

A thermo-economic based method for the design of process heat solar systems

A Franco¹, G Bertola¹

¹ Department of Energy, Systems, Territory and Constructions Engineering, University of Pisa, Largo Lucio Lazzarino, 56122 Pisa

Corresponding author e-mail: alessandro.franco@ing.unipi.it

Abstract. In this paper, the perspectives of production of thermal energy for industrial process heat from solar energy are considered. This represents a quite relevant topic for an overall containment of using fossil fuels with the objectives of reducing the impact of fossil fuel use. In particular, the paper outlines a thermo-economic design methodology taking into account the main variables problem (solar source, system architecture, design constraints, load type and distribution, design criteria and optimization criteria). The innovative element of the methodology is the consideration, among the various costs, of an economic penalty given to the operation of the auxiliary boiler. The results of the application in a particular case are shown in the final section of the paper, showing how it could be possible to increase the value of the solar share, up to 80% with respect to the conventional design method, that often limit this value at 60%.

1. Introduction

The potential for solar thermal generation of process heat is relevant: in Europe, it is estimated that more than 25% of the total final energy demand is heat use for industrial processes. A relevant part of the energy demand occurs at temperature below 100 °C: this can be generated by solar thermal energy systems, [1-2]. If solar heat for domestic and service applications had a relevant development in recent years, not the same has been observed for systems producing “solar” heat for industrial processes. This is a relevant field of analysis but those kind of applications are still in an early stage of diffusion, [3].

Interesting opportunities for the integration of solar thermal in industrial application can be identified for a series of fields, for which use of water (or sometimes air) at temperature in the range 50-80 °C is required; those are for example heating of hot water for washing or cleaning, heating of make-up water for steam networks, heating of baths or vessels or producing convective drying with hot air.

One of the main element of future project activities include, among others, targeted awareness raising for government and industrial decision makers in order to promote an increasing diffusion of solar energy in connection with industrial processes.

For a defined profile of the thermal load the design of a solar thermal system consists in the definition of the area of the solar collectors (in general flat plate collectors) and of the size of the storage volume and of the fossil fuel based thermal integration system (auxiliary boilers).

Because solar thermal energy profile is periodical, solar thermal energy systems can be integrated into the processes directly or into the heat distribution network (high temperature water network). In general, the result is a solar production ratio ranging from 40 to 60% of the annual total energy amount. A solar thermal energy system of this kind requires an additional thermal input from one or more auxiliary
thermal devices that operates mainly during winter and mid-seasons: this, from the point of view of the Second Law efficiency it is not a good element.

The design Method for Solar Water Heating System (SWHS) are available in the literature since the late 70s. A series of references, like [4-8], propose design method for SWHS based on statistical considerations. Starting from the late 90s it is possible to find methods for the optimum design: a typical example of such a kind of approach is provided in [9].

After an analysis of the studies, available in the literature, for the design of a solar thermal system, the paper provides a possible strategy for increasing the solar production share of the systems. The idea is of combining the perspectives of the Second Law of Thermodynamics, for reducing the irreversibility of the system, in general caused by the operation of the auxiliary boiler (that operates with quite high value of the First Law Efficiency, but with very low Second Law Efficiency) and the general economic objective of minimizing the total operational cost of the system. The optimum design can be obtained through the minimization of the operational cost of the system, including both economic and energetic elements.

The novelty of the methods stands in the definition of a specific objective function, including a term of penalization to the irreversibility caused by the operation of the system, mainly connected with the use of integrative systems. The method is tested in a specific case; even if the analysis is limited to the cases discussed, the results expected with the application of the proposed method can be summarized by the following elements. Considering a conventional economic analysis, the method determines an increase of size and operational time of solar thermal system with respect to auxiliary boilers, increasing the solar fraction and obtaining guidelines for modification of economic support systems of solar heating for process heat.

2. The potential for solar thermal energy use in industrial sector

Solar heat for domestic applications has increasing market shares across Europe while solar process heat appears to be not fully developed. In almost all European countries there are subsidy programmes covering solar thermal process heat installations even if, in many regions the subsidy programmes are frequently changing because of short-term political decisions.

In principle, the potential is relevant: considerable part of the total industrial heat demand is at temperature levels below 100°C can be provided with commercially available solar thermal collectors. Solar energy can support a large variety of industrial processes. Solar process heat can be technically and economically viable in a range of industries for cleaning and washing, heating of baths & vessels, drying, pre-heating of make-up water for steam networks, raw material production, etc.

