1
Introduction

Worldwide energy demand is increasing significantly to meet population growth requirements and industrial production. The energy supplied can be categorized, on the basis of its origin, mainly as fossil fuel energy, nuclear energy, and renewable energy [Ummadisingu *et al.* 2011, Moriarty *et al.* 2009]. Among these energy sources, fossil fuel utilization is motivated by its high energy density, easy availability, and cost [Schulz *et al.* 2005, Ngoh *et al.* 2012, Agrafiotis *et al.* 2015, Chen *et al.* 2015]. The shift towards renewable energy is desirable due to the depleting fossil fuel reserves and emission of greenhouse gases leading to global warming [Agrafiotis *et al*. 2015, Chen *et al*. 2015, Barlev *et al.* 2011, Behar *et al.* 2013]. Renewable energy is a source that is harnessed and renewed naturally and is a sustainable source with almost zero emission of GHG (greenhouse gases) and pollutants [Güney *et al*. 2019, Harjanne *et al.* 2019, Verbruggen *et al*. 2010, Şener *et al.* 2018]. Some examples of renewable sources are solar energy, wind energy, tidal power, geothermal energy, etc. [Alrikabi *et al.* 2014, Ellabban *et al.* 2014].

Solar energy offers a promising option to fulfill future energy demands due to its availability, cost-effectiveness, accessibility, capacity, and efficiency compared to other renewable energy sources [Kannan *et al.* 2016]. Many countries receive an immense amount of solar irradiance ranging from 2.2 to 7.4 kWh/m² (see Figure 1. 1). For example, the daily average solar irradiance over India varies from 4 to 6.6 kWh/m2 with the sunshine hours ranging between 2300 to 3200 per year, depending upon location [Sharma et al. 2011].

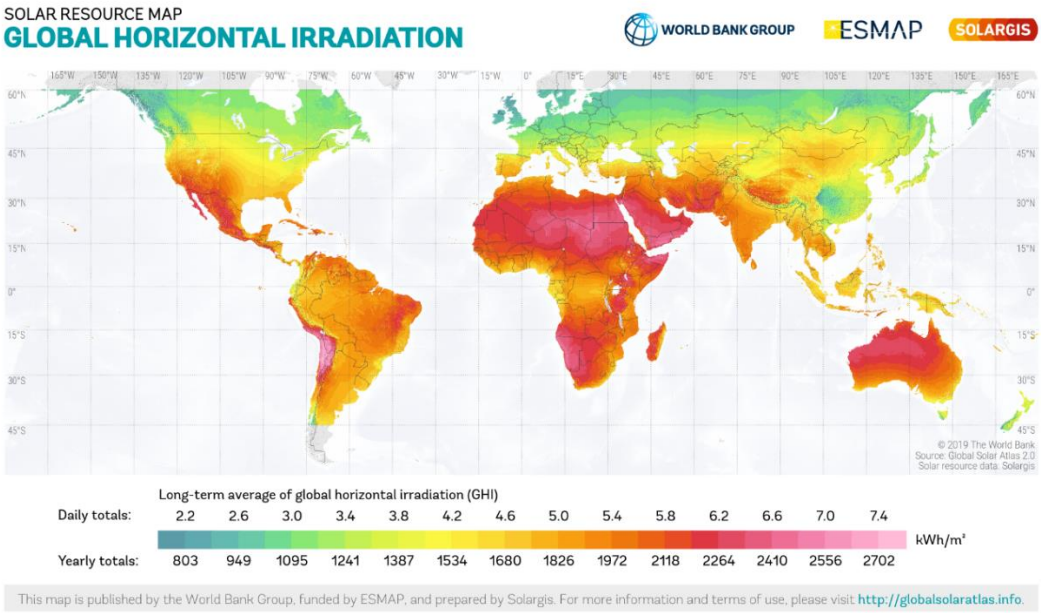

Figure 1. 1: World map of global horizontal irradiation (GHI) [Source: https://globalsolaratlas.info]

