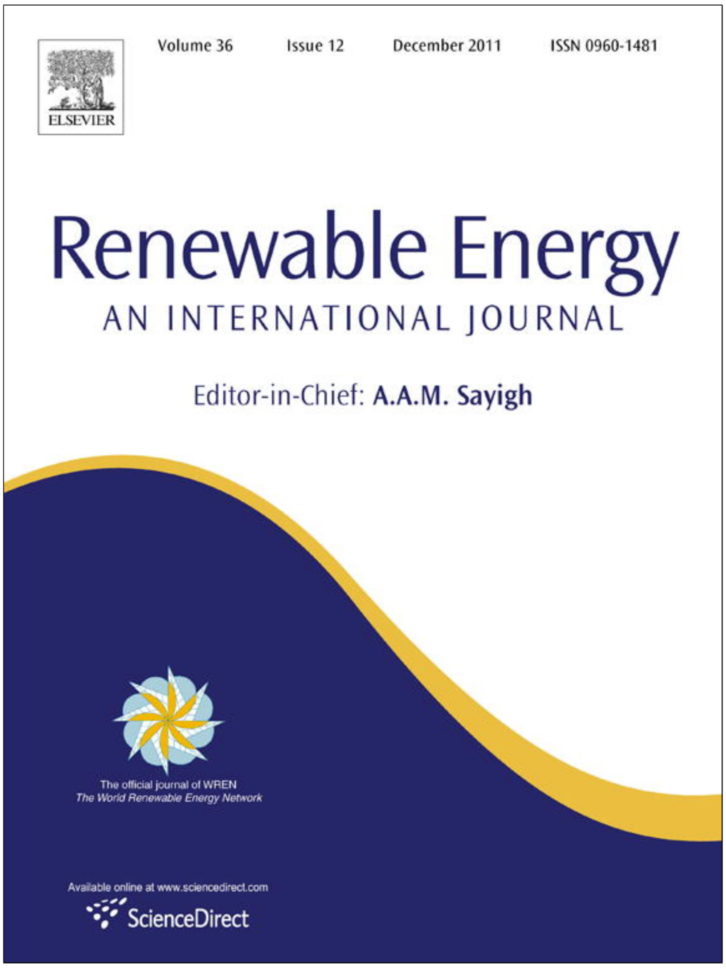
Investigation on the feasibility of integration of high temperature solar energy in a textile factory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Investigation on the feasibility of integration of high temperature solar energy in a textile factory

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ABSTRACT

Thermal energy production from fossil fuels is very common in many applications, especially in industrial processes. In a global context where great attention is being focused on reducing pollution and greenhouse gas production, the integration of renewable energy in industrial applications is very interesting. This is even more important considering that greenhouse gas emission for industrial processes is a great portion of their total emission. Considering the above, it appears that the integration of high temperature solar panels in industrial processes is quite an attractive prospect. The working temperatures of parabolic solar collectors are, for example, generally close to those of the thermal fluids used in many industrial processes, and parabolic solar collectors are a well known technology with several applications primarily used in electric production systems. Nonetheless, only a few examples of industrial integration have been studied or built. In this study, the integration of a concentrating solar thermal plant in a textile factory has been examined both from the thermodynamic and economic point of view. An existing textile factory was chosen as a case study and its annual consumption of thermal energy characterized. A model of the plant with solar energy integration was developed and simulated with TRNSYS over a one year time period. The plant was simulated considering the panel characteristics provided by the manufacturer and the local irradiation data. The influence of several plant parameters has been investigated in order to estimate their importance on performance and plant suitability.

1. Introduction

Reduction of greenhouse gas emissions due to fossil fuel consumption for energy conversion is one of the most important environmental topics of the moment. With the Kyoto Protocol, many industrialized countries agreed to reduce their collective greenhouse gas emissions in respect to those of 1990. One of the greatest sources of equivalent carbon dioxide emission is the production of energy for the industrial processes. Possible solutions in this context can involve the use of cogeneration plants, but the electric-thermal balance of industrial consumption makes these plants suitable only rarely. While the emissions due to electric energy production can be reduced only by considering an improvement of grid production efficiency, for those processes where thermal energy is needed a great benefit would be achieved by using local integration of solar energy [1]. In particular, high temperature solar energy collected by parabolic mirrors could be used as an augmentation to industrial boilers, thus reducing the consumption of fossil fuel.

Parabolic solar collectors seem to be the most suitable technology for these applications since they allow the collection of solar energy at temperatures which are compatible with those typical of several industrial processes (above 200 °C) [2].

Currently many applications of these devices can be found in the literature [3], but they are generally limited to electric energy production. One example is the Solar Electric Generating Systems (SEGS) in Southern California (354 MWe) [4]. Other applications of parabolic solar collectors are reported by Bakos et al. [5] for electricity generation and A. Thomas [6] and Kalogirou et al. [7] and [8] for low temperature steam generation, but the applications of integrated systems to industrial processes are few [9,10]. Other uses of parabolic solar collectors can also be found in the sea-water desalination applications [11,12]. Other examples are related to the study of concentrating photovoltaic/thermal solar collectors [13].

Italy, like other Mediterranean area countries, has very favorable climatic conditions for these applications with an annual averaged solar radiation of about 1400 kWh/m^2

Abbreviations: ET100, EuroTrough100; FrTan, Collector optical efficiency; FrUl, Slope of collector efficiency curve [W/m^2 K]; NPV, Net Present Value [€]; PBP, Pay Back Period [years].

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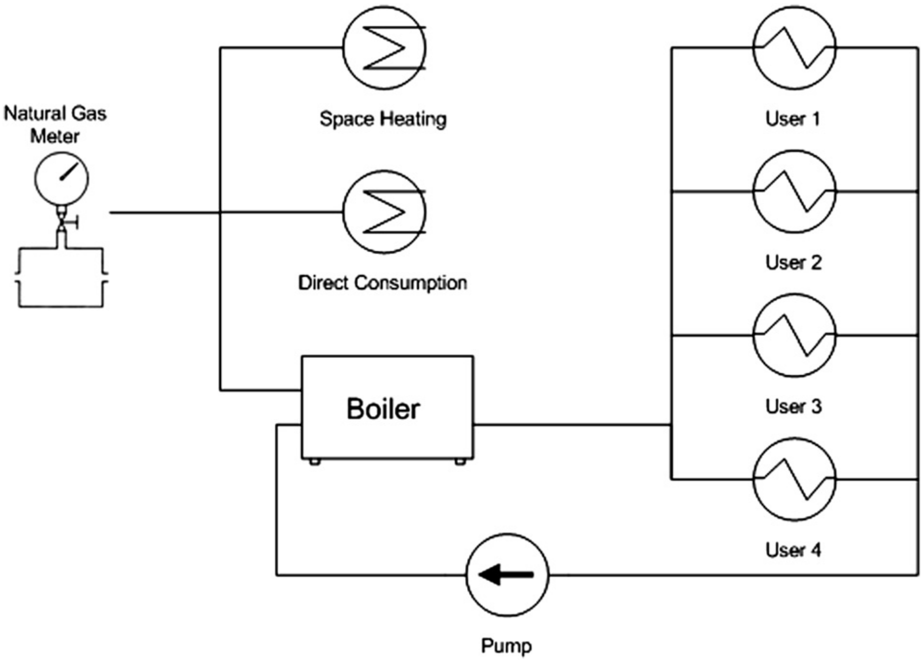

Fig. 1. A diagram of the factory plant layout.

In order to investigate the feasibility of the integration of a high temperature solar system in an industrial context, a textile factory in Prato (latitude 43.53°N; longitude 11.06°E; altitude 61 m at sea level) has been chosen as a case study. Even though this is a specific analysis, results can be easily applied to many similar industrial applications.

The analysis was carried out starting from the evaluation of energy consumption profiles of the factory in order to determine the dimension of the parabolic solar collector field. A new plant layout including solar integration was then designed and simulated with TRNSYS over a one year working period. Several plant parameters were investigated (pump mass flow rate, solar field extension and storage dimension) in order to evaluate their influence on plant performance. Thermodynamic results were then compared and used to perform an economic analysis of the different options.

