Integration of a concentrating solar thermal system in an expanded cork agglomerate production line

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Abstract

The expanded cork agglomerate, known by its remarkable insulation properties, is one of the many products offered by the traditional cork industry in Portugal. Its manufacture process is carried out in autoclaves that require the use of a high temperature steam flow to expand the cork resins. Nowadays, most industries produce this thermal energy with steam generation units powered by fossil fuels or biomass. On the other hand, solar heat for industrial processes is a growing market that seeks to increase renewable energy use and sustainability in the industrial sector, therefore the present work aimed to assess the use of concentrating solar collectors in the thermal energy production system of an operating facility: Sofalca, Lda, which uses an on-site produced residue called cork powder to power its boiler.

In order to satisfy thermal demands, a parabolic trough solar system was studied with the purpose of preheating the feedwater of the boiler via an external heat exchanger. The solar field model was dimensioned to provide the water with sufficient heat to reach a maximum temperature of 170ºC at 8 bar of pressure.

The criterion of the analysis was the maximization of solar energy supply at the most economically favorable conditions, which resulted in a system configuration capable of achieving a solar fraction of 41% at a levelized cost of energy of 8.3 c€/kWh. However, calculations also indicated that the economic feasibility of the studied scenario is dependent on the market price of sale of the saved cork powder.

Keywords: Parabolic Trough, Expanded Cork Agglomerate, Solar heat, TNRSYS, Concentrating Solar Power.

I. INTRODUCTION

The cork industry is a traditional and important activity in Portugal, offering a wide variety of products derived from the bark of the cork oak; and among them, the Expanded Cork Agglomerate (ECA). ECA is used in thermal insulation, acoustical absorption and vibration damping applications, as well as a raw material for furniture, decoration and other products, with the advantage of a strong ecological nature. The production of the mentioned agglomerate involves a significant heat demand, considering the high temperature steam requirement in part of the manufacture process. In general, the procedure is based on the expansion of natural resins using water vapor at temperatures above 300ºC. To generate it, specialized industries are equipped with steam boilers that operate mainly with biomass.

When thinking on alternatives or complementary technologies for this heat generation scenario, many commercially mature options are found, namely conventional fossil fueled or biomass boilers. Nevertheless, current energy trends walk towards sustainability and nature preservation paths, acknowledging that the future world panorama is certainly focused on the use of renewable solutions for heat and electricity generation. In this context, concentrating solar energy stands as one of the most promising areas, embracing both industrial and utility scales.

The present project aimed to study the integration of concentrating solar thermal (CST) systems in the ECA manufacture process, analyzing if the collected energy is capable of satisfying the thermal demands, and characterizing its technical and economic performance under certain conditions of operation. Among the technology alternatives, a linear focus CST system, specifically the parabolic trough, was the one selected, since it is the most commercially mature and presents attributes that are suitable for the application.

The project aimed to evaluate real data provided by the industry in order to model and simulate the integration of the mentioned processes, thus looking for adequate and technically and economically attractive solutions. Annual performance results, complemented with daily behavior information helps in the selection of the most favorable integration scenario.

II. CASE STUDY

Within the scope of international activities, such as Task 49 from IEA-SHC and Task 11.1 from STAGE-STE (SHC, 2015) (STAGE-STE, n.d.), focused on Solar Heat for Industrial Processes, the present work studied the use of parabolic trough systems to supply heat for the production line of the Expanded Cork Agglomerate.

The study is performed with data from an operating facility, specifically from *Sofalca – Sociedade Central de Produtos de Cortiça, Lda*, specialized in expanded agglomerates production. They currently use cork powder (biomass) as a feedstock for the steam generation unit thus the combination of systems seeks to replace or hybridize the existing one, analyzing the economic and industrial value of the cork powder, and its potential savings during the year.

A. Expanded Cork Agglomerate

Cork agglomerates is a subsector of the cork industry that provides an outlet for the residual by-products, residual raw materials and virgin cork (that does not enter any other processing line), which are, in a first process, passed through the trituration and grinding sections. Three main products come out of this sector: agglomeration with adhesives, Cork agglomerate composites with rubber, and Expanded Cork Agglomerates (ECA).

