



Modeling and economic analysis of a parabolic trough solar collector used in order to preheat the process fluid of furnaces in a refinery (case study: Parsian Gas Refinery)

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Abstract

Nowadays, due to the increased greenhouse gas emissions and high energy prices, it is essential to use renewable energy sources in different industrial applications. In this study, the technical and economic assessment of using solar energy in order to preheat the process fluid before entering the furnaces in refinery is carried out. The furnace unit 400 (an indirect furnace) used in Parsian Gas Refinery, which uses natural gas as a fuel, is studied. Mid-temperature solar energy is a practical energy source in this case with respect to the temperature range of the heated process fluid by furnaces which is about 300 °C. Among different types of solar thermal systems for collecting the solar energy, the parabolic trough solar collector is selected in this research because of the advantages it offers including its temperature range and lower cost. The proposed solar thermal preheating system coupled with the furnace is modeled using TRNSYS software. In the optimum condition, the maximum amount of fuel that can be saved using solar energy for the studied furnace is 1,996,000 m³ per year which is about 23.8% of the fuel consumption of the furnace and is responsible for 3557.7 ton CO₂ emissions per year. Finally, using solar heat exchanger before the furnace considering different sizes of solar farm is economically evaluated, taking into account different fuel prices and different mortgage rates. The results show that at natural gas prices more than 45 cents per m³ as the fuel, in different sizes of the system, it is perfectly economic to use solar thermal collector as a preheating system.

Keywords Parabolic trough collector · Solar heat exchanger · Furnace · Economic analysis

Introduction

Utilization of conventional energy sources such as fossil fuels and nuclear energy impacts the environment and indirectly imposes some side effects on human health. Moreover, nonrenewable energy sources such as fossil fuels will gradually run out [1]. The global energy demand

has been escalating on average with an annual rate of 1.4% for the period 2000–2012, accompanied by a growth in population and an increasing economic development and adopting higher-class lifestyle [2]. As a result, a possible solution seems to be utilization of other energy sources, in particular renewable energy sources. Among renewable energies, solar energy as revealed by recent research is considered a promising energy source. Nowadays, in countries that receive a high level of solar radiation, the trend is toward utilization of solar energy by applying solar radiation concentrators [3].

Solar energy can be used to produce electricity. In order to reduce the cost of electricity production and CO₂ emission, the thermal energy of the sun can be used directly or in conjunction with fossil fuels. Several thermal cycles have been proposed for these applications such as Brayton cycle, Rankin–Brayton cycle, supercritical Brayton cycle, solar Stirling and Kalina cycle [4–6].

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Solar energy can also be used for different purposes. Haghghi et al. [7] studied the medical and dental applications of renewable energies. The results showed that in addition to usual practice of solar energy in HVAC applications in hospitals and other health centers, this energy can be used in autoclaves and medicine drying systems.

Refineries, as the center for the production and refining of different types of fossil fuels, have high levels of energy consumption. One of the most energy-consuming parts in a refinery is the furnace, which is used for different applications such as heating the process fluid. Based on the amount of fuel consumption per furnace and the number of furnaces in the refinery, a huge amount of fuel is consumed annually, and consequently, a large amount of greenhouse gases is released. In this study, observations are based on the real data from the furnace unit 400 in Parsian Gas Refinery. The temperature range of the furnace unit 400 is approximately 300 °C that is used in order to increase the temperature of the process fluid up to 280 °C. For such temperature range, an appropriate choice is the usage of parabolic trough collectors. In the following, the mid-temperature solar thermal energy utilization projects based on parabolic trough collectors in diverse industries will be reviewed, and the literature review in this field will be presented.

Recently, solar farms based on parabolic trough collector technology have been constructed to harness the solar thermal energy. In the South California desert, nine solar electricity generation systems (SEGSs) have been built. In each power plant, a solar farm with parabolic trough collector technology is used to heat up a heat transfer fluid (HTF). The nominal capacity of these power plants is 354 MW, and the total area of the installed parabolic trough collectors in this power plant is 2 million square meters [8]. The combined cycle solar power plant in Yazd that simultaneously makes use of fossil fuels and solar energy includes two units of gas turbine with a capacity of 159 MW and a steam unit with the capacity of 143 MW, and the solar thermal unit 17 MW that is supplied by the solar farm with parabolic trough collector [9]. The Integrated Solar Combined Cycle System Hassi R'mel in Algeria includes a combined cycle of 130 MW and a solar farm 25 MW comprising an area of 180 thousand square meters. The solar farm includes 216 parabolic solar collectors in 54 rings with the input HTF temperature of 290 °C and the output temperature of 393 °C [10]. ESCCS power plant of Kuraymat in Egypt makes use of a combined cycle of 140 MW and the solar farm designed for 61 MW. This farm includes 1920 modules in 160 parabolic trough collectors with the reflector surface area of about 131 thousand square meters. In this solar farm, in order to decrease the effect of wind, windshields have been installed against two dominating wind directions. This power

