guided heliostat reflector can be adjusted its surface to the sun throught the day for maximizing the amount of solar radiation for a specific application. The investigator worked in detailed on multiple applications of solar heliostats and for varying altitudes and sun positions (Sattler et al., 2020). It is observed that the heliostat-augmented STS results in a lower performance than its concentrating type collector counterparts. However, most of the studies agrees that it is more convenient to use heliostat-augmented STS due to its lower cost compared to concentrating type collector. Similar conclusion was drawn by literature when the performance of STS is with FPTR. Typically, the primary purpose of STS with FPTR is to collect solar radiation and redirect it to the receiver with the help of a tracking under a single axis, second axis under this arrangement is already aligned through the day (this type of arrangement is popularly known as the azimuthal alignment of the solar reflector). FPTR-assisted STS can also be used to get over the issue with STS using heliostats, which is the tracking mechanism for the dual axis.

Furthermore, when comparing performance of CTR and FPTR, literature observed that CTRs found advantagious in that they effectively focus sunlight onto a smaller region however they have certain disadvantages. These reflectors' complex forms and curved geometry make fabrication even more difficult, leading to raise production costs (Aktar et al., 2021). Precise engineering is required to manufacture the curved parts of CTRs, which is not necessary for FPTRs, making them easily available in the local market. In comparison to CTRs, FPTRs are more durable due to their simpler manufacturing methods. These aspects play a significant role in making FPTRs an option that can replace many solar thermal applications. In summary, the FPTRs' simplicity, affordability, and convenience of use have made them an obvious choice. In one of the literature, research has highlighted that due to FPTR’s simple design and construction makes it a perferred options for a variety of solar heating systems, including solar water heaters, cookers, and some solar power plants (G. Zhu et al., 2014).

Reviewing open literature, the large-scale utilization of FPTR is very rare due to a lack of information about its application for significant thermal purposes and the unavailability of numerical tools to analyze FPTR (Pauletta, 2016; Y. Zhu et al., 2017). A systematic study of determining the performance for large scale applications can certainly change the scenario. An experimental study on the use of FPTRs when employed to improve the performance of the photovoltaic solar energy conversion systems noted that the modififed solar photovoltaic increase overall efficiency by 12% when compared to photovoltaic system without FPTR (Shakeriaski et al., 2021). However, it is observed that very few literature actually attempt numerical analysis of the FPTR that provides therotically the information about its behavior at a single point. An extensive investigation into the solar funnel cooker made of FPTR for low sun elevation and light levels has been conducted both numerically and experimentally, taking into account the azimuthal solar tracking method. The sudy suggest that, thermal performance is roughly 29% higher compared to a typical solar cooker without opting for any reflector (Chauhan et al., 2022). Considering the complex computational nature involved in determining the performance of a solar cooker, several commercial as well as open-source analysis tools are available. It is advantageous to utilize such analysis tools.

However, few investigator questioned the use of commercially avaiable software and cautioned the users. They made their point valid by considering certain cases wherein the result obtained by these commercial softwares disagree to a great extent with their theoretical predictions. The large error observed in validating the result obtained using commercial software with experimental results emphasises a strong need to develop a simplified yet a reliable testing procedure for determining optical performance of FPTR. With an aim that such procedure should equally work well even when applied for a complicated topology (Ghodbane et al., 2021; Jathar et al., 2022; Pujol-Nadal et al., 2017).

Besides, certain litrature also demonstrated an alternate way of analysising similar sysem, under this they claimed that the direction that rays would take after reflecting off from a reflector can be predicted numerically using the shadow of the the reflector casted by the surface on a hoorizontal surface or ground. Altough sounds simple and straighforward, this approach is also not the best when applied to a large systems involving number of small reflectros (Apaolaza-Pagoaga et al., 2023; Getnet et al., 2023). In one of the study the experiment on CTR based solar system was carried out and it was observed that the study followed a simplified and effective testing method to predict the behaviour of a single ray for testing of a CTR system (More et al., 2018). Under this study, a dedicated and simple testing facility was designed and used during the experiments. In this set up use of a laser as a light source was successfully demonstated. The path traced by the ray of the light is simulated by the laser and is systematically tracked. The collected results demonstrate that there is only 2% of rays found inaccurately tracked and resulted in error when compared to the theoretical and numerical path of rays.

Inspired by such simple methodoly and study of this particular literature a firm discision was made that the ray behavior can be tested by using a simple model and under similar approach for the presetn study. Letter on it was demostrated that similar testing method can also be adapted or modified to the solar system based on FPTR. In line with this understnding a dedicated numerical tool can be developed which will deduce a quantifiable understanding of the chosen geometric elements and the same can be compared with the corresponding experimental results. The application of this methodlogy and neumerical tool may be used to optimise the shape of geometry and to better comprehend the overall system under different diarnual or territorial conditions.

1.3 Thesis Outline

The entire thesis is divided in to seven chapters. It begins with an introductory section that discusses the motivation and background of the present work. The chapter -1 introduction section also gives the information about the existing technology of solar thermal system and required changes or possibilities of the research can be done. The chapter -2 covers a comprehensive literature review that includes, the solar thermal system with CTR and FPTR, numerical tools, grid refinement processes and its limitations in solar thermal system, and certain optimization strategies. Finally, the proposed objective of the present study are given at the end of the chapter 2. Moving to Chapter -3, the mathematical and numerical modelling of STS with FPTR are dicussed. Herein the numerical model which is coined as Ray tracing algorithm (RTA) is discussed in detail. Chapter – 4 discusses requirement of an optimum grid size and its need. The details about the proposed guidelines for obtaining N and its implementation with help of a case study, along with discussions on the outcome of its implications and the results covered in this chapter. Chapter - 5 explores into the experimentation of FPTR having Square type configuration (STC). It also discuss the corresponding ray classification, CAD modelling of the same design, and its validation with experimental results. Following this, Chapter - 6 explain about optimizing FPTR based STS with for a) optimum height-to-bright ratio and presenting comparative results. Additionally, the comparative behaviour FPTR having STC, Hexagonal type configuration (HTC) and Octagonal type configuration (OTC) were analysed and results were presented. Lastly, Chapter - 7 discusses the conclusion and future scope of the present work. The thesis ends with; comprehensive reference section, list of publications, and is followed by appendix section for additional and detailed information for interested readers.