Decarbonization of industrial processes: technologies, applications and perspectives of low-temperature solar heat (80-150°C)

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Summary

Low-temperature (80-150°C) solar collectors guarantee a very high efficiency (up to 60%) in the conversion of solar radiation into useful thermal energy. Moreover, solar thermal technologies are already reliable solutions, relatively cheap and widely available in the market. For that reason, solar collectors operating at low temperatures are among the most important sustainable technologies that can reduce the fossil fuel consumption of industrial processes and their corresponding carbon footprint. Unfortunately, Solar Heat for Industrial Processes (SHIP) is still mostly unused for several reasons, e.g., not easy identification of the appropriate applications (e.g., cleaning processes, drying, desalination) or lack of knowledge of the potential environmental and economic benefit of the use of SHIP technologies. For that reason, this work includes i) an overview of solar technologies for low/medium -temperature SHIP (80-150°C) ii) results obtained on the innovative design of the mirrors used in evacuated receiver tube by means of a variation in the shape of its internal reflector iii) estimation of CO_2 saving using a solar field based on evacuated tube collector (ETC). The work also includes a comparison of the standard ETC solar plant with an ETC solar plant embedded with reflectors with innovative shape.

Keywords: ETC, new reflectors, predictive simulation tools, advanced control systems, solar process heat, decarbonization

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1. Introduction

More than 30 billion tons of CO_2 are released into the atmosphere every year, and this is causing climate change (Jackson *et al.*, 2018). For this reason, nowadays, it is necessary to organise large-scale decarbonization of energy processes (Gao *et al.*, 2018). Solar thermal energy is an alternative energy source to fossil fuels, it is already available, and it does not produce CO_2. The industrial sector consumes approximately 29% of the

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world's total energy consumption, which is more energy than any other end-use sector (Bolognese, Viesi, *et al.*, 2020). This value in Europe is 22.8% of which heat demand is 71% (Valencia *et al.*, 2017). The use of alternative sustainable and carbon-free technologies for the generation of thermal energy is now a compulsory choice. Solar heat has enormous potential for thermal applications but is still mostly unused, for industrial processes. In the industrial field, more than 30% of processes work in a temperature range from 60 - 150°C. For these reasons, the development of systems able to efficiently transform solar energy into heat is crucial for many industrial applications such as drying process, desalination, distillation, pasteurization and many others (Platzer, 2015). Heat production using solar energy is based on photo-thermal conversion; the photo-thermal effect is produced by a) photoexcitation due to absorption of solar photons using an optical absorber surface (black surface), b) energy release by photons to the absorber surface (heat production) and c) transfer of the produced heat using a thermodynamic fluid (Fudholi and Sopian, 2019)(Atkinson *et al.*, 2015)(Gao *et al.*, 2018). The efficiency of the photon-thermal conversion, at low temperatures (80-150°C) in particular, is very high, up to 60%, (Papadimitratos, Sobhansarbandi and Pozdin, 2016) (Wäckelgård *et al.*, 2015,). For this reason, this kind of conversion is one of the most efficient methods to convert solar energy into usable energy. The solar collectors are devices that are able to use the photo-thermal conversion in an effective manner by reducing infrared losses using appropriate optical-structural configurations. Furthermore, the solar collectors, assembled as a solar plant, are able to efficiently transport the heat produced by a solar collector a to specific thermal processes, e.g., industrial processes. Currently, the industrial sector is responsible for approximately 22.8% of Europe's total energy consumption, 71% of which is heat (Valencia *et al.*, 2017). The extensive use of fossil fuels in the industrial sector produces billions of tons of carbon dioxide (CO_2) each year, contributing to climate change. Solar heat can mitigate this problem, especially considering that in the industrial sector, more than 30% of processes work within a temperature range of 60-150°C. Unfortunately, Solar Heat for Industrial Processes (SHIP) is still mostly unused for several reasons e.g. not easy identification of the appropriate applications (e.g. cleaning processes, drying, desalination or integration in existing supply systems.), problem related on space occupation, or lacking knowledge of the great techno-economical potentials of SHIP. For this reason, in this paper includes first a brief overview of available solar technologies and applications for low/medium-temperature SHIP (80-150°C). In the second part we reported the results obtained using evacuated receiver tube with internal reflector with different shape, where we observed, and potential improve of optical performance of solar collector. Finally, taking into account the performance of solar collector we estimate the potential CO_2 emission reduction, in a agro-food industry. Moreover, we compared the performance of a solar field and a solar field with enhanced optical performance, considering the result obtained in the second part.