Also known as Insulation Cork Board (ICB) or simply Black Cork Agglomerate, the ECA is a material that comes from the aggregation of the raw cork granules, which is a consequence of the volumetric expansion and natural resin exudation that takes place under the action of the temperature of a thermal fluid (SOFALCA, 2015).

B. ECA Manufacture

The manufacture process begins with the extraction of the virgin cork from the branches or prunings, followed by the trituration and grinding previously addressed. As described by Gil (1996), the particle size attained depends on the type of agglomerate to produce. The preparation process continues with a cleaning section that removes impurities like cork powder and wood log pieces, mainly with densimetric separators. The final step in the preparation covers the drying, with a flow of hot air (at around 110ºC) or heating of the storage silos until reaching the ideal humidity (Gil, 1996).

The next phase is the agglomeration, which is performed through thermochemical treatment in autoclaves. This process consists of a block production where the granules are heated with superheated steam in an autoclave that is the mold itself (Pereira, 2007), therefore it provides the rectangular shape (or any other required shape) that is seen in Fig. 1.

The detailed agglomeration procedure inside the autoclave is now described: the dry granulate is introduced into the autoclave until reaching a predefined level, which is selected according to the desired volumetric mass of the product (Gil, 1996). Afterwards, a light compression of the matter is done to compact the mix and define its final density; at this point a flow of “steam is injected through the openings in the bottom face and bottom edge of the lateral faces of the autoclave” (Pereira, 2007). This superheated steam *bakes* the materials at temperatures of around 300-350ºC and under a 40 kPa gauge pressure, for approximately 20 minutes. For the same process, Gil (1996) specifies that the range of temperatures is around 300-370ºC with an average of 340ºC, and in terms of pressure, the value is the same but could vary between 30 and 60 kPa (gauge).

Fig. 1. ECA production and detail *(ModernEnviro, 2014)*.

The high temperature steam flow is responsible for the thermochemical degradation of the cork cell wall, with its previous increase in volume; this degradation originates byproducts that act as natural adhesives between the granules, thus forming the expanded agglomerate (Silva, et al., 2005).

C. Thermal energy production

It has been reported that steam is mainly produced by biomass fired boilers, usually with the cork powder residue that is obtained from almost every processing phase of the cork. Technically speaking, the steam flow required for each autoclave is estimated around 700 kg/h in a 400ºC operation. For 6 autoclaves, pressure in the boiler should be around 785 kPa (Gil, 1996). The same author also refers that: for an ECA production of 40.000m^3/year, the steam consumption is around 7.000 kg//h, which is equivalent to a consumption of 1,5m^3 of water per cubic meter of agglomerate (if cooling water is included and no reuse is performed). Then, energy demand could be established as: 26,7 MJ of energy from biomass for one kilogram of agglomerate.

D. Cork powder

Cork powder is a residual material from the many industrial cork processes, constituted mainly by gross impurities, dust and particles of insufficient dimension (lower than 0,25 mm) (Pintor, et al., 2012), and heavy granules. The biggest share comes from suction of residues in several operations: trituration, separation, etc. Note that the “industrial transformation of cork generates up to 25% (weight) of cork dust as byproduct” (Silva, et al., 2005).

The main use of this cork dust is as fuel for steam generation in boilers, since its High Heating Value is said to be between 15-28 MJ/kg (Gil, 1996).

E. Parabolic Tough technology

To benefit from the solar beam (or direct) radiation that reaches the surface of the Earth, Concentrating Solar Thermal systems employ an array of mirrors that concentrate the rays of the sun into a special receiver, thus transforming the solar irradiance in useful energy, such as heat, electricity and fuels. (Lovegrove & Stein, 2012). One of the available technologies is the Parabolic Trough collector.

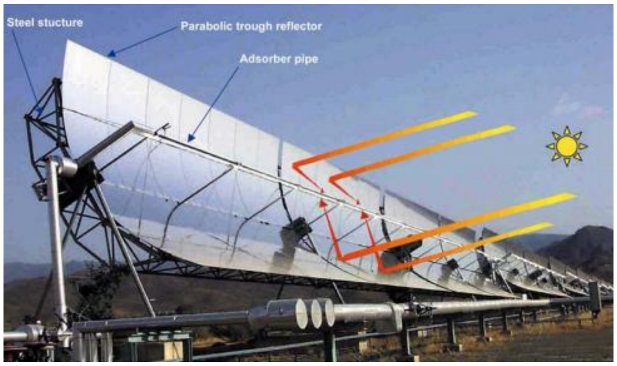

Fig. 2. Parabolic Trough collector assembly *(Kearney, 2007)*.

