MODELLING OF A SMALL-SIZED PARABOLIC-TROUGH SOLAR COLLECTOR FIELD FOR PROCESS HEAT IN THE CORK INDUSTRY

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Abstract

The potential of solar energy for industrial processes has been demonstrated by International Energy Agency (IEA) Task 33 Solar Heat for Industrial Processes. A large number of industrial process heat (IPH) facilities with parabolic-trough collectors (PTCs) erected since the eighties, mainly in the U.S.A., but also in Europe, some of which are still in operation, confirm that small-sized parabolic-trough collectors are the best solar option in a temperature range from 80 to 250ºC. This paper presents design process and simulation results of a small-sized PTCs field pilot plant for supplying process heat in the cork industry in Badajoz (Spain), in which raw cork must be processed by immersion in hot water at 98ºC for one hour to eliminate any taste before being used in the food industry. There is no previous experience in application of solar heating in processing cork. A model with TRNSYS simulation environment of the PTC solar field was developed to take design decisions, such as PTC type, optimum size and configuration of the solar field and piping layout. This simulation environment was also used to analyze the performance of the selected solar field configuration over the operation period. According to results obtained, the solar field supplies 65% of the industrial process heat demand, with 50% annual system efficiency and 50% savings in the fossil energy required for conventional cork processing. Implementation of the system designed is expected to produce references and guidelines for future installations in the geographic area of the pilot project, characterized by high solar resource availability as demonstrated by the rapid deployment of CSP facilities in recent years.

1. Introduction

According to latest statistics from the IEA, it is expected that energy demand in 2030 will be of the order of 17 TW, volume whose satisfaction seems insufficient taking into consideration only the traditional energy sources (IEA, 2010). Therefore, a sustainable future in terms of energy will hardly be feasible without the outstanding participation of renewable energy in general, including in particular solar energy, since it is the one with the highest potential development. This research focuses on the provision of the thermal energy required for an industrial process by solar energy. Statistics of the IEA (corresponding to 2008) show that industry is globally one of the sectors that consumes a greater amount of energy, with around a 30%. In Spain, the industry is not only the largest user of energy (more than 50% of total demand), but also a 35% of it takes place in the medium temperature range, for which the PTCs are very appropriate (Schweiger *et al.*, 2000). This paper aims to further research and development of a pioneer technique in the field of optimization of energy resources.

A number of initiatives, such as the already finished IEA Task 33 and the recently in creation IEA Task 49, have attracted increasing attention to the development of specific PTCs for industrial applications. Small-sized PTCs are able to work up to temperatures of 250ºC, which is an appropriate range for the energy needs of a wide range of industrial processes, as well as the production of large volumes of hot water. Some industries with high needs of thermal energy at temperatures below 250°C are food and beverages, textiles, wood, plastics and chemical industry. To be noted that there is no special legislation or regulations governing the production of IPH using solar energy. There exist some examples of demonstration plants that use PTCs to provide the thermal energy needed in industrial processes. A pilot plant was operating for six years in *Lactaria Castellana* in Madrid (Spain), providing the solar thermal oil at 220ºC to produce steam for sterilization. There is a plant currently in operation coupled to an industrial process in El Nars, near El Cairo, Egypt. This is a 1900-m^2 solar field, circulating pressurized water at 8 bar, with an outlet temperature of 173ºC, to produce steam for pharmaceutical products (Fernández-García *et al.*, 2010a).

2. Methodology

A PTC solar field is integrated by a number of parallel loops, being each loop composed of several collectors connected in series. The design of the solar field consists of determining the optimal number of collectors in each loop (N) to achieve the temperature increase, as well as the number of loops necessary to reach the energy needs required by the industrial process (M). In order to know those energy needs (mainly the thermal power and the temperatures that the solar field has to supply) the specific industrial process, the cork processing, was studied. With these energy data required by the industrial process, the solar field was calculated in two stages: a pre-design or first estimation of the solar field (at a given moment of the year), and the simulation of the thermal performance over a long period of time. The most suitable solar field configuration is thus optimized following the thermal and hydraulic performance of PTC models.