There are mainly, two different technologies to harness abundant solar energy. One is the photovoltaic (PV) technology, in which PV cells directly convert solar radiation into electrical energy by the PV effect. The other is the concentrated solar thermal (CST) technology, in which the direct

normal solar irradiance is first concentrated and subsequently converted into heat, and then the heat is used in different applications such as power generation, processing, heating, cooling, etc. [Ju *et al.* 2017]**.** CST can potentially satisfy thermal and electrical needs [Conrado *et al.* 2017, Kumar *et al.* 2015, Zou *et al.* 2017, Espinosa-Rueda *et al.* 2016, Cheng *et al.* 2013]. The CST systems can be classified as line focussing or point focussing. The solar concentrator can be classified using the geometry of the reflecting surface like parabolic trough concentrator (PTC), linear Fresnel reflector, paraboloid dish concentrator, and heliostat. Figure 1. 2 shows the schematic of these concentrators **[**Fuqiang *et al.* 2017, Zhang 2013**].**

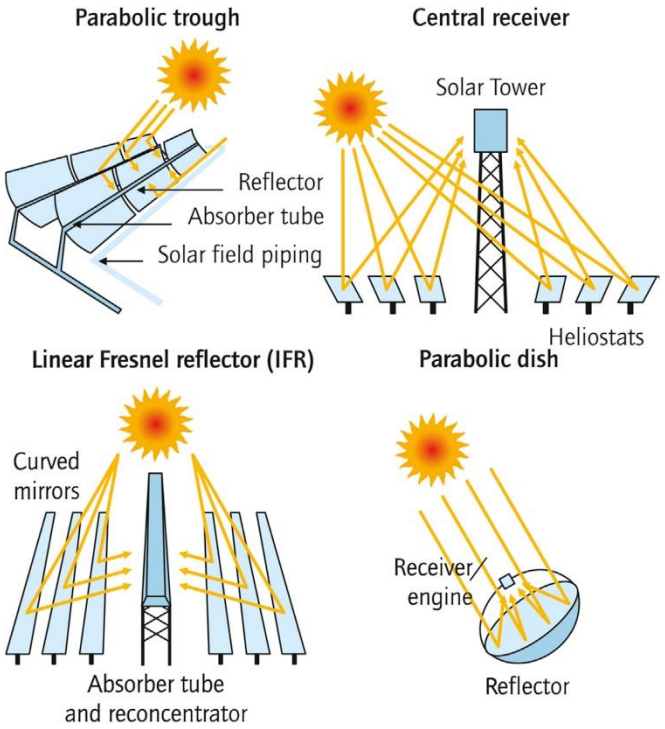

Figure 1. 2: Types of solar concentrators: parabolic trough concentrator, heliostat field concentrator, linear Fresnel reflector and paraboloid dish concentrator [Fuqiang et al. 2017]

Some operating details for the different CST systems are tabulated in Table 1. 1. The PTC and LFR with a linear tubular receiver can achieve a flux concentration of up to 50 Suns and provide a high-temperature fluid up to, say 500 °C. Using a point focussing receiver, the paraboloid dish and heliostat can achieve a flux concentration beyond 1000 Suns and provide a high-temperature fluid beyond 1000 ^{o}C [Barlev *et al.* 2011]. Therefore, it may be argued that point-focussing technology is more versatile for applications. However, the need for an accurate two-axis tracking mechanism and focussing accuracy remains challenging for point-focussing concentrators. The different types of CST technologies are summarized in Table 1.1.

Table 1. 1: Operating conditions for the different types of concentrated solar thermal technologies

Concentrator	**Temperature**	**Concentration ratio**	**Tracking**
Parabolic trough	up to 500 °C	up to 50 Suns	One-axis
Linear Fresnel			

Paraboloid dish	beyond 1000 ^{o}C	beyond 1000 Suns	Two-axis
Heliostat			

Heliostats or mirrors require maximum reflectivity, silver coating, multilayer coating such as silver with copper, aluminum, silvered polymers, and advanced solar coatings with reflectivity up to 94% can be used (Raza *et al.* 2018, Kennedy *et al.* 2005). On the other hand, the absorbers/receivers require such coatings whose absorptivity is maximum, and emissivity is minimum. There are several types, such as intrinsic absorbers (Al2O3, Fe2O3, etc.), semiconductor metal, multilayer interference stacks, cermets, etc. (Al-Rabeeah *et al.* 2022). Using selective coatings is also useful in minimizing heat loss.