1.1 Overview of solar technologies for low temperature heat for industrial processes

The importance of and interest in solar energy is not new; for instance, one of the first methods to preserve food was through drying by exposing the food to natural ventilation and solar radiation. Taylor and Hayashi (2007) reported that in ancient times, pieces of meat were dried and preserved by people living around the Don River in southern Moscow (9000 BC). Solar saltworks were common in the Greek and Roman ages, such as the Salina di Trapani or Salina di Ostia. Solar drying using the sun has also been used for several centuries for many other foods, including fish and grapes. Nowdays many applications and scientific works are dedicated to solar technologies, e.g water heating(Ekechukwu and Norton, 1999)(Pangavhane and Sawhney, 2002). Heat production using solar energy is based on photo-thermal conversion. The photoexcitation can be observed in inorganic materials, such as noble metals and semiconductors, as well as in organic materials such as carbon-based materials, dyes and conjugated polymers. The efficiency of photon-thermal conversion, particularly at low temperatures, is remarkably high (>60 %). The main component of a solar thermal system is the solar collector. Solar thermal collectors capture the sunrays and convert the solar radiation into thermal energy that is then transferred to a working fluid termed Heat Transfer Fluid (HTF). The HTF can be air, steam or liquid such as water, glycol, diathermic oil, molten salt or ethanol (Kalogirou, 2009). Tracking the sun allows the design of concentration systems with reduced acceptance angles, in comparison with stationary systems, to achieve higher efficiency at higher working temperatures., but with an increase of the cost of a solar field. In the Tab 1 we reported some applications of solar thermal collectors in the industrial processes. For low temperature applications (80 -150 °C) the most suitable technologies are stationary collectors like flat plate collectors (FPC), evacuated tube collectors (ETC) compound parabolic collectors (CPC) and Flat evacuated collectors (FEC) thanks to their excellent efficiencies at low temperatures (80-120 °C), simplicity of installation and low cost. Small-scale sizing of Linear Fresnel Reflector (LFR) and Parabolic Trough Collector (PTC) are used in particular when temperatures required for industrial processes are higher than 120 °C. Parabolic Dish (PD) and Solar Tower (ST) are used when concentration ratio and high temperature is needed, for instance, for the thermochemical reaction or for production of solar thermal electricity (STE) ('Concentrating Solar Power', 2012).

Tab 1: Examples of type of solar collectors used in different sectors, for various processes and the typical temperature of solar loop.

Sector Industrial	Process	Solar Collectors types	Process temperature C°	Reference
Automotive	Paint application	ETC	90	(Hisan *et al.*, 2018)
Chemical Pharmaceutical	Cleaning Process Drying Water treatments	FPC	55	(Hisan *et al.*, 2018)(Mehrdadi *et al.*, 2007)
Mining	Galvanic Bath	ETC	60-80	(Hisan *et al.*, 2018)
Metal	Circulation	PTC	95	(Hisan *et al.*, 2018)
Food & Beverage	Pasta production	LFR	100-150	(A. Buscemi, D. Panno, G. Ciulla, M. Beccali, 2018)(Bolognese, Viesi, *et al.*, 2020)
	Drying of vegetables	FPC	30°-80°	(Fudholi and Sopian, 2019)
	Milk pasteurization	FPC	66°-118°	(Panchal, Patel and Chaudhary, 2018)
	Pasteurization	PTC	90-110°	(Rawlins and Asgcroft, 2013)
	Sterilization	PD	55°-100°	(Salim, 2018)
	Drying of agriculture water sludge			
Water treatment	Disinfection of Contaminated water Desalination	CPC FPC CPC	80 70 60-90	(Vidal and DÃ-az, 2000) (Alarcón *et al.*, 2005)

As reported in table 1 there are already several examples of study and applications of solar heat in industrial processes, and many of these examples are related directly or indirectly to food and beverage sector. For this reason one of the main interesting sector of SHIP technologies is the food and beverage sector where several processes required heat at relative low temperature (80°C-150°C) such a: drying, pasteurization, washing and sterilization (Lauterbach *et al.*, 2012). For this range of the temperature the evacuated collectors show and good thermo-optical performance and low cost. The improvement of the performance of this collector, in any case can promote the reduction of the CO_2 emission and a reduction of the capital cost of the solar field. For these reasons we studied the optical performance improvement induced by internal reflectors in evacuated tube collectors.