2.1. The cork processing facility

This section describes the case study of this project, the integration of a PTC solar plant in the cork processing. The *Instituto Tecnológico del Corcho, la Madera y el Carbón Vegetal* (Technology Institute of the Cork, Wood and Charcoal), belonging to the *Junta de Extremadura* (a public entity of a region of Spain), is working on a series of projects to improve the quality of its final product, cork cap, by eco-efficient treatment of process water. In the framework of the ECOTRAFOR project, a facility with the same name has been built in *San Vicente de Alcántara* (Badajoz, Spain), which implements a number of improvements over the traditional cork processing. Today, this facility is in beta and not yet in operation. Through the collaboration of this public entity with the CIEMAT-*Plataforma Solar de Almería* (PSA), it is planned to establish a pilot solar plant that supplies the thermal energy needed for cork processing so as to improve the energy efficiency of their facilities.

Fig. 1: ECOTRAFOR plant in San Vicente de Alcántara (Badajoz, Spain)

Raw cork must be processed by immersion in hot water at 98ºC for one hour to eliminate any taste before being used in the food industry, following a specific quality system called *Systecode*, which certifies compliance with the International Code of Cork Stopper Manufacturing Practice (CELIÈGE, 2006). This is done on farms in auxiliary facilities usually for six months a year, from April to September. This process operates for eight hours a day, from Monday to Friday. The cork industry is therefore a very interesting process, not only for its temperature range but also for its coincidence with the maximum solar irradiation levels in Spain along the year. Figure 1 shows the ECOTRAFOR plant, where the cork is stored in the yard and processed in boilers.

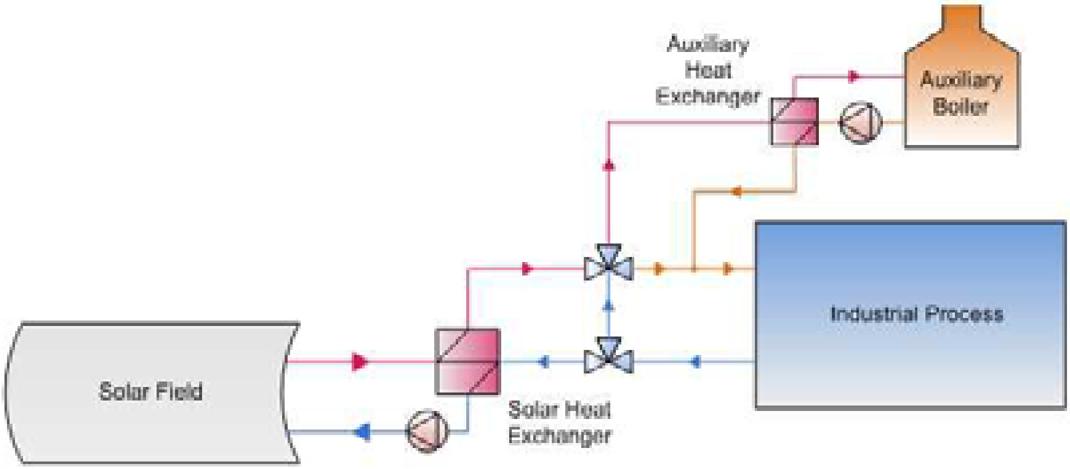


Fig. 2: Simplified scheme of the PTC solar field connected to the ECOTRAFOR plant

Figure 2 represents a simplified scheme of a PTC solar field connected to the ECOTRAFOR plant; the scheme includes the solar field, an auxiliary fuel boiler and, the box depicts the industrial process under study. The use of a heat exchanger is essential to separate the working fluid from the solar field circuit or primary circuit and the industrial process circuit, because the primary circuit requires a special fluid suitable for solar collectors.

As preliminary data for the solar field design, a first estimate of the power demand and the temperature increase required to carry out the cooking was made, taking into account that the volume of water to heat is about $15\ m^3$, the filtered water returns at about $85°C$ and the whole system is isolated to minimize heat losses. Therefore, considering the pipes and heat exchangers losses, the thermal power to be supplied by the solar field (P_t) was established as $P_t = 260\ kW$. Due to thermal losses in the heat exchanger, the expansion tank and pipes between the solar field outlet and the industrial process inlet, the solar field outlet temperature (T_{out}) was set at about $10°C$ above that required in the industrial process, in this case, $T_{out} = 110°C$. The fluid temperature at the solar field inlet (T_{in}) is fixed, as is the case of solar power plants, not only by the return temperature of the heat exchanger, but also taking into account that in this type of application, to provide an adequate mass flow to the power required, a suitable temperature increase would be $20°C$. Therefore, taking the above into account, $T_{in} = 90°C$.

