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Solar thermal plant integration into an industrial process

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Abstract

The present abstract summarizes the main analysis and design steps made for the integration of a solar thermal plant of one thousand square meters into the dyeing process of Benetton industrial facility in Tunisia. The analysis of the actual process load is done by a static model based on assumed energy and water consumptions and the real performance of the heat recovery system. The methodology to build the simplified model and its validation by monitored data will be presented. The results show the optimization potential of the heat recovery system and the temperature constraints for a good integration of the solar plant.
This study presents some choices to reach an optimized integration of the solar plant and the sizing of the main components. The main design alternatives are evaluated in this article based on dynamic simulations and personal experience.

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Keywords: solar thermal for industrial process heat; dyeing process heat; design guideline; hydraulic balancing of collector arrays.

Nomenclature

CCW	Cold Clean Water
HCW	Hot Clean Water
HDW	Hot Dirty Water
λ_i	Colebrook coefficient of the pipe i
ξ_i	Experimental singular coefficient of the component i which are given in standard table in books related to

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	fluid mechanics and thermo-hydraulics
L_i	Length of the pipe i
Di	Diameter of the pipe i
v_i	Fluid velocity in the pipe or component i
Re	Reynolds number
ε_i	grain height of the pipe i

1. Introduction

This article is the follow-up of a feasibility study campaign for integration of solar thermal systems into industrial processes in Tunisia [1]. According to the results of the campaign, the Italian Ministry for Environment, Land and Sea (IMELS) decided to co-finance one large solar plant for one of the selected end-users, that is the textile manufacturer Benetton.

The current average price of natural gas for industrial end users in Tunisia is 0,25 TND/m^3 (Tunisian Dinars, related to 2011), which equals to around 0,12 €/m^3. Such low price is possible due to high incentives on natural gas provided by the Tunisian government. This incentive will progressively be reduced in the future and this transition period could be a good opportunity for renewable energy technologies, in particular solar thermal, to increase its market penetration.

This solar thermal demonstration plant is seen as an opportunity to realize a good practice example of solar thermal plant integration into industrial processes. This is why special care has been put on analyzing the actual process in order to choose the suitable integration of the solar plant, considering especially the investment costs issue.

2. Description of the industrial process and of the load profile

Dyeing processes have large water and energy consumption due to multiple sub-cycles. In fact a classical cycle of dyeing follows at least 10 steps and each of them requires fresh water. The most important sub-cycle is the "dyeing + fixing" one, that defines the quality of a dyeing process. It contains positive and negative temperature gradients in order to fix the dye on the textile and thus it is not possible to feed-in water above a defined level of temperature, since this would reduce the positive gradient. The maximum inlet temperature of this sub cycle has been fixed at 60 °C by Benetton's technicians to ensure the necessary dyeing quality. Further increase in temperature occurs inside the machine.

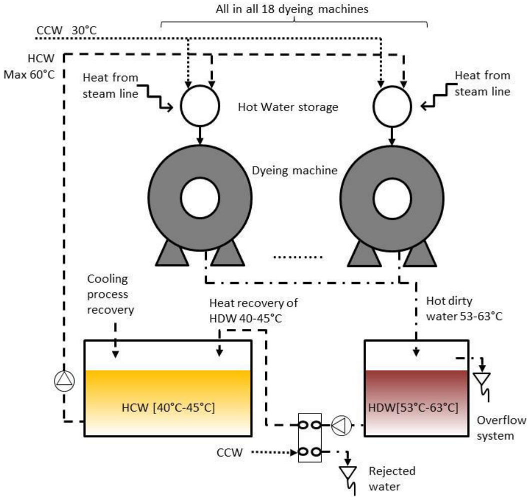

Fig 1: Process scheme

Natural gas boilers are used to produce steam, which is partly used to heat up water at the desired inlet temperature inside the hot water tank of each dyeing machine, see Fig. 1, and partly to follow the desired temperature curve inside the machine. Thus only the part of the gas consumption used to pre-heat the inlet water to 60 °C can be covered by solar energy.

Three kinds of heat recovery mechanisms are used into the process. The first one consists of re-using the water at the end of some processes, if possible, and send it into the CCW pool. This water at the end of the process could be hot thus it will heat-up the CCW pool. Indeed during the monitoring period (summer) the CCW water was around 36 °C whereas the cold water was 30 °C. The second one consists of recovering heat from the process (hot and dirty) water of the pool HDW through a heat exchanger. Finally, the third one consists of sending cold water CCW, which is used to cool the machine, into the pool HCW.