The solar energy is collected in great parabolic curved mirrors (Fig. 2), capable of tracking the sun in one axis; directing it to an absorber tube, where temperatures can reach the 400ºC range (Castro, 2012). Inside the tubes, a heat transfer fluid receives the concentrated energy as it flows through it; until reaching a certain temperature. At this point, it fulfills the conditions to supply heat for a thermodynamic cycle or any industrial process.

The called PTC (from the term Parabolic Trough collectors) facilities consist of modular arrays of single-axis-tracking collectors disposed in many parallel rows, which compose solar fields of hundreds or thousands of assemblies usually aligned in a North-South axis disposition (NREL, 2010). The commercially available systems include large and small collector schemes; the large ones are evidently of higher dimensions and considerable aperture areas and aimed at the electricity generation sector.

Small collectors were developed for process heat applications, considering the lower heat demand if compared with CSP power plants. A wide range of industrial applications could be covered by this alternative: agricultural sector, food industry, biofuel production, desalination, among others. Concerning the collector design, several were developed according to the temperature required, so the materials and dimensions are suited for the specific industrial applications (Zarza, 2012).

This kind of collectors are mainly composed by: a concentrator structure, reflector surfaces and linear receivers.

III. SOLAR HEAT INTEGRATION ASSESSMENT

The manufacture facility from *Sofalca, Lda*., and its steam generation system are assessed to evaluate its potential solar heat integration and its thermal demand parameters.

A. Company visit and measurements

A total of two technical visits to the manufacture facility of the company were completed during the first stages of the project, with the main objective of acquiring data from the heat generation process itself.

In terms of the currently installed heat generation system, in order to obtain the required steam parameters, the company utilizes a steam boiler unit with the *water-tube* variant.

The basic operation consists of a biomass furnace working with cork powder as fuel, which is fed by a worm screw that controls the feedstock entering the system. The hot combustion gases flow inside the boiler case, heating the water that passes through the tubes. A water drum collects the incoming fluid, while the steam drum separates the mixture of saturated water and steam. The installed equipment also possesses a superheating stage linked to the steam drum outlet. Summarizing, the unit is capable of vaporizing and superheating water at the required conditions.

To estimate the thermal demand of the ECA manufacture process, data from the boiler's operation is measured, obtaining average values of 5070 kg/h for the water flow rate and inlet and outlet temperatures of 21ºC and 354ºC respectively (at 8.19 bar and 4.19 bar). Water consumption records for a year of operation were also collected, as represented in Fig. 3.

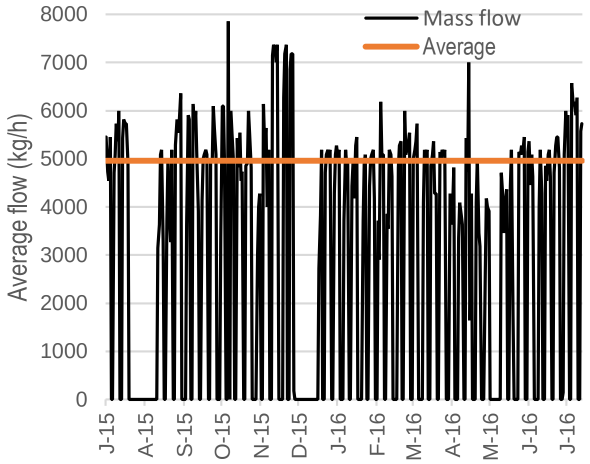

Fig. 3. Water flow annual records of the boiler.

B. Thermal energy demand

Having operation data from the steam generator and the process water consumption, estimations on the thermal power and on the annual heat demands are obtained. Table 1 summarizes the power of the boiler in its various stages.

Table 1. Boiler power per stage.