The usual practice is that a solar field does not provide the total energy needs of the industrial process, but, together with a conventional energy source, takes part of the overall energy supply to the industry. A conventional fuel boiler, connected in series to the solar field, may be added. The use of thermal storage in the solar field has been ruled out because, among other reasons, is an extra cost, not only associated with the design of a much larger solar field to perform the storage charging cycles, but also the raw material stored. In addition, there is a limited space on the parcel where the facility is currently located. Apart from that, most of the operation hours of the industrial process match up with the highest solar gain ones, so it is cheaper to design the solar system without thermal storage, and the solar field feeds directly the industrial process. Hence, the auxiliary fuel boiler is sufficient to deal with hours with no or not enough direct solar irradiation, and absorb small variations on it, such as the passing of clouds. The main advantage of the auxiliary fuel boiler in front of the thermal storage is that it allows, if necessary, the use of higher temperatures in the industrial process than those provided by the solar field itself. As shown in figure 2, the boiler would be in series with the solar field and coupled to it through a heat exchanger. The boiler would come into operation when the temperature of the solar field outlet temperature does not reach the one needed by the industrial process. Also, in days under unfavorable weather conditions in which there is no direct solar irradiation (totally cloudy or rainy days), the boiler would provide the thermal demand of the industrial process, thanks to some 3-way valves on the installation that would isolate the solar circuit of the boiler.

2.2. Pre-design of the PTC solar field

A pre-design of the solar field was made considering the power and temperature data set by the industrial process, meteorological and geographical location of the facility, and the data set by the solar field, in accordance with the technical specifications for each collector, working fluids and other elements of the hydraulic circuit. At this stage, the number of collector per loop is calculated depending on P_t and the temperature difference between T_{out} and T_{in}.

Since the solar height varies throughout the year at the same site, the incident irradiation on the collector aperture plane depends on its tracking-axis orientation. Since the period of operation of the industrial process throughout the year coincides with the peak months of irradiation, the optimal orientation for this application is the North-South one. The design point is the moment of the year chosen for the calculations of the pre-design. The solar noon on the summer solstice was chosen, which provides energy values in the most suitable time of year, where the incidence angle would be smaller. The Typical Meteorological Year (TMY) at the site is available and contains mean values in 10-minutes time periods of the ambient temperature (T_a), and direct normal irradiance (DNI). The annual average of the direct irradiation in the area of study is 1641 kWh/m^2. Data at the design point are: $T_a = 31.65ºC$, DNI $= 907\ W/m^2$. The incidence angle (Θ), taking into account the location of the site and the orientation of the collector, is $\Theta = 15.9^o$.

The PTC selected for the solar field, after considering other technology options presently available, was the CAPSOL-02 prototype, designed, constructed and tested under the CAPSOL Project (Fernández-García *et al.*, 2010b). The collector has a flat glass cover in the aperture plane and the concentrator is made of composite materials. Its soiling factor is higher than other collectors because the flat glass cover is the only surface exposed to dirt. Cleaning the collector is considerably easier than in other ones. Also, the flat cover reduces the collector torque, thus improving its interception factor. CAPSOL-02 maximum operating temperature is 250ºC and the heat transfer fluid is pressurized water. Figure 3 shows the CAPSOL-02 prototype and its test facility. A third and commercial prototype, CAPSOL-03, is currently being developed.

Fig. 3: CAPSOL-02 prototype and its test facility

To sum up, taking into account the data described above and known collector-performance parameters (thermal losses, the peak optical efficiency and the incidence angle modifier), some technical collector features (the cross-sectional area of the absorber tube and the aperture area) and the properties of the working fluid under operation conditions of the plant (density, specific heat, etc.), we are able to perform the pre-design of the solar field (González, 2008). It is also necessary to reach a compromise between the limitations of space where the facility will be located and other further calculations such as turbulent flow, the quality of heat transfer between the fluid and the receiver losses (analyzing the convection heat transfer coefficient in the inner metal absorber tube wall), and parasitic loads associated with pumping through the solar field (that depends, among other things, on the shape and size of the field) (Zarza, 2007). As a result of the pre-design process, the most suitable configuration consists of 9 parallel loops of 6 collectors in series in every loop. A collector area of 432 m^2 would be required to reach the energy needs of the industrial process described above.