Based on a static model that was partially validated with monitored data, a large optimization potential of the heat recovery system could be observed. As a matter of facts, due to the priority given to time saving rather than to energy efficiency, the HCW pool is filled with high flow rates of cooling water (which is necessary for reducing cooling times), thus it harms the recovery the process water of the pool HDW [53 °C; 63 °C]. Additional savings could therefore be reached with an improvement of the heat recovery strategy, adding a three-way valve on the cooling process recovery, before HCW, in order to divert the water directly towards CCW tank when its temperature is lower than the current temperature of HCW. It is not possible to quantify the exact amount of the potential energy savings without specific measurement tools, but it is reasonable to expect additional savings in the range of 100-300 MWh.

An estimation of the yearly energy contribution to the dyeing process consumption based on a static model has been carried out for the current situation and the expected situation with the solar plant, see Fig.2. The recovery CCW included the first heat recovery, whereas the recovery HCW included the second and the third ones. Due to the maximum allowed water temperature of the inlet water (60 °C) plus a safety margin of 5 °C, a maximum recovery HCW is estimated, which represents twice as much of the expected solution with solar plant, see third column of Fig.2.

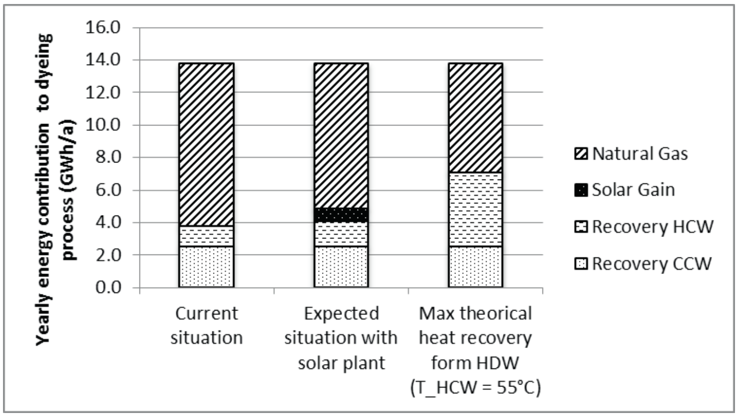

Fig. 2:Yearly energy contribution to the dyeing process

3. Integration of the solar plant into the industrial process

Many are the possibilities to integrate a solar thermal plant in industrial processes. Each solution has obviously advantages and disadvantages, from a technical, economic and energy point of view. In this case the crucial objective has been to choose a simple integration scheme, which requires no or little changes on the existing process. The main solutions analyzed during the design phase are described in the following paragraphs. At first the final scheme will be described, while comparison with other possible schemes will be shown in the subsequent paragraphs.

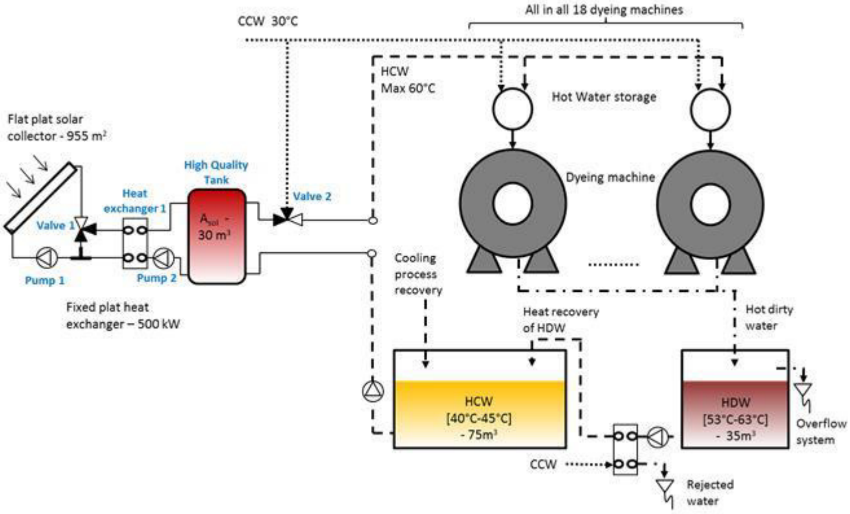

Fig. 3: Pressurized tank on the process circuit

3.1. Pressurized tank on the process circuit (chosen integration scheme)

After comparing different options, the final decision was to integrate the solar tank on the process side and always feed the dyeing machines with water stored in the solar tank. The plant scheme is shown in Fig. 3.

