Hybrid Solar Thermal Field (FPC-PTC) Applied for Solar Heating and Cooling Process in the Agroindustry Sector

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Abstract

In the Agroindustry, as in the rests of productive sectors, the current need to reduce CO_2 emissions and reaching sustainable growth justifies the necessity to integrate renewable energy sources. Greenhouses facilitate the improvement of the agricultural production process, but they also need an adequate energy supply to ensure the ideal ambient conditions for crop growth. The use of solar energy is a convenient solution due to its easy access in rural locations in many world areas. However, sizing the solar field for greenhouses, both in terms of area and technology, has the challenge of supplying the seasonal demand of thermal loads. The objective of this work is to evaluate the advantages of using a hybrid solar field with FPC-PTC in series integrated with an absorption chiller to provide the heating and cooling demand of a greenhouse of tomatoes in Almería, Spain. It was considered solar fields between 80 m^2 to 540 m^2. The results show that a hybrid configuration with 50% of PTC increases the energy contribution of the solar systems in the summer months and allows a solar fraction over 0.96 with a solar field area smaller than half of the greenhouse area. In comparison with the solar field with FPC, the hybrid configuration increased the solar fraction in summer months up to 32 percent.

Keywords: absorption chiller, hybrid solar field, greenhouse

1. Introduction

Industry requires a decrease in fossil energy consumption and CO_2 emissions, especially the food sector, which is highly related to population growth to reach the goal of decarbonized energy. In this sense, temperature control is a key factor in industrial production for cooling and heating processes (Villarruel-Jaramillo et al., 2021). Furthermore, high-efficiency agricultural production is one of the essential tools to satisfy the growing demand for food. Modern agrarian production facilities are designed for the optimal use of land, water, and energy, making agricultural exploitation a semi-industrial production process (Cabrera et al., 2017). Greenhouses are ideal for the optimal use of the resources required for agricultural production because they allow controlling primordial variables for crop growth like ambient temperature, and the correct irrigation of water and fertilizers (Cabrera et al., 2017). Depending on the location's weather characteristics and temperature requirements of the crop, temperature control inside greenhouses produce heating and cooling demands that need to be supplied with sustainable energy resources. The agricultural sector is mainly located far from residential areas and tends to burn liquefied petroleum gas (LPG) for heat processes. One of the solutions for sustainable agroindustry is the incorporation of solar energy into the production process (Prieto et al., 2021). However, the demands for heating and cooling can generate a sizing challenge when considering the variables given by the quantity of product, weather conditions, and characteristics of the space to be heated (Gil et al., 2021).

Solar systems have been shown to be able to satisfy the energy requirements of greenhouse facilities (Lazaar et al., 2015; Mahmood and Al-Ansari, 2021; Prieto et al., 2021; Sajid and Bicer, 2021). However, using solar energy to meet thermal demand in summer for cooling could be a challenge due to the high energy consumption of the absorption chiller, and the flat plate collectors (FPC) tend to generate low heating rates in the first hours of the day. Consequently, it is necessary to use an auxiliary boiler to supply heat that increases fossil fuel consumption in hours with solar radiation availability. For this reason, implementing schemes that improve the solar system's energy performance under the seasonal energy demand of greenhouse applications could encourage the application of solar technologies in the agro-industrial sector. Tian et al. (2018) evaluated the behavior of a hybrid solar field (HF) with parabolic trough collectors (PTC) connected in series with FPC for district heating. The HF showed the ability to

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improve the energy output on summer days of the solar system compared to an individual field with FPC. However, the system's behavior has not been explored considering high demands in cooling processes during summer with thermal machines, a seasonal period in which the HF mostly benefited. In this sense, HF could have the potential to outperform the seasonal performance of FPC solar systems in thermal cooling applications, where demand increases simultaneously when HF performance grows. This works aims to evaluate the energy performance of FTC-PTC hybrid systems under the seasonal energy requirements for cooling and heating a greenhouse.