2.3. Simulation of the solar field thermal performance

The simulation of the solar-field thermal behavior over the six months of operation of the industrial process was carried out, based on the configuration obtained by the pre-design. To make the simulation is necessary to have a model of the system. In this case, a computer program, whose tool is the TRNSYS simulation environment, was used. The program, composed of TRNSYS blocks specially created for this work, mainly contains the mathematical model of thermal and hydraulic behavior of the collector. The model also contains other blocks such as piping models, the load profile of the industrial process of the case study, the power supply provided by the auxiliary fuel boiler and its starting consumption. The model is stationary but includes a 10-minute time step and a transport delay to simulate behaviour during transients. The program is completed with standard library of TRNSYS blocks, mainly for TMY data reading and processing (i.e., to estimate the incidence angle at each instant by calculating the sun position in the location of study), and the integration of meteorological variables, such as power, for energy calculations. This makes possible to analyze the thermal and hydraulic behavior of the solar field, taking into account the connection between collector pipes, the supply and return pipes of the solar field, the transients in direct irradiation or in the ambient temperature due to the thermal inertia of the system, the facility start up, and the losses due to shading of parallel rows.

In order to carry out the calculations, the user has to introduce several inputs to the program. Some of them (N, M, nominal flow rate, Moody's friction factor, etc.) are previously calculated in the pre-design stage. The time-varying inputs (DNI and T_a) are loaded from the TMY file, 10-minute averages to account for cloud transients. Other possible inputs are the set point temperature and the load profile of the industrial process, the collector nominal reflectance, the mechanical-electrical efficiency of the circulation pump and so on. The main results of the program are shown in the following section. It should be pointed out that the models used for this particular application are flexible, capable of being used for other types of collectors or working fluids, and for any other application, whether for the production of process heat in any other industry or for electricity generation plants.

3. Results

This section presents TRNSYS simulation results of the solar field that was confirmed as the best option in the design process to supply the energy needs of the industrial process under study: 9 parallel loops of 6 CAPSOL-02 collectors in series in every loop, that is a collector area of 432 m^2. Figure 4 shows the main simulation results, particularized for a clear day in June. These results are listed below:

- Curve 1: DNI.
- Curve 2: DNI available due to the cosine effect of the incident angle.
- Curves 3 and 4: inlet and outlet temperatures of the solar field (T_{in}, and T_{out}, respectively).
- Curve 5: solar power incident onto the solar field
- Curve 6: power demanded by the industrial process (P_t) throughout the day.
- Curve 7: useful power provided by the solar field, taking into account thermal losses pipes.
- Curve 8: solar power used by the industrial process (P_u), taking into account the thermal inertia of the system.
- Curve 9: fossil power supplied by the auxiliary fuel boiler (P_{aux}).
- Curve 10: mass flow rate of the solar field.

The pressure losses and the electrical pumping power required by the solar field are not represented because they are not visible in this scale. All simulation results can be obtained both graphically and in 10-minute data files. By analyzing figure 4, the maximum of the useful power curve does not match the solar noon but is shifted to the right along the time axis due to the effect of thermal inertia. Moreover, it is necessary to use the auxiliary boiler when the solar field can not reach either the outlet temperature of 110°C (typically during the first and last hours of the day) or a useful power equal to the demand (usually when there is not enough solar radiation). Finally, the mass flow is being adjusted to achieve the required outlet temperature.