The solar tank is integrated into the process circuit and filled with pre-heated process water coming from HCW pool. The tank is further heated by the solar plant, to which it is connected through a 500 kW plate heat exchanger. Water in the storage tank is heated according to available solar irradiation and may reach up to 95 °C. As long as its temperature is below 60 °C, it will directly reach the dyeing machines. If, however, temperature rises above 60 °C, cold water will be mixed in order to keep it at the maximum acceptable level.

Such solution requires the following main components: a secondary loop pump to charge the solar tank, a mixing valve to control the tank output temperature, proper tank material in order to avoid corrosion and guarantee that the process water is always pure. The stainless steel solution gave the highest guarantee for water quality, but it was discarded due to cost issues. A common steel storage with surface treatment, such as 200 micrometer epoxy primer, which is to be realized after a sandblasting process, can be selected.

3.2. Using two heat exchangers

An alternative with two heat exchangers has been considered. The second heat exchanger is placed between the solar tank and the process, as shown in Fig. 4.

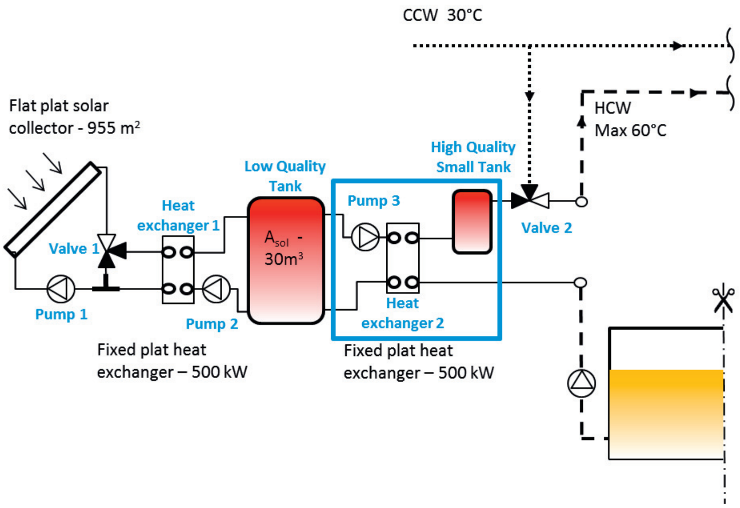

Fig. 4: Integration with two heat exchangers

This solution makes tank requirements much simpler, as the tank is integrated into a closed loop, which avoids direct contact with process water. A cheaper steel tank without surface treatment can be used. On the other hand, additional costs for a second heat exchanger of approximately the same power as the solar one have to be considered. Furthermore, to guarantee hydraulic and temperature stability of process water, an additional, smaller tank is anyway needed on the process side. The main drawback is the reduction of solar energy gain due to a higher average working temperature in the solar field, caused by the mean temperature difference of the second heat exchanger.

3.3. Solar tank in the primary circuit

Another way to avoid the need for expensive tanks is to integrate the solar tank into the primary circuit, as water inside it will not change during system's operation, except in case of maintenance. Only one heat exchanger is needed, that is between the tank and the process. Fig. 5 shows the plant scheme.

The crucial issue when applying such solution concerns antifreeze liquid in the primary circuit: if one wanted to use it, huge quantities would be required, since the tank volume would as well be filled with water-glycol mixture. A possible solution is to avoid antifreeze liquid and fill the whole primary circuit with pure water. In this case at least two strategies can be put in place:

- Drain back system: the drain back solution enables emptying of collector field whenever the pump stops.Freezing of water in the primary circuit is therefore not possible. Applying drain-back to this specific plant, however, would have caused several technical difficulties concerning the good emptying behavior, considering that the collector field is located at a significant distance from the tank (approximately 120 m) and that collectors are to be installed on the ground (no significant height difference available between collector field and other components).
- Antifreeze control strategy: whenever ambient temperature falls below a certain set point (e.g. + 3 °C), the pump is activated in order to use energy stored in the tank to keep collector temperature above freezing level. The main limit of such choice is the dependence of the safety strategy from electricity availability. If freezing risk (very rare in Tunisian climate) occurred at a time when no electricity is available, water would freeze in the collectors.