plant was initialized in July 2011. This power plant has been very positively evaluated, since studies showed that the solar farm produces almost 8% more energy than the estimated value [11]. In eastern Morocco, a combined cycle power plant of 470 MW with a solar farm 20 MW with more than 180 thousand square meters of parabolic trough collectors is built. The combined cycle is highly versatile, as it is composed of two gas turbines of 150 MW capacity and one steam turbine of 150 MW capacity. This project was initialized in May 2011 [12]. In Sicily Italy, a solar farm 5 MW with a combined cycle 750 MW is constructed. The solar farm consists of 30 thousand square meters of parabolic trough collectors. HTF used in this solar farm is the molten salt (60% of sodium nitrate, 40% of potassium nitrate). Usage of molten salt as HTF enables higher operational temperatures as high as 550 °C. The molten salt is then poured into a hot container and used for steam generation in the Rankin cycle. This configuration reduces the consumption of fossil fuels, to the extent of 7300 tons [13]. In northeastern Spain, there is a solar farm with 336 parabolic trough collectors, with the total reflector surface area of 118 thousand square meters. The power generation in the renewable part of this power plant is 98,000 MWh per year with a performance of about 6500 h per year that supports the electricity generation of 27 thousand houses and prevents 24,500 tons of carbon dioxide to be released to the environment [14]. As far as the authors have searched, the solar farms with parabolic trough collectors have been so far only used in power plants and have not been used in refineries.

In recent decades, extensive researches have been conducted on solar farms with parabolic trough collectors. An instance is the work done by Biencinto et al. who presented a new model for the direct generation of steam using parabolic trough collectors by evaluation in the TRNSYS that leads to an enhancement in the efficiency of the parabolic trough collector. The generated steam in this system can be used in a Rankin cycle or other industrial processes [15]. Alguacil et al. studied the most important challenge in direct generation of steam in farms with parabolic trough collectors, namely the stability control. They also deal with the analysis of collector at 550 °C temperature and the commercial system of the direct steam generation [16].

Beemkumar et al. [17] studied the performance of a dual-material parabolic trough collector consisting of glass reflective sheet and high-reflective stainless steel sheet. They showed that using of glass as the reflective material will result in higher heat gain and the average of efficiency of this type is greater than that of stainless steel. However, considering costs and facility, the high-reflective stainless steel sheet may be preferred when using parabolic trough collectors.

One proposed method to enhance the performance of parabolic trough collectors is to utilize nano-fluids as the working fluid. Bellos et al. [18] investigated the applications of a few nano-fluids including Cu, CuO, Fe₂O₃, TiO₂, Al₂O₃ and SiO₂ disseminated in the heat oil Syltherm 800. The results showed Cu nano-fluids are more efficient than others and the efficiency order of others is CuO, Fe₂O₃, TiO₂, Al₂O₃ and SiO₂.

Silva et al. studied the process of heat generation in solar farms with parabolic trough collectors for the industry of vegetable preservation at South Australia. The results of their research demonstrate that for this industry, a shift of the input energy toward this technology is appropriate [19]. Mesfin et al. presented a model for parabolic trough collector farm for power generation taking into account different losses related to solar radiation and thermal loss. In their study, they used MATLAB for modeling reference state points in the power plant. Then, they apply MATLAB code to find the reference values which is used as input in TRNSYS software for modeling and simulation of the power plant [20]. Borunda et al. presented a new configuration for a concentrating solar power plant with parabolic trough collectors and an organic cycle. In order to analyze the new configuration, a case study in the industrial textile process in mid-temperature was conducted and the performance of the solar power plant with TRNSYS was simulated in order to test the conditions of real-time operation. Their results show that this system is a promising option for the practical operations in mid-temperature range, where electricity and heat generation is needed [21]. Bakos et al. conducted a technical feasibility study and economic capability of a solar power plant with parabolic trough collectors in Greece. The output power of the studied power plant was 8.55 MW. Simulation of the power plant using TRNSYS software was carried out, and the economic aspects of the project such as the initial cost of investment, operational, maintenance costs as well as the energy costs were analyzed. It was shown that for special investment, the turnover period will be about 13 years, given that 75% of the initial cost of investment is covered by a mortgage (with a 10-year settlement period) [22]. In another study, Bakos et al. simulated a 300 MW electricity power plant with a parabolic trough collector solar farm using TRNSYS software in both turbopower and fuel conservation modes. In this simulation of the performance, changes in the output power, fuel consumption and CO₂ generation were considered. In addition, an economic analysis for both power states was made and they assessed the optimum solar energy portion for the fuel conservation mode [23].