2. Evaluation of the optical efficiency of an evacuated receiver tube with internal reflector of different shapes.

In this paragraph we studied an evacuated tube collector ETC made by parallel evacuated glass tubes. Each evacuated tube consists of two tubes, the inner and outer. We considered the configuration with the outer tube is a transparent glass tube and the inner is can be made of copper applied with a selective coating, (this is the typical configuration for direct flow evacuated tube). Solar irradiation passes through the transparent outer tube, and it is absorbed by the inner tube. To minimize heat losses, the annular space between these two tubes is kept in a vacuum (M.A. Sabiha, R. Saidur, S. Mekhilef, 2015). According to many researchers, ETCs have considerably higher performance than flat plate solar collectors since they can collect a higher share of both direct and diffuse radiation during the day. In the literature, many studies have discussed the optical and thermal properties of the evacuated tube collectors. Back in 1974, Winston (Winston, 1974) studied a novel collector with a trough-like reflecting wall light channel with a concentration factor of 10 without diurnal tracking of the sun. One year later (Winston, 1975), they further proposed the use of a receiver for maximizing the concentrating radiation, having different cross-sections; circular, oval and fin. Rabl (Rabl, 1976) compared a variety of solar concentrators in terms of concentration ratio, acceptance angle, sensitivity to mirror errors, size of reflector area and average number of reflections, leading to a design method for maximum concentration. Rabl's next study (A. Rabl, 1976) presented the equations of the convective and radiative heat transfer and the performance of a collector with compound parabolic concentrator CPC. Lately, Telesa et al. (M. Telesa, K. Ismail, 2019) investigated the optical and thermal performance of a new ETC with and without solar tracking system, by building and validating a numerical code that calculated the effect of tilt angle, reflectivity, vacuum quality and eccentricity of the absorber. Mao et al. (C. Mao, M. Li, N. Li, M. Shan, 2019) studied theoretically and experimentally the positioning of an external reflector in an all-glass ETC. Unfortunately, there is limited research work regarding the optical design aspects in evacuated tube collectors with internal reflectors and even fewer on the geometry of the internal reflector. This work discusses the impact of the different geometries of the internal reflector on the optical efficiency of the evacuated tube collector. The receiver tube considered in the present study addresses the medium temperature applications, 100-250^{o}C, and consists of an evacuated tube, inside which an absorber tube that hosts the thermal fluid is placed. A reflector is also placed inside the evacuated tube and underneath the absorber tube, in order to provide concentration and thus, to increase the optical efficiency.

2.1 Mirror shapes for ETCs receiver tubes

ETC receivers can differ in their design in terms of materials and geometries (Felinski and Sekret, 2017). The solar receiver under investigation consists of an evacuated glass tube with an absorber tube inside and a reflector underneath the absorber. The solar radiation that penetrates the glass tube either hits the absorber directly or hits the surface of the reflector, and it is then reflected to the absorber's surface. In the surface of the absorber tube, the solar energy is absorbed and converted into heat which is then transferred to the heat transfer medium that flows inside the absorber. This section describes the research work implemented for direct flow receivers. The use of a reflector sheet inside the receiver tube, instead of outside, is the central concept, since it enables a performance enhancement and simultaneously, it addresses the durability and modularity issues that are common in this type of collectors. Also, it allows the use of higher reflectivity aluminium reflectors that cannot be used outdoor in open air. The four different configurations of internal reflectors that have been studied are shown below (Fig. *1*).