Solar thermal energy can be used for domestic as well as industrial purposes. Some well-known applications are solar water heating, space heating and cooling, cooking, refrigeration, industrial process heating, solar furnaces, heat treatment, solar desalination, chemistry applications, power generation, etc. **[**Kalogirou *et al.* 2004, Naik *et al.* 2017, Thirugnanasambandam *et al.* 2010, Ghafoor *et al.* 2015**].** Kumar *et al.* (2019) reported that this is about 32–35%, which is significant in terms of the consumption of fossil fuels and the generation of greenhouse gases. Iron and steel-making process produces about 2.6 Gt/yr of CO_2, which is about 6% of global carbon emission Olabi *et al.* 2022.

India has a large potential to manufacture components for CSP. The Government of India has launched programs like Jawaharlal Nehru National Solar Mission (JNNSM) for the use of solar energy in India, many policies are also made for the promotion and demonstration of CSP plants. Manufacturing the components in India itself could lower the costs of some components by up to 40%. Developing a local supply chain which includes local manufacturing companies such as APS India (Gujrat) and Karmtara (Maharashtra), can generate a manufacturing ecosystem in India in the field of solar energy (Kulichenko *et al.* 2013, Purohit *et al.* 2017).

1.1. Solar thermal in drying, process heating, food, and agriculture

Besides the high-temperature application, CSP is also widely used in low-temperature applications such as drying, process heating, food, agriculture, etc**. [Lingayat *et al.* 2021**]**. Many are reported in various literature and listed in Table 1. 2.

Table 1. 2: List of literature reporting solar thermal application in drying, process heating and agriculture

Industry	**References**	**Application**
Agriculture and food industry	Lingayat et al. 2020, Zachariah *et al.* 2021, Baniasadi *et al.* 2017, Atalay 2019	Drying of red chilli, garlic, apricot, apple, orange, bitter gourd, etc.
Tea industry	Pou et al. 2020, Kane 2008	Drying of tea leaves
Automobile industry	Giampieri *et al.* 2020	Surface treatment, drying of the finished product
Rubber industry	Janjai *et al.* 2015, Jitjack *et al.* 2016	Drying rubber sheets, preheating

Pulp and paper industry	Hjort *et al.* 2014	Drying of paper sheets
Lignite coal industry	Liu *et al.* 2017, Xu *et al.* 2018	Pre-drying of coal

1.2. Solar thermal in thermochemical, metal processing, and metallurgy

The concentrated solar thermal system can be used for the treatment and surface modification of metals. List of some reported literatures are given in Table 1. 3. For high-temperature processes, such as welding and cladding, surface treatments, coatings and surface hardening, and powder metallurgy, CST offers a viable and cost-effective option [Herranz *et al.* 2010, Fernández-González *et al.* 2018**].** Moreover, there is an immense potential for using CST as a heat source for high-temperature applications such as the decomposition of alumina, calcination of limestone to lime in solar kilns, production of syngas from natural gas, thermochemical production of hydrogen, and for various metallurgical processes, including nickel and direct reduced iron production [Eglinton *et al.* 2013, Villafán-Vidales *et al.* 2017**].** It is worthwhile to mention that CST-based systems can be easily adopted by industry for such processes to reduce the emission of GHG**.** Some of these high-temperature applications of CST systems are summarized in Table 1.3.