2. Methodology

2.1 Case Study

The evaluations were carried out considering the meteorological data of a location in the Andalusia Province in Spain (Lat: 36.85°, Long: -2.38°) and the thermal demand of a tomato production greenhouse with an area of 680 m2. The cooling and heating loads were calculated using the methodology presented by (Cabrera et al., 2017), considering set-point temperatures of 12 ºC and 27 ºC for the night and day periods, respectively, and relative humidity inside the greenhouse of 80%. The monthly cooling and heating demand are shown in fig. 1c. The system is configured with a hot thermal storage tank (HTES), a solar field, an absorption chiller with a nominal capacity of 70 kW for cooling, and a gas auxiliary boiler to supply the required heat when the solar systems cannot supply all the chiller or heating demand. Two configurations of solar fields are evaluated: 1) individual solar field with FPC (FPC-IF), and 2) hybrid solar field with FPC and PTC with east-west tracking integrated in series with an area proportion of 50 % of FPC. The scheme of the system with the hybrid solar field is shown in fig. 1b. A seasonal operation strategy with two control modes is implemented. In control mode 1, solar energy is stored to supply the night heating demand, and only excess energy is used to supply the chiller's energy requirements. In control mode 2, solar energy is used to supply the chiller's demand, and the stored energy is used for the night heating load. In fig. 1c is shown the periods of the year when control modes 1 and 2 are activated.

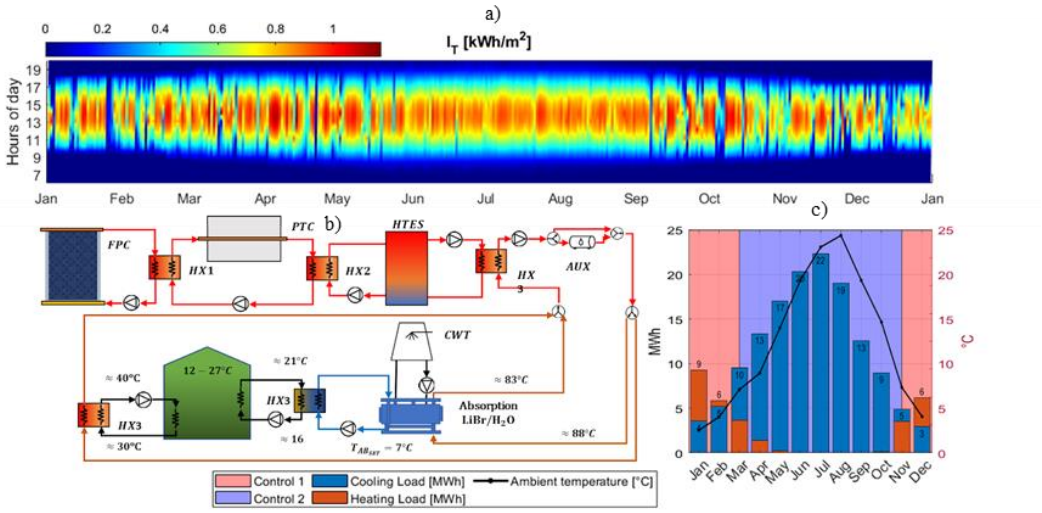

Figure 1: a) Total irradiance on tilted surface; b) FPC-PTC+ABS hybrid solar field diagram for greenhouse air conditioning and c) Monthly thermal demand for cooling and heating, and intervals of control strategy

2.2 Numerical model and system sizing

The software to simulate the proposed scheme is TRNSYS, which uses the norm EN12975-2 Dynamic Efficiency Approach with the types 1289 and 1288 for resolving the numerical model of the FPC and PTC, respectively (TRNSYS, 2017). On the other hand, thermal storage (HTES) is modeled with Type 158, simulating a constant volume stratified storage tank with a vertical configuration. Type 91 simulates heat exchangers with constant effectiveness (ε) of 0.7. Finally, the chiller is modeled using Type 107, which requires a data file that contains the instant capacity and the capacity fraction for each inlet temperature of the generator (T_{gen}), cooling water tower (T_{cwt}), and the setpoint temperature for the chilled water (T_{chi}) obtained from the nominal data and operation curves of the catalog (TRNSYS, 2019). Table 1 shows the types and parameters used in the numerical simulation.

