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ScienceDirect

Energy Procedia 48 (2014) 1134 – 1143

Energy Procedia

SHC 2013, International Conference on Solar Heating and Cooling for Buildings and Industry
September 23-25, 2013, Freiburg, Germany

Design and simulation of a solar field coupled to a cork boiling plant

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Abstract

Cork production and processing are important sectors of activity in Portugal and Spain. The cork boiling consists of cork immersion for approximately 1 h in boiling water (100ºC). This industrial process demands thermal energy that is suitable to be provided by solar energy. In this work, the results of coupling a solar field with thermal collectors with the cork boiling plant ECOTRAFOR, placed in Extremadura (Spain), are presented, including solar field sizing, simulation and annual yield analysis of the system.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: cork industrial process; solar energy; solar field; solar collector

1. Introduction

Cork production and processing are important sectors of activity in Portugal and Spain. Portugal has the highest cork oak density in the world (33% of the worldwide area), and is the first cork producing country (52% of the world production). In Spain (22% of the worldwide area), Extremadura is the second region with the 30% of the national forest production and the 34.83% of the industrial production [1].

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1876-6102
Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG
doi:10.1016/j.egypro.2014.02.128

Nomenclature

A_c	Net collection area of the solar concentrator, m^2
c_1	Linear heat loss coefficient of the solar collector, W/m^2K
c_2	Quadratic heat loss coefficient of the solar collector, W/m^2K^2
c_3	Capacitive heat loss coefficient of the solar collector, J/m^2K
c_p	Specific heat capacity at constant pressure of the thermal fluid, kJ/kg-K
I_b	Direct solar irradiance on the collector plane† (DNI multiplied by the cosine of the incidence angle), W/m^2
K_l	Longitudinal incidence angle modifier
K_l	Transversal incidence angle modifier
m	Mass of water demanded by the cork process, kg
$\dot{m}$	Mass flow rate through the collectors, kg/s
$N_{cols,\min}$	Minimum number of collectors in the solar field to cover the thermal energy demand
$N_{cols,loop}$	Minimum number of collectors per loop to reach the required temperature increase
Q_{demand}	Thermal energy demanded by the industrial process, kWh
$\dot{Q}_{useful}$	Useful thermal power of the solar collector, kW
T_{amb}	Ambient temperature, ºC
T_m	Mean temperature of the fluid in the collector, ºC
x_s	x coordinate of the sun position in the collector coordinates system
y_s	y coordinate of the sun position in the collector coordinates system
z_s	z coordinate of the sun position in the collector coordinates system
α_s	Sun elevation angle (Horizon = 0º, Zenith = 90º)
β_c	Collector slope angle with respect to the ground (>0º towards South, <0º towards North)
γ_c	Collector orientation angle with respect to the North-South axis (>0º towards West, <0º towards East)
γ_s	Sun azimuth angle (South = 0º, East = -90º, West = 90º)
ΔT_{boil}	Temperature increase to heat the water up to the boiling point, K
$\Delta T_{loop,ref}$	Reference temperature increase of the fluid in a loop of collectors, in nominal condition, K
$\eta_{opt,0^o}$	Peak optical efficiency of the solar collector
η_{clean}	Cleanliness factor of the solar collector
η_{edge}	Edge factor of the solar collector
θ_l	Longitudinal incidence angle of incoming solar rays on the collector, º
θ_t	Transversal incidence angle of incoming solar rays on the collector, º

After the harvest from the producer trees (Quercus suber L.), the cork is stabilized by drying in open air for approximately three months. After this period, one of the first stages of industrial preparation of cork, known as "Cocido" or "Raspado", consists of its immersion for approximately 1 h in boiling water (100ºC). The objectives of the boiling are to clean the cork, to extract water-soluble substances, to increase thickness and thus reduce density, and to improve cork textural and plastic properties, making this material more homogeneous, flat and elastic. This process is repeated after some time, in a second boiling, for approximately 1/2 h in the same boilers and with the same water conditions. This boiling process is commonly carried out from November to April, but there are some installations operating the whole year.

This stage of cork process requires thermal energy, which is suitable to be provided by renewable sources as solar energy, through a solar field with thermal collectors. This paper summarizes the previous works done to know the

† The interpretation of I_b was modified after SHC 2013 conference and hence the results presented in this work are different with respect to the initial ones.

industrial process described in detail, including its thermal energy demand, the solar field design and the annual yield analysis of the system.