These studies show that parabolic trough collector is one of the best ways to utilize solar thermal energy. Taking into account the fact that thermal energy usages of furnaces in

the Refinery section are of high magnitude, constructing parabolic trough collector solar farms seems to be a practical solution. The theme of the present study is modeling and economic analysis of such system.

Methodology

Heat exchanger model description

The schematic diagram of the operation of the indirect furnace along with the heat transform of the solar pre-heating with parabolic trough collector farm for the heating of the process fluid is demonstrated in Fig. 1. As shown in the figure, HTF is in circulation in a closed cycle using the pump between the solar farm and the heat transfer. HTF after the absorption of heat and rise in temperature flows toward the thermal transfer, and after thermal exchange with the process fluid inside the converter and giving up part of its internal energy to the process fluid, exits the converter and returns to the solar farm. This circulation of HTF continues until solar radiation. The output process fluid from the solar thermal transfer enters the thermal transfer of the furnace in order to increase to a certain temperature. In such circumstances too, the HTF is used in order to transfer heat from the furnace to thermal transfer in a closed cycle. Using the solar thermal transfer before the furnace thermal transfer at the time of solar radiation provides part of the necessary energy for the increase in the temperature of the process fluid with parabolic trough collector. Therefore, the consumption of the furnace in order to raise the temperature of the fluid is decreased as compared to the case where no solar thermal transfer is used at the solar radiation time. In the following, the different parts of the system as well as the parameters and modeling of the schematic diagram of Fig. 1 will be presented.

Type of heat transfer fluid

The HTF type is one of the significant factors in the design of a solar heat farm. In order to transfer heat from the solar farm and furnace to the process fluid and since the temperature is high, special oils are utilized as HTF. The choice for HTF depends on the temperature range of the furnace and solar farm. The HTF for the studied furnace in Parsian Refinery is the Therminol 66 oil. This oil is very stable, lasts very long and has a high resistance against sedimentation as well. This leads to a decrease in the operational costs. Therminol 66 leads to potential saving in the investment and operational costs, especially when used in systems that operate at atmosphere pressure or pressures close to it. The maximum operational temperature for this