A crucial element is the process temperature level: the best systems have process temperatures below 50 °C. Process temperatures above 100 °C even in open systems often increase the available temperature level and requires consistent energy integration. In this case, a scheme including an auxiliary boiler is required, like those depicted in figure 1 and figure 2, rearranged from the schemes of the various configurations available in [2].
The first and foremost prerequisite for success in a solar system application is adequate insolation, with only infrequent interruptions during the day. The duration and intensity of solar radiation must suffice to allow the use of a solar system for prolonged, worthwhile regular periods. While the use of solar energy is always possible in Central Europe, where a minimum irradiation of 1500-1600 kWh/m² per year (corresponding to an average daily insolation in the range 3.7-4 kWh/m² per day) should be available. The irradiation level is reduced in Northern Europe conditions, where level of 1000-1200 kWh/m² per year can be observed in connection with lower average environmental temperature. However, these annual data can sometimes be misleading.

While the use of solar thermal energy based systems is largely diffused for typical summer time applications, the highest potential for the integration of solar thermal can be possible considering processes suitable for which:

- demand more than 80% of the year, including summer;
- demand at least 5 days for week;
- daily demand in summer sometimes lower than in the rest of the year.

In order to examine the feasibility of coupling a process with solar thermal energy, process schemes are very helpful to understand all mass and energy flows.

Considering all the above-mentioned elements in order to define the specific requirements for thermal energy the design of the solar thermal plant is in general based on an economic analysis. The trade-off size is given by a balance between the cost of the system and the comparative cost of the system based on fossil fuel input.

For this reason and due to the fact that the surface of the collectors is often quite high, the convenience of solar thermal plant is often clear only when economic support is available.

As suggested in the practical design guides for solar energy, as [10], the performance of the thermal solar system will be determined by the following components and parameters:

- characteristics of the collectors according to market standards (type, area, efficiency, cost, etc.);
- storage parameters (type of storage, sizing, etc.);
- collector loop losses and transmission losses between storage and backup system (those depend on total length, type of insulation, heat exchanger efficiency, etc.);
- running conditions (temperature difference, mass flow rate; etc.);
- climatic conditions (ambient temperature and insulation profile);
- energy required for the auxiliary systems;
- heat demand (temperature, mass flow rate and temporal load profile);

The relevance of these effects on the total amount of energy produced depends on the type of system, on the location, on the running conditions (temperature, control, and sizing) and on the control strategy. For the design of a SWHS for industrial process heat, the following steps can be suggested:

- calculating the thermal load for the solar thermal system and define an overall thermal load profile (temporal distribution of the thermal load along the single day, week and year);
- identifying one or more different configurations for the solar thermal system considering economical, technical, public relation and future aspects of the industrial company;
- determining the collector area and storage volume;
- performing simulations varying the collector type, the size of the collector field and the storage volume.

Due to the stochastic nature of the demand and of the solar radiation and mainly because the energy production is required in each month of the year, the solar thermal plant is usually equipped with an auxiliary boiler operating with a fossil fuel (in general oil or natural gas) to provide heat integration.

A very important element is the parameter known as a solar fraction, $sf$, defined as the ratio between thermal energy produced by means of the solar system and the total energy required:
In many of the cases observed, the contribution of solar energy is a reduced amount of the total energy required: this means that the operation of the auxiliary boiler is quite high and consequently the exergy losses (irreversibility) in connection with the operation of the system.

3. The design of solar thermal energy systems: some quantitative elements

For defining the size of the various components of the SWHS it is important to know the thermal load and in particular the mean daily demand of hot water, since the daily or weekly loads can be different. Figure 3 provides the thermal requirements of a company that requires an amount of hot water for cleaning purposes for each working day. The water is required at 60 °C. A constant temperature of the input cold water is assumed (the typical value of 15 °C). The consumption profile of the company is a quite common type: during working hours, there is always a certain demand of cleaning water, but the profile is discontinuous because there is a very high demand of cleaning water from 8 to 10 pm when all the production equipment is cleaned before closing time.

![Figure 3](image-url)  
**Figure 3.** Example for the discontinuous load profile of the hot water demand for cleaning of production equipment in a small factory for washing and cleaning purposes

The amount of energy we can get from solar heating system depends on available insolation and on the efficiency of the solar collectors. Indeed, insolation differs widely and is crucial for each solar system and efficiency is defined as the ratio between the amount of energy produced and solar energy falling down on collector.