2. Cork boiling system

The cork boiling plant ECOTRAFOR is the industrial installation considered in this study. It belongs to Instituto Tecnológico del Corcho, la Madera y el Carbón Vegetal (ICMC), and is placed in San Vicente de Alcántara (Extremadura-Spain). This facility (Fig.1) is composed of three water tanks (with a volume of 50 m^3 per unit), two cork boilers (with a volume of 24 m^3 each one), placed in a water circuit, and a propane gas boiler (1400 kW) used to heat the water through three heat exchangers. The first tank stores clean water, the second tank stores filtered water that comes from the third tank through a filter, and the third tank collects the dirty water coming from the two cork boilers. These tanks are insulated to reduce heat loss. The filter installed between the second and third tank cleans and makes it possible to recycle waste water.

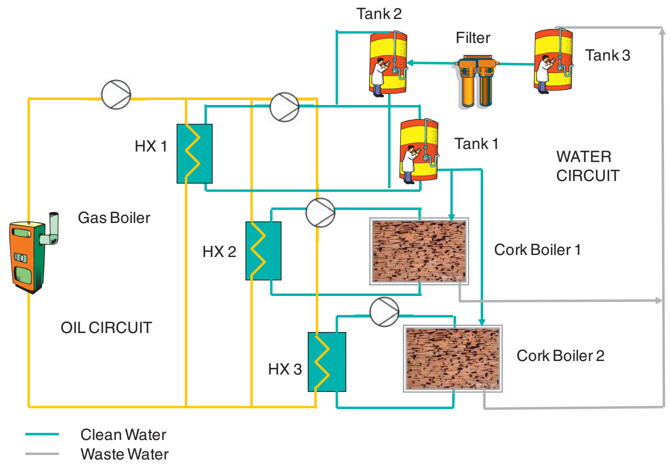

Fig. 1. Diagram of ECOTRAFOR plant.

The beginning of boiling process is the filling up of each cork boiler with cork and 14 m^3 of water at 100ºC. The gas boiler heat up this water, which comes from tank #1 or tank #2. After one hour, the cork is extracted, maintaining the water in the boiler at boiling temperature with the fossil fuel. This process is repeated throughout the working day. The thermal energy supplied by the solar field depends on the coupling point with the industrial process. In this case the solar field will be coupled to the first tank, increasing the water temperature up to the boiling point.

3. Design and modeling of solar field and process

3.1. Solar collector description and modeling

The solar collector used for the analysis has been the collector type CCStaR, designed and manufactured by Tecnología Solar Concentradora S.L. [2]. CCStaR is a fixed mirror solar concentrator with a rotatory absorber. It has a self-supporting structure which integrates the support for reflectors, tracking and control system. Since the reflectors are fixed, it is only required to move the mesh of receivers to follow the focus [3]. It is designed to work in a medium temperature range (90-200ºC) with liquid water, distilled or with additives.

Fig. 2. CCStaR solar concentrator.

The main parameters of CCStaR concentrator are summarized in Table 1.

Table 1. Main parameters of CCStar concentrator.

Parameter	Value
Peak optical efficiency, $\eta_{opt,0°}$	68.7 %
Cleanliness factor, η_{clean}	97%
Length	8.3 m
Width	5.2 m
Net collection area, A_c	37.4 m^2
Maximum temperature	200ºC
Linear heat loss coefficient, c_1	0 W/m^{2}K
Quadratic heat loss coefficient, c_2	0.004 W/m^{2}K^2
Capacitive heat loss coefficient, c_3	3918 J/m^{2}K

The values of longitudinal and transversal incidence angle modifiers, K_l and K_t, have been provided by the manufacturer, and are depicted in Fig. 3 as function of longitudinal and transversal incidence angles.

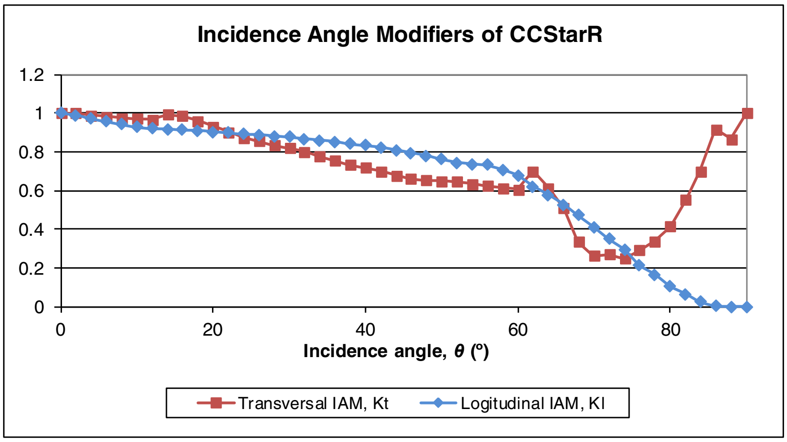

Fig. 3. Incidence angle modifiers of CCStar concentrator.