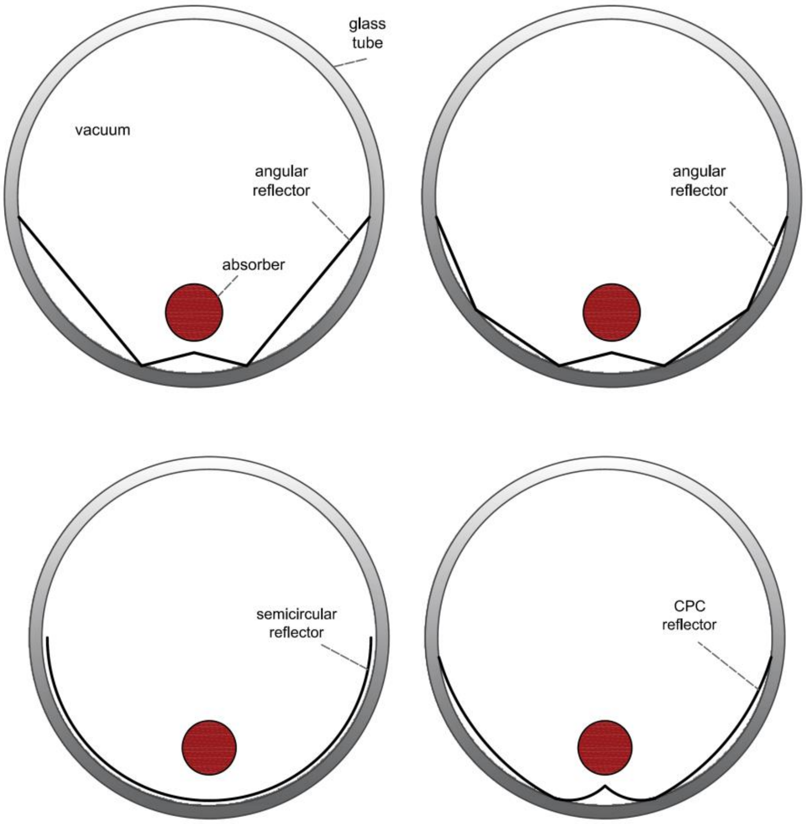

Fig. 1: Different configurations of internal ETC reflectors, from left to right: 4-sided angular, 6-sided angular, semi-circular and compound parabolic (base scenario).

The studied configurations include the most used Compound Parabolic Concentrator CPC (base scenario), the less used Semi-Circular (SC) concentrator and two simpler configurations; the 4-sided and 6-sided angular reflectors (hereafter defined as W4 and W6), (***Fig. 1***). These simple designs are studied because they are considered as simple approaches to the SC and CPC reflectors, but with an expected lower production cost due to the absence of curves. Initially, a theoretical, fully developed CPC curve was built and simulated in order to evaluate the accuracy of the results. *Tab.* **2** shows the input variables for the theoretical fully developed CPC curve and the CPC base scenario. The solar conditions set are: Sunshape type: Pillbox; irradiance: 1000W/m^2; theta$_{Max}$: 0.00465 rad (circumsolar ratio). The simulation results for the fully developed curve showed an intercept factor of 0.998, and therefore, the accuracy of the developed model is considered acceptable.

Tab. 2: Technical characteristics of ETC-CPC under investigation and for the fully developed CPC curve.

Parameter	ETC-CPC	Fully developed curve	Unit
Outer diameter of glass	0.1	not applicable	m
Inner diameter of the glass	0.093	not applicable	m
Outer diameter of absorber	0.015	0.015	m
Inner radius of CPC curve	0.0075	0.0105	m
Outer radius of CPC curve	0.0105	0.0105	m
Acceptance angle	20	20	deg
Truncation angle	0	0	deg
Truncation height	0.025	not applicable	m
Reflectivity	0.95	1	-
Length of tube	1	1	m
Aperture area	0.1…	0.193	m^2
Direct Normal Irradiance	1000	1000	W/m^2
Power received on the absorber surface	84.9	192.7	W
Efficiency	84.9	99.8	%

The dimensions used for the 4-sided angular reflector are: sides length 0.0506 m and 0.0143 m and the respective internal angles are 116° and 208°. The 6-sided angular reflector: sides length 0.0263 m, 0.0265 m and 0.0143 m and the respective internal angles are 147°, 132° and 208°. The diameter of the semi-circular reflector is 0.09 m.