Efficiency is different for the various collector types and depends on solar intensity and on the structure, that define thermal and optical losses; higher losses means lower efficiencies, but higher efficiencies means quite high costs. Thermal losses are low if the temperature of water used for application is close to environmental one.

In general, the combination between collector efficiency and solar irradiation permits of defining the production rate of solar collector. Typical characteristics of the most common types of solar collectors, according to the European normative, [11] are summarized in the Table 1, where general reference data both for conventional Flat plate collector type and for advanced Evacuated-tube, which can be used for applications at temperature below 100 °C, are referred.

| Category | Collector type | Temperature range [°C] | Net Production [kWh/m²/year] |
|----------|----------------|------------------------|-----------------------------|
|          |                | North Europe | South Europe                  |
| Low T    | Flat-plate     | 30 – 70      | 250-450                  | 450-650                  |
| Medium T | Evacuated-tube | 50 – 100     | 350-500                  | 500-800                  |

\[ sf = \frac{E_{Q, \text{solar}}}{E_{Q, \text{year}}} \]  
(1)}
In cases like the one described above, in general the sizing of the solar collectors (definition of the area of the collectors) and of the storage system (volume) is based on the assumption of a fixed amount of the annual thermal load, covered with solar energy: typical values ranging from a minimum of 40% and a maximum of 60% are in the main cases considered.

In this way the operation of the auxiliary boiler is relevant so that the total amount of the thermal load can be completely covered with solar energy only during the summer period, while only a reduced amount is covered during the cold season (10-15%) and a growing amount during mid-season and hot season (up to 100%). Considering for example a case like the one described in figure 3, considering about 240 working days during the year, the estimated amount of energy required can be expressed (in MJ or in kWh) as

\[
E_{Q,wd} = m_{wd} \cdot c_p \cdot \Delta T / 3600
\]

For a reference quantity of water required (e.g. 1 m³ = 1000 kg) and a typical value of 45 °C for the temperature rise of water \(\Delta T\), considering a final value of (60-65 °C), considering \(c_p = 4.2 \text{ kJ/kg K}\) for water, an energy amount of 52.25 kWh is required. This means that for 1 year of operation (about 240 working days according the profile described in figure 3) a total amount of 12540 kWh in necessary. Considering the net energy produced with the solar collector, obtained taking into account the combination of solar radiation and average collector efficiency, it means a collector surface, can be roughly estimated as:

\[
A = E_{Q,year} \cdot \text{sf} / E_{solar,net}
\]

Considering a net production rate, \(E_{solar,net}\) of 500 kWh/m² year (a reference lower limit value for Southern Europe conditions and a typical average value for Italy) and a solar fraction (sf) ranging between 0.4 and 0.6, for the specific case described in figure 3, it is possible to obtain a rough estimation of the collector surface required for each cubic meter of water produced in the single day:

- \(A = 10 \text{ m}^2 /\text{m}^3\) if sf = 0.4
- \(A = 15 \text{ m}^2 /\text{m}^3\) if sf = 0.6

For a preliminary sizing of the storage volume, some reference data can be selected and in this case the design is based on the maximum production level of the collectors: typical values of 50-80 liter of storage volume for each m² of solar collector can be used for a preliminary sizing, even if this volume will depend also by the typical load profile of the user and the service required for the factory.

4. Basic steps of the design of the solar system and optimum design methodology

The evaluation of the cost of solar energy system appears to be not a particularly difficult task. Considering the general structure of a solar thermal plant, the investment costs are mainly referred to the costs of the three four main elements: solar collectors, storage system, piping and auxiliary heaters. The cost of the installation (\(C_{ins}\)) can be evaluated according to Bejan et al., [12], considering the various components (i) and using a reference value of the cost (using the same technology of the reference case considered) with a relation of type:

\[
C^* = C_{ref} \left( \frac{X^*}{X_{ref}} \right)^\alpha
\]

where \(X_{ref}\) is the reference size of the component and \(C_{ref}\) is the reference cost, \(X^*\) is the scaled value of the component and \(C_i\) is the actual cost. In general, the scaling exponent \(\alpha\) assumes value less than unity (for example in the range between 0.6 and 0.8). This express the fact that the percentage increase in equipment cost is smaller than the percentage increase in equipment size. A first analysis of the costs of the solar-based energy systems can be performed, identifying three main items: installation costs, \(C_{inst}\), operating and maintenance costs, \(C_{O&M}\) and the cost of the resource used, \(C_{res}\); in case of solar energy input this cost can be considered null. To them the cost of operation of the
auxiliary boiler, in general based on fossil fuel or sometimes on electricity, is added. The total cost function, defined as the sum of all costs, is given by:

\[ C_{\text{tot}} = C_{\text{inst}} + C_{\text{O&M}} + c_{\text{fuel}} \cdot E_{Q,\text{aux}} \]  