The longitudinal and transversal incidence angles, θ_l and θ_t, are defined according to Fig. 4 [4].

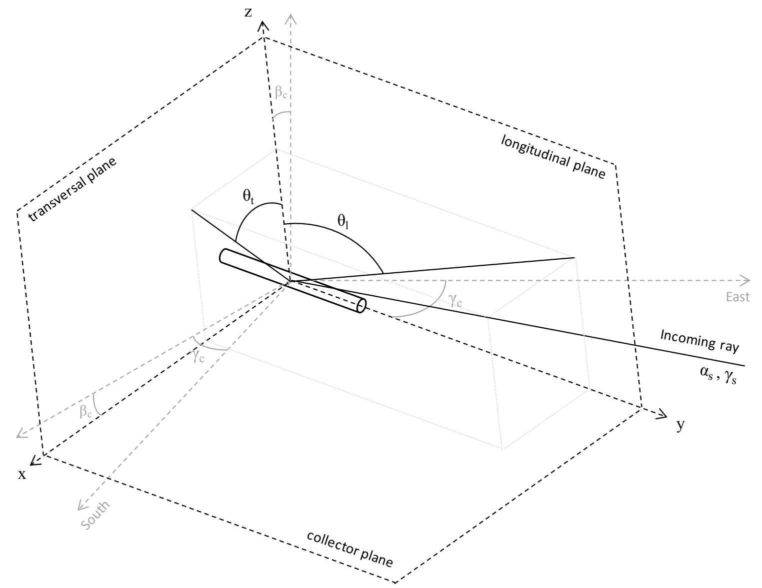

Fig. 4. Definition of incidence angles for CCStar concentrator.

According to trigonometric relations, expressions (1), (2) and (3) are obtained to characterize incoming solar rays in the collector coordinates system, as function of sun elevation α_s, sun azimuth γ_s, collector orientation γ_c and collector slope β_c.

$$x_s = (\cos\gamma_s \cos\gamma_c - \sin\gamma_s \sin\gamma_c)\cos\alpha_s \cos\beta_c - \sin\alpha_s \sin\beta_c \tag{1}$$

$$y_s = (\sin\gamma_s \cos\gamma_c + \cos\gamma_s \sin\gamma_c)\cos\alpha_s \tag{2}$$

$$z_s = (\cos\gamma_s \cos\gamma_c - \sin\gamma_s \sin\gamma_c)\cos\alpha_s \sin\beta_c + \sin\alpha_s \cos\beta_c \tag{3}$$

Hence, the transversal and longitudinal incidence angles, i.e. the angles between the normal vector to collector plane and each projection of the incoming ray on transversal and longitudinal plane, can be calculated by means of equations (4) and (5):

$$\theta_t = \arccos\frac{z_s}{\sqrt{x_s^2 + z_s^2}} \tag{4}$$

$$\theta_l = \arccos\frac{z_s}{\sqrt{y_s^2 + z_s^2}} \tag{5}$$

The curves for both incidence angle modifiers have been adjusted by means of polynomial regressions to be implemented in a computer model. In addition, an edge factor η_{edge} must be considered regarding both incidence angles and collector geometry [4]. If the contribution of diffuse radiation is neglected and a cleanliness factor η_{clean} is included, the useful thermal power obtained from the collector can be calculated with the expression (6):

$$\dot{Q}_{useful} = A_c \left(\eta_{opt,0^\circ} \eta_{edge} \eta_{clean} K_t K_l I_b - c_1 \left(T_m - T_{amb}\right) - c_2 \left(T_m - T_{amb}\right)^2 - c_3 \frac{dT_m}{dt} \right) \tag{6}$$

3.2. Solar field sizing and design

The solar field consists of a number of collector loops connected in parallel to each other. Each loop is composed of a number of collectors in series. The heat transfer fluid would be distributed to the loops in the solar field by means of insulated pipes. The heat transfer fluid selected for the solar field is Antifrogen® SOL HT, developed by Clariant Company, due to its working temperature (up to 200ºC), which is suitable for the process, and its low freezing temperature (-23ºC) [5]. Antifrogen® SOL HT is a liquid based on an aqueous solution of higher boiling glycols, which is used as a heat transfer medium in solar heating systems.