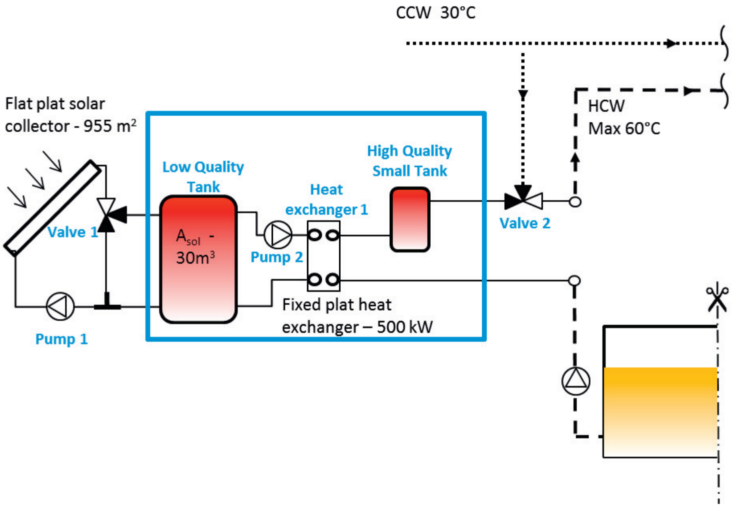

Fig. 5: Solar tank in the primary circuit

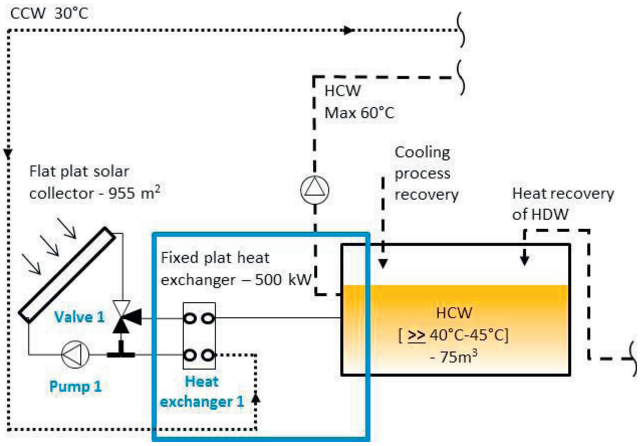

Fig. 6: Heating of HCW pool

3.4. Heating of HCW pool

Direct heating of HCW pool has also been analyzed. In this case, two strategies have been considered: heating via heat exchanger (no mass addition to HCW pool), and adding water to HCW pool, basically pre-heating CCW. In the former case level conditions in HCW pool would not change, but temperature conditions would. In the latter case HCW pool level would increase in average.

In case water is added, HCW pool will reach the maximum level more often during the year, which will cause a reduction in heat recovery, as, on the other side of the recovery circuit, hot, dirty water will not flow inside the heat exchanger, but directly wasted despite its energy content.

The common risk of both strategies is the capability of HCW pool to withstand high temperatures. HCW pool is made of concrete, but no technical details about it were available during design phase. The fact that is can withstand 40-45 °C does not assure that temperature increase (e.g. up to 60 °C) would be feasible.

Another risk of adding water to HCW pool is that its level would more often reach the maximum. If this happened during sunny days, no space for further heat addition would be available and the solar plant would reach stagnation conditions.

In Fig. 6 heating of HCW pool with mass transfer is shown.

4. Hydraulic and thermal design of the collector field

The solar system has been modeled and simulated using the dynamic simulation software TRNSYS.
The following, main plant characteristics have been considered in the simulation (not exhaustive list):

Primary loop:

- Pipes (and pipe losses)
- Collector orientation and slope angle
- Collector array shadow
- Specific heat capacity of water-glycol mixture
- Stagnation events
- Night circulation to reduce the stagnation during the summer Sundays.
- Heat exchanger
- Pumps heat loss

Secondary loop :

- Process load (based on Monitoring values)
- Storage (and storage losses)
- Cold water temperature variation during the year

Table 1 shows the main energetic performance indicators of the proposed solar thermal system:

Table 1. Main energetic performance.