The specific cost of the energy produced depends on the operating hours and on the total amount of energy produced. The cost of solar thermal collectors in Europe ranges from 150 to 500 Euro/m², depending on the collector type and on different specific factors. In this case, considering the specific application, a high quality collector has to be considered. Moreover, extrapolating some data from what is reported in recent papers or technical reports, [13, 14], for medium to large size systems, the following cost distribution can be considered:

- 50% of the total cost is due to the cost of collector field, support structure and installation;
- 20% of the total cost is for piping system, for collector’s field and other parts;
- 10% of the cost is for the storage system and heat exchanger;
- 5% of the cost can be referred to the auxiliary boiler;
- 5% of the cost can be referred to the control system;
- 10% of the total cost is connected to planning and design activity.

Considering this, it seems reasonable to assume the following reference cost, \( C_{\text{ref}} \), and exponents \( \alpha \): \( C_{\text{ref}} = 800 \) Euro/m² and \( \alpha = 0.8 \) for the solar collectors (including the support structure, piping system, heat exchangers, installation and operation and maintenance); \( C_{\text{ref}} = 1200 \) Euro/m² and \( \alpha = 0.6 \) for the storage system; \( C_{\text{ref}} = 2500 \) Euro/20 kW and \( \alpha = 0.75 \) for auxiliary boiler. The above exposed data, that are used by the authors in the analysis, have been defined with reference to the Italian market, as it can be extrapolated from a producer, [15].

The cost of the system, as defined by equation (4), assumes a great relevance if joined with the productivity. In particular, it can be referred to a specific temporal basis (one year or the economic lifetime of the system) so that it could be compared with the energetic costs.

It is clear that in case of fossil fuel based thermal energy production, the costs of installation are quite low (only the boiler) but the third term, i.e. the cost of resources used, can be quite relevant (for example in case of natural gas). On the opposite side, in case of system based on solar energy only, the cost of the installation can be the higher one (including collectors, storage systems, auxiliary boiler and piping system), while the cost of the fuel is zero. An economic compromise between solar energy production and total amount of energy required (represented by a well-defined value of the surface of the collectors), often leads to define a quite reduced value of the solar fraction of the plant (sometimes less than 0.4) and sometimes the choice of excluding the possibility of installing a solar thermal plant, mainly when economic support systems are not active.

5. Multi-objective optimum design methodology for the design of solar systems

The optimization methodology proposed in this work for the optimum design of the solar energy system is based on the idea of assigning a penalty cost to the irreversibility or exergy losses. Exergy analysis and Thermoeconomic analysis of energy systems are developed since forty years ago, as well exposed in [12], even if practical applications are not so diffused.

Moving from the general perspective of thermos-economic analysis but using a simplified approach, the idea is that in the economic comparative analysis of the solar system the energy destruction (irreversibility) connected to the operation of auxiliary boiler assumes an economic value and therefore constitutes a cost item. The minimization of the indicator so defined permits of obtaining a kind of multi-objective optimization in which economic and energetic elements are considered together, and special penalty is given to the use of the auxiliary boiler. For the implementation of such a methodology, a first analysis of the costs of the solar systems is performed, identifying three main items: installation costs, \( C_{\text{inst}} \), including all the components (collectors, storage volume, backup system, piping and other expenses), operating and maintenance costs, \( C_{\text{O&M}} \) and the cost of the resource used for the operation of the systems, including fossil fuel or electricity for backup systems, \( C_{\text{fuel}} \). The cost is referred to a single
year of operation, and is defined considering the lifetime of the plant. With respect to terms present in equation (5), it is added the cost assigned to the irreversibility of the system, indicated with $C_I$. The total cost, defined as the sum of all costs, is:

$$C_{tot} = C_{inst} + C_{O&M} + C_{fuel} + C_I$$  \(6\)

referred to the unit energy produced in the selected temporary basis. The most important element of the methodology is the definition of an appropriate value of the cost of irreversibility (exergy losses), $c_I$.