The solar field sizing is going to depend mainly on the industrial process demand and the available space in the foreseen plot. First of all, the solar field must provide sufficient heat to fill, once a working day, the two cork boilers with boiling water in a typical sunny day. The first tank will be refilled with mains water, at 20ºC. This means that the solar field should be able to raise the temperature of the water entering the cork boilers from 20 to 100ºC. Accounting for the amount of cork, the remaining water volume in each cork boiler is 14 m^3. Assuming liquid water with 4.2 kJ/kg-K of specific heat capacity and 1000 kg/m^3 of density, the typical energy demand of the process could be calculated with the expression (7):

$$Q_{demand} = m \cdot c_p \cdot \Delta T_{boil} = 2 \cdot 14\ m^3 \cdot 1000\ \frac{kg}{m^3} \cdot 4.2\ \frac{kJ}{kg\,K} \cdot (100-20)K = 2613.3\ kWh \tag{7}$$

According to the manufacturer [2], the peak thermal power for a single CCStaR collector is 23 kW. For a sunny day, an average value of 20 kW during 8 hours could be assumed for the initial solar field sizing. Accounting for these figures and the process demand, the minimum number of collectors for the solar field would be given by (8):

$$N_{cols,\min} = \frac{Q_{demand}}{\dot{Q}_{useful,average} \cdot 8\ h} = \frac{2613.3\ kWh}{20\ kW \cdot 8\ h} = 16.5\ collectors \tag{8}$$

The proper number of collectors per loop is defined according to a desired temperature increase, in nominal conditions. The return temperature from the storage tank could range from 50ºC at the beginning of the day to 90ºC at the end. In order to reach the boiling temperature as soon as possible, avoiding an excessive temperature of the working fluid, 30ºC per loop has been established as a reference temperature increase. Considering a mass flow rate of 0.5 kg/s and a peak useful power of 23 kW per collector, the number of collectors per loop would be given by (9).

$$N_{cols,loop} = \frac{\Delta T_{loop,ref}}{\dot{Q}_{useful,peak} \big/ \left(\dot{m} \cdot c_p\right)} = \frac{30\ K \cdot 0.5\ {}^{kg}\!/_{s} \cdot 4.2\ {}^{kJ}\!/_{kg\,K}}{23\ kW} = 2.7\ collectors \tag{9}$$

Therefore, at least 3 collectors per loop are required. Regarding available space criteria, there is a free area of 67.5 x 40 m in which the solar field could be arranged. For a ground installation of collectors at this latitude, the manufacturer recommends an East-West orientation of receiver tubes and a collector slope of 30º. This slope has been estimated as optimum from the point of view of annual energy yield. Accounting for CCStaR dimensions, a distance between collector rows to avoid shading and an extra space for maintenance purposes, the total area required for each collector would be 15 m x 9.5 m.

Considering that field symmetry would be preferable, and the calculation of minimum number of collectors and available area, the proposed configuration for the solar field arrangement is 6 loops (3 in each side of the field) of 3 collectors per loop. The complete ECOTRAFOR plot is depicted in Fig. 5 (a), as well as the proposed solar field lay-out (b).