Stage	***Heat rate (kW)***
Pre-heating	898.33
Vaporization	2882.18
Expansion	0
Superheating	574.61
TOTAL	4355.12 kW

The thermal energy demand for a year of operation is estimated by simulating a simple boiler on TRNSYS (Fig. 4). The equipment is modeled with Equation 1, and software types that yield thermodynamic properties.

$$\dot{Q} = \dot{m}(h_2 - h_1) \tag{1}$$

The estimated annual thermal demand of steam is shown on Table 2

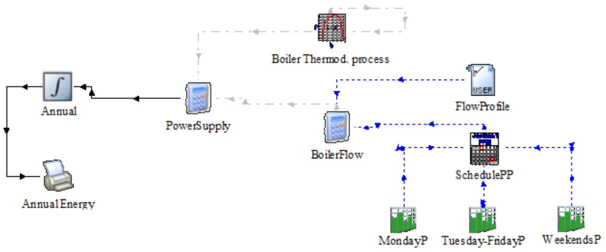

Fig. 4. Boiler annual generation model.

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Table 2. Annual thermal energy produced in the boiler.

Stage	*Boiler total energy*	*Preheating + Vaporization*	*Preheating*
Annual energy (MWh)	9952.61	8639.69	2051.81

C. Solar integration approach

One of the crucial steps of the assessment is the identification of integration points; in this particular case, and given the fact that not much information is known about the process level, the suitability of integration is defined for the supply level of steam. Analyzing the system, it seems feasible to consider the preheating of the boiler feedwater as the integration point of the study, since modifications on the already existing circuit would not be significantly deep and, most importantly, the power level is reachable (around 900 kW). A solar system designed to supply between 3000-4500 kW of thermal power would have dimensions and capital costs that might not be available or supported by the company. If desired, a steam generation by the solar system is a possible approach if just a fraction (in terms of mass flow) is generated by the solar field and the rest by the conventional boiler.

Concerning the latter, the solar heat integration concept defined for this case study is: *Preheating of boiler feedwater via external heat exchanger*. Besides easier implementation, the selection of an external heat exchanger over an internal one obeys the possibility of addressing steam generation in future model studies; leaving this option open. For preheating, the fact that water enters almost at saturated liquid might be advantageous in terms of work capacity relief of the system, and fuel consumption reduction.

IV. SYSTEM DESIGN

A system designed to preheat the water flow rate of 5070kg/h at a maximum temperature of 170ºC was assembled on TRNSYS, considering solar field loops, heat exchanger equipment, thermal energy storage, and control systems. Fig. 5 shows the built model including the mentioned components.

The components (types) used are available at the libraries embedded in TRNSYS Simulation Studio, nevertheless, a description on the type used for the solar field is shown below.

A. Type 536 – Solar field

The main expressions that rule the calculations performed by the component are based on theoretical equations from Duffie & Beckman (2013).

The useful energy gain equation is based on standard collector performance expressions plus a series of corrections applied to account for incidence angles, use of more than one collector in series, and flow rates other than used under test conditions. Equation 2 shown below is then the modified overall useful energy gains from the solar field. The terms between brackets indicate simple energy gains for a square meter of collector aperture, where $F_R(\tau\alpha)_n IAM\ I_{beam}$ is the quantity of energy in the receiver considering the optical losses and radiation incidence angle, while the negative term accounts for the thermal losses in the tubes. The factors R_1 and R_2 modify the energy yield computation according to test information and the number of collectors connected in series. Finally, the aperture area of each collector is included and the number of parallel rows of the solar field is taken into account.

$$Q_u = R_1 R_2 A_{aperture} N_{parallel} \left[F_R(\tau\alpha)_n IAM\ I_{beam} - \frac{F_R U_L}{ConcRat}(T_{in} - T_{amb}) \right] \tag{2}$$