	Value	Unit	Comment
Delivered solar heat	803.000	kWh/year	thermal energy delivered by the solar thermal loop to the storage tank
Saved fuel	82.000	m3 gas	amount of gas saved thanks to the solar system
Saved CO2 emissions	161	t/year	according to average CO2 emissions of natural gas (reference: 200 g/kWh)
Solar fraction	8.0	%	Ratio of total energy consumption covered by the solar system, [Estimated energy consumption for dyeing process = 10 GWh/year]
Average system efficiency	43	%	Solar system's energy delivery divided by incident radiation on collector surface
Average temperature increase of HCW pool	2.6	°C	In average over 8.760 h
Average temperature increase of HCW pool during the day	8	°C	In average over 8 h per day, when the solar system is supposed to be running

4.1. Design steps

The process of simulating the solar thermal plant followed the steps listed below:

- Modeling of dyeing process and estimation of thermal consumption
- Monitoring of dyeing process consumption and validation of the model
- Construction of load profile as input for plant simulation
- Modeling of solar thermal plant
- Sizing of the main components and choice of anti-stagnation control strategy
- Detailed design of solar thermal plant

Output of the sizing process is summarized in the Table 2.

Table 2. Main components sizing.

Component	Size	Unit
Collector area	955	m2
Collector orientation	15° south – south-west	-
Collector slope	25°	-
Tank volume	30.000	l
Heat exchanger	500	kW

During the detailed design process several difficulties had to be faced. Among them, the most significant in the author's view are related to the thermal expansion of collector pipes and to the hydraulic balance of the flow inside the collector rows.

4.2. Tank sizing and anti stagnation control

Aiming at reducing investment costs as much as possible, lots of effort was necessary in order to reduce tank volume as much as possible, as tank requirements make this component very expensive (see paragraph 3.1). Starting from a 50 m^3 tank, which is a usual value for sizing solar tanks for domestic hot water applications in Europe (and corresponds to a specific storage volume of approximately 50 l/m^2collector area), parametric dynamic simulations have been realized with decreasing tank volume. Stagnation hours per year have been analyzed, aiming at reducing such value as much as possible. The critical issue is the fact that Benetton process stops one day per week (on Sundays): the lack of heat consumption makes storage temperature raise over the day, until, in hot in summer days, up to 95 °C can be reached. Whenever this happens, solar pump is stopped and stagnation in the collector field occurs, which is acceptable for little stagnation hours per year.

In order to reduce tank volume as much as possible, keeping at the same time stagnation hours at a low value, a dedicated control strategy ("anti-stagnation control) has been implemented in the simulation model: during summer Saturday nights the control activates the pump in order to benefit from relatively low ambient temperature to discharge heat from the tank.

The final choice is to install a 30 m^3 storage tank (corresponding to approximately 30 l/m^2collector area), accepting 30 h (plus the two weeks of no working days of Benetton) stagnation hours per year. If anti-stagnation control was not used, at same tank volume plant performance would increase by 1% (due to higher amount of energy available on Monday mornings after bad weather Sundays), but stagnation hours would increase by 80%.

4.3. Thermal expansion

Considering that one of the project's aims is to reach low investment costs in order to reach acceptable pay-back time for the plant owner, components produced locally are considered to be more suitable, although even foreign products can be basically accepted in the tendering phase. Since no large modules are nowadays being produced in Tunisia as far as the author knows, small modules have been chosen and described in the tendering documents.

Given that thermal expansion is always an issue when designing large collector fields, it is particularly critical when using small collectors: large modules' internal piping is usually designed by the manufacturer in a way that thermal expansion phenomena are absorbed inside each collector and do not have significant influence on the connections between modules. Small collectors are usually not designed in the same way and may therefore lead to significant expansion phenomena which could damage connections between collectors. Following experience with similar plants, expansion bellows have been introduced between each collector, as shown in Fig. 7. A diameter of 22 mm and material resistance up to 200 °C are required. Expansion length need has been set to 8 mm in axial direction and 4 mm in side direction. Bellows are supposed to contribute to the total investment between 1 and 2.5%.

Thermal expansion might as well cause damage in the connection between each collector row and the main piping: stretching of the collector's internal pipes may lead to a significant angle variation in the connection area (see detail in Fig. 7 on the right), which might as well cause damage. For this reason the vertical pipe is relatively long to reduce such angle variation.