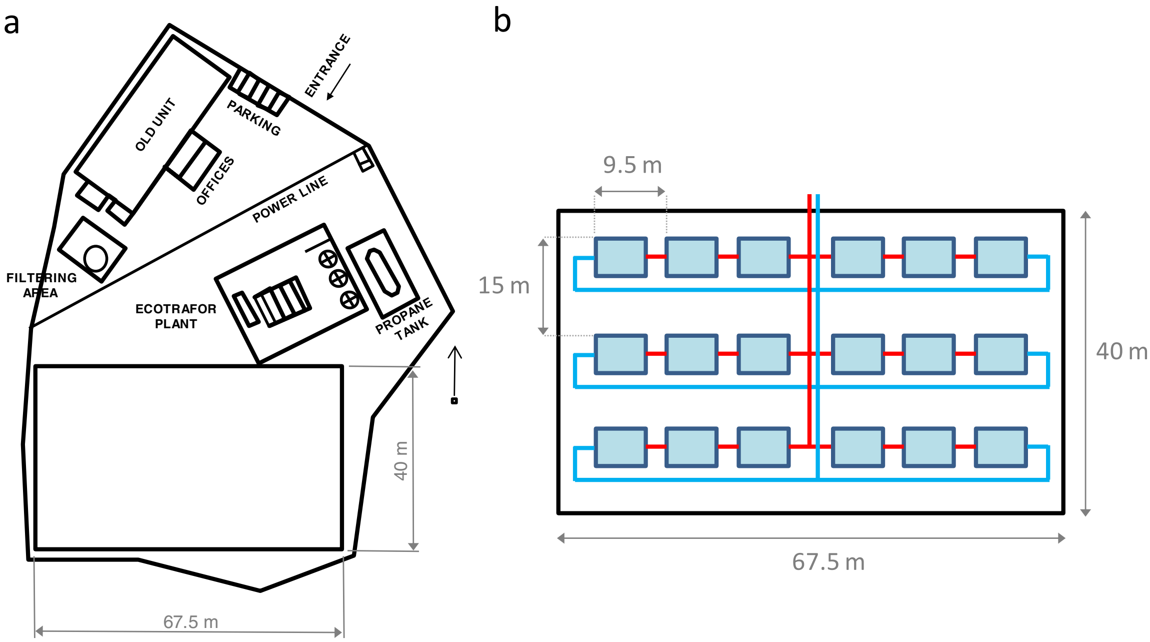

Fig. 5. (a) Available space in ECOTRAFOR plot; (b) solar field lay-out.

3.3. Modeling of the solar field and process

A complete model has been developed in TRNSYS simulation tool [6]. Its general layout is displayed in Fig. 6.

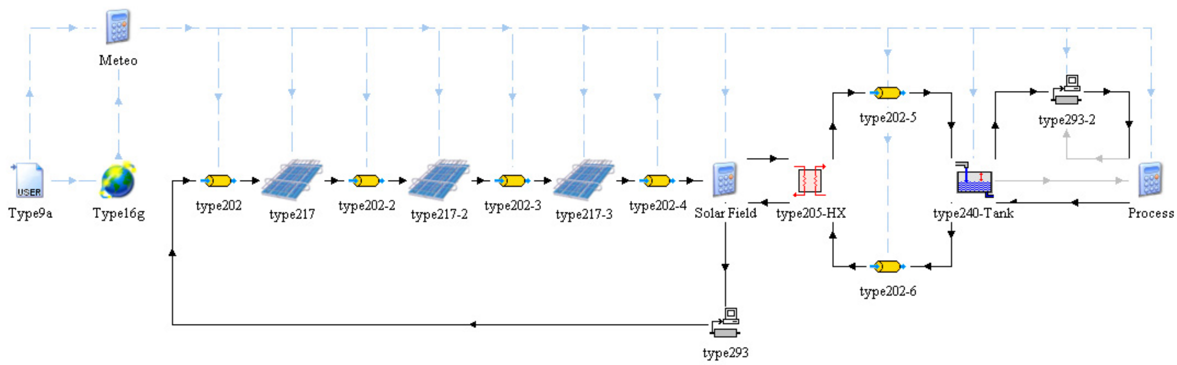

Fig. 6. TRNSYS simulation model of the solar field and process.

The model is composed of two main circuits: a primary circuit, including solar field and distribution pipes between collector loops and heat exchanger, which uses Antifrogen® SOL HT as heat transfer fluid, and a secondary circuit, between heat exchanger and industrial process, which uses liquid water. The thermodynamic properties of both working fluids have been incorporated into the corresponding elements.

The solar field model is carried out by means of the simulation of one collector loop, and the result is extrapolated to the complete field multiplying it by the total number of loops. Basically, a stationary approach is followed to determine the thermal power yielded by the solar field in stable conditions. Nevertheless, the capacitive term of equation (6) allows the model to account for thermal inertia when collector temperature is not stationary, and thus estimate the evolution of circuit temperatures.

