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# Integration of Solar Thermal Energy and Heat Pump in a Fish Canning Process Combining Pinch and Exergy Analysis

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## 1. Introduction

Many industrial processes work in temperature intervals where solar thermal technology would be able to provide a main amount of the needed energy at a reasonable cost. However solar technology presents some difficulties for its implementation in productive scale: intermittence of the source, low density and some heat integration handicaps (Philibert, 2006). The main objective of this investigation was to evaluate the potentiality of a thermosolar-heat pump set in an industrial process, using a systematic methodology which combines the pinch analysis and the exergy analysis for heat integration and optimization. The methodology was validated in the context of a tuna fish canning industrial plant, located in the seaside of the Basque Country of Spain, a zone subjected to non-favourable climatic conditions for thermosolar system implementation on industrial scale, due to diffuse irradiance is mainly relevant than direct irradiance (Basque Government Energy Entity, 2002). The study was focussed on heat improvement, starting with the establishment of the mass and energy balances of the process, and continued investigating and proposing feasible improvement. Then, it was evaluated the contribution of a solar thermal subsystem in combination with an adequate heat pump, and reinforced by a conventional fossil fuel resource (a natural gas boiler). Finally, the optimum heat integration of the overall system was determined through pinch and exergy analysis, taking into account main environmental and economical parameters.

## 2. Methodology and tools

The studied canning process operated by batches and The Time Average Model (TAM) was chosen for the pinch analysis, taken in account time limitations when streams were matched by the Time Event Chart. The Grand Composite Curve GCC was the fundamental tool when comparing evaluated scenarios of heat integration (Krummenacher and Favrat, 2001). Pinch analysis was applied to the process in the context of a Total Site Integration, where two coincident processes were considered: the fish processing process and the energy supplying process.
In the canning process, heat transfer related, primarily, with raw material, product, water and steam flows. There was no-change in concentration of substances or chemical reaction to consider. Exergy was fundamentally physical type where only thermal and mechanical exergies were considered. For exergy analysis, energy efficiency (*η*) and exergy efficiency (*ψ*) were fundamental tools when comparing evaluated scenarios, added to some other thermodynamic parameters: entropy generation

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($S_{gen}$), irreversibility of the system (*I*), and exergy improved potential (*IP)* (Gunerhan H., Hepbasli A., 2007).

In order to determine the optimum integration of thermosolar energy and a heat pump in the process, the following scenarios were analyzed:

- Scenario 1. The present process, using only on a natural gas boiler.
- Scenario 2. The integration of a heat pump with the boiler and an economizer, considering three technologies (compression heat pump, gas driven compression heat pump, and a heat transformer). The choice of the more suitable technology and the degree of water evaporation in the pump was decided evaluating technical, environmental and economical variables.
- Scenario 3. The integration on thermosolar energy, linked in series arrangement with the mentioned elements of the energy providing system; in this context, different solar fractions and solar field surfaces were analyzed.

The adopted forced circulation solar thermal installation of the plant included, basically, a solar field with evacuated tubes-heat pipe technology (Weiss and Rommel, 2008) in parallel arrangement, a plate heat exchanger and an accumulator stratified in three levels.

## 3. Heat integration of the process

### 3.1 The current fish canning process. Scenario 1

Figure 1 shows a diagram of the current tuna fish canning plant (temperatures are given as annual average values). One batch of fish is processed for one working day.