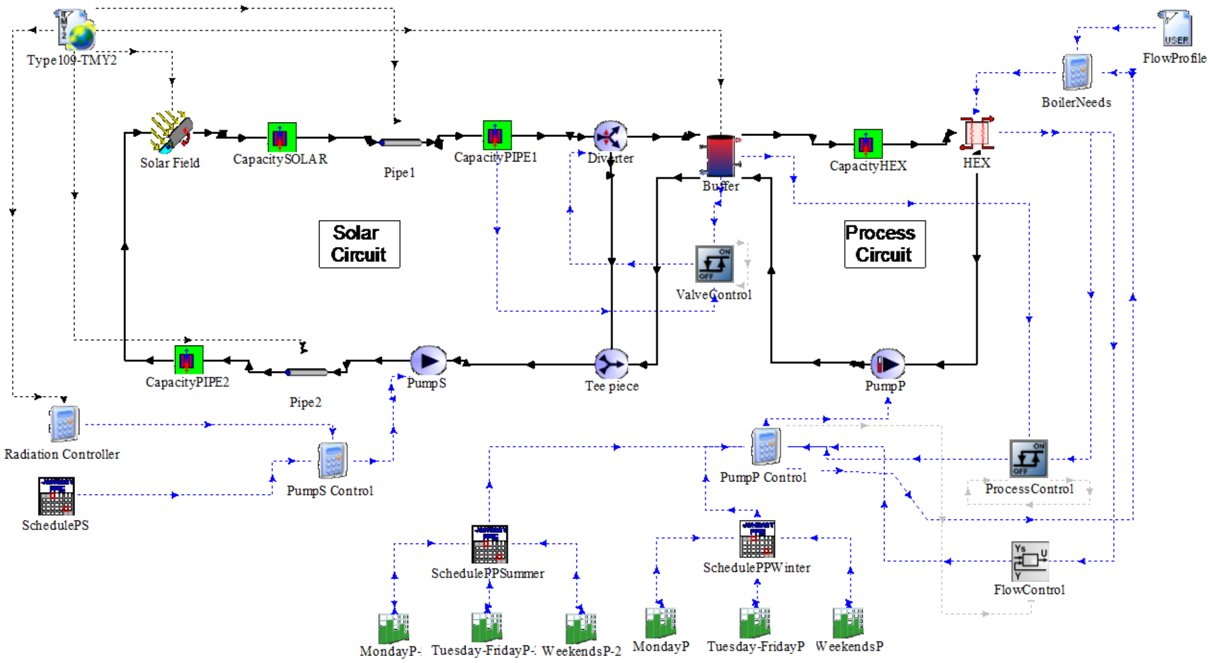

Fig. 5. Solar heat integration model.

Also, the temperature of the fluid leaving the collector is:

$$T_{out} = T_{in} + \frac{\dot{Q}_u}{\dot{m}_{fluid} Cp_{fluid}} \qquad (3)$$

Equations presented are taken from the documentation of Type 536 available in the software folder. For more information on the used variables, consulting the TRNSYS Documentation file is recommended.

B. NEP PolyTrough 1800 Parabolic Trough collector

For the simulation of the solar field, a market available parabolic trough collector assembly is selected: the NEP PolyTrough 1800. Its main characteristics are presented on Table 3.

Table 3. Technical and performance characteristics of the PolyTrough 1800 *(SPF, 2013) (NEP Solar)*.

Dimensions	**Aperture area**	36.9 m^2
	Length	20.9 m
	Width (aperture)	1.845 m
	Height	1.75 m
	Concentration Ratio	54
	Specific weight of the assembly	30 kg/m^2
Performance	**Minimum flow rate**	900l/h
	Nominal flow rate	1800 l/h
	Maximum flow rate	3600 l/h
	Fluid content	19.6 l
	Maximum pressure	40 bar
	Thermal capacity (Empty)	7.2 kJ/K
	Tested flow rate	1400 l/h
	Tested fluid	Water
	η_o	0.689
	a_1	0.36 W/m^2K
	a_2	0.011 W/m^2K

Prior analysis of the heat exchanger dimensions and parameters aided in the definition of the characteristics of the rest of the equipment and its operation conditions. Among them, the analysis of the flow rate required to assure the thermal exchange between fluids, yielded the number of collector lines in the solar field, being 7 rows for an overall heat transfer coefficient of 142316.4 kJ/hK in the heat exchanger.

Main aspects of the model are listed below:

- Heat transfer fluid (HTF): Therminol® 66.
- Heat exchanger: counter-flow: cold side is water; hot side is the HTF from the solar loop.
- Storage tank: stratified tank that stores HTF.