Following the guidelines explained in section 3.1, a new component (type217) that models the CCStaR solar concentrator has been developed in TRNSYS. It implements the described expressions (1-6), modifiers and the rest of parameters in Table 1. The connecting pipes between collectors have been modeled with a component (type202) that simulates the thermal behavior of an insulated tube with a monophasic fluid. Basically, the model calculates thermal losses by means of an energy balance regarding fluid temperatures and pipe characteristics (dimensions, materials, insulation, etc.). The storage tank modeling is based on the variable volume tank from the TRNSYS standard library. This component has been modified to include a new input to subtract an amount of energy from the tank in order to simulate the filling of cork boilers every day. The heat exchanger has been modeled following the NTU (number of transfer units) effectiveness method for counter-flow heat exchangers [7].

Three equation editors have been included to perform meteorological data calculation, solar field control and process simulation (i.e. the control of the fluid entering and exiting the storage tank). Three additional components have been required from the TRNSYS standard library: Type9a, to read input file data, Type16g, to determine solar zenith and azimuth angles, and type293, to store values for the next time step.

The system operation starts at the beginning of the morning. The cork boilers are filled with hot water extracted from the first tank. The number of cork boilers filled with this tank depends on the water temperature: zero cork boilers if the water temperature in tank #1 is below 70ºC; one cork boiler when the temperature is between 70 and 90ºC; or two cork boilers when the temperature is beyond 90ºC. Fossil fuel is used to reach the boiling temperature (100ºC) if required. A fixed mass flow rate is circulated for each circuit when there is solar radiation: 3 kg/s for the primary circuit (0.5 kg/s per loop in the solar field) and 2.5 kg/s for the secondary circuit with the first tank. In the model, the thermal energy demanded by the process to maintain the water temperature during consecutive boilings in a working day, is supplied by the gas boiler and/or the tank #2, and is not considered in this work. The daily amount of extracted hot water, useful solar energy and fossil consumption are recorded by the simulation model, and used to calculate the annual results.

3.4. Meteorological data

The file used as meteorological data input for the model is a Typical Meteorological Year (TMY) corresponding to San Vicente de Alcántara (Extremadura-Spain). It includes data of direct normal irradiance (W/m^2) and ambient temperature (ºC) for a typical whole year, with a time step of 10 minutes. The time step of the simulation is 5 minutes, so the intermediate values between data records are interpolated by TRNSYS program.

A global analysis of the meteorological data gives a yearly balance of 2104.69 kWh/m^2 of direct normal irradiance and 4096.5 hours of sunlight (solar radiation > 2 W/m^2). The ambient temperature is between -4.6°C and 44.9°C, and its annual average value is 15.7°C.

4. Simulation results and annual yield analysis

Fig. 7 displays the main outputs of the simulation for some typical days, a sunny and cloudy day of winter (a) and summer (b). The variables included are: loop outlet and inlet temperatures (ºC), tank water temperature (ºC), solar power on the field (kW) and useful thermal power (kW).

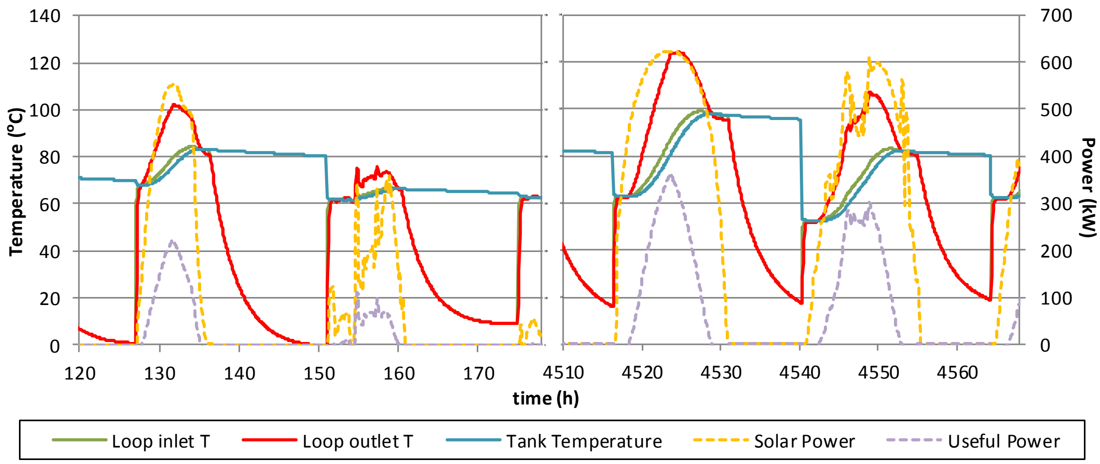

Fig. 7. Simulation results for typical days, sunny and cloudy: (a) winter; (b) summer.