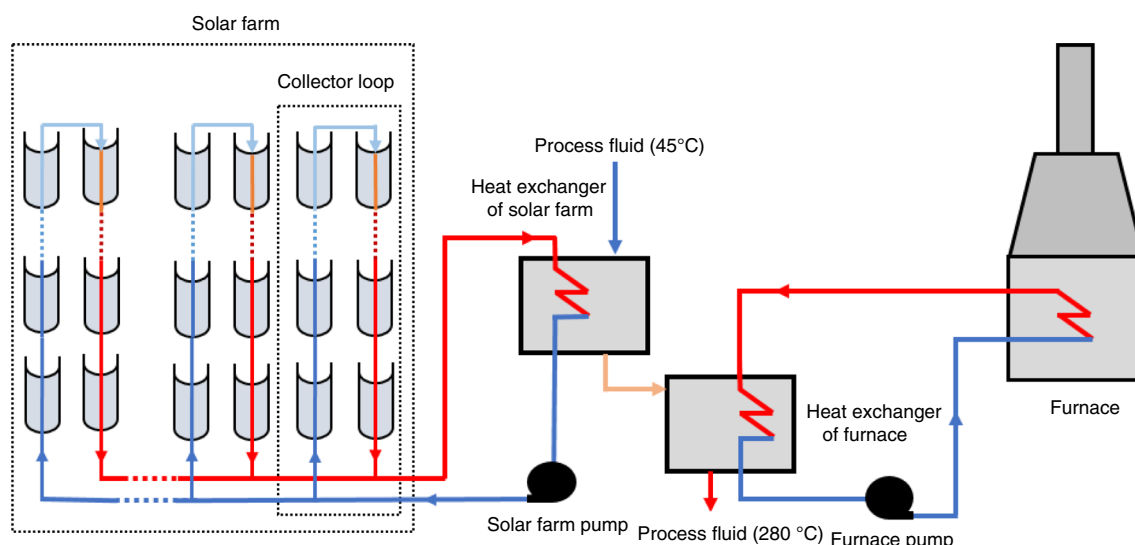


Fig. 1 Schematic diagram of the furnace heat exchanger and solar preheating system

oil at volume state is 345 °C, while the minimum temperature is -3 °C. One of the important properties of the HTF is its density and special thermal capacity. For Therminol 66 oil, such properties vary with temperature. The changes in density and special thermal capacity of Therminol 66 oil with temperature can be calculated as follows [24]:

$$\rho \text{ (kg m}^{-3}\text{)} = -0.614254 \times T - 0.000321 \times T^2 + 1020.62 \quad (1)$$

$$C_p = 0.003313 \times T + 0.0000008970785 \times T^2 + 1.496005 \quad (2)$$

Due to the mentioned characteristics of Therminol 66 oil and its range of operational temperature, in this study of the solar land, this oil has been used as HTF.

Furnace properties

In Parsian Gas Refinery, furnaces are used for heating the process fluid in order to be used in different processes. Such furnaces can be categorized into two types: direct and indirect, which differ in terms of properties and consumption according to the flow rate and the required temperature for the process. The studied furnace is the indirect unit 400 furnace in Parsian Gas Refinery that is used for heating the process fluid. The type of the process fluid is natural gas with a low percentage of impurity that is used for different processes. The fuel used in the furnace unit 400 in the Parsian Gas Refinery is natural gas. The type of HTF used between the furnace and the thermal transfer is Therminol 66 oil. The summary of the furnace unit 400 data is presented in Table 1 for review (this information is provided by the Parsian Gas Refinery).

Dimension parameters of solar farm

Solar farm location in Parsian Gas Refinery

Parsian Gas Refinery with a nominal capacity of generating 82 million cubic meters of natural gas per day as the third largest gas refinery in Iran produces 17% of the required gas and 10.5% of the energy budget of Iran. This refinery is located at 52° and 27° of longitude and latitude distance at the southeast part of Mehr district in Fars Province.

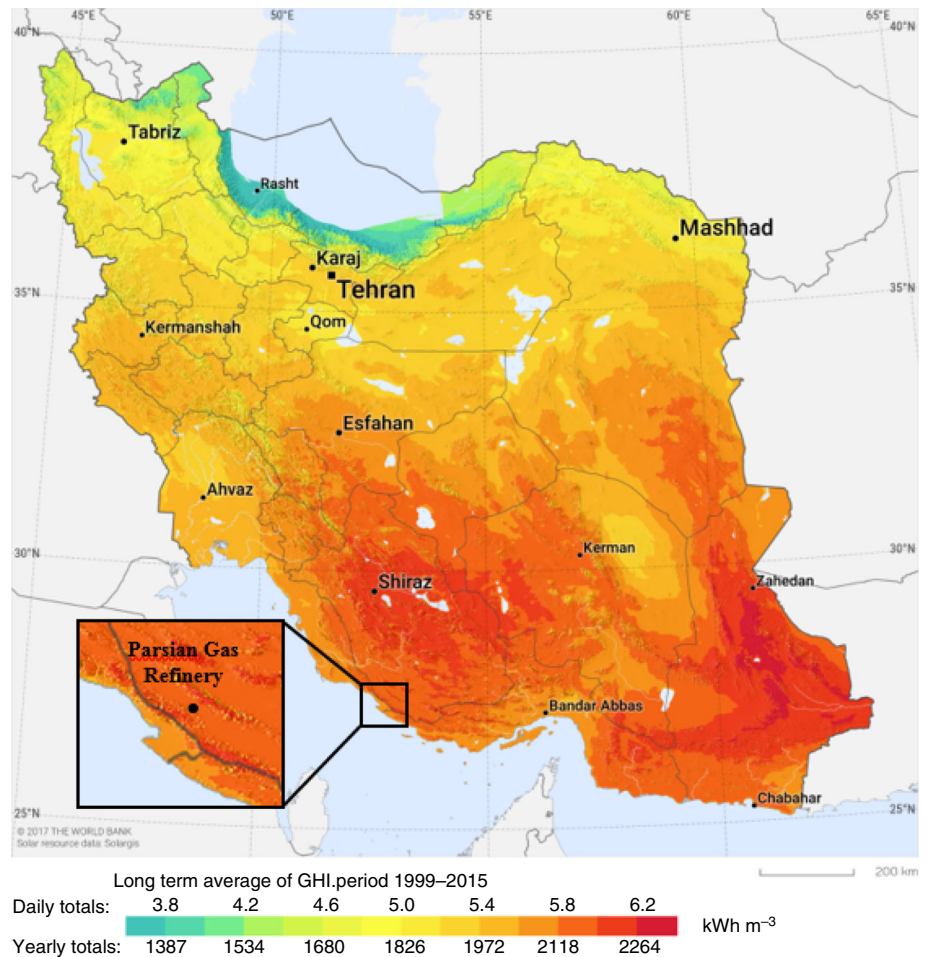
Figure 2 shows the geographical conditions and solar irradiation of the case study, Iran. As can be seen, the Parsian Gas Refinery is located in a rich area which makes utilizing solar energy in this place more profitable.