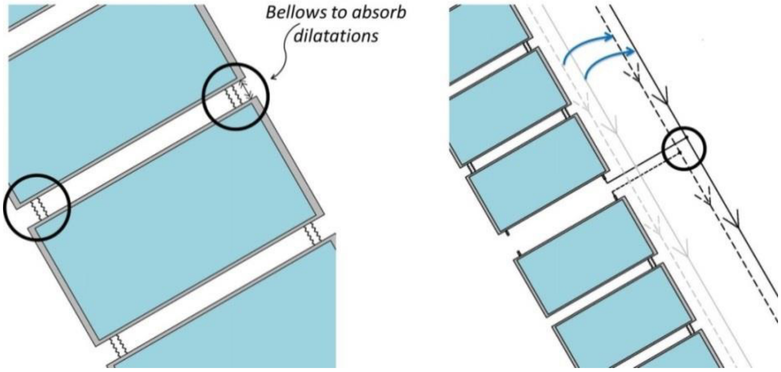

Fig. 7: Solving the thermal expansion problem

4.4. Flow rates balance

Flow rate balance inside solar collector is very important to design an efficient solar field. Three alternatives have been considered to improve it:

- Using balance valves for each collector row is the cheapest solution, but requires high maintenance effort, which is not suitable in case of an industrial application.
- Pipe diameter variations in order to balance the solar field is obtained by under sizing the pipe diameter inside each row and oversizing it between each row. This solution will significantly increase the overall pressure drop of the solar field.
- Tichelmann configuration is the most expensive solution due to cost of extra pipes but it requires low maintenance effort.

Thus the Tichelmann configuration will be investigated to understand the improvement of this configuration against a non-balanced system. Furthermore, the potential improvement of the flow rate balance of a classic Tichelmann configuration will be considered.

The pressure drop for each section is calculated summing up the linear pressure drop of the n pipes (Darcy formula (2)), the singular pressure drop of the m special components in the same section (eq.3) and the solar collector pressure drop (if present) (1). The contribution of the solar collector is estimated based on the manufacturer formula which is proportional to the square of the flow rate in the solar collector.

$$\Delta P = \Delta P_{lin} + \Delta P_{\sin g} + \Delta P_{coll} \tag{1}$$

$$\Delta P_{lin} = \sum_{i=1}^{n} \lambda_i \cdot \frac{L_i}{D_i} \cdot \frac{v_i^2}{2 \cdot g} \tag{2}$$

$$\Delta P_{\sin g} = \sum_{i=1}^{m} \xi_i \cdot \frac{v_i^2}{2 \cdot g} \tag{3}$$

The coefficient λ_i is calculated based on the Colebrook formula by an iteration process (4).

$$\frac{1}{\sqrt{\lambda_i}} = -2 \cdot \log_{10}\left(\frac{2.51}{\mathrm{Re} \cdot \sqrt{\lambda_i}} + \frac{\varepsilon / D_i}{3.71}\right) \tag{4}$$

And finally the singular coefficient ξi of the special component i can be found in standard table in books related to fluid mechanics and thermo-hydraulics.

As the pressure drop in each section is proportional to the flow rate, it is possible to estimate the distribution of this flow rate in each section of the solar field using an iterative process to get a single pressure for each intersection.

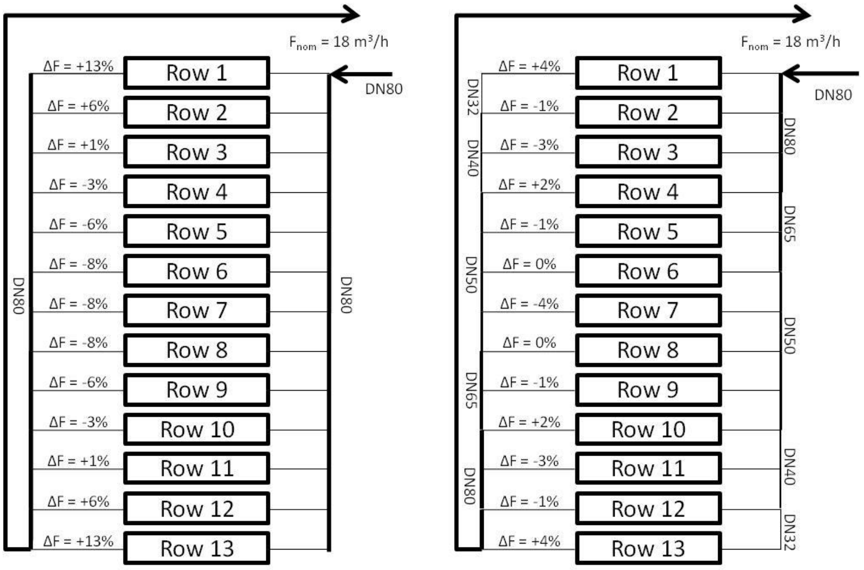

Fig. 8: Flow rate balance

A classic Tichelmann configuration does not allow a perfect flow rate distribution for large solar fields: indeed the flow rate in one row varies from +13% to -8%. By using conventional diameters for the pipes between each row it is possible to improve significantly the flow rate balance see Fig. 8.