2.2 Description of the Ray Tracing simulation model

The optical analysis is implemented through the development of an optical simulation model in Tonatiuh ray-tracing software (Christodoulaki, Tsekouras P. and Drosou, 2019) (*Tonatiuh software*). Tonatiuh is an open-source Monte Carlo ray tracer software for the optical simulation of solar concentrating systems and it was selected due to its high accuracy and adaptability to model modifications. Once the geometry and the materials of the solar receiver are inserted, Tonatiuh simulates the system's optical behaviour, under different solar conditions. These conditions are characterized by the Sun position in the sky, which define the main direction of the incoming direct solar radiation, and the direct solar irradiance, which defines the amount of radiant power per unit area normal to the main direction of the incoming solar radiation associated with that radiation.

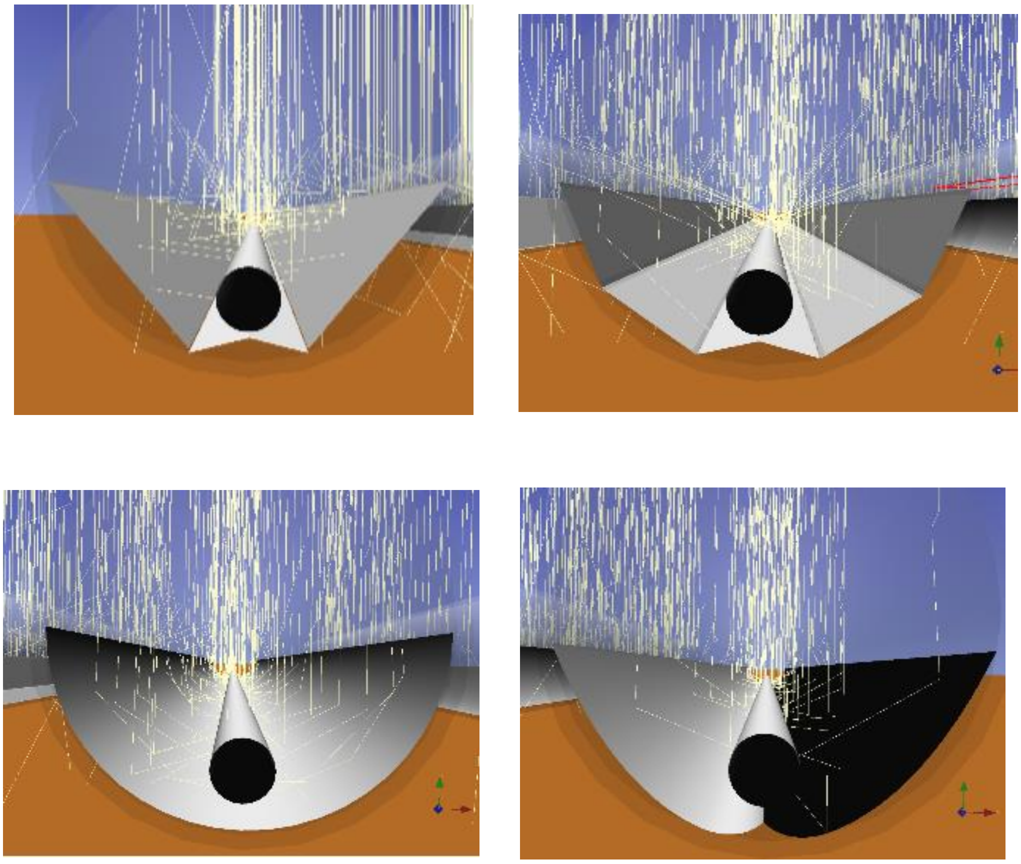

Fig. 2: Ray tracing figure of the four different evacuated tube receivers, under 90° Sun elevation. From left to right: 4-sided angular, 6-sided angular, semi-circular and compound parabolic reflector.

The ray-tracing analysis shows that the CPC reflector outperforms in terms of ray concentration, followed by the SC reflector, as shown in ***Fig. 2***. The high optical efficiency of the CPC is expected (power production >85W) since CPC is the ideal optics. At the same time though, this design incorporates some construction complexities, since the exact CPC shape has to be tailored for each specific pipe geometry (depending on the diameter of evacuated tube, on its position inside the absorber, and the dimension of the absorber tube) and its curvature is continuously varied. Regarding the simpler design of the 4-sided and 6-sided angular reflectors, the raytracing reveals that many rays escape from these tubes, ***Fig. 2***. Their poor performances were expected since they both have a simpler geometry than the SC and CPC reflectors.