As mentioned earlier, the aim of this study is the design of the thermal converter of the solar preheater for the available furnaces in the Parsian Gas Refinery. The solar converter needs a solar farm, which due to its capacity can have a large or small area. For construction of a solar farm, a flat ground is required. The refinery is located in a rather flat area. Because of the furnaces and the flares in the refinery, the solar farm should not be situated on the exit path of the outgoing air from the chimneys. The reason is that any pollution resulting from the output of the chimneys can affect the collectors in the solar farm and decrease its efficiency. As a result, due to the dominating direction of wind as shown in Fig. 3 (the weather data of the site of the Parsian refinery have been extracted using Meteonorm7 software), directions north, northwest and south are not suitable for the solar farm, because wind is strong in these directions. Therefore, as shown in the diagram 1, the direction east from 30° to 150° has the least amount of dominating winds.

Table 1 Furnace unit 400 parameters

Parameter	Unit	Value
Heat exchanger inlet temperature of process fluid	°C	45
Process fluid pressure	bar	85
Heat exchange exit temperature of process fluid	°C	280
Process fluid flow rate entering the heat exchanger	m ³ h ⁻¹	50,000
Heat exchanger capacity	kW	8816
Furnace exit temperature of HTF	°C	300
Furnace consumption	m ³ h ⁻¹	958
Furnace efficiency	%	80

Fig. 2 Geographical conditions and solar irradiation of the case study, Iran, and the Parsian Gas Refinery [25]



Characteristics of solar farm

Nowadays, the parabolic trough collectors are constructed in different models whose technology is developed by several companies around the world. Such collectors like any other solar collectors can be constructed in different dimensions. The Chinese company Gaia Solar Energy is one of the active companies in the area of solar collectors. This company presents different models of parabolic trough collectors for different applications such as steam generation, air conditioning, water heating and solar power

concentration. Taking into account the operational temperature of the furnaces in 300 °C and the relative high consumption of energy as well as the suggested price by Gaia Solar Energy, the collectors type PT-5760 are more suitable as compared to other models. In such collectors, the coating of the absorbing pipe is black chrome and the space between the absorbing pipe and the glass coating is vacuum. The dimensional parameters of a parabolic trough collector module of type PT-5760 are demonstrated in Table 2.

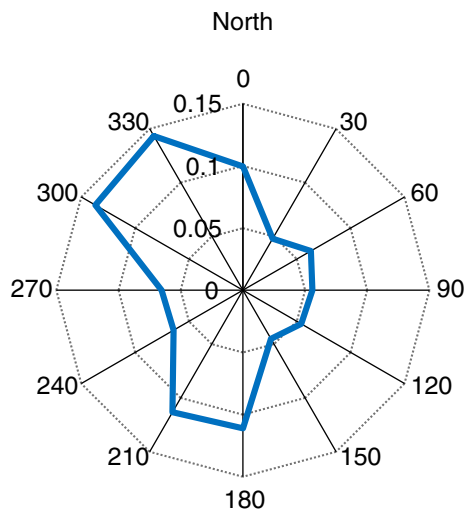


Fig. 3 Frequency distribution of wind directions—Parsian Gas Refinery

Table 2 Geometric characteristic of the parabolic trough solar collector [26]