2. Industrial process heat demand

The chosen plant has been active in the textile sector for more than 40 years, dealing mainly with non woven fabric. Many of the numerous processes which are needed to obtain the final product

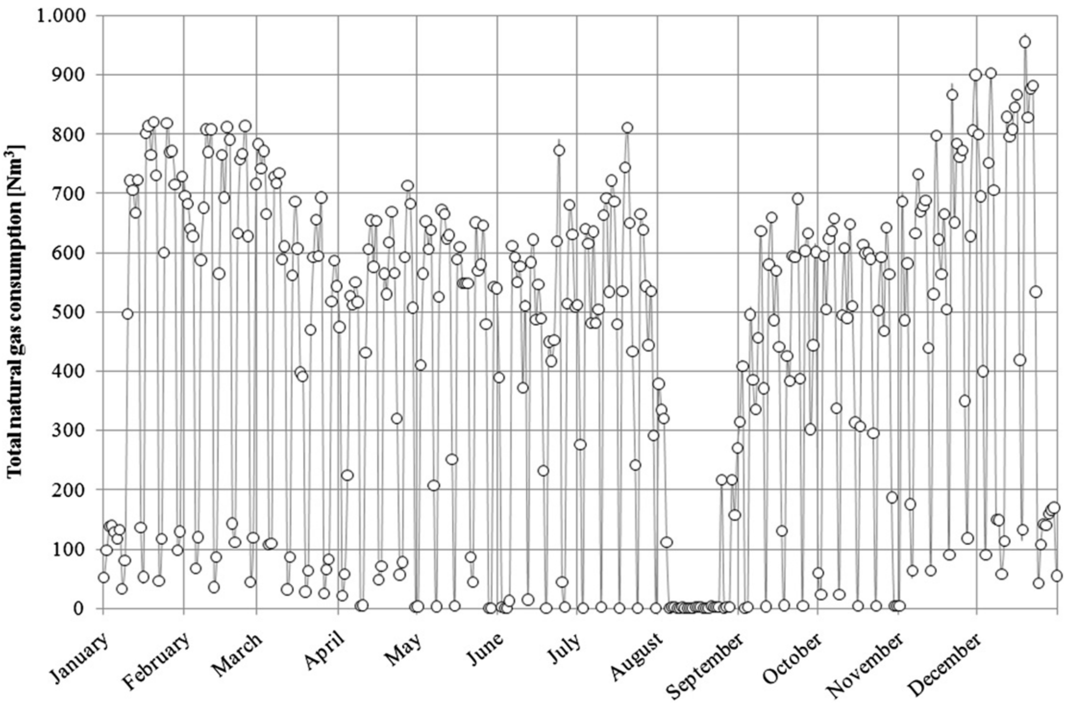

Fig. 2. Daily natural gas consumption over one monitored year.

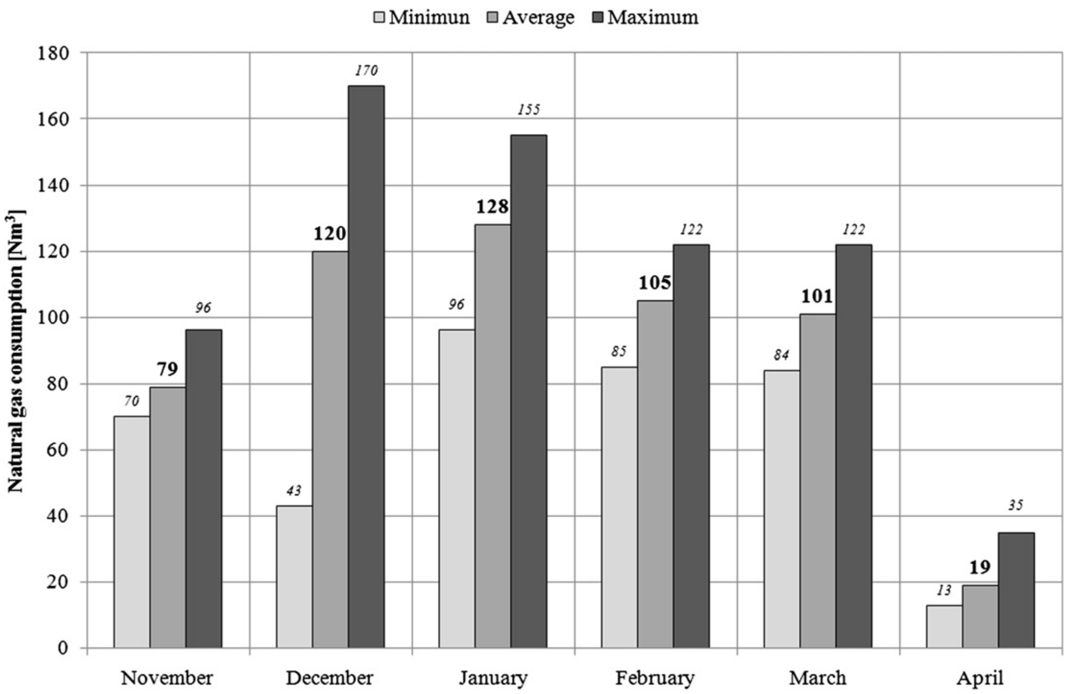

Fig. 3. Daily natural gas consumptions due to space heating during cold months.

require a great consumption of thermal energy. The thermal plant is primarily composed of a natural gas boiler (1160 kW) and a primary diathermic oil loop at a target temperature of 240 °C (the actual temperature varies typically from 230 to 250 °C). A pump (4.5 kW – 22 m^3/h) constantly assures the circulation of the oil in the loop during the plant's operating hours (6 a.m.–6 p.m.). Four main thermal users are connected to the oil loop: each machine is responsible for treating the fabric in a different manner.

In addition to the boiler, the plant has two other natural gas users: the space heating plant and a particular fabric treatment unit, called stenter. A diagram of the plant layout is shown in Fig. 1. Considering the plant layout, the most suitable integration is a configuration where part of the thermal energy from the boiler is supplied by solar energy.

2.1. Estimation of daily plant consumption

The first step of this study was to characterize the thermal consumption of the plant in order to perform a first projection of the solar plant. As in many industrial contexts, this factory does not calculate the different consumptions of all the processes. The only data that was available to estimate the factory thermal consumption were the bills of the natural gas supplier over a year's time. Since the

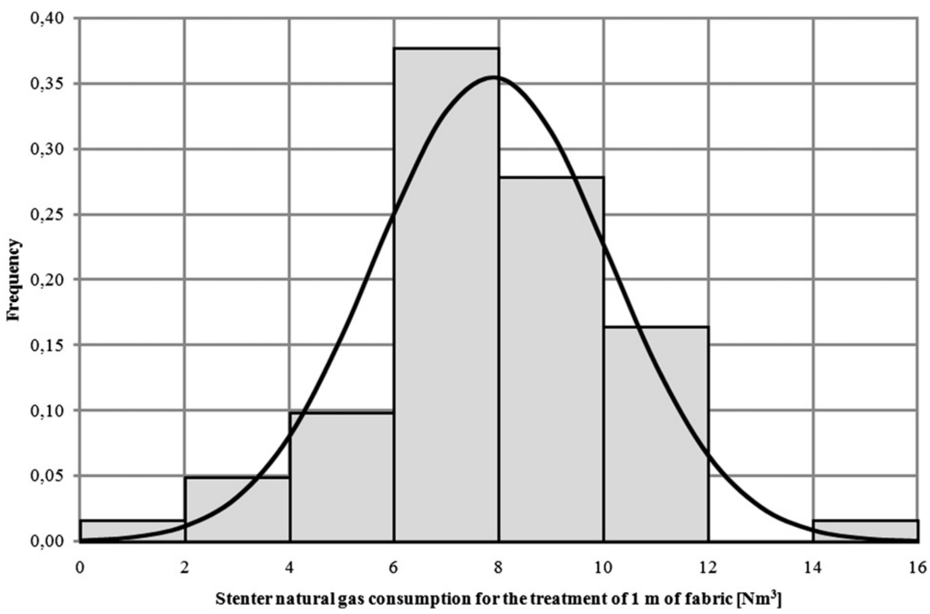

Fig. 4. Statistical distribution of the amount of natural gas needed to treat 1 m of fabric by the stenter.