The basic idea of the method is the following: considering a typical solar thermal plant with an auxiliary boiler for the thermal integration from a qualitative point of view the classic economic approach, represented in figure 4 determines a reduction of the size of the solar plant and a relevant use of the auxiliary boiler, that has a low economic cost and a quite high First Law efficiency, even if very low Second Law efficiency and quite high irreversibility. This is not good in general because does not permit to really appreciate the beneficial effect of solar energy integration. An approach like the one proposed in the paper and represented schematically in figure 5, by means of an introduction of an additional penalty to the irreversibility (represented by the cost $c_I$) will surely an increase of the size of the solar plant (meaning an increased surface of the collectors and of the storage volume) and a consequent reduction of the size and of the operating time of the auxiliary boiler. The method exposed in figure 5, that can be considered similar to a “thermo-economic” based approach, has been already used, for different energy systems, characterized by the operation of an auxiliary (fossil fuel backup) boiler, [16].

Considering an economic perspective, the analysis of a power plant takes into account only the cost of the fuel and the cost of the components. From this perspective, it is difficult to appreciate the convenience of a small size solar thermal energy system.

From a more general point of view, a different way to analyze the system is to combine energetic and economic elements from a Second Law analysis. The approach proposed in the present paper is to consider not only the conventional costs but also the cost associated to the exergy losses connected to the cost of the operation of auxiliary boiler. Assuming the schematization of figure 5, the total cost of the plant operation can be composed as the sum of the costs related to plant installation, operation and maintenance, plus the cost of the exergy losses associated to the solar thermal energy production system operation, $I$, plus the cost of the energy input (dependent on fuel or electricity used).

According to the schematization given in the previous section, considering a general case in which both fossil fuel and electricity based backup systems are present, the total cost can be expressed as:

$$C_{tot} = C_{inst} + C_{O&M} + C_I + C_{fuel} = C_{inst} + C_{O&M} + c_I \cdot I + c_{fuel} \cdot E_{Q,aux} + c_{elec} \cdot E_{Q,elec}$$  \(7\)

The idea is quite simple: an additional penalty is attributed to the irreversibility (exergy losses) related to the use of fossil fuel for auxiliary boiler. This “penalty” is computed at a well-defined cost; in this way, the operation of the auxiliary boiler can be reduced and the solar fraction increases. The key element is the definition of the cost of the exergy losses, $c_I$. Different values can be considered:
1) $c_I = 0$: in this case a typical economic analysis; no penalty is applied to the operation of fossil fuel backup systems and to the derived irreversibility (exergy losses);
2) $c_I = c_{\text{fuel}} \bar{\eta}_C$: in this case the cost of the exergy losses is fixed equal to the price of fuel reduced with a coefficient $\bar{\eta}_C$, correspondent to an average efficiency of the solar collectors;
3) $c_I = c_{\text{fuel}}$: in this case the cost of fuel is assumed equal to the cost of the input energy. This could be the cost of a fossil fuel, like natural gas or electricity.

Considering the three different options, if in the first case the typical economic analysis is obtained, the last represents a kind of “ecological vision” because the result is to minimize as much as possible, the use of support backup system, based on fossil fuel or electricity use. On the contrary, the second option represents a sort of compromise, which partially contributes to reduce the use of fossil fuels.

The methodology has been implemented using a macro in Excel, requiring the definition of the solar irradiation of the place under analysis and an expression of the efficiency of the solar collector.

Figure 6 provides a qualitative analysis of the results obtained in a case similar to the one discussed in section 3, considering the same economic scenario, described in section 4 (for the costs of the main components of the system), values of the cost of natural gas (for auxiliary boiler) and varying the value of the cost of irreversibility, according to the three different scenarios above exposed.

In figure 6 all the cost voices are reported, $C_{\text{fuel}}$, $C_{\text{inst}}$ (including all the components of the solar heating system and operation and maintenance), $C_I$ and $C_{\text{tot}}$, obtained as the sum of the three previous terms, are reported as a function of the solar fraction of the plant (in abscissa). As it is possible to observe, the cost of the system, $C_{\text{inst}}$ increase with the rise of the solar fraction, while the other two voices decreases. A minimum of the total cost function is present in all the cases considered. Analyzing the results it is possible to observe that the optimal value of the solar fraction, $sf$, shifts from 0.35 (case 1, corresponding to the classic economic analysis) up to values ranging around 0.8 (case 3, corresponding to the maximum penalty attributed to the irreversibility).