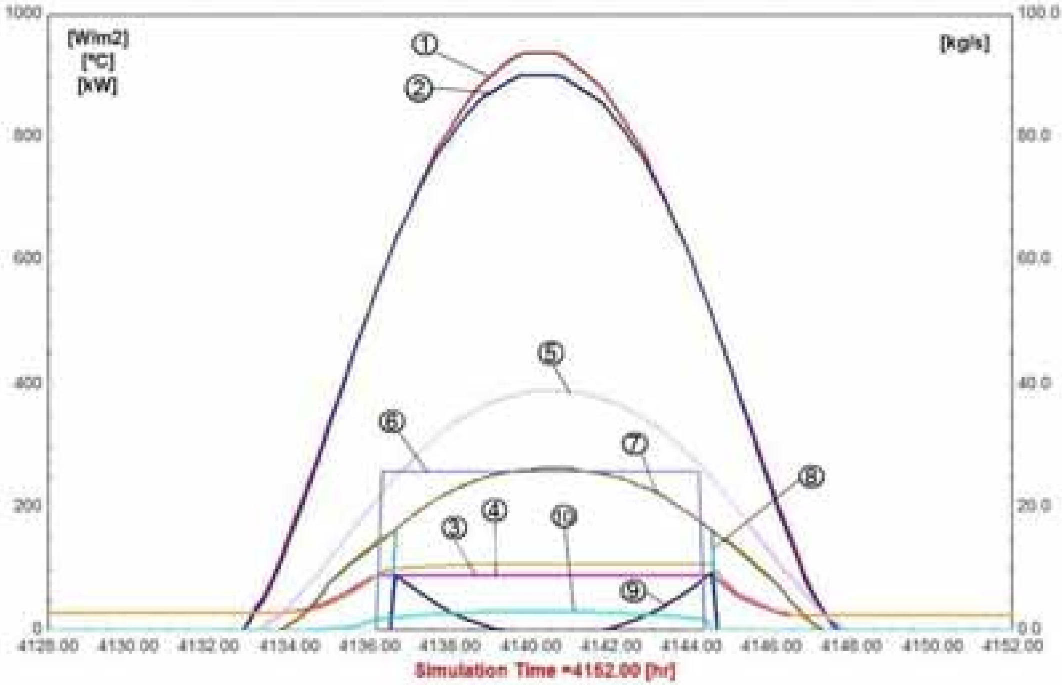
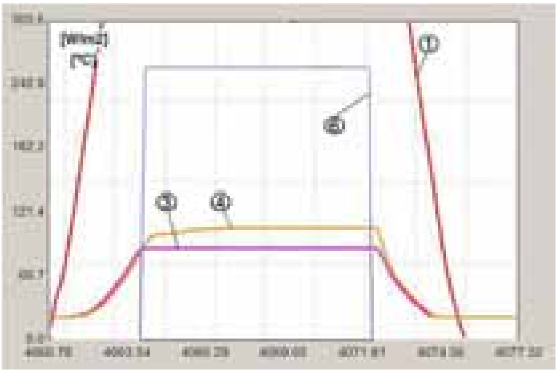


Fig. 4: Simulation results of a clear day in June

Then some variables of the simulation are discussed in more detail and in two different situations: a clear day and a cloudy day. DNI (curve 1), T_{in}, and T_{out}, (curves 3 and 4, respectively) and P_t (curve 6) are shown in figures 5 and 6. Figure 5 depicts that the outlet temperature on a clear day in June respond adequately to both the input temperature, since the field can reach 90 ºC by itself before 8:00 am, and the outlet temperature, which is very stable around the set temperature of 110 °C. Since there are no disturbances, the delay in the outlet temperature is not significant. However, with an interval cloud around the solar noon (figure 6), the outlet temperature, which is not stable at all, oscillates around 110 °C and that temperature does not recover as well as irradiation and with a lag.



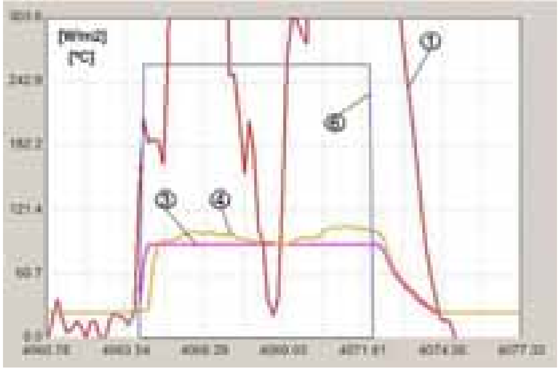


Fig. 5. DNI, P_t, T_{in}, and T_{out} in a clear day of June

Fig. 6. DNI, P_t, T_{in}, and T_{out} in a cloudy day of June

DNI (curve 1), P_t (curve 6), P_u (curve 8) and P_{aux} (curve 9) are shown in figures 7 and 8. Similarly, they show that the output power provided by the solar system is very close to the demanded by the industrial process in clear days (figure 7). The support of the auxiliary system is only needed in the first and the last hour of the workday. On cloudy days (figure 8), power output curve follows the solar irradiation curve, but with a lag.