2.3 Results of the optical analysis

Following the model's development, simulations with varying sun position (i.e., elevation and azimuth) were performed to generate the Incidence Angle Modifier (IAM) curve for each receiver. Additionally, the power production from each receiver under different sun positions was also calculated. Fig. 3 shows the power production (W) and presents the Incidence Angle Modifier curve for all receivers considered and for Sun incidence angles from 0° to 60°. It can be seen that for small angles of incidence, from 0° to 15°, the CPC reflector outperforms. The second-best option in terms of optical performance would be the SC reflector, as it presents two crucial features: its power production is more even for all the incidence angles considered, and its power production is higher than that of the CPC for incidence angles higher than 15°. At this point, it should be noted that the CPC reflector has the most significant variation of power production under different Sun elevations (i.e., 81W at 10° but 41W at 20^{0}), whereas the SC reflector has the most even power production. Moreover, the 6-sided angular reflector has slightly better performance than the 4-sided one for incidence angles up to 30°. Finally, for incidence angles higher than 40°, the SC reflector has a clear advantage over the other three (CPC, 6 sided and 4 sided), in which the presence of the reflector seems insignificant since all three tubes have almost the same performance.

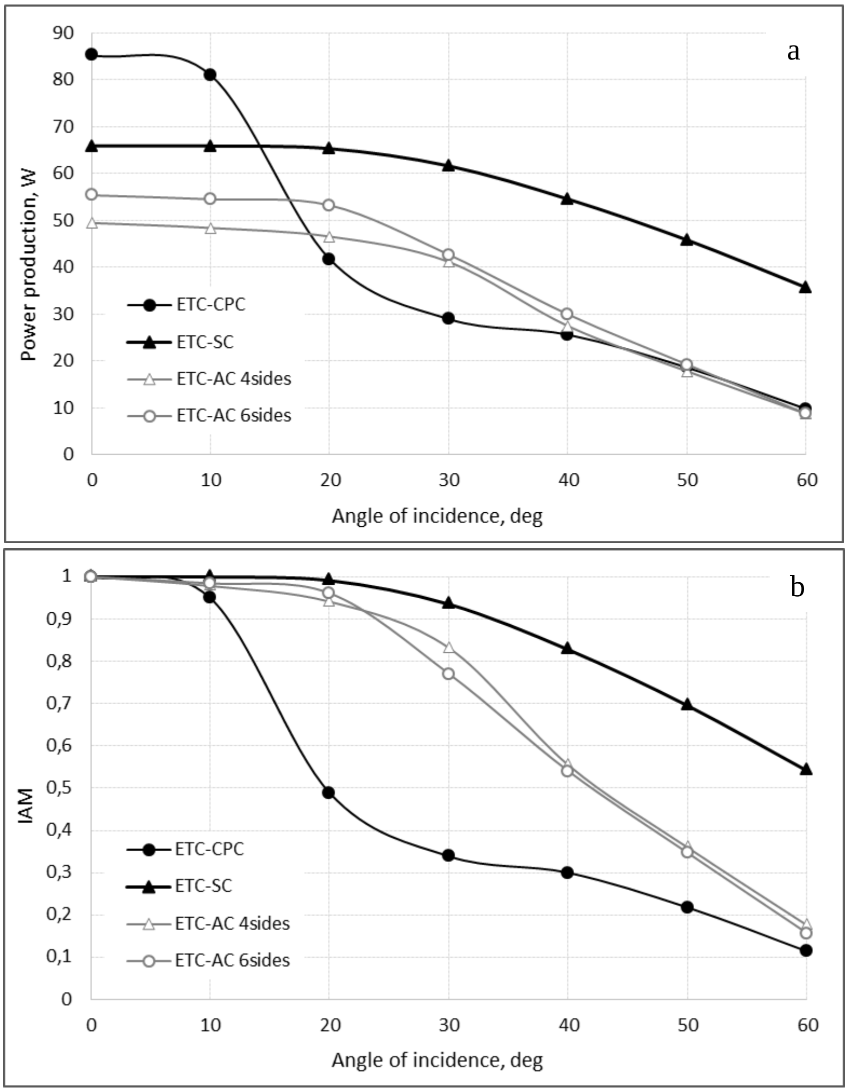

Fig. 3 **Power production (W) of the four different evacuated tube receivers for various sun incidence angles(a). Right: IAM curve of the four different evacuated tube receivers for various sun incidence angles(b).**