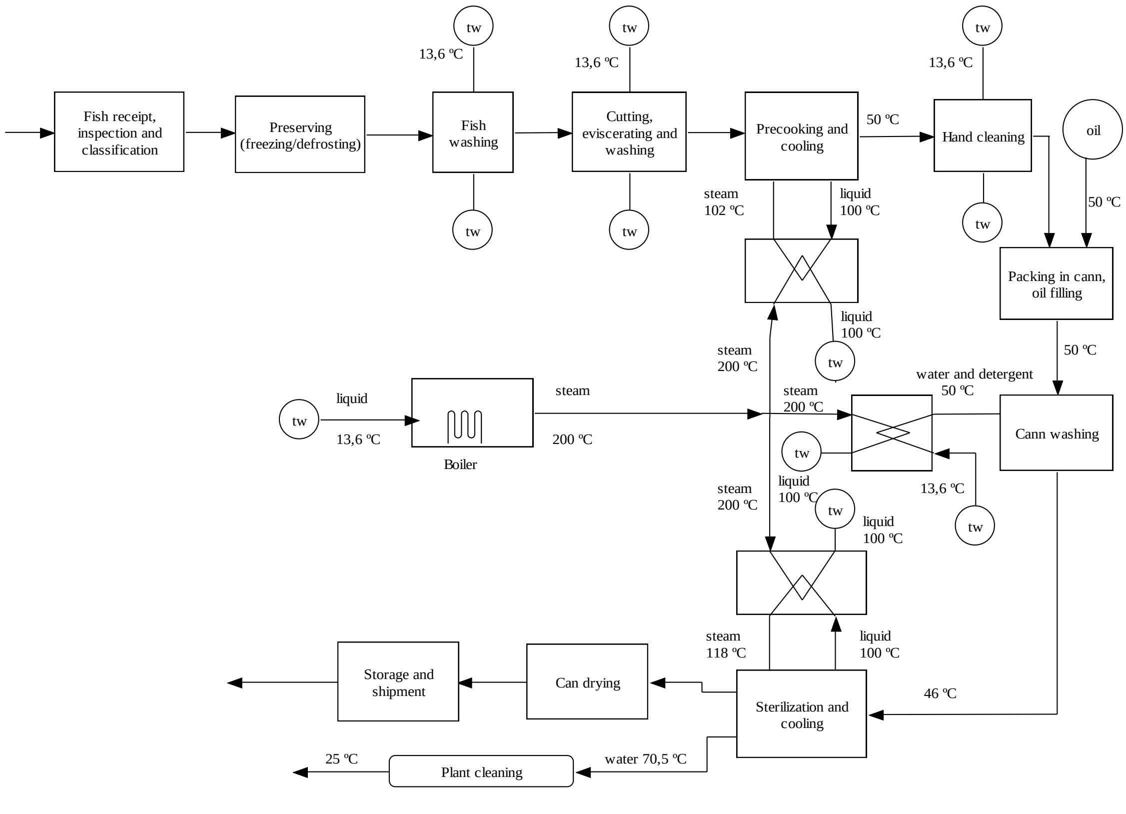


*Figure 1. Scheme of the canning facility (tw: tap water)*

The current process utilizes a natural gas boiler to generate steam at 200 ºC, hot primary fluid which is sent to three heat exchangers. Heat of steam is transferred to water to obtain different hot secondary fluids for precooking as steam at 102 ºC, can washing line as water at 50 ºC, and can sterilization as steam at 118 ºC. In this Scenario 1, the current boiler must provide an amount of 5,623.019 kWh/d of heat, as steam at 200 ºC, to the productive process with a consumption *C* of natural gas of 615.841 $Nm^3/d$. Table 1 resumes the results of mass and energy balance of the present process.

*Table 1: Data base of preliminary mass and energy balances in the canning process*

| Mass balance | Components of the product | .1 day (kg) | 1 year (t) |
|---|---|---|---|
| | Row fish | 50,000.000 | 12,500.000 |
| | Flesh | 27,086.400 | 6,771.600 |
| | Olive oil | 14,585.000 | 3,646.500 |
| | Brass can | 6,875.700 | 1,718.925 |
| Energy balance | Operation | *Q* (kWh/d) | *Q* (MWh/y) |
| | Precooking | 1.567,575 | 391,893 |
| | Sterilization | 2.368,816 | 592,203 |
| | Can washing | 1.018,584 | 254,646 |

Initially, all hot and cold streams taking part in the process where considered, but some of them were later eliminated due to their big amounts of contamination and difficulties to recover residual heat from them. On the basis of the showed stream date set and mentioned criteria, and considering the transference of available waste heats to the process, pinch analysis proposed a net tendency thermal objective of 3,875.020 kWh/d to the boiler (TAM), while the current design needs 5,623.019 kWh/d.
The GCC of Scenario 1 is presented in Figure 2.a. for a $\Delta T_{min}$ of 10 ºC. The pinch point was fixed at 105 ºC. It is noticed the big amount of energy, as latent heat, which was needed for water vaporization in the boiler, represented by the horizontal superior line, and its recovery in the heat exchangers when it is necessary (lowest horizontal line). In fact, it resulted interesting for the energy system to assign internal residual heats of the process for this thermal level where the maximum consumption was detected.