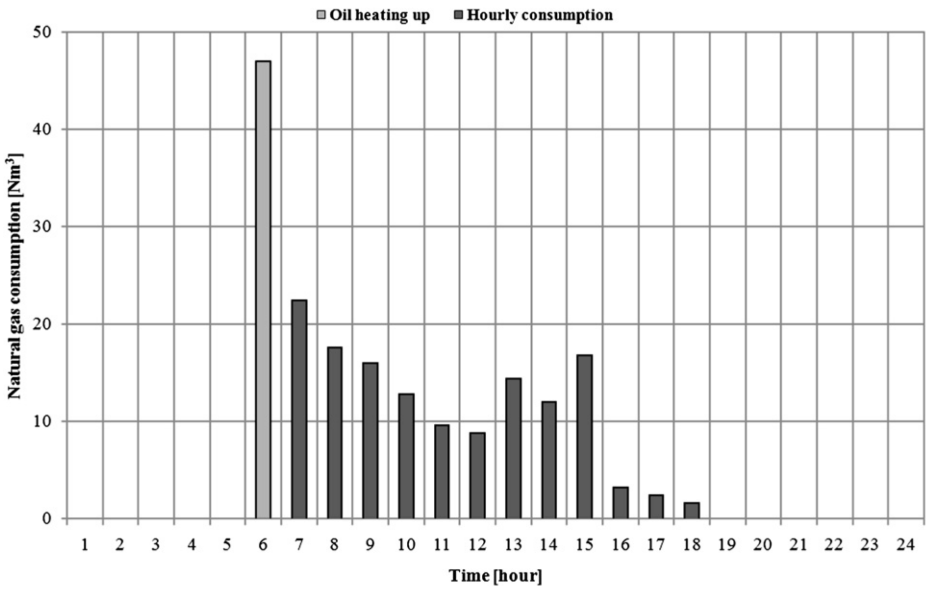

Fig. 5. Monitored hourly consumption of the boiler between March and April.

factory has only one metering station at the supplier delivering point, these bills reported the daily total plant consumption and then the sum of boiler, direct users and space heating natural gas consumptions (Fig. 2). In order to estimate the boiler consumption it was necessary to perform an indirect calculation by estimating the room heating and the direct consumption.

Natural gas consumption due to space heating was estimated by considering that during the cold season (from November to April) there were particular days (for example during weekends or national festivities) in which the space heating was turned on although the production was not in operation. A check of the amount of natural gas charged by the supplier during those days allowed the estimation of the average consumption for space heating. In Fig. 3, the amounts of natural gas consumptions due to space heating are shown as minimum, maximum and average values for the investigated months. The last was assumed as representative of the natural gas consumption for the space heating of each month.

Estimation of natural gas consumption due to those processes with direct use (stenter) was performed taking into account the consumption in those days when the boiler was turned off. When necessary, the portion due to space heating was subtracted from this amount. The resulting amount of gas (Nm^3) was correlated to the amount of fabric treated in the process (linear meters) during those days.

In Fig. 4, the statistical distribution of the amount of natural gas needed to treat 1 m of fabric is reported. Considering the normal distribution that approximates the observation distribution best, an average value of 7.87 Nm^3/m of natural gas is needed for the treatment of fabric in the stenter.

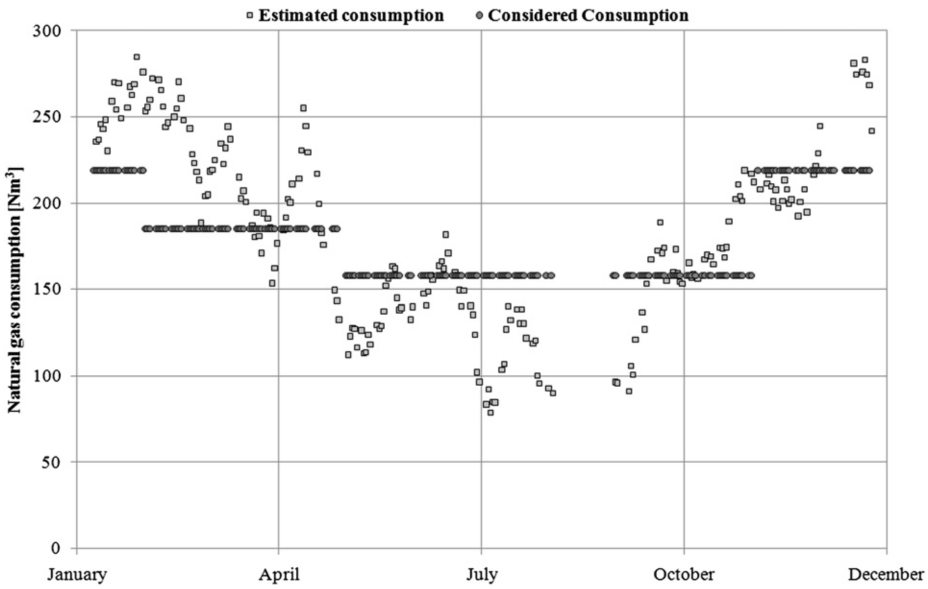

Fig. 6. Year-round comparisons between the daily estimated consumption and that resulting from the adopted approximations.

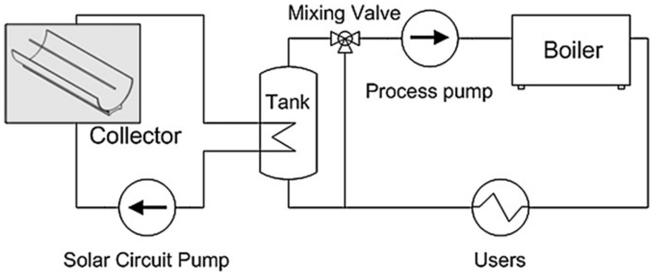

Fig. 7. Diagram of the investigated plant layout.

Since the amount of produced fabric treated by the stenter is precisely controlled by the firm management, it was possible to estimate with accuracy the portion of natural gas consumption due to direct use during the investigation year.

The natural gas consumption of the boiler and then its thermal energy request were calculated as a subtraction between the results of the previous analyses over the entire investigation year (Eq. (1)):

$$C_{boiler} = C_{total} - C_{heating} - C_{stenter} \quad (1)$$

The amount of natural gas consumption was then converted to thermal energy request by considering the heat coefficient given by the supplier (34534 kJ/Nm^3).

2.2. Estimation of hourly plant consumption

In order to estimate the natural gas consumption distribution during the day, an hourly monitoring at the gas meter was carried out for two mid-season months (March and April). The average hourly consumption was then calculated taking into account the space heating and the direct consumption. In Fig. 5, the hourly consumption of the boiler during the March–April period is reported. Natural gas consumption between 6 and 7 a.m. is mainly due to the heating up of the diathermic oil loop before the production starts. This consumption, as stated by the firm energy manager, can be assumed as a constant over the entire year regardless of the season.

The factory production was not constant during the year and for this reason the hourly profile had to be scaled by considering the annual production trend. Since it was not possible to have an hourly monitoring of the plant over the entire year, for the sake of simplicity in the present analysis only three hourly profiles have been considered according to the firm's typical production trend:

- The first for the months from February to April, as reported in Fig. 5
- The second from May to September with the hourly consumption reduced by 20% according to the lower firm production

Table 1
Geometric characteristics of the solar collector.

EuroTrough100	ET100
Focal length (m)	1,71
Receiver diameter (m)	0,07
Area (m^2)	545
Collector aperture (m)	5,77
Length (m)	99,5
N° collector modules	8
N° mirror panel	224
N° absorbing duct	24
Glass envelope transmittance	0,94
Weight structure per m^2 (kg)	19

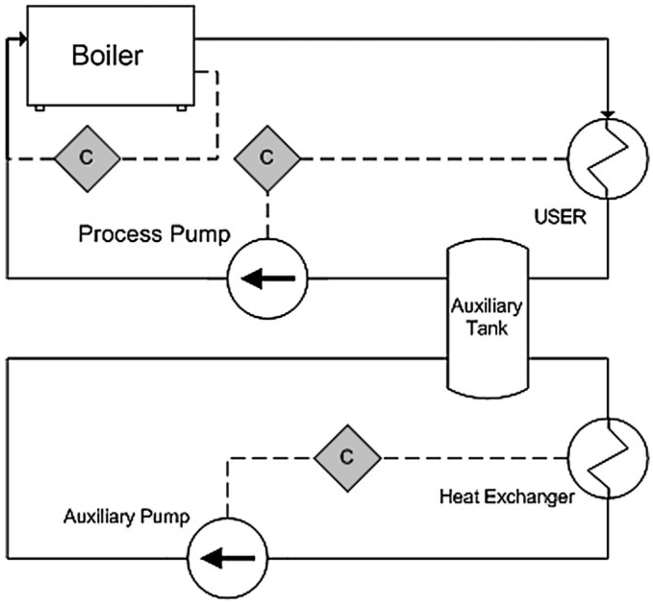

Fig. 8. Diagram of the model of the original plant.

- The third from October to January with the hourly consumption increased by 20% according to the higher firm production.

In Fig. 6, a year-round comparison between the daily estimated consumption and that resulting from the previous approximation is reported.