Tab. 1: Model parameters for TRNSYS simulation (Janotte et al., 2009; SP Technical Research Institute of Sweden, 2016)

Component	TRNSYS Type	Parameters	Value	Unit
Flat plate collector (HTHEATboost 35/10)	1289	$\eta_{0,b}$	0.779	-
		C_1	2.41	$W/(m^2K)$
		C_2	0.015	$W/(m^2K^2)$
		C_5	6.798	$kJ/(Km^2)$
		K_d	0.98	-
Parabolic trough collector (Solitem PTC1800)	1288	$\eta_{0,b}$	0.683	-
		C_1	0	$W/(m^2K)$
		C_2	0.015	$W/(m^2K^2)$
		C_5	6.798	$kJ/(Km^2)$
		K_d	0.012	-
Storage tank	158	Loss Coefficient	0.923	$W/(m^2K)$
Heat exchangers	91	ε	0.7	-
Absorption chiller (Yazaki SC-20)	107	$Cap_{nominal}$	70.33	kW
		Q_{Gen}	100.5	kW
		COP	0.7	-
		T_{gen}	70-95	°C
		T_{cwt}	26-33	°C
		m_{chi}	10992.6	kg/hr
		m_{gen}	17283.8	kg/hr
		m_{cwt}	36725.3	kg/hr

The solar field pre-sizing is based on the F-Chart method, which estimates the solar field's monthly heat production in function of the monthly irradiation on the inclined plane (IT), temperature ambient (Tamb), and the thermal demand of the process. In that sense, the solar field is designed to reach different solar fractions between low to high solar coverage of the energy required for heating (Q_{LH}) and the energy needed for the generator (Q_{Gen}) of the absorption chiller to meet the cooling demand. For the case of the hybrid solar field, a criterion parameter is introduced for the area sizing called fraction area (FA), as shown in the flow chart in Fig. 2. FA estimates the area of FPC based on a fraction of the total area of the solar field, for this work FA=0.5.

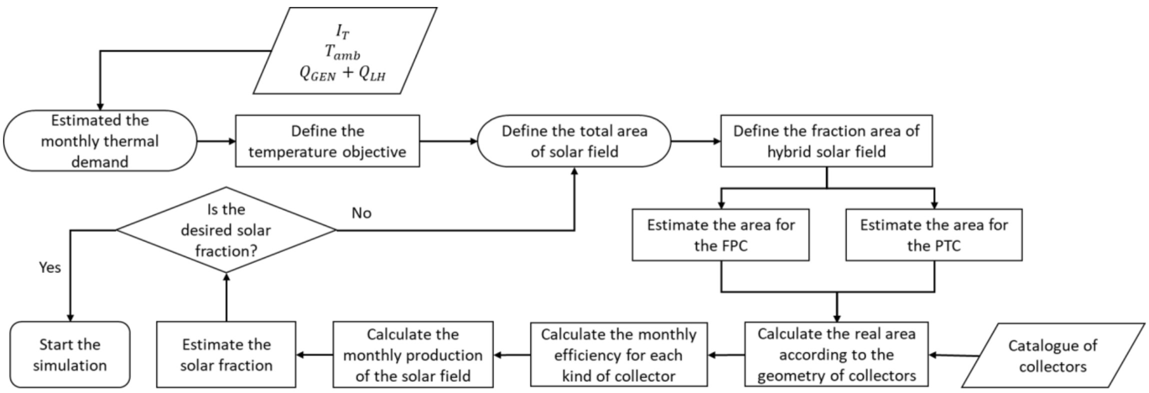

Figure 2. Flow chart for the pre-sizing of the hybrid solar field.