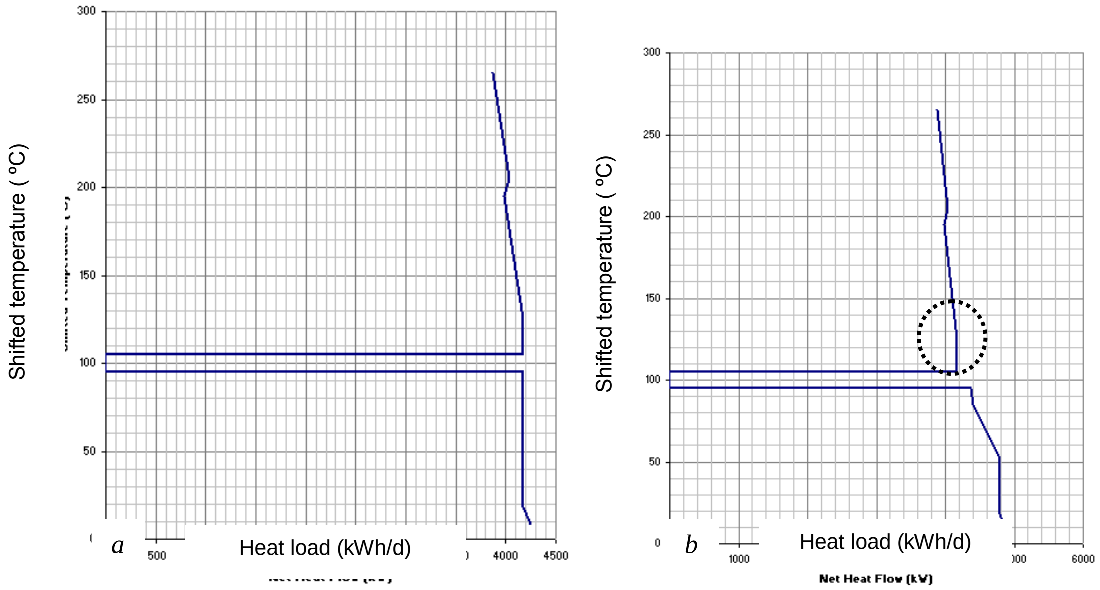


*Figure 2: GCC of Scenarios before incorporating thermosolar energy; a. Scenario 1, and b. Scenario 2*

Exergy analysis results of this previous scenario are showed in Table 2. Obtained energy and exergy efficiencies where related to the performance of the boiler.

*Table 2: Summary of the exergy analysis results for the evaluated three scenarios*

| Scenario | $\eta$ (%) | $\psi$ (%) | $S_{gen}$ (kWh/d·K) | $I$ (kWh/d) | $IP$ (kWh/d) | $C$ ($Nm^3$/d) |
|---|---|---|---|---|---|---|
| 1 | 83.333 | 26.375 | 15.224 | 4,536.860 | 3,340.243 | 615.841 |
| 2 | 97.638 | 30.903 | 11.689 | 3,483.295 | 2,406.107 | 525.618 |
| 3 ($f$ = 0.115) | 87.032 | 26.942 | 14.804 | 4,411.510 | 3,222.961 | 468.538 |

### 3.2 Energy optimization of the process. Scenario 2

In order to optimize de present fish canning process and for better usage of the combustion heat of natural gas in the boiler, an economizer was introduced. The economizer allows the preheating of incoming tap water from 13.6 ºC to 57.4 ºC using combustion exhausted gasses. Then, to recuperate quality waste heat from streams of the process, water was sent to the condenser of a heat pump for its partial evaporation (*β)*. Finally, the mixture vapour-liquid water was sent to the boiler for its total evaporation and overheating to 200 ºC. From the boiler, steam was sent to the three heat exchangers of the fish processing line for precooking, sterilization and can washing. After evaluation, the more convenient heat pump technology resulted a water-water gas driven heat compression pump (GHP), including an exhausted gas and heat recovery unit. The cold stream for the evaporator of the heat pump was the condensed water from the three heat exchangers of the production process of the plant at 90 ºC (limiting factor for heat recovery for the heat pump). It was determined a $COP_{pt}$ for the heat pump of 3.864 and a global $COP_g$ of 1.35, considering a partial evaporation $\beta$= 3.091 %. For the Scenario 2, the total consumption of natural gas (boiler and heat pump) reached to 519.534 $Nm^3$/d, which supposed a reduction of the 14.65 % in fuel dependence respect to Scenario 1.