Parameter	Unit	Value
Collector length	m	12
Collector width	m	5.76
Absorber tube length	m	4.06
Collector height	m	5
Surface reflectance	–	0.94
Reflective area of each module	m ²	69.15

By cascading parabolic trough collectors, there is no need for a separate tracking system for each collector. In such conditions, for a certain number of cascaded collectors, a single tracking system is used [27]. The number of controllable collectors with a single tracking system depends on the model of the collector and its producing company. According to the data presented by Gaia Solar Energy, for collectors type PT-5760 a full set of tracking system can be used at most for 12 cascaded collectors. Therefore, in order to reduce the costs, the design and the modeling has been based on cascades of 12 collectors in a row, in which two rows of collectors are attached at the end to form a ring.

By increasing the distance of the rows of the collectors from one another, the amount of the shading of collectors on one another can be reduced at the beginning and ending hours of day. However, because of the ground area of the solar farm and other costs, an optimum distance proportional to the collector width exists. Moher et al. [28] determined the optimum distance of the collector rows for collectors with a width of 5.76 m to be 16.5 m apart.

The direction of the solar farm with parabolic trough collector can be different. In the direction north to south, the solar tracking is associated with the direction east to west. In the direction east to west, the solar tracking is associated with the direction north to south. In accordance with the latitude of the site of the solar farm, different orientations have different effects on the performance of the solar farm. For the solar belt at the latitude below 40° and in general 15° above equator, the annual energy efficiency for the orientation north to south is higher [29]. Due to the latitude 27° of the Parsian Gas Refinery, the orientation north to south is appropriate.

Weather condition

Weather conditions are one of the determining factors in a solar farm. In Figs. 4 and 5, the direct normal irradiation (DNI) and the total radiation for the geographical location of the refinery on the horizontal plane for an annual period (8760 h) are shown that have been extracted using Meteororm software. Hour zero as shown in these diagrams is the zero Gregorian hour. In the modeling of parabolic trough collector, DNI is regarded as the input flow. As shown in Fig. 4, the amount of DNI has a relatively high range and does not have significant fluctuations during the year. Its difference is mainly due to cloudy days when the weather is sultry in hot months of the year. However, the total radiation on the horizontal plane according to the direction of the solar irradiation differs significantly during the year.

Among other factors affecting the performance of the solar farm are the ambient temperature and the velocity of the wind in the region. The changes of air temperature and wind speed in different hours per year are shown in Fig. 6. The air temperature oscillates between 5 and 45 °C. As a result, since the lowest operational temperature of the used HTF is – 3 °C, the choice of this fluid as HTF is appropriate. Referring diagram 4, the maximum wind velocity is 13 m s⁻¹, which does not influence the operation of the collector.

Modeling

In this study, the TRNSYS software has been utilized for thermodynamic modeling as well as economic analysis. The modeling of the solar thermal transfer as well as the variables in the TRNSYS software is shown in Fig. 7. TRNSYS software has two types of general and TESS libraries. Type 109-TMY2 is used for entering weather data, and type trough in STEC library is used for modeling solar farm.

Parabolic trough collector feature is developed in TRNSYS software using Lippke [30] model which defines