C. Control strategy

The control methods applied to the model have as main objectives to maximize solar energy yield of the system while considering the operation schedule of the ECA manufacture line. Specific types were included to address these aspects, apart from differential controller models that limited the outlet temperature of the water in the heat exchanger as a vaporization safety measure.

V. ANNUAL SIMULATIONS

With the model assembled, simulations of the system are performed considering the next features:

- Solar field orientation: both North-South (NS) and East-West (EW).
- Size of the tank: Variable.
- Number of collectors in series: Variable.

Combination of this features generate a set of solar integrated system configurations that are tested under the same load and weather conditions. To compare the alternatives, indicators like solar fraction or Levelized Cost of Energy (LCOE) are used for the technical and economic comparisons.

The aim is to select a solar system configuration that stands out from the rest in terms of solar energy utilization and favorable economic characteristics, which does not necessarily mean the one with the cheapest investment cost, but one that comprises both aspects. On the other hand, the seasonal behavior is not critical, this is, solar energy generation does not have to be regularly distributed along the year, since the saved cork powder can be stored for use during months in which the incident solar energy is lower. However, daily stability characteristics are important for the analysis.

A. Solar fraction analysis

Extracting the quantity of useful energy exchanged in the counter-flow heat exchanger, the solar fraction of the integrated system can be computed.

$$SolarFraction = \frac{Useful\ energy\ in\ the\ HEX}{Boiler's\ preheat\ energy} \qquad (4)$$

Said parameter describes the percentage of energy delivered by the entire system as a function of the supplied energy of the current heat generation system. In this particular case, the useful energy of the exchanger is compared to the quantity of heat used by the boiler in its preheat stage.

Annual time periods are considered for the energetic evaluation of the model alternatives; thus the simulation obeys the next considerations: 8760 computations hours with a 1-minute time step.

Knowing beforehand that the solar field is designed to have 7 collector rows in parallel, the number of collectors in series on each line is increased from 3 to 7 between simulations. The volume of the tanks is also variable between simulations, according to specific storage capacities: liters per square meter of aperture area. These solar field and storage sizes are applied both for NS and EW simulations.

Result of the TRNSYS simulations are represented in Fig. 6 for different orientations of the solar field.

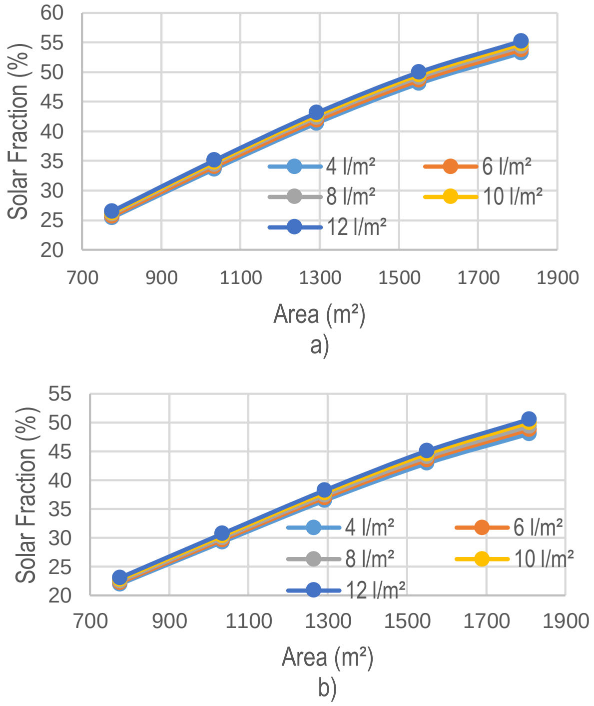

Fig. 6. Solar fraction results for NS (a) and EW (b).

The main conclusion from the graphical results is the evident greater solar fraction obtained when increasing the number of collectors in series and the storage capacity of the system, knowing beforehand that more collectors per line yield higher temperatures of the HTF. It also seems that storage capacity increase has a deeper influence in greater fields, probably related to the capacity of generation of such a big aperture area. Between collector orientations, the North-South approach presents overall higher values of solar fraction if compared to its East-West competitor; reaching a difference of 5 percentage points for the biggest configuration.