3. Solar plant layout and integration

Integration of solar energy in an industrial context is not only limited by the economic feasibility but also by the installation feasibility. Solutions leading to major changes in plant layout or plant stops are generally avoided by investors. For this reason, each case deserves a separate analysis. In the investigated case study, the most suitable plant layout for the integration of solar energy is that where the thermal energy from the collectors is exchanged with the diathermic oil loop upstream the boiler. If the solar energy is not sufficient to increase oil temperature to the desired values, the boiler can act as a backup. This configuration needs only minor modifications to the existing plant and is interesting from the industrial point of view whose primary target is to avoid production plant stop for long periods. In addition, in case of solar plant malfunctioning, the original set-up could be easily restored. A diagram of the investigated layout is shown in Fig. 7.

A tank receiving the thermal energy from the solar plant is inserted into the diathermic oil loop upstream the boiler. This element has the main task of storing the thermal energy from the solar plant when the request from the processes is lower than that captured by the mirrors. Maximum storage temperature of diathermic oil in the tank was assumed to be even higher than that of the process loop. In order to get the proper temperature of the diathermic oil, a mixing valve is placed at the tank exit to mix the flow rate from the tank with that at a lower temperature coming from the users.

EuroTrough100 installed on flat ground and oriented to the south was considered as a one-axis sun-tracking parabolic solar collector [1]. This kind of collector is one of the most mature solar technologies for generating heat at high temperature and its characteristics are easily documented in literature [1,2]. Geometric characteristics of EuroTrough100 are reported in Table 1 [14,15].

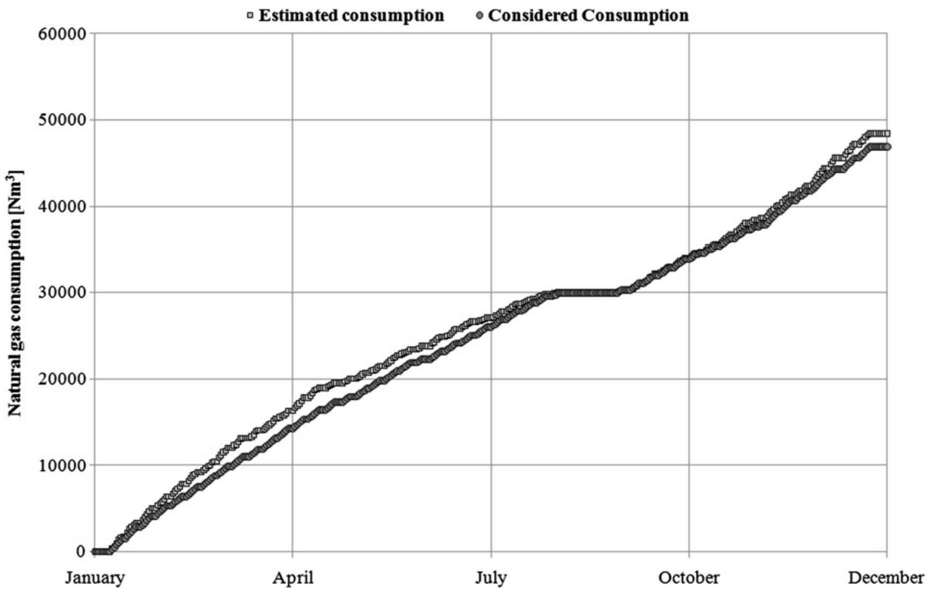

Fig. 9. Natural gas consumption cumulates as estimated by plant monitoring and resulting from plant modeling.

The performance equation of the collector as provided by the manufacturer is ([1,12], Eq. (2)):

$$\eta = 0,75 - 0,000045\Delta T - 0,039\frac{\Delta T}{G_r} - 0,0003G_r\left(\frac{\Delta T}{G_r}\right)^2 \quad (2)$$

Where ΔT is the temperature difference between the ambient and the oil in the absorber duct (in K), while G_r is the average solar irradiance (in W/m^2).

4. Plant simulation

In order to develop a full year-round simulation of the system, the software TRNSYS was used. This software is commonly utilized for this kind of analysis primarily because of its capability to solve transient dynamics of energetic systems and for the large amount of meteorological data available in its database [16–18]. Two simulations have been carried out: the existing plant and the integrated plant.

4.1. Original plant

The first step was to model the original plant (without solar integration) in order to obtain a reference value for the boiler energy consumption with the assumed seasonal absorption profiles. The process plant was modeled considering a boiler, a reference temperature for the diathermic oil of 240 °C, a heat exchanger (thermal users) and a constant speed pump (Fig. 8, where the control units are also indicated). Pump start and stop was controlled in order to operate during the working days between 6 a.m. and 6 p.m. as the existing pump does. In order to improve the model, two topics had to be investigated:

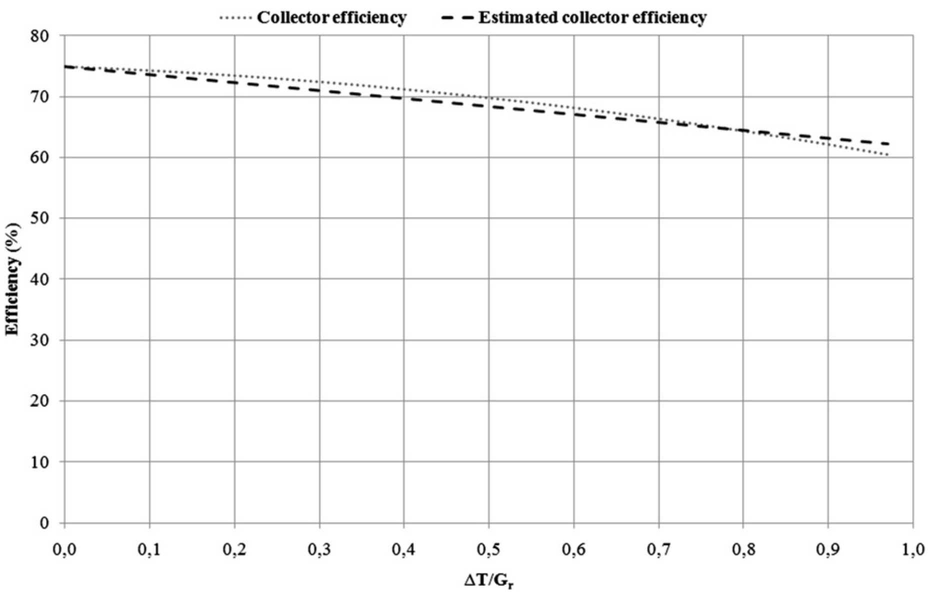

Fig. 10. Comparison between the efficiency curve of the collector and that considered in the calculation.

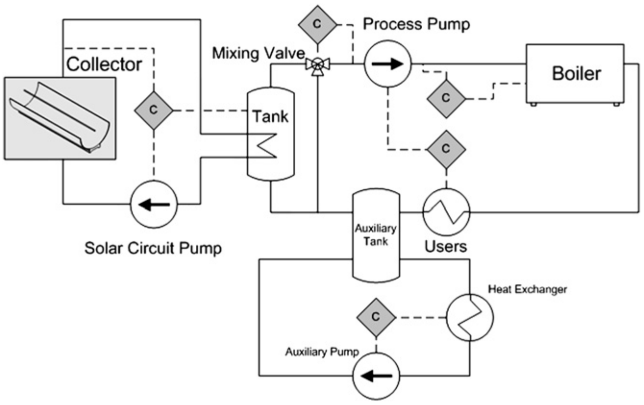

Fig. 11. Diagram of the integrated plant model.

- the first was to reproduce the cooling of the oil in the plant during the night;
- the second, a consequence of the previous one, was to reproduce the additional natural gas consumption during morning due to the heating of the oil.

To simulate the two aspects a tank with a volume equal to the volume of the whole plant piping was introduced into the model. This guaranteed the proper thermal inertia at plant start up. In addition, since the auxiliary tank thermal losses during the night were not sufficient to lower the diathermic oil temperature down to the values measured on the plant, a secondary loop with a pump that turns on at 6 p.m. and turns off at 12 a.m. was introduced. This secondary loop decreases the diathermic oil temperature down to 60 °C as observed during the monitoring of the existing plant. This is in agreement with the measured value between 6 and 7 a.m.

Thermal energy request of the user was reproduced by means of a heat exchanger. During the simulation, the heat exchanger thermal load was determined taking into account the hourly consumption previously defined (e.g. Fig. 5). This consumption was modified according to the season as previously described and, to avoid calculating the consumption for the heating of the morning oil twice, the consumption between 6 and 7 a.m. was removed.