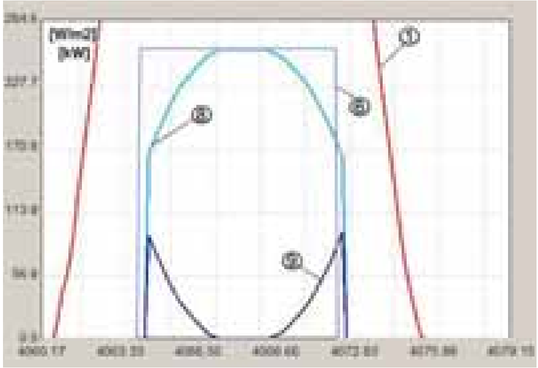


Fig. 7. DNI, P_t, P_u and P_{aux} in a clear day of June

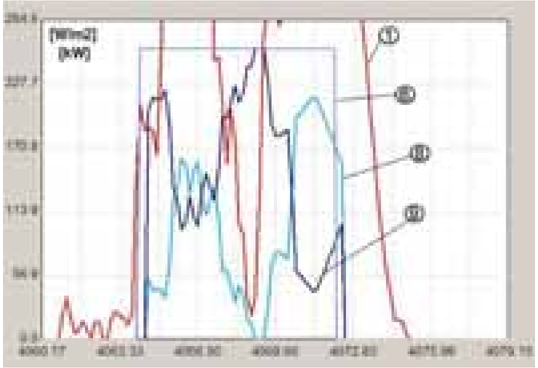


Fig. 8. DNI, P_t, P_u and P_{aux} in a cloudy day of June

The analysis of the solar-field energetic behavior is possible by integrating performance data over the six months of operation of the industrial process. Simulation results were used to calculate the facility efficiency, pressure losses, energy balance, solar fraction and conventional energy saved, under different operating and weather conditions. The solar field efficiency is defined as the ratio of the solar energy incident onto the solar field and the useful energy that it can supply; and the solar fraction as the ratio of useful solar energy used by the plant and the energy demand.

During the semester in which the plant is in operation, the efficiency reaches values well suited to an average of almost 64% and its value is very steady throughout the working period (figure 9). The solar fraction indicates how much energy is supplied by the solar energy system. According to data obtained in this plant, average solar fraction is 65% (figure 10), which is considered quite high. The value of solar fraction grows during the summer months due to an increase of the available solar irradiance.

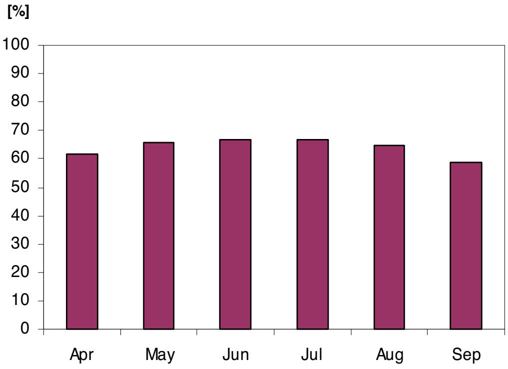


Fig. 9. Solar field efficiency

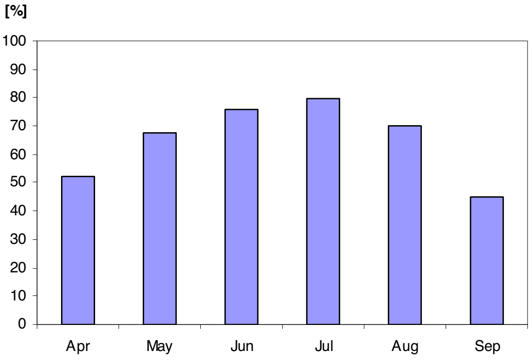


Fig. 10. Solar fraction

Figure 11 shows the energy required by the industrial process, the useful solar energy, the fossil auxiliary energy needed to reach the demand and the energy used in pumping, whose value is not appreciated because it is several orders of magnitude smaller than the rest. Moreover, 50% savings in the fossil energy required for conventional cork processing during the six months of its operation was achieved.