2.3 System energy efficiency

The system energy efficiency is calculated like the ratio between the useful energy delivered by the system to the greenhouse and the input energy from the solar radiation and gas consumed by the auxiliary boiler (Dias et al., 2019). The system energy efficiency for the FPC-IF and the HF are calculated from Eq. 1 and Eq. 2 respectively.

$$\eta_{sys_{FPC-IC}} = \frac{Q_{heating}+Q_{cooling}}{Q_{FPC-IC}+Q_{backup}} \quad \text{(eq. 1)}$$

$$\eta_{sys_{HF}} = \frac{Q_{heating}+Q_{cooling}}{Q_{FPC-HF}+Q_{PTC-HF}+Q_{backup}} \quad \text{(eq. 2)}$$

Where $Q_{heating}$ and $Q_{cooling}$ are the energy delivered for the system to the heating and colling demand respectively, Q_{FPC-IC} is the solar energy received by the FPC solar field with individual configuration, Q_{FPC-HF} and Q_{PTC-HF} are the energy received by the FPC and PTC solar fields of the HF and Q_{backup} is the energy consumed by the auxiliary boiler.

3. Results

Fig. 3 shows the monthly solar fields' energy losses ($QL_{SolarField}$), the solar fields' useful energy ($QU_{SolarField}$), the backup energy (Q_{BackUp}) and the solar fraction (SF) for the smallest evaluated area and the area with the best relation between solar fraction and efficiency (204 m^2 and 208 m^2 for the FPC and HF, respectively). Results indicate that the HF allows having a more constant SF throughout the year while FPC presents higher differences between the summer and winter months. Fig. 3(a2) and Fig. 3(b2) show that for similar solar field areas, the HF reaches higher SF from April to September, where the highest demand requirements for the greenhouse are concentrated. In these months, the HF allows SF improvements with 32 % and 25 % values over the FPC in June and July, respectively.

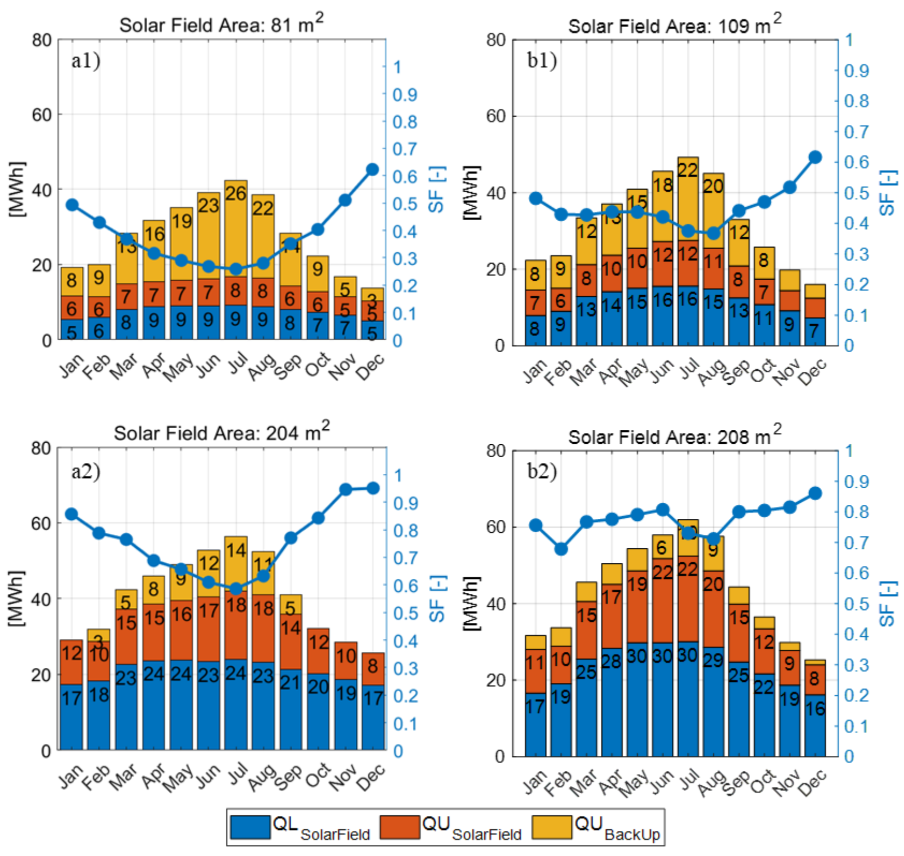

Figure 3: Monthly energy for the two solar field configurations (a. FPC solar field and b. FPC-PTC solar field)