In Fig. 7, the difference between a day of winter (a) and summer (b) is summed up by the area covered by the curve of useful power. In addition, the sudden drop in tank temperature at the beginning of every day reflects the number of cork boilers that the solar field has been able to fill. In the winter example (a), one cork boiler is filled after the sunny day and zero after the cloudy day. In the summer example (b), two cork boilers are filled after the sunny day and one after the cloudy day.

The results of the annual yield analysis are shown in Table 2. In order to illustrate the seasonal evolution, monthly results are depicted in Fig. 8. The extracted water that is included in Table 2 and Fig. 8 denotes the volume of water heated with solar power and transferred from the first tank to the cork boilers. The fossil energy consumption represents the amount of additional thermal energy from fossil fuel that is required to heat the water from the temperature reached by the solar field up to the boiling point.

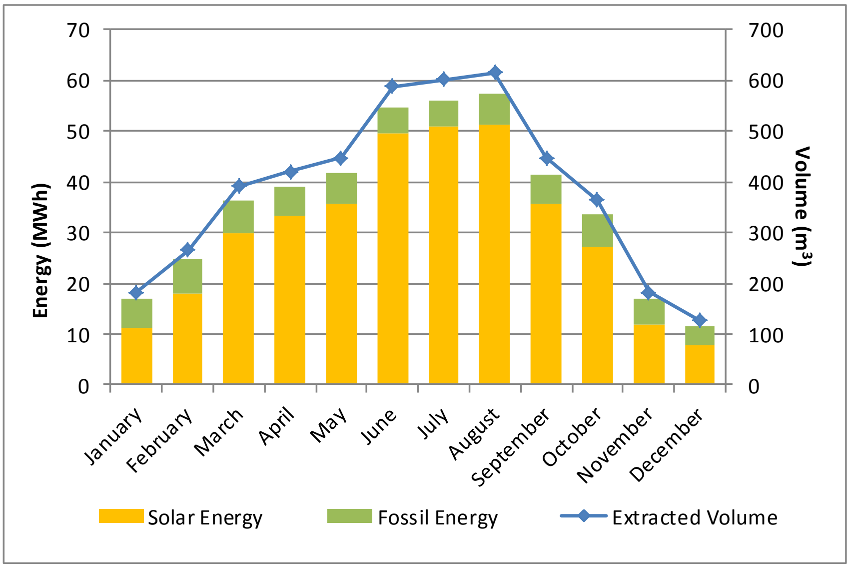

Fig. 8. Monthly yield results of extracted water, useful solar energy and fossil consumption.

Table 2. Results of the annual yield analysis.

Output	Annual result
Extracted water volume	4634 m^3
Useful solar energy	362.45 MWh
Fossil energy consumption	67.76 MWh

5. Conclusions

A solar field design and sizing for the ECOTRAFOR cork boiling plant, located in San Vicente de Alcántara (Extremadura-Spain), was carried out, with its corresponding annual yield analysis. A new model for the CCStaR concentrator and the solar field coupled to the cork boiling process was developed in TRNSYS simulation tool.

A solar field composed of 18 units of solar concentrators type CCStaR, arranged in 6 loops of 3 collectors per loop, is proposed for this plant, with an East-West orientation and a slope of 30º. This solar field would be capable of yielding an annual solar energy of 362.45 MWh for the cork boiling process. In case that the cork boiling was required to be a seasonal process, it is recommended to be performed between March and September, with more than 390 m^3 of hot water produced and more than 30 MWh of useful solar energy per month. Nevertheless, the best months to use the solar contribution are June, July and August; each of them generates around 600 m^3 of hot water and 50 MWh of solar energy per month.

This kind of solar installations would help the cork industry to reduce fossil fuel consumption, providing that the involved process is able to be adapted to the solar power conditions.

Acknowledgements

This work was supported by RITECA-II network through the ERGOSUBER project: "Integration of Renewable Energies into the cork boiling system" [8]. RITECA is the Cross-border Research Network of Extremadura, Centro and Alentejo, made up of 23 partners from Spain and Portugal. The project is in its second phase and is 75% co-funded by the European Regional Development Fund (ERDF) through the Operational Programme for Cross-border Cooperation: Spain-Portugal (POCTEP) 2007-2013 [9]. The authors also want to thank Ramón Pujol and Víctor Martínez, from Physics Department of Balearic Islands University, for their help to develop the solar collector model.

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