This model was simulated over a one year period with 15-minute steps with the following annual results:

- Boiler energy consumption: 1.620 GJ/year
- Natural gas consumption: 46.904 Nm^3/year (in full accordance with the estimated one which was approximately 48.800, and then confirming the accuracy of the model, Fig. 9)
- Boiler statistics:
  - 3052 working hours per year
  - 238 start and stops, corresponding to the working days

4.2. Integrated plant

Energy transfer from the solar plant and the tank was managed taking into account the temperature difference between the collector outlet and the tank inlet. If the temperature at the collector outlet is at least 10 °C greater than the temperature in the tank, the control system turns on the solar circuit pump (constant speed). This pump keeps on operating until the temperature at the collector outlet is 2 °C greater than the temperature in the tank. This control logic was adopted to assure that the fluid from the collectors always be at a temperature higher than that in the tank, whatever it may be. Maximum storage temperature in the tank was assumed to be 320 °C; if diathermic oil temperature reached values higher than that, the panels were turned off center to drastically reduce the collected radiation.

As in the simulation of the existing plant, the target temperature for the diathermic oil loop was considered 240 °C. Average storage temperature is generally greater (about 280 °C) so a mixing valve was positioned at the tank exit to keep it as close as possible to that value. Should the diathermic oil from the tank reach a temperature that is lower than the target value, the boiler would turn on to guarantee a temperature of 240 °C.

Parabolic solar collector behavior has been simulated using the model already present in TRNSYS. Due to the constraints imposed by that model, it was necessary to reduce the efficiency given by the

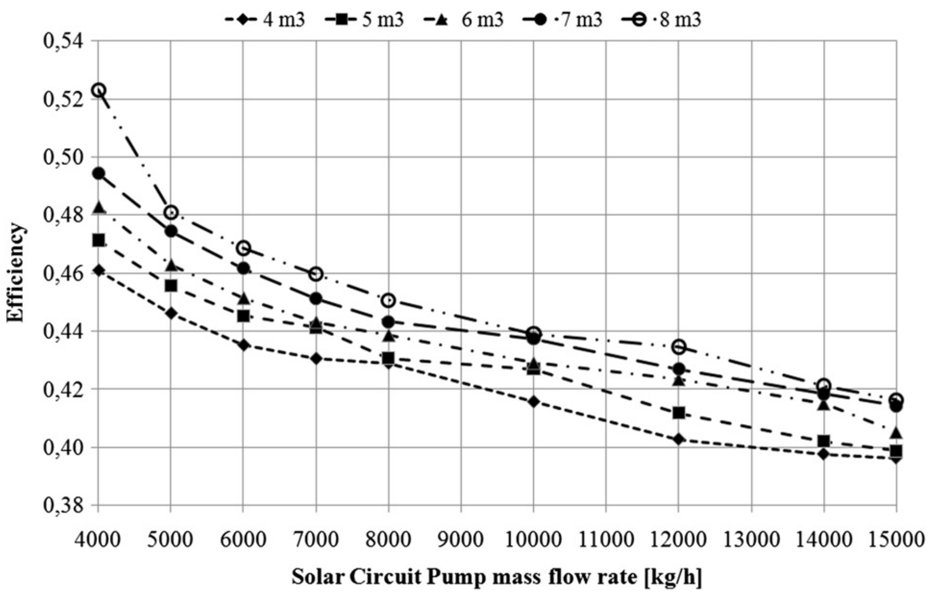

Fig. 12. Efficiency for different solar circuit pump mass flow rates and tank sizes (1 collector configuration).

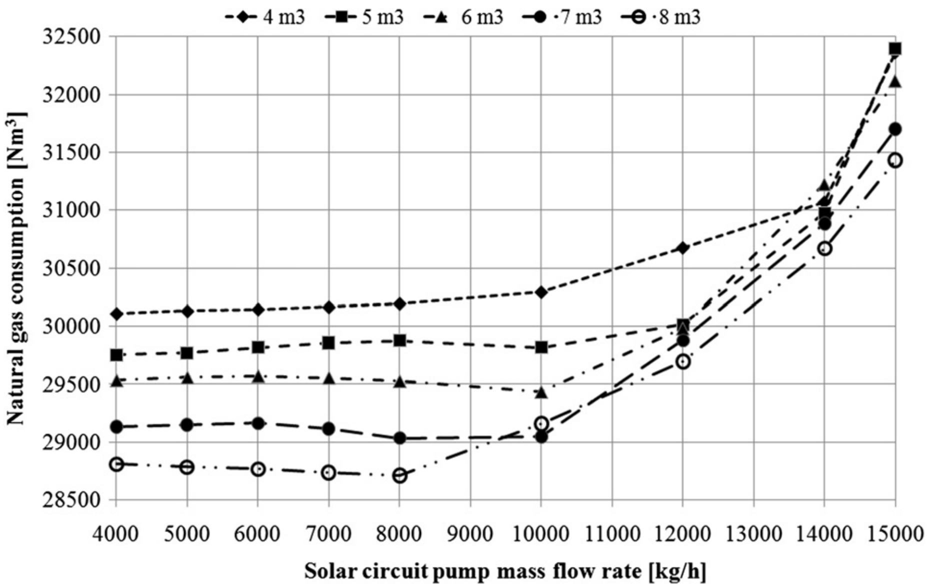

Fig. 13. Natural gas consumption for different solar circuit pump mass flow rates and tank sizes (1 collector configuration).

manufacturer to a first order expression taking into account the average value of local irradiation. Efficiency then becomes a linear function of the difference between the central duct oil temperature and the ambient temperature with an intercept value (FrTan) and slope value (FrUl). A comparison between the two efficiency curves is reported in Fig. 10.

The model of the integrated plant was developed originating with that of Fig. 8 by including the solar plant element. The final diagram of the model is reported in Fig. 11 where the control units are also indicated.

The tank of solar circuit was simulated considering a thermal stratification of 10 layers and a thermal heat loss coefficient of 0.83 W/m^2K. A year-round simulation with 15 min steps was carried out starting from the steady conditions reached in the simulation of a previous year and taking into account the local irradiation at the plant location and the users thermal energy request previously defined.

5. Thermodynamic results

Several simulations were carried out in order to investigate the sensitivity of the thermodynamic and economic results to the plant configuration. The main parameters investigated are:

- Collector surface of 545 or 1090 m^2 (one or two collectors).
- Volume of the tank from 4 m^3 to 8 m^3 with step of 1 m^3.
- Mass flow rate of solar circuit pump from 4000 to 15000 kg/h

In order to compare the results from the different configurations, the following parameters were considered:

- Efficiency, defined as the ratio between the energy from the solar collector that reaches the tank and the incident radiation on the collectors,

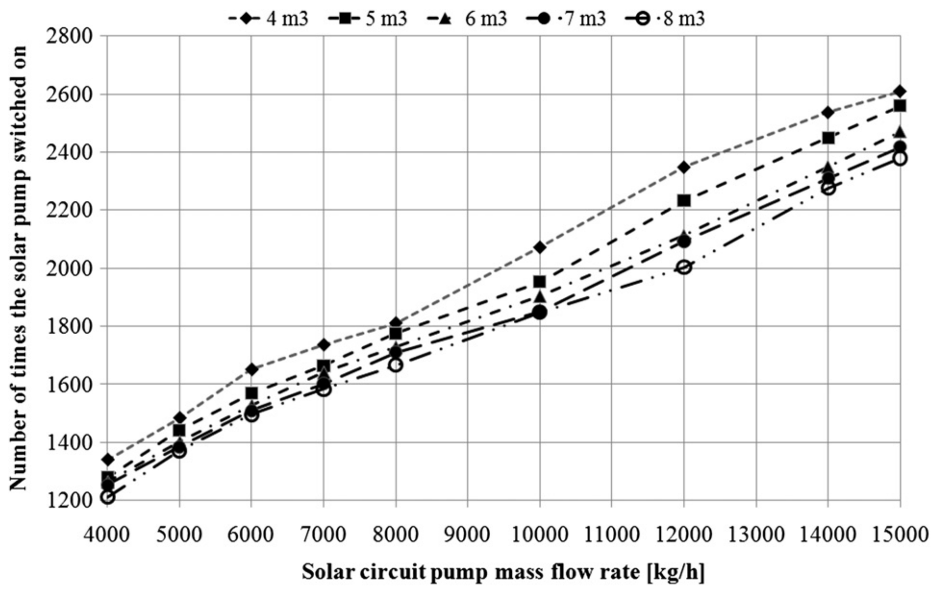

Fig. 14. Number of times the solar circuit pump switches on over one year for different mass flow rates and tank sizes (1 collector configuration).