6. Conclusions

The development of a diffused use of solar energy for low to medium temperature process heat industrial applications can be strictly connected to the definition of a compromise between positive aspects, like reduced cost of energy input and reduction of fossil fuel use and of the consequent greenhouse gas emissions and the negative aspects connected with the quite high costs. A compromise is often represented by the design of the solar heating system, with a well defined value of the solar fraction, identified as the ratio between the energy amount produced with solar energy input and total amount of energy required. This ratio, often obtained with energetic (solar irradiation of the site) and economic (cost of the various components) considerations, usually ranges from 0.4 and 0.6, depending on the solar irradiation of the site and in some cases it results to be lower than 0.4.
Considering that in all the systems a fossil fuel backup is always present, the approach proposed in the present paper combines on a common basis, energetic and economic elements, introducing an additional cost, connected to the operation of the auxiliary boiler. The objective of defining an opportune balance between the irreversibility of the system, represented by the exergy losses connected with the use of fossil fuel and the economic cost of the system. In this way it is possible define a “thermoeconomic optimum value” of the solar fraction, sf, dependent both on the operation of the system and on the additional cost considered for the irreversibility.

In the final part of the paper, using a specific test case referred to a medium temperature production (60-65 °C) it is shown how, considering different values of such a penalty parameter (cost of the irreversibility), it is possible to obtain a design of the solar systems with higher solar fraction values. This corresponds to an increased area of the solar collectors installed and an increased share of use of solar energy with respect to fossil energy. In particular cases it is possible to approach values of the solar fraction well higher than those obtained with a simple economic analysis, up to 0.8-0.85.

The method proposed in the paper, though if simplified, permits a comparison among solutions characterized by different value of the solar fraction. It can be proposed an useful instrument for decision making process before the installation of a solar thermal energy process heat system and for defining a possible basis for future economic support system.

7. References

[1] Duffie J A and Beckman W A 1980 Solar Engineering of Thermal Processes, John Wiley, NY.
[2] Kreith F and Yogi Goswami D 2016 Handbook of Energy Efficiency and Renewable energy, CRC Press - Taylor & Francis, NY, pp. 916-970.
[3] Solar Process Heat Generation: Guide to solar thermal system design for selected industrial processes, SO-PRO: Solar Process Heat, available on-line at www.solar-process-heat.eu, Techn_Bro_SoPro_en-fin.pdf
[4] Klein S A and Beckman A 1979 A general design method for Closed-Loop Solar Energy System Solar Energy 22(3) 269-282.
[5] Braun J E, Klein S A and Pearson K A 1983 An improved design method for Solar Water Heating System Solar Energy 31(6) 597-604.
[6] Collares-Pereira M Gordon J M Rabl A and Zarmi Y 1984 Design and optimization of solar industrial hot water system with storage, Solar Energy 32(1) 121-133.
[7] Gordon J M and Zarmi Y 1985 An analytic model for the long-term performance of solar thermal system with well-mixed storage, Solar Energy, 35(1) 55-61.
[8] Reddy T A Gordon J M and De Silva I P D 1987 Mira: a one-repetitive day method for predicting the long-term performance of solar energy system, Solar Energy 39(2) 123-133
[9] Kulkarni G N Shireesh B K and Santanu B 2007 Determination of design space and optimization of solar water heating systems Solar Energy 81(8) 958-968.
[10] Viessmann 2008 Technical guide - Solar Thermal Systems, Viessmann Werke, available on-line at www.viessmann.com.
[11] ISO 9806-3:1995, 1995b. Test Methods for Solar Collectors, Part 3: Thermal Performance of Unglazed Liquid Heating Collectors (Sensible Heat Transfer Only) Including Pressure Drop
[12] Bejan A Tsatsaronis G and Moran M J 1996 Thermal design and optimization, John Wiley, NY
[13] IEA-ETSAP and IRENA Technology Brief E21, 2015. Solar Heat for Industrial Processes Technology Brief, available at http://www.inship.eu/docs/sh5.pdf
[14] Tulus V Abokersh M H Cabeza L F Vallès M Jiménez L and Boer D 2019 Economic and environmental potential for solar assisted central heating plants in the EU residential sector: Contribution to the 2030 climate and energy EU agenda, Applied Energy 236 318-339.
[15] Sunerg Solar Company, Solar Energy Systems solutions, catalogue of Solar Thermal available at: www.sunergsolar.com/media/all_categoria/1_Cat.SolarTermico2020_compressed.pdf
[16] Franco A and Bellina F 2018 Methods for optimized design and management of CHP systems for District Heating Networks (DHN) Energy Conversion and Management 172 21–31.