The results of the optical analysis show that the receiver with the SC internal reflector has a competitive performance towards the CPC reflector and could act as an alternative option, under specific circumstances, as shown in Fig. 3. The reflector as an internal component of an ETC-CPC collector has been tested on an ad-hoc test bench hereafter called ETC-Test bench; a modular prototype that simulates an evacuate pipe has been realized at lab scale. The modular test bench is composed of a glass vacuum chamber with Viton seal (simulate the external glass of ETC), a black receiver connected with an aluminium cover, a metallic holder with O-ring seal for glass, a connection to the vacuum sensor and vacuum pump and a connection for the venting (nitrogen or air). The glass cylinder has an internal diameter of 15.8 cm, which allows the easy insertion of mirrors with different shapes.

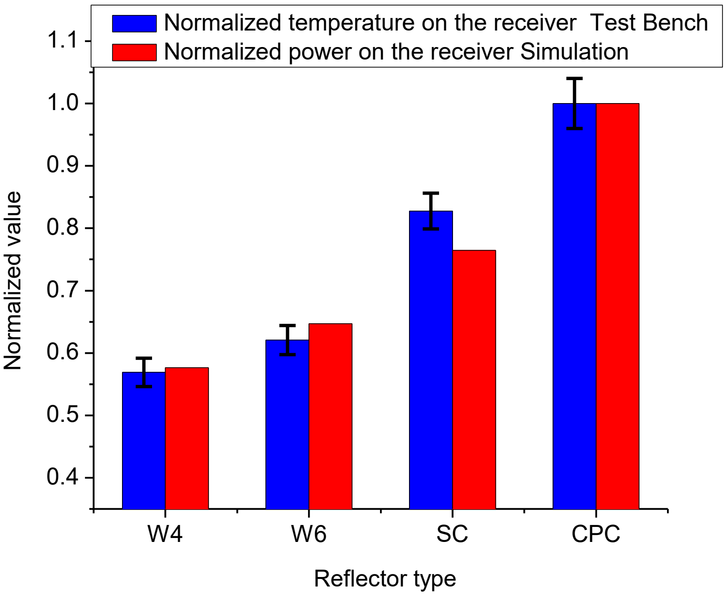

Fig. 4. Comparison of the result obtained in the test bench and obtained by simulation

A solar illuminator of 900W/m^2 was used in the ETC-Test bench. Temperatures were recorded by thermocouples on the surface of the receiver. The reflectors with the different shapes have been tested in the test bench (W4, W6, SC, and CPC). The normalized temperature recorded has been compared with normalized power on receiver estimated by simulations, Fig. 4. The results show a similar trend indicating a good correlation between the simulations and experimental results. The experimental results show the mirror with CPC profile has better performance (normal illumination) as predicted by the simulation. The experimental improvement in terms of the temperature of CPC mirror with respect to the circular mirror was >10%.

3. Decarbonization of industrial processes using SHIP technologies

The use of solar heat in industrial processes leads to a reduced consumption of fossil fuels and consequently to a lower emission of tons of CO$_2$ per year. To understand the reduction of emission of CO$_2$, the yearly thermal energy production of solar thermal field was estimated. (Bolognese, Grigiante and Crema, 2019) (Koffi *et al.*, 2017)(Bolognese, Crema, *et al.*, 2020). In particular, the drying process in a food and beverage industrial sector was considered (Food an beverage processes) (Brunetti *et al.*, 2015)(Migliori *et al.*, 2005). In the calculation, an industry "virtually" located in Rome, with a space availability of a 1000 m^2 (≈ 32*32 m) and a yearly thermal energy consumption of about 700 MWh/year, was considered. In order to avoid self-shading phenomena, the number of conventional ETC solar collectors is 174, resulting from the inclination of the panels, their size and their south-facing orientation (Bolognese, Viesi, *et al.*, 2020). The hourly data of solar radiation and environmental temperature of the TMY by PVGIS (*PVGIS*) were used. Moreover, in order to calculate the longitudinal e transversal components of incidence angle modifier, the apparent motion of the sun is calculated on an hourly basis considering the right geographical position of the location. The calculation of useful thermal power has been hourly calculated as follows:

$$Q_{sf} = A_g\, GHI\left[K_{\theta_l} K_{\theta_t} c_0 - a_1(T_{es} - T_{env}) - a_2(T_{es} - T_{env})^2\right] \qquad \text{(eq. 1)}$$

in which A_g is the total net surface of the solar field, K_{θ_l} and K_{θ_t} are the components of the incidence angle modifier that depends on geographical location (Morin *et al.*, 2012; A. Buscemi, D. Panno, G. Ciulla, M. Beccali, 2018), T_{env} is the environmental temperature, GHI is the hourly solar global horizontal radiation c_0,

a_1 and a_2 are the coefficients used for the calculation of efficiency and T_{es} is the industrial process temperature. Assuming a continuous day time heat load profile and a typical process temperature in the range from 137 °C, the yearly thermal energy production of the conventional solar field is 314 MWh/year. The CO_2 saved has been calculated considering the natural gas as conventinal fuel to produce thermal energy and considering a gas standard emission factor of 0.202 tCO2/MWh (Brigitte Koffi and Cerutti, 2017) .The results show that a ETC solar field of 1000 m^2 shows excellent performanc , in fact it can avoid the emission of a huge amount of CO_2 70 ton /years. Moreover, the ETC solar field performance, considering improvements induced by the increased efficiency of the optics, reported in the paragraph 2, (hereafter ETC-CPC, internal mirror improvement of optical proprieties of 10%) was calculated. With these enhancements, the thermal energy production resulted of 345 MWh/year. In this case we estimate that the solar field can avoid that emission of 77tons of CO_2.peryear. The payback time for each set-up was in first approximation estimated. The payback time can be estimate considering the total capital expenditure (CAPEX) and Operating and maintenance costs (OPEX). The CAPEX has been calculated considering an average price per unit of the gross occupied area of 110 €/m^2 (Luca Prattico, et.al. 2018) and a number of additional costs due to the installation and equipment necessary for piping and, operating and maintenance costs (OPEX) for this type of collector were considered as a percentage of total CAPEX (i.e. 20%). Moreover, in the evaluation of payback time we considered a) the incentives available in Italy for sustainable energies *Conto Termico 2.0* (Energetici, 2016). b) cost of fossil fuel taking into account increase in fossil fuel costs (about 1.5 % per year) for 25 years (solar field lifetime). The results are reported in table 3. In the first approximation, in 25 years there is a potential saving in economic terms of about 300 K€ for the solar field while considering the solar field with improved optics is possible to save 330 K€. Therefore, the payback time of approximately 6 years and avoids the emission of 70 tons of CO_2 per year. While the payback time of for solar field with the innovative optics is approximately 5.5 years with the avoiding of 77 tons of CO_2 per year as summarized in Table 3.

Tab. 3: Environmental/Economic impact

Ex. Rome (Italy)	**Solar fraction**	**Saved CO_2**	**Payback time**
Solar Field ETC	45	70 ton per year	≈6
Solar Field ETC-CPC optimized optics	50	77 ton per year	≈5.5

4. Conclusion

This work includes i) an overview of solar technologies for low/medium -temperature SHIP (80-150°C) ii) results obtained on the mirrors with innovative shape used in evacuated receiver tube iii) estimation of CO_2 saving using a solar field based on evacuated tube collector. As a summary, the food and beverage sector are one of the most interesting sectors for the SHIP technologies, in particular for the evacuated collectors. For this reason, we studied how to improve optical performance in ETC. The results on mirrors show that internal mirror with CPC design in ETC collector allows a sensible improved on optical performance (10%). Considering the performance of evacuated collector, we calculated CO_2 saving in a industry in a food and beverage secto.We observed that a solar field-based on ETC of 1000m^2 is already able to reduce remarkably the CO_2 emissions of industrial processes. We estimated a reduction of CO_2 emission of 70 tons per years. While considering the solar field with optimized optics a saving of 77 ton per years is possible.

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