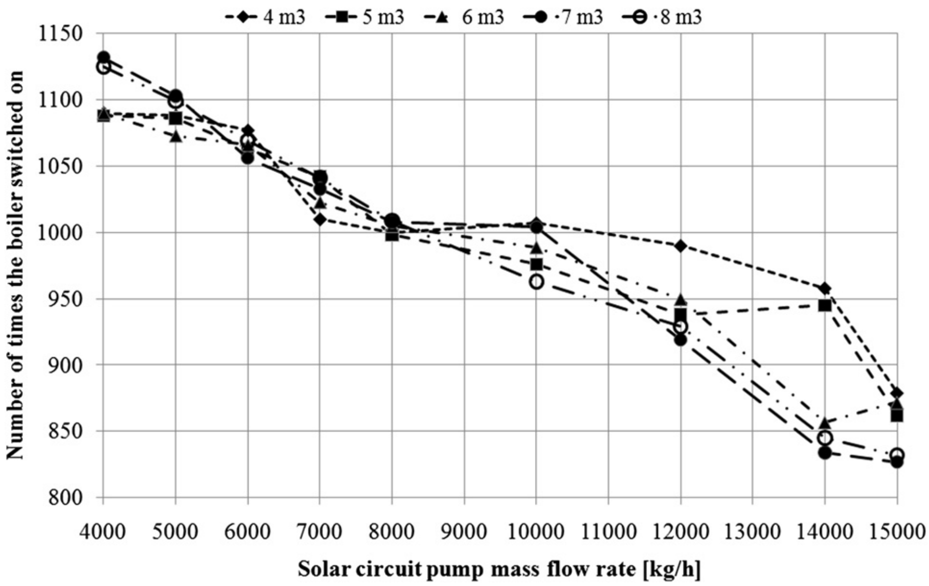

Fig. 15. Number of times the boiler switches on over one year for different mass flow rates and tank sizes (1 collector configuration).

- Number of times the solar circuit pump and boiler switched on; this parameter has a strong influence on the maintenance costs
- Natural gas consumption for the given absorption profiles (remains unvaried for all the configurations tested).

As defined here, efficiency takes into account the solar energy losses due both to the collecting efficiency of the panel and to those particular working conditions when thermal energy from the panel is not delivered to the user (for example when the solar collectors are out of focus because the maximum oil temperature has been reached in the tank). The influence of solar circuit mass flow rate and tank size on system efficiency and natural gas consumption are reported in Figs. 12 and 13 (one collector configuration).

Efficiency has a proportional trend with the mass flow rate; in addition, an increase of tank size leads to an increase of efficiency for all the mass flow rates. Solar circuit pump mass flow rate has a great influence on natural gas consumption: for low values, the amount of consumed natural gas depends only on tank volume, for high values natural gas consumption becomes almost independent from tank size and has a linear trend with solar circuit mass flow rate. In these last configurations, the mass flow rate in the panels is so high that the increase in diathermic oil temperature is very low; the tank temperature remains low and therefore great natural gas consumption is needed to satisfy the energy request.

In Figs. 14 and 15, the influence of mass flow rate and tank size on the yearly amount of solar circuit pump and boiler switching on are reported (one collector configuration). As for the efficiency, the best configuration corresponds to a big tank and a small pump. On the other hand, as for natural gas consumption, the best results are achieved for a tank size of 8 m^3 and a mass flow rate 8000 kg/h.

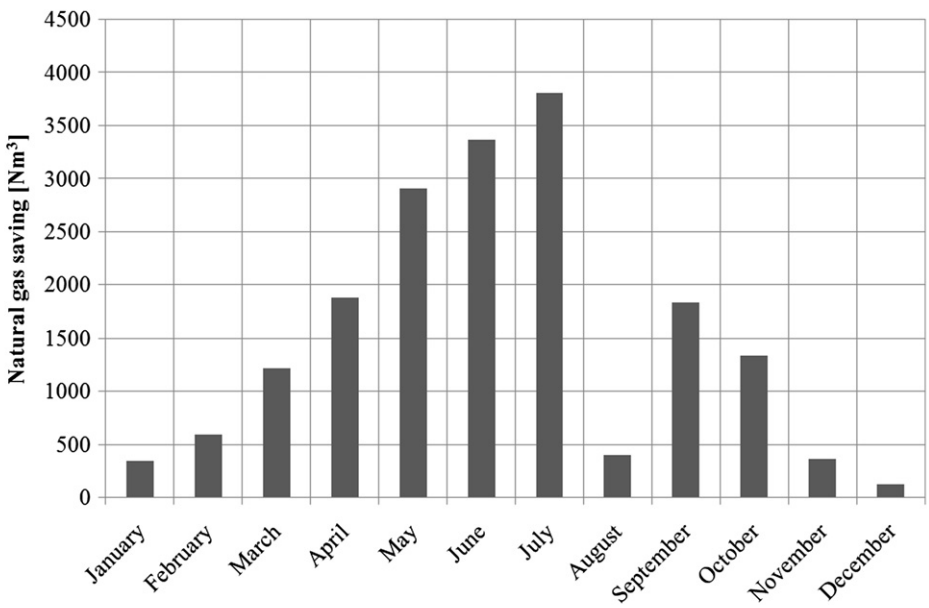

Fig. 16. Monthly natural gas saving (1 collector configuration).

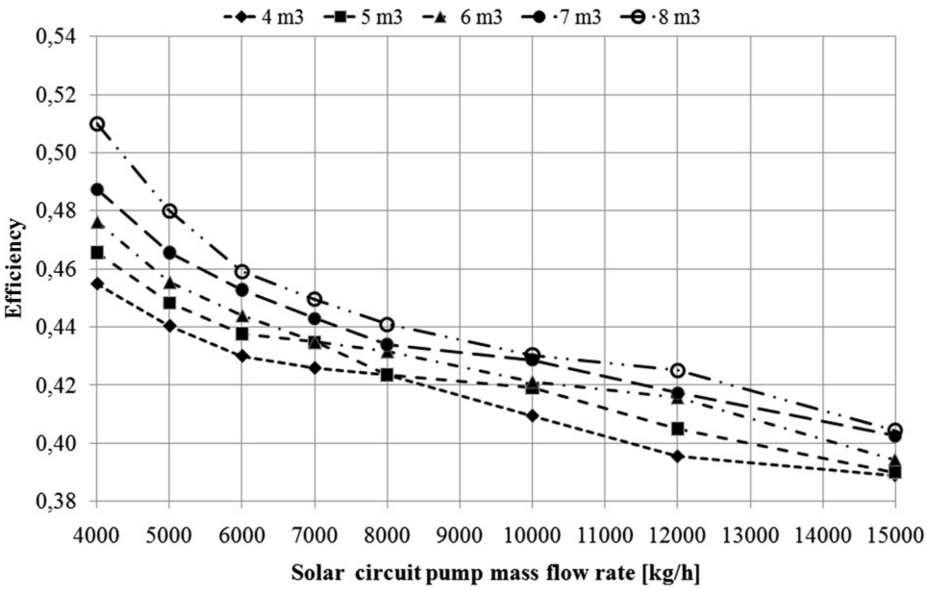

Fig. 17. Efficiency for different solar circuit pump mass flow rates and tank sizes (2 collectors configuration).

Regarding the number of times the boiler and solar circuit pump switch on, the increase of solar circuit mass flow rate has a greater influence than tank size. By increasing solar circuit pump mass flow rate, the number of times the pump starts and stops increases whereas that of boiler decreases. High solar circuit pump mass flow rate leads to a fast temperature decrease of the panel when the pump turns on. When the collector temperature is below that of the tank plus 2 °C, the pump stops. The overall effect, therefore, is a frequent start and stop of the pump, with a small increase in the temperature of the tank and then more continuous boiler activity.

In Fig. 16, the saved natural gas is reported for the configuration with one solar panel that shows the lowest consumption (tank of 8 m^3 and pump mass flow rate of 8000 kg/h). With this configuration the amount of saved natural gas over one year is about 40%. In August, the plant is in operation for only one week, therefore the amount of solar energy used (and subsequently the natural gas saved) is low. In that period the collectors are often out of focus.

The same analysis was carried out considering two parabolic collectors with a collecting surface of 1090 m^2. In terms of a general trend, the results are similar to those obtained for a single collector. For example, in Figs. 17 and 18 the influence of solar circuit mass flow rate and tank size on system efficiency and natural gas consumption are reported for the configuration with two collectors.