Figure 2.b. presents the GCC for Scenario 2 for $\Delta T_{min}$ of 10 ºC and pinch at 105 ºC. In comparison with the GCC of Scenario 1 (Figure 2.a.), the incorporation and increasing of a waste heat from combustion and at the heat pump allowed reducing the heat demand to the boiler at thermal levels around the pinch, reflected by a distance difference between the both horizontal lines.

Exergy analysis in this scenario (Table 2) presented better values of energy and exergy efficiencies in comparison to Scenario 1, as some internal heats were now incorporated to the energy structure of the plant, through the economizer and, notoriously, by the GHP. Entropy generation decreased; implying less irreversibility and reducing the potential for exergy improvement.

### 2.3 Incorporation of thermosolar energy. Scenario 3

Figure 3 shows the diagram of the energy supplying system for Scenario 3. In this scenario, solar energy was incorporate to the process through a solar thermal subsystem with a fundamental premise: to avoid as much as possible steam production and storage in the solar accumulator. The same GHP technology was adopted for this new scenario. After preheating incoming tap water at the economizer until 57.4 ºC, water was sent to the thermosolar subsystem where it resulted heated to 99.0 ºC, and stored in the upper stratification level of the solar accumulator at 95.0 ºC. From there, water was pumped to the condenser of the GHP, achieving a $\beta$ of 10.05 %. From here, when needed, vapour-liquid water mixture delivered to the boiler to be overheated until 200.0 ºC. At last, water was pumped to the three heat exchangers of the fish processing line. It was determined that a maximum solar fraction $f$ of 0.115 could be incorporated to the energy chain of the process by an absorber solar field of 358.6 $m^2$. Of course, lower $f$ was possible through shorter solar field surfaces, but for $f$ < 0.056 heat losses in the accumulator cancelled any solar contribution. The consumption of natural gas could be fixed in 468.538 $Nm^3$/d for the Scenario 3.

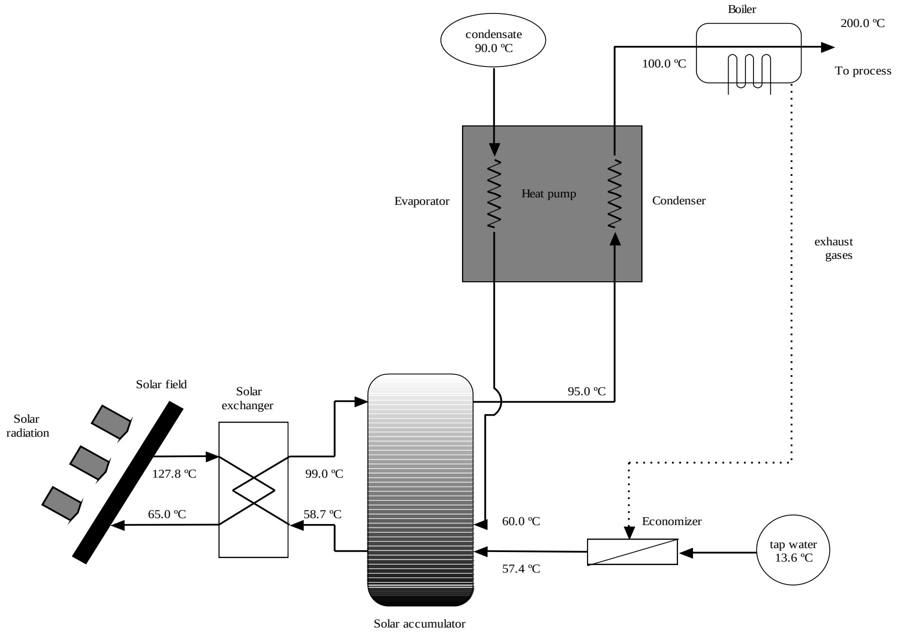


*Figure 3: energy supplying system for Scenario 3*

Figure 4 shows the GCC of Scenario 3 for *f* = 0.115. The specific stream data set was modified including thermosolar subsystem streams in the context of total site integration. For a $\Delta T_{min}$ of 10 ºC, the pinch point was 98.2 ºC. In this case, solar contribution is reflected by the increase of net heat loads in the region under the pinch, which promotes, also, a bigger difference between both horizontal sections, as a result of the GHP contribution in this thermal level.