A non-balanced system will have two negative effects. The first one consists of a small decrease of the overall efficiency during normal conditions and the second one is an higher stagnation risk of some rows of solar field that will reduce dramatically the overall production.

To estimate the benefit of solar field balance, two extreme situations will be compared:

- The Tichelmann configuration combined with a pipe variation diameters between each row (final design solution)
- The simple solution of a non-balanced solar field with pipe diameter variation between each row in order to reach a smaller pipe investment.

To highlight this risk typical conditions of a sunny day have been chosen, see Table 3, with a reasonable inlet collector temperature occurring more than 12% of the hours during normal running of the solar plant (results found with the dynamic simulation).

Table 3. Nominal conditions

Test condition	Value	Unit	Efficiency collectors	Value	Unit
Irradiation	800	W/m2	η_0	0.79	-
External temperature	30	°C	a_1	4.243	$W/m^2.K$
Inlet collector temperature	70	°C	a_2	0.0042	$W/m^2.K^2$

In the second scenario with these normal sunny conditions three rows will go in saturation. This saturation will lead to a drop of the overall efficiency and to a higher risk of breakdown of these three rows, see Fig. 9.

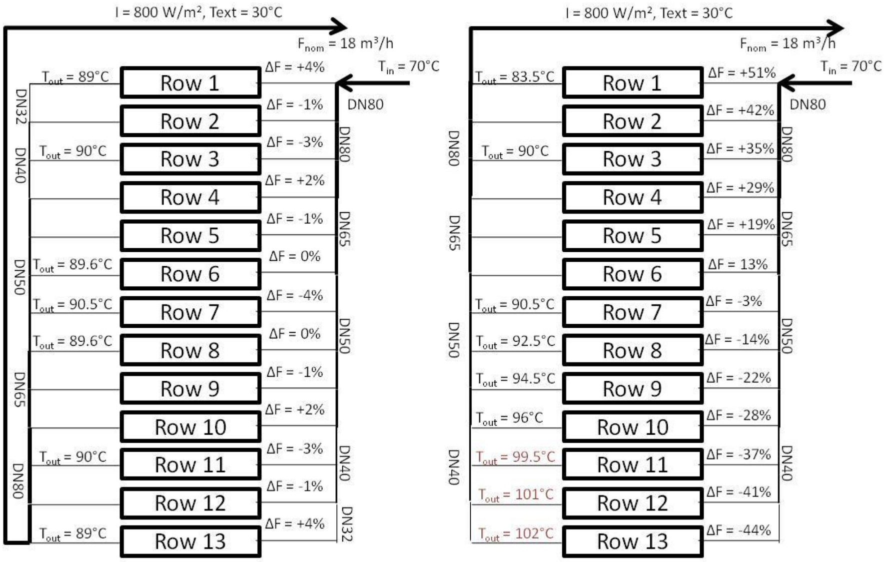

Fig. 9: Comparison of two alternative solutions

5. Conclusions

Due to significant subsidies on fossil fuels (mainly natural gas) for industrial end-users, solar thermal technologies in the Tunisian industrial branch are currently not economically appealing. Nevertheless, this demonstration plant could have a large impact as a “good practice” example of solar energy integration into the industrial process heat.

The design process showed that several technical choices have strong impact on investment costs, which must be reduced as much as possible, in order to try reaching relatively good economic performances. On the other hand, one must ensure that the solar plant will not cause any problem to the existing process, and that maintenance effort is as low as possible. The final design choices are a trade-off between these considerations.

The plant will be highly subsidized by the Italian Ministry for Environment, Land and Sea, which will make the plant economically feasible. Without such subsidies no economic pay-back during system's lifetime would be reached. Changing energy policy in Tunisia might nevertheless modify the economic boundary conditions for solar thermal plants (e.g. raising gas prices, raising incentives for renewable energy) and make similar projects feasible even without foreign contributions.

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