Table 1. 3: List of literature reporting solar thermal application in thermochemical**,** metal processing**,** and metallurgy

Reference	**Application**
Herranz *et al.* 2010	Material science, material treatment, surface modification
Eglinton *et al.* 2013	Minerals processing industries
Villafán-Vidales *et al.* 2017	Chemical industry (hydrogen and syngas production)
Fernández-González *et al.* 2018	Metallurgy
Catana *et al.* 2019	Surface modification, improvements in physical properties

Heat treatment or processing of metals, such as annealing, tempering, stress releasing, etc., are performed at predefined temperatures. Some of the examples of metal treatment with their temperature range are given in Table 1. 4. The use of solar furnaces for metals processing has already been investigated and with interesting findings. Solar furnaces, making use of concentrated solar irradiance for materials processing, are classified as direct or indirect types. In a direct solar furnace, a material is directly exposed to concentrated solar irradiance [Suresh *et al.* 1979]. In an indirect solar furnace, a receiver/absorber is used to heat a fluid, which is transported to the furnace [Alonso *et al.* 2015, Villafán-Vidales *et al.* 2017]. The problem associated with a direct solar furnace is the non-homogeneity of heat flux on the surface of exposed materials [Oliveira *et al.* 2016]. A concept called solar convective furnace (SCF) has been proposed for the heat treatment of metal [Patidar *et al.* (2015a and 2015b)]. They argued that an SCF would be more appropriate for heat treatment operations than a direct-type solar absorption furnace to generate the process heat. Solar energy is abundant and freely available, however, its intermittent nature necessitates the use of thermal energy storage for the off-hour operation of a solar thermal system [Fath 1998, Powel *et al.* 2012**].** Findings reveal that CST system-based heat treatment is ecological-friendly and yields a product of comparable quality to that of a conventional energy source [Catana *et al.* 2019].

Table 1. 4: Heat treatment with their temperature ranges of some common metals [Laleh et al. 2022]

Material	Melting point (°C)	Stress relieving (°C)	Solution annealing (°C)	Aging (°C)
Austenitic stainless steels	1371–1399	400	1010–1120	~300
Precipitation hardening stainless steels	1404–1440	650-750	1025–1050	480–620
Duplex stainless steels	1410–1460	475	1020–1100	280-320
Tool steels	1400–1425	550-650	~1010	450-500
Maraging steel	1425–1505	480-500	~815	455–510
Ni-based super alloy Inconel 718	1260–1336	1065 ± 15	926–1010	621–718
Aluminum alloys	475–655	200–400	300–410	115–190
Titanium alloy Ti-6Al-4V	1604–1660	480–800	1000–1200	400–750

Considering the above-mentioned aspects, Sharma *et al.* (2015a) proposed the concept of a central solar tower-based, indirect heating-type, integrated SCF system for the heat treatment of aluminum. A schematic of the SCF system is shown in Figure 1.3. In this system, heliostats are used to concentrate solar radiation onto an open volumetric air receiver (OVAR) for heating ambient air to the desired temperature level. The hot air from the receiver is transported to SCF directly or via a pebble bed, sensible thermal energy storage. The relatively cold air from thermal energy storage and from SCF is returned to the receiver for its internal cooling and redistribution of heat.

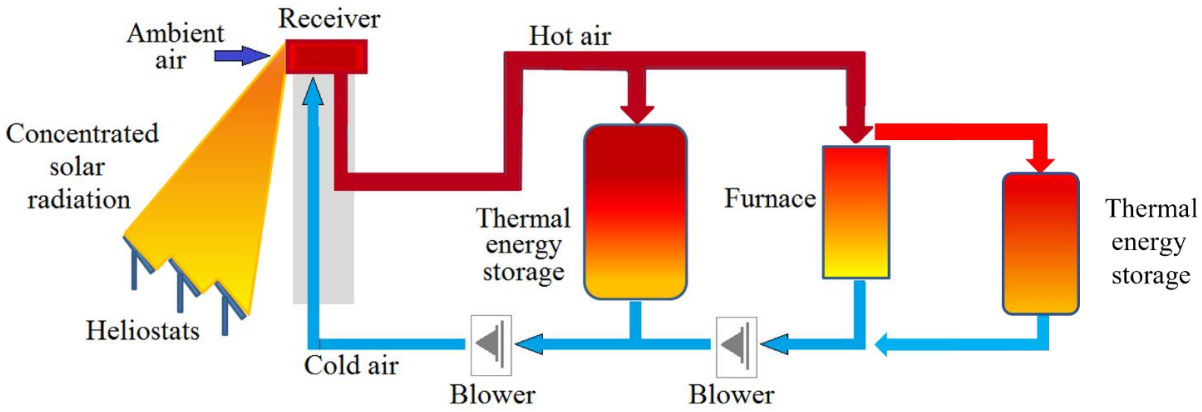

Figure 1. 3: A schematic showing the concept of a central solar tower-based solar convective furnace system