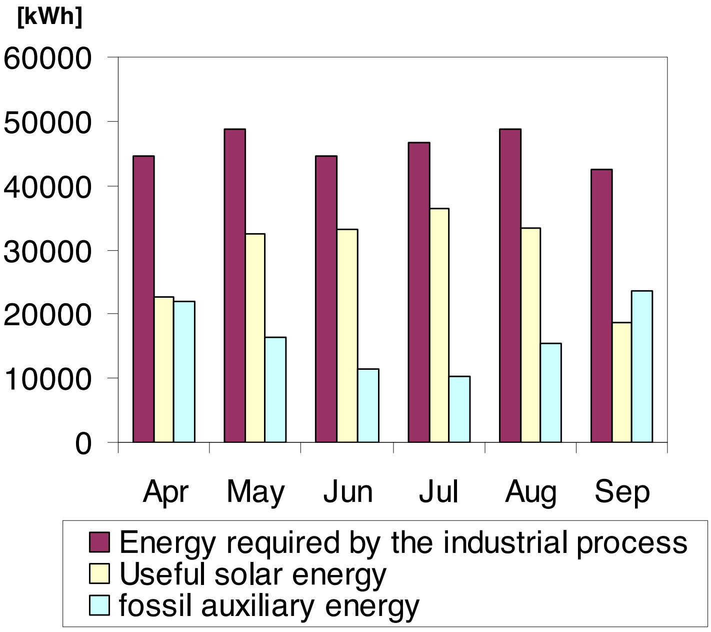


Fig. 11. Energy required by the process, supplied by the solar system and requested to the auxiliary system

4. Conclusions

This project is the first step to erect the first small-sized PTC pilot plant for IPH applications currently in Europe. A software tool for design and optimization of PTCs solar fields for IPH has been successfully developed. Despite of the fact that it was developed for a specific case of study, the flexibility of the programs allows analyzing the behavior of any PTC solar field, providing heat to any application, whether for process heat or for power generation. However, the model developed in this specific case of study, the CAPSOL-02 PTC solar field connected to the ECOTRAFOR plant, will be validated after the construction and start-up of the pilot plant.

Small-sized PTCs with pressurized water as working fluid are the best candidates for process heat in industry, in the temperature range of cork processing (around 100ºC). The collector chosen for this application, CAPSOL-02, is the one with longer life, lower soiling rate and less torque. According to results obtained, the designed solar field supplies the 65% of the thermal energy demand of ECOTRAFOR facility, with an overall efficiency of 64% over the six months of operation of the industrial process (from April to September).

On the other hand, the implementation of solar systems in the industry requires the set up of solar pilot plants with the help of public funds or other incentives and, the market introduction of small-sized PTCs for IPH applications in order to achieve a reduction of the manufacturing costs and to improve their quality. In this regard and since concentrated solar technology for electricity generation has entered the commercial stage, a trend in recent European projects for the promotion of research on concentrated solar thermal technology for process heat has been detected.

Acknowledgements

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References

CELIÈGE. 2006. International Code of Cork Stopper Manufacturing Practice. Version 5. Confédération Européenne du Liège, Paris.

Fernández-García, A., Zarza, E., Valenzuela, L., Pérez, M., 2010a. Parabolic-trough solar collectors and their applications. Renewable and Sustainable Reviews 14, 1695-1721.

Fernández-García, A., Zarza, E., Pérez, M., Valenzuela, L., Rojas, E., Valcárcel, E., 2010b. Experimental assessment of a small-sized parabolic-trough collector. CAPSOL Project. Eurosun 2010, Graz.

González, L. 2008. A New Methodology for Optimum Design of Solar Power Plants with Parabolic Trough Collectors. Eurosun 2008, Lisbon.

IEA. 2010. Key world energy statistics, Paris.

Schweiger, H., Mendes, JF., Benz, N., Hennecke, K., Prieto, G., Cusí, M., Gonçalves, H., 2000. The potencial of solar heat in industrial processes. An estate of the art review for Spain and Portugal. Eurosun 2000, Copenhagen.

TRNSYS. 2007. A Transient System Simulation Program. Solar Energy Laboratory, University of Wisconsin.

Zarza, E., 2007. Pérdida y Balance de Energía en un CCP. Máster en Energía Solar, Universidad de Almería.