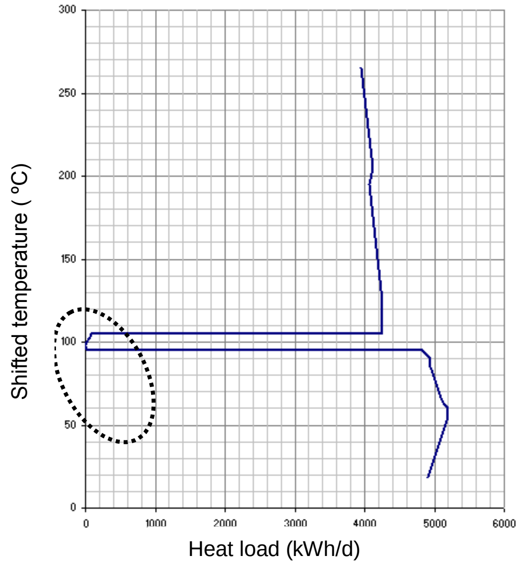


*Figure 4: GCC of Scenario 3, incorporating solar energy, the economizer and the heat pump*

The Scenario 3 presented better values for energy and exergy efficiencies than Scenario 1 for all the showed thermodynamic parameters (Table 2), but it has to be noticed the decrease of all of them in comparison to the results of Scenario 2, which could be explained by the low energy and exergy efficiencies of current thermosolar technologies in comparison to the efficiencies of natural gas boilers, and heat pumps. Sun collectors receive important amounts of renewable energy of quality, but they are not able to take good advantage of this contribution and they lose a big quantity, destroying, at the same time, many of the quality of this incoming energy; as result, their intrinsic energy and exergy efficiencies are low. In the case when thermosolar energy is incorporate to the system, the overall efficiencies tend to decrease, being these drops higher as more solar fraction is reached. When short solar fractions are implemented, efficiencies of the process depend more on the efficiencies of conventional fuel based technologies, and overall efficiencies tend to increment. However, more solar fraction means higher reduction of natural gas consumption (environmental and economical advantages) and more independence from conventional resources.

## 4. Results and conclusions

The energy optimization of the process (economizer, GHP and reincorporation of intern heats), with the integration a thermosolar energy, promoted a notorious reduction of the fossil fuel consumption, from the present 615.841 $Nm^3$/d, until 468.538 $Nm^3$/d. This performance of the process supposed a drop in percentage of 23.919 %. In the economical order, the investment for the thermosolar installation (maximum solar fraction) could be recovered in 6.5 y, while the payback time for the GHP could be fixed in 4.3 y, considering the economical cost as reasonable. Environmental analysis, linked to the reduction of natural gas consumption, showed a reduction of $CO_2$ emissions of 5,542.026 t/y. The integration of the proposed energy system was based on one energy supplying chain with all the elements connected in a series arrangement (economizer, thermosolar, heat pump, boiler), and conforming a heat net with the operations of the fish processing line through reincorporation of internal heats previously assumed as residual in fish processing. All mentioned components of the chain promoted the production of one utility stream (steam at 200.0 ºC), and the utilization of its energy was developed as an energy cascade from one operation to the next.

As a conclusion, it can be said that the proposed conventional-renewable energy system for the studied process presents a better utilization of the energy which incomes to the system and, also, it preserves better its quality, at the same time that the current productivity of the plant can be maintained. The process utilizes an important amount of renewable energy resource, separating it self in a correspondent measure from fossil resource. The obtained results have demonstrated the feasibility of using thermosolar technology, linked to a heat pump, to provide energy to a tuna fish canning installation located in a zone with a specific climatology.

It has to be mentioned that applied methodology, based on the combination of pinch and exergy analysis, resulted appropriate for the evaluation of the heat integration opportunities for the process.

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