One of the key components of the integrated SCF system (SCFS) is OVAR. This comprises multiple high-temperature resistant porous absorbers. These absorbers are made up of metallic or ceramic foams, metal wires, matrix of metal or ceramic, metallic or ceramic cylinders with pores, tubular, etc. The OVAR can provide hot air at a temperature >800 °C with appropriate metallic absorbers and >1200 °C with ceramic absorbers. An OVAR developed and tested by Sharma *et al.* (2015a, b), is selected for the SCFS. This receiver comprises one central and six peripheral, straight-pore-based, cylindrical absorbers. Experiments with a lab-scale 2kWth-level OVAR for different operating conditions were reported to achieve hot air up to 360 °C. Singh *et al.* 2021 developed a two-zone, 1D, unsteady heat transfer model for analyzing the OVAR and to identify important parameters for its scaleup, which is foreseen considering a realistic heliostat field exceeding e.g., 100 m^2. Thus, the inclusion of intermediate absorber layers between central and peripheral absorbers is

considered. The details are presented in Chapter 2, highlighting the need for a comprehensive model, including all the modes of heat transfer, for the scaleup of OVAR design.

Another important sub-system of SCFS is thermal energy storage (TES), in which widely available, low-cost pebbles are used for the storage of heat. A TES is commonly used for solar thermal systems, buildings, waste heat recovery systems process industries, etc. In particular, the intermittent nature of solar energy necessitates the use of TES for 24 x 7 operation of a CST system and is beneficial in terms of efficiency and economy. The details of a TES, employed for operating the SCFS, are presented in Chapter 3. Also, this chapter includes a literature review, highlighting a wide variation among the data and the need for an in-depth experimental assessment of TES.

The SCFS also includes the retrofitted 1:15 scale-down model of an industrial aluminum soaking furnace as in Aditya Birla Science and Technology Center, Mumbai. SCF can be used for heat treatment of aluminum via forced convection. The need for in-depth assessment of SCF is realized for its implementation. Therefore, experimental and numerical investigations are performed and reported in Chapter 4. Finally, a system-level numerical tool is developed for the entire SCFS to enable its scaleup in Chapter 5. This also includes the heat transfer analyses for an insulated piping network, which transports and redistributes hot air from OVAR to other sub-systems. Finally, an operating strategy for SCFS is presented.

1.3. Objective of thesis

The need for various experimental and numerical investigations for the SCFS sub-systems and the entire system level is highlighted. Detailed literature review concerning each of the sub-systems are presented in the corresponding chapter. Here, considering the literature review, the following objectives of the thesis are framed:

a. A comprehensive, unsteady heat transfer model is developed to enable the scaleup and practical implementation of an OVAR. This includes all the modes of heat transfer, viz. conduction, convection, and radiation. A detailed investigation is performed to identify the important parameters and their effect on the thermal performance of an OVAR, especially for design scaleup.
b. An in-depth experiment-based energy and exergy assessment of a sensible, pebble bed, TES is performed. This allowed identifying the different heat transfer processes and some ways to improve the thermal performance of the TES. Also, a numerical model is developed and validated for an experimental TES. The findings will be useful for its scaleup and its performance improvement.
c. Experimental investigations are performed for the feasibility assessment of the retrofitted, industrial, scale-down SCF system. A provision for in-situ heat recovery is discussed for the developed SCF system. Also, a mathematical model for heat transfer in SCF is developed and validated with the experimental data. Finally, an integrated numerical model is developed for the entire SCF system, including all the sub-systems viz. OVAR, TES, piping network, and SCF. The experimental and numerical findings will enable the scaleup of SCF system and its implantation in an industry.