The maximization of solar energy criteria would define the system with the biggest dimensions as the most favorable, however the assessment considers other indicators to select the final system, thus leaving the decision for deeper approaches.

B. LCOE Analysis

Economic analysis of the simulated configurations is approached by estimating the Levelized Cost of the Energy produced (LCOE), which is no more than the total cost of installing and operating a project expressed in € per unit of generated energy over the lifetime of the system. Castro (2012, p.33) develops a simplified model of the indicator, as seen in the expression shown next:

$$LCOE = \frac{I_t(i + d_{om})}{E_{annual}} \tag{5}$$

Therefore, the required data for the LCOE is:

- Total investment (global system costs).
- Interest and inflation rates.
- Lifetime of the project.
- O&M specific costs.
- Annual yield of energy of the system.

Total investment costs and annual yield of energy depend on the configuration and size of the system, but the rest of the parameters can be established beforehand, as seen in Table 4.

For the investment, and considering the characteristics and dimensions of the common equipment, investment expenses are obtained using chemical engineering design databases: *Matches* online database (Matches , 2016) and the *Cost Estimator Tool* (Peters, Timmerhaus, & West, 2016) from Plant Design and Economics for Chemical Engineers, 5th edition.

Table 4. Economic parameters of the LCOE analysis.

Parameter		***Value***	***Source***
Lifetime of the project		25 years	(Silva, Berenguel, Pérez, & Fernández-Garcia, 2014)
O&M specific costs		2% of the Investment	(Kalogirou, 2003)
Rates	**T_1**	3.41%	(Banco de Portugal, 2016)
	T_2	0	*Not considered*
	T_3	1.80%	(Trading Economics, 2016)

For the rest of the components (that vary between simulations):

- Storage tank: Shop fabricated carbon steel tank with 6.35mm. Costs individually obtained for each volume (Peters, Timmerhaus, & West, 2016).
- Solar collector assembly costs are estimated based on an existing industrial facility that coupled its production line with a 627m^2 NEP PolyTrough 1800 collector loop. Specific costs are 502.4 €/m^2 of aperture area (AEE INTEC, 2015). This value is used for the present work given the difficulty of finding approximate costs reported by the manufacturer.
- Storage tank insulation: Fiberglass with a 25.4 mm thickness, with a price of 81€/m^2 (Peters, Timmerhaus, & West, 2016).
- Therminol® 66 market price: 5.5-6 €/kg, as reported by the Eastman Chemical Company when directly contacted.

By joining theses aspects and including the common costs, the global investment for each configuration is obtained. Finally, the LCOE (in eurocents per kWh) for the NS and EW fields is estimated, yielding the following curve (Fig. 7).

Notice that solar fraction curves are included to compare the energy yield and the cost of said energy for each system. East-West orientations present the same behavior but with higher LCOE values and lower solar fractions, thus the NS orientation is seen as the best option for this particular case.

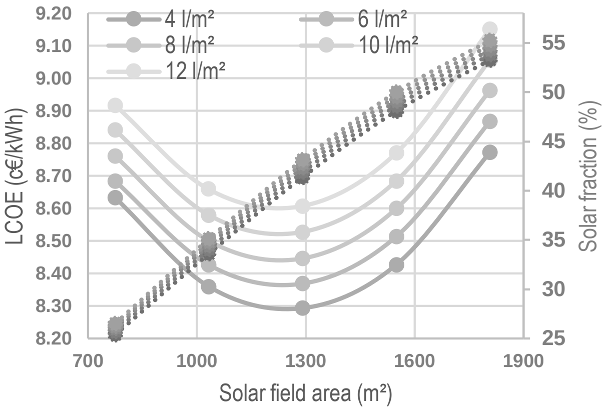

Fig. 7. LCOE for the NS configurations.

Looking at the behavior of the NS LCOE curve, the cheapest configurations are defined, corresponding to a solar field area of 1291.5 m^2, i.e. a solar array with 7 rows of 5 collectors in series. However, this might not yet be the most favorable option, since the difference between LCOE of diverse system configurations is small, but its difference in terms of produced energy is significant. This is, a system might produce slightly costlier energy but at quantities that the cheapest system is not capable of generating. To address this aspect, payback period analysis is performed.