In Fig. 19, a comparison between the annual natural gas consumption of the system with one and two collectors is reported. Both solutions have been calculated for different solar circuit pump mass flow rates and with a tank size of 8 m^3. It can be readily noticed that the trends are very similar even though the amount of natural gas consumption with two collectors is lower. The configuration with two collectors, 8 m^3 tank size and a mass flow rate in

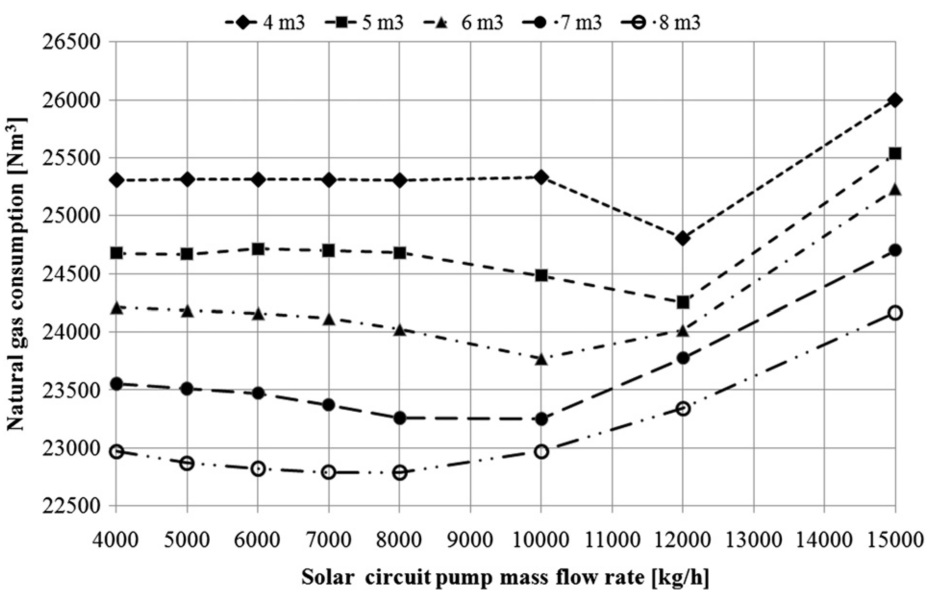

Fig. 18. Natural gas consumption for different solar circuit pump mass flow rates and tank sizes (2 collectors configuration).

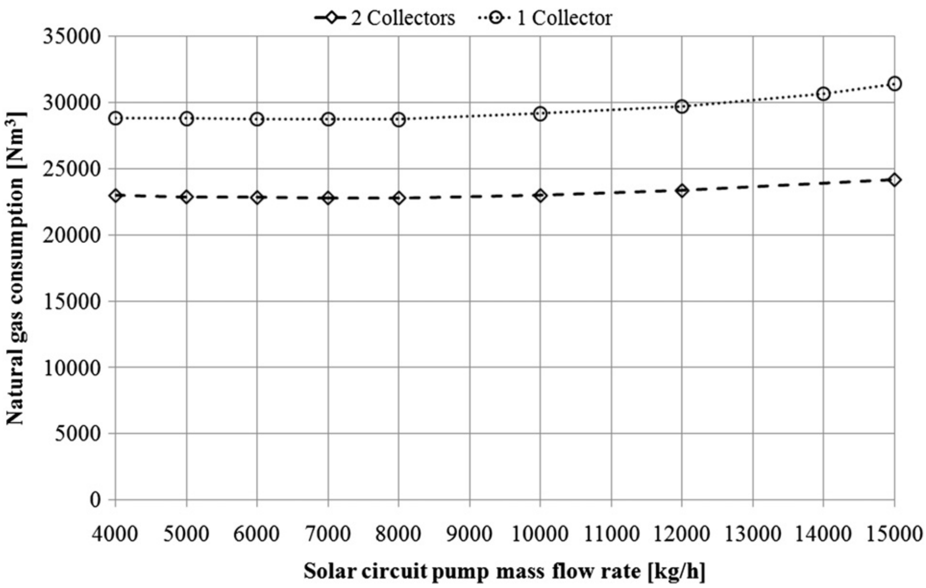

Fig. 19. Comparison between the annual natural gas consumption of the system with one and two collectors.

the solar circuit of 8000 m^3 leads to a natural gas consumption reduction of 52%.

6. Economic results

Based on the thermodynamic results, a simplified economic analysis was carried out considering both start-up and management costs. Eight different configurations were analyzed: two solar field extensions and four tank sizes. For each configuration the working mass flow rate of the solar circuit was chosen by considering the value that leads to the lowest natural gas consumption (Figs. 13 and 18). These values are reported in Table 2.

The investment costs were estimated by considering a collector cost of 200 €/m^2 increased by an installation cost of 20% [1,14,19,20]. As for the tank, piping, valves, pump and diathermic oil, a preliminary design of the plant was carried out in order to request a quote for the plant cost (including installation) for each configuration investigated (Table 3).

In Fig. 20, the cost of each component has been highlighted on the overall cost: collector cost is the leading cost. In order to evaluate the investment cash flow a revenue of 0.35 €/m^3 has been considered for saved natural gas and an additional cost of 0.15 €/kWh was considered for the electric energy consumption due to the solar circuit pump, according to current Italian prices. The obtained values are reported in Table 4.

Table 2
Configurations selected for the economic feasibility estimation.

One collector	Tank size [m^3]	Solar pump m. f. r. [kg/h]
A1	5	5000
B1	6	8000
C1	7	8000
D1	8	8000
Two collectors		
A2	5	12000
B2	6	10000
C2	7	10000
D2	8	8000

Maintenance costs have been considered in these terms

- 10% of the initial diathermic oil cost every 5 years for refill and filtering of diathermic oil in the tank and in the solar circuit (from factory experience)
- Pump replacement every 10,000 switching on as stated by supplier
- 5% of collector cost every 7 years as stated by supplier

For each configuration, the Net Present Value (NPV) was considered in order to compare the economic revenue (Eq. (3))

$$NPV = -I_0 + \sum_{k=1}^{n} D_k(1+i)^{-k} + V_R(1+i)^{-k} \quad (3)$$

Where I_0 is the investment cost, V_R is the recovered amount for each year, n is the life plan (years), i is the discounting rate and D_k is the net cash flow, this defined as (Eq. (4)):

$$D_k = (1-\alpha)(R_k - O_k) + \alpha A \quad (4)$$

Where α is the tax rate (40%), A is the depreciation rate, R_k is the management proceeds and O_k is the overhead. As depreciation

Table 3
Breakdown of the cost for the analyzed configurations [€].

Configuration	A1	B1	C1	D1
Collector	130.800	130.800	130.800	130.800
Tank	7.609	8.494	9.030	9.870
Diathermic oil	10.500	12.600	14.700	16.800
Piping	1.949	2.144	2.144	2.144
Investment cost	150.858	154.038	156.674	159.614
Configuration	A2	B2	C2	D2
Collector	261.600	261.600	261.600	261.600
Tank	7.609	8.494	9.030	9.870
Diathermic oil	10.500	12.600	14.700	16.800
Piping	1.949	2.144	2.144	2.144
Investment cost	281.853	284.838	287.474	290.414

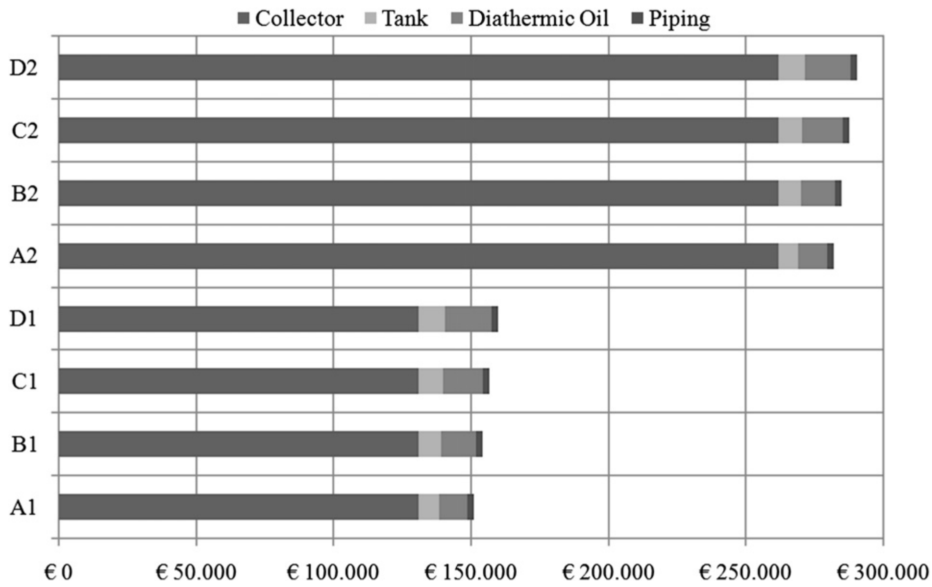

Fig. 20. Cost breakdown for the different configurations analyzed.

Table 4
Revenues from natural gas savings and additional costs for increased electric energy consumption.