In Fig. 4 are presented the heat flow rate maps of heating and chiller's heat demand (Fig. 4a), the heat flow rate produced by the FPC-IF with a total area of 204 m^2 (Fig. 4b), and the heat flow rate produced by the HF with a total solar field area of 208 m^2. Fig. 4a shows that heating requirements occur at night and in the early morning and late afternoon. Fig. 4b, while Fig. 4c indicates that the HF supplies more heat than the FPC-IF in the morning and noon hours of days in summer, allowing it to reach higher values of SF in the months with the biggest heat requirements of the greenhouse, which is consistent with the behavior observed in Fig. 3. In Fig. 4 we can also observe that the seasonal operation strategy allows that in winter months the FPC-IF and the HF have similar and high coverage of the heating demand, but the FPC-IF has slightly better coverage of the small cooling energy requirements in this period.

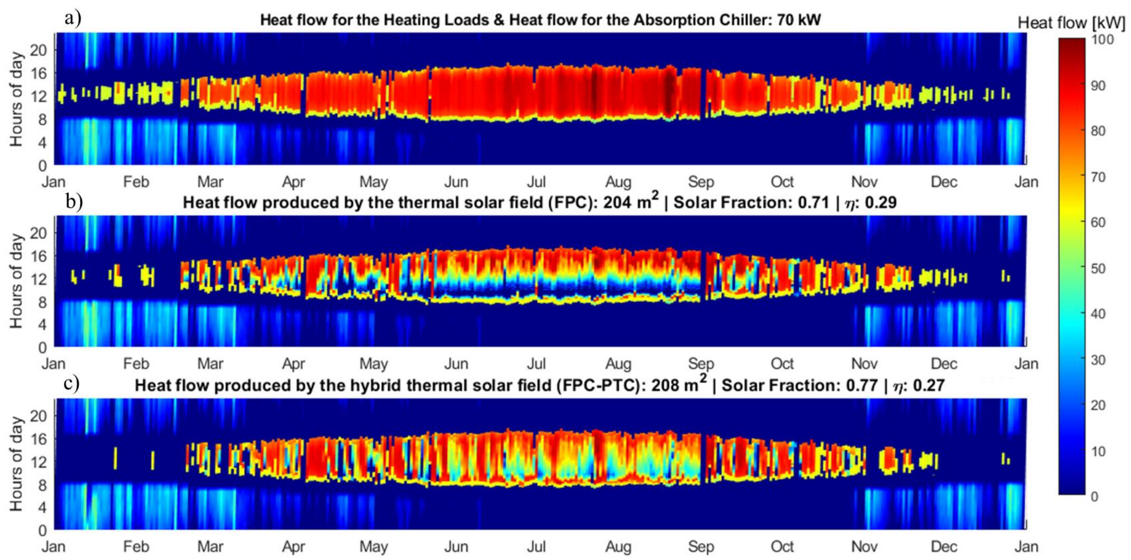

Figure 4: Heat flow rate maps of a) heating and chiller's heat demand; b) heat flow rate produced by the FPC-IF with a total area of 204 m^2 and c) heat flow rate produced by the HF with a total solar field area of 208 m^2

In Fig. 6 is shown the comparison of the solar fraction and efficiency of the FPC-IF and HF for different values of the total solar field area. Results indicate that for the smallest areas evaluated, both configurations have similar values of SF. Nevertheless, for larger areas, the HF has higher values of SF than the individual configuration, presenting a difference of 7% for areas of 300 m^2, allowing the HF to reach values of SF over 0.96 with areas smaller than half of the greenhouse area.