C. Payback period analysis

The payback period economic indicator gives an idea of the number of years that would be necessary to recover the investment. The annual cash flows include the operation and maintenance expenses and the possible incomes. Since this system seeks to replace part of the biomass consumption, the revenues are represented by the savings of cork powder, that has a potential market value.

Since no precise data is available, the calculations are performed for a range of cork powder price values in order to obtain behavior curves and estimate the price at which the cork powder should be sold to make the project feasible. The results of the payback analysis are presented below, for 5 economically favorable systems chosen.

As expected, an increase of the price of sale yields smaller periods of investment return. Concerning the assessment of the five systems, the differences are not significant, but the lowest LCOE system still presents the most favorable conditions.

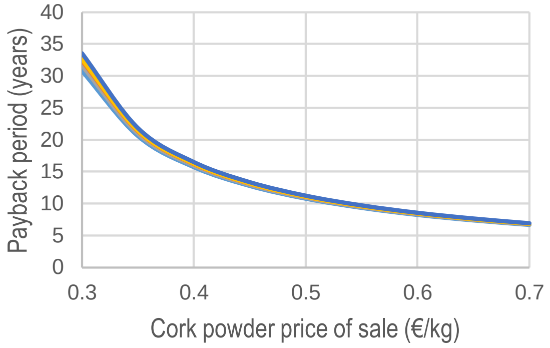

Fig. 9. Payback period per price of cork powder.

D. Technical performance

In order to show the daily performance of the equipment that integrate the system, simulations for typical winter and summer days are executed. The most economically favorable system is used: 7 parallel rows of 5 collectors each (1291.5m^2) aligned in a NS axis. The storage volume is 5.166m^3.

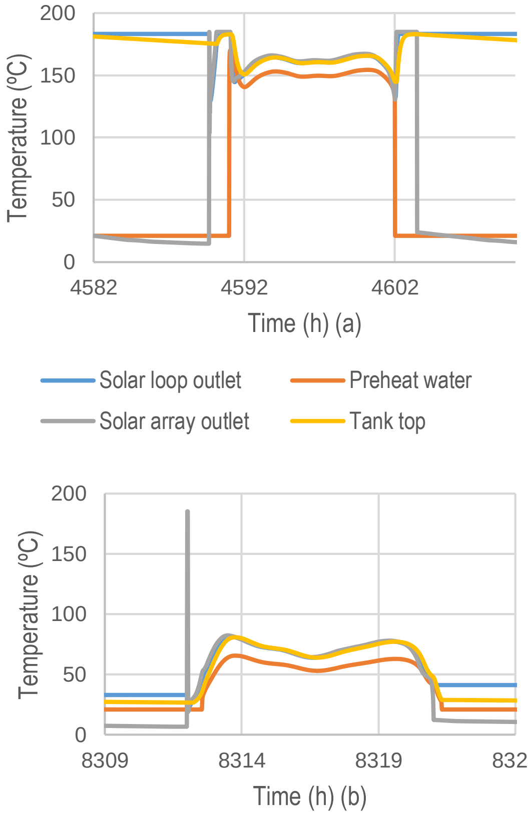

Fig. 8. System's temperature behavior for clear days of summer (a) and winter (b).

A summary of the most significant results is presented in Table 5.

Table 5. Summary of the system annual analysis.

Useful energy	848.60 MWh
Energy gain in the field	1380.40 MWh
Incident beam energy (Surface)	2060.51 MWh
Dumped energy	8.35 MWh
Solar fraction	41.36 %
LCOE	8.30c€/kWh

VII. CONCLUSIONS

The design of a parabolic trough solar collector system integrated into the feedwater preheating stage of the steam generation unit of *Sofalca, Lda.* was achieved, yielding performance indicators of its technical and economic behavior. It is technically feasible to integrate solar process heat in the supply level of steam of the Expanded Cork Agglomerate manufacture process, but the selection of the solar system configuration depends on the criteria of investors and/or facility owners. Also, the economic feasibility is only accomplished if adjustments on the cork powder price of sale are made, even though the LCOE obtained is between the range of values of other sources. In the technical aspect, the most economically favorable configuration presents good temperature stability characteristics.

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