Configuration	Natural gas savings		Electric energy consumption	
	[Nm]^3	[€]	[h]	[€]
A1	17133	5997	2752	593
B1	17377	6082	2617	886
C1	17868	6254	2647	897
D1	18191	6367	2684	909
A2	22652	7928	2419	1229
B2	23133	8097	2527	1089
C2	23651	8278	2575	1110
D2	24115	8440	2677	907

charge the following equation is used (Eq. (5)) with $i = 10\%$, duration of depreciation charge of 10 years and a life plant of 25 years:

$$A = I_0 \times \frac{i \times (1+i)^n}{(1+i)^{n-1}} \tag{5}$$

In Table 5, the NPV obtained for all configurations are reported. None of them represents a suitable investment from an economic point of view. A sensitivity analysis has been carried out in order to estimate the influence of solar collector costs, natural gas cost and discount rate on economic feasibility of this integration. As expected, natural gas costs and solar collector costs have a great influence on present value: an increase of NPV of 66% can be achieved with a decrease of 50% in the cost of the solar collector. In this case the Pay Back Period (PBP) would be 6 years.

Table 5
Estimated NPV for the analyzed configurations.

	A1	B1	C1	D1
NPV	−€ 61,063	−€ 64,710	−€ 65,612	−€ 67,011
	A2	B2	C2	D2
NPV	−€ 134,550	−€ 134,509	−€ 135,343	−€ 134,955

7. Conclusions

The feasibility of the integration of high temperature solar energy in an industrial plant has been carried out utilizing a textile factory as a case study. This factory uses a diathermic oil loop to transfer the required thermal energy from the boiler to the users where the production takes place. Since it was not possible to have the direct measurement of boiler natural gas consumptions, an extensive analysis was performed to estimate its daily and hourly consumptions. A model of the existing plant was then developed in order to have the reference values for the comparison with the integrated solution.

Among the possible solutions for solar energy collection, parabolic solar troughs seem the most suitable technology for this application thanks to their relatively wide-spread diffusion and existing applications. Concerning the integrated plant layout, the configuration that introduced the smallest number of modifications in the existing plant has been chosen. In addition, the new configuration would have to allow a quick return to the original set up in case a failure of the solar plant should occur. Therefore the chosen solution was to include a tank in the existing plant upstream the boiler. Thermal energy collected by the solar plant can be stored in the tank. If the outlet temperature of the diathermic oil from the tank is too low, the boiler provides the thermal energy needed to reach the target temperature.

The integrated plant was modeled by means of TRNSYS taking into account the thermal energy needs of the factory as determined in the initial analysis. The simulation was carried out considering a year long period with 15 min steps and the local weather conditions. The main parameters investigated were the efficiency of the solar plant (considered as the ratio between the energy from the solar collector that reaches the tank and the incident radiation on the collectors), the number of start and stops of the solar circuit pump and boiler (which have a strong influence on the maintenance costs) and the natural gas consumption. Many plant configurations have been investigated to highlight the sensitivity of the achieved results to plant parameters (i.e. number of collectors, mass flow rate in the solar circuit, tank size). Efficiency has a proportional trend with the mass flow rate; in addition, an increase of tank size leads to an increase of efficiency for all the mass flow rates. Solar circuit pump mass flow rate has a great influence on natural gas consumption: for low values, the amount of consumed natural gas depends only on tank volume, for high values, natural gas consumption becomes almost independent from tank size and has a linear trend with solar circuit mass flow rate. Regarding boiler and solar circuit pump start and stops, the increase of solar circuit mass flow rate has a greater influence than tank size. By increasing solar circuit pump mass flow rate, the number of times the pump switches on increases whereas that of boiler decreases. The trend is similar when considering one or two collectors even though the natural gas consumptions are greatly reduced in the second configuration. The thermodynamic results show that the integration can lead to an annual natural gas savings of 40% with one collector and about 52% with two collectors.

Based on the thermodynamic results, an economic analysis was carried out considering both the installation and the management costs. These costs were gathered from a market survey and by contacting the principal manufacturers. The revenues were estimated considering the annual natural gas savings. The main results of this analysis showed that even if the annual natural gas savings was noteworthy, it was not sufficient to repay the high installation costs of the plant and, in particular, of the collectors. Solar collector costs have a great influence on net present value: an increase of NPV of 66% can be achieved with a decrease of 50% in the cost of the solar collector. In this case the PBP would be 6 years. A greater diffusion of this product would surely lead to a cost reduction; the diffusion of state incentives that promote the solar integration in industrial processes would also be a desirable prospect. Future development of the activity involves the realization of a small solar concentrating plant by the textile factory in order to experiment its functionality.

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References

[1] Kalogirou SA. The potential of solar industrial process heat applications. Applied Energy 2003;76:337–61.
[2] Kalogirou SA. Solar thermal collectors and applications. Progress in Energy and Combustion Science 2004;30:231–95.
[3] Li J. Scaling up concentrating solar thermal technology in China. Renewable and Sustainable Energy Reviews 2009;13:2051–60.
[4] Kearney DW, Price HW. Solar thermal plants—LUZ concept (Current status of the SEGS plants). In: Proceedings of the 2nd renewable energy congress, vol. 2. Reading UK: Pergamon Press; 1992. 582–588.
[5] Bakos GC, Adamopoulos D, Tsagas NF, Soursos M. Design and construction of a line-focus parabolic trough solar concentrator for electricity generation. In: Proceedings of ISES solar world congress. ISES, Jerusalem, Israel; 1999.
[6] Thomas A. Solar steam generating systems using parabolic trough concentrators. Energy Conversion Management 1996;vol. 37(2):215–45.
[7] Kalogirou SA. Parabolic trough collector system for low temperature steam generation: design and performance characteristics. Applied Energy 1996; 55(1):1–19.
[8] Kalogirou SA, Lloyd S, Ward J. Modeling, optimization and performance evaluation of a parabolic trough solar collector steam generation system. Solar Energy 1997;vol. 60(I):49–59.
[9] Kalogirou SA. Parabolic trough collectors for industrial process heat in Cyprus. Energy 2002;27:813–30.
[10] Maxoulisa CN, Kalogirou SA. Cyprus energy policy: the road to the 2006 world renewable energy congress trophy. Renewable Energy 2008;33: 355–65.
[11] Kalogirou SA. Use of parabolic trough solar energy collectors for sea-water desalination. Applied Energy 1998;60:65–88.
[12] Blanco J, Alarcon D, Sanchez B, Malato S, Maldonado MI, Hublitz A, et al. Technical comparison of different solar-assisted heat Supply system for a multi-effect seawater distillation unit; 2003. ISES solar world congress 2003. Solar Energy for a Sustainable Future. Göteborg Sweden.
[13] Coventry JS. Performance of a concentrating photovoltaic/thermal solar collector. Solar Energy 2005;78:211–22.
[14] Geyer M, Lüpfert E, Osuna R, Esteban A, Schiel W, Schweitzer A, et al. Euro-Trough – parabolic trough collector developed for cost efficient solar power generation. In: Proceedings of the 11th SolarPACES International Symposium, Zurich, Switzerland; 4–6 September 2002.
[15] Fernández-García A, Zarza E, Valenzuela L, Pérez M. Parabolic-trough solar collectors and their applications. Renewable and Sustainable Energy Reviews 2010;14:1695–721.
[16] TRNSYS Program Manual. Madison, USA: University of Wisconsin; 1996. Solar Energy Laboratory.
[17] Kalogirou SA. Use of TRNSYS for modeling and simulation of a hybrid pv–thermal solar system for Cyprus. Renewable Energy 2001;23:247–60.
[18] Hobby A, Siddiqui K. Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS. Solar Energy 2009; 83:700–14.
[19] Brown H, Hewett R, Walker A, Gee R, May K. Performance contracting for parabolic trough solar thermal systems. Energy Engineering 1997;94(6): 33–44.
[20] Sargent & Lundy LLC Consulting Group, Chicago, Illinois. Assessment of parabolic trough and power tower solar technology cost and performance forecasts; October 2003. NREL/SR-550–34440.

Glossary

A: depreciation charge [€]
C_{boiler}: boiler natural gas consumption [Nm^3]
$C_{heating}$: space heating natural gas consumption [Nm^3]
$C_{stenter}$: stenter natural gas consumption [Nm^3]
C_{total}: overall natural gas consumption [Nm^3]
D_k: net cash flow (year k) [€]
G_r: average solar irradiance [W/m^2]
i: discount rate
I_0: investment cost [€]
n: life plan [years]
O_k: overhead (year k) [€]
R_k: management proceeds (year k) [€]
V_R: recovered amount for each year [€]

Greeks
α: tax rate
η: efficiency
ΔT: temperature difference [K]