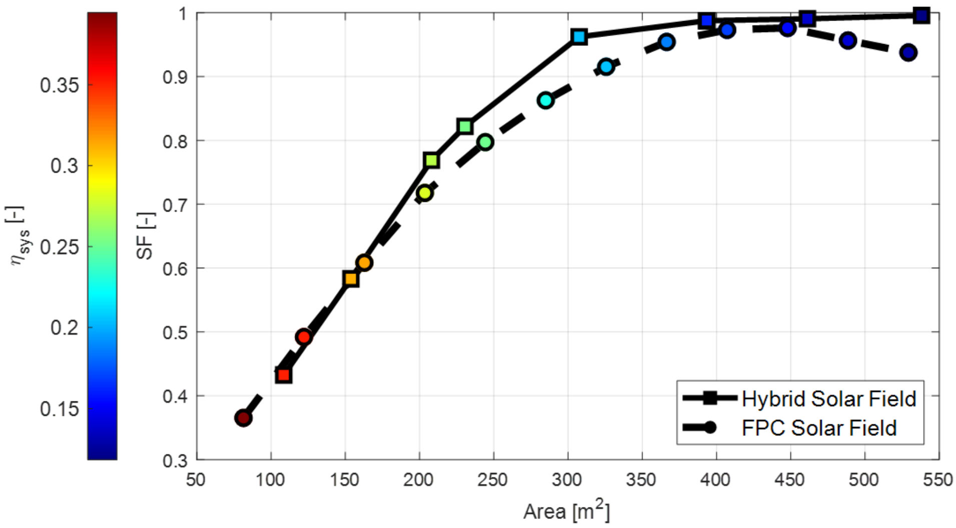

Figure 6: Comparison of solar fraction and efficiency of the system between FPC and hybrid solar field (FPC-PTC) schemes.

According (Sadi and Arabkoohsar, 2020), the solar cooling systems with PTC presented low performance with respect to the use of FPC due to the highest temperature of PTC reducing the coefficient of performance (COP) of the absorption chiller. In contrast, the results observed in this study show that the hybridization of FPC-PTC allows higher solar coverture with a smaller area, representing a clear advantage with respect to the FPC due to the backup energy savings during summer.

Results of this work indicate that the HF allows a more constant SF throughout the year, attenuating the decrease in energy production observed in the FPC in the summer months. The HF has been shown to produce a better energy coverage than the FPC in most hours of summer days, a period of time when the heat requirement of the greenhouse is bigger. This is due to two main factors: 1) the improvement in the PTCs performance with the higher levels of direct radiation in summer; 2) the higher reduction of the FPC efficiency with the increment of the solar field operation temperature due to the requirements of the chiller generator. The improvement of the solar energy coverage with the HF in the summer months agrees with the findings of (Tian et al., 2018), and shows the potential of this type of configuration to supply solar energy to facilities with seasonal energy demands of cooling and heating.

4. Conclusion

This work evaluated the energy performance of hybrid solar systems with FPC-PTC to satisfy the energy requirements for heating and cooling of a greenhouse for tomato production in the south of Spain. The energy performance of the hybrid solar field was compared with an FPC solar field with individual configuration. The comparison was made in terms of heat flow rate, total monthly energy and annual solar fraction, and the systems were simulated using TRNSYS software.

Results show that a HF can mitigate the reduction of the energy coverage observed in the FPC in the months with higher greenhouse energy consumption. The HF allows improvements in the solar fraction up to 32 % and 25% in June and July, respectively, and significant enhancements in the other months between April and September. The findings of this work indicate the capacity of the FPC-PTC hybrid configuration to improve the energy performance of solar systems under seasonal energy demand for heating and cooling. Also, the HF system shows the potential to provide energy to other productive processes with seasonal energy demand and higher temperature requirements. In future works, the economic feasibility of this system and its performance under other solar resources and process temperature requirements will be evaluated.

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