Fig. 4 Direct normal irradiance data for 1-year period in hours

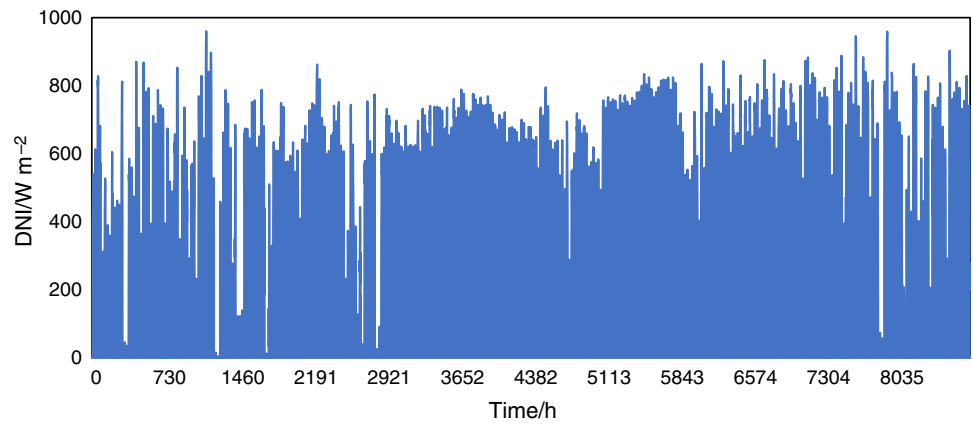


Fig. 5 Total radiation on the horizontal surface data for 1-year period in hours

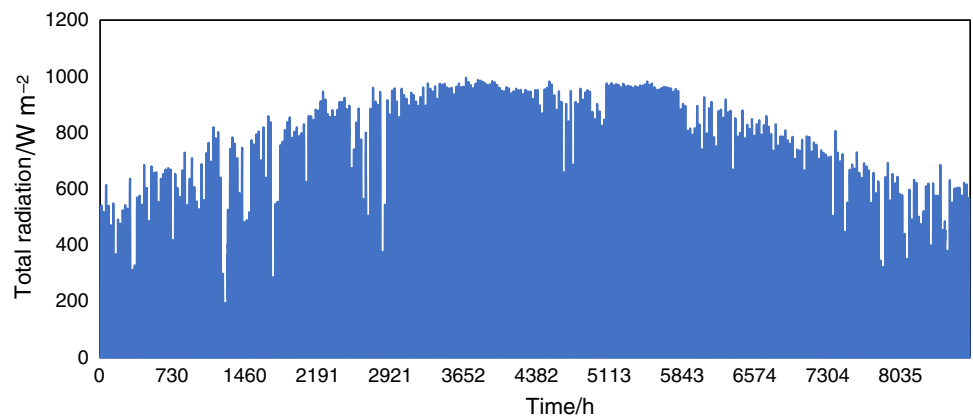
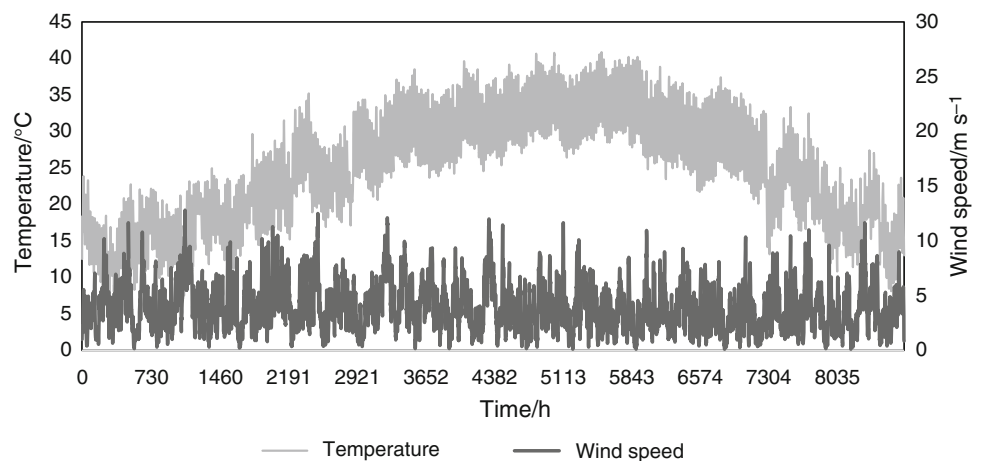


Fig. 6 Hourly variations in ambient temperature and wind speed during a year



thermal efficiency of the collector as the proportion of the absorbed heat to the direct normal irradiation:

$$\eta_{th} = \frac{Q_{abs}}{I} = K[A + B(\Delta T)] + C \frac{\Delta T}{I} + D \frac{\Delta T^2}{I} \quad (3)$$

Q_{abs} is the absorbed heat by HTF, and the four parameters in the equation, A , B , C and D , are determined regarding the type of cover of the absorption tube and the space between absorption tube and the glass cover. Considering

the type of collector selected in this study, these parameters are as follows:

$$A = 73.6, \quad B = -0.0004206, \quad C = 7.44, \quad D = -0.0958$$

Moreover, in the above equation, ΔT is the temperature difference between the environment and the HTF and K is the correcting coefficient of radiation and a function of the angle of impact I_a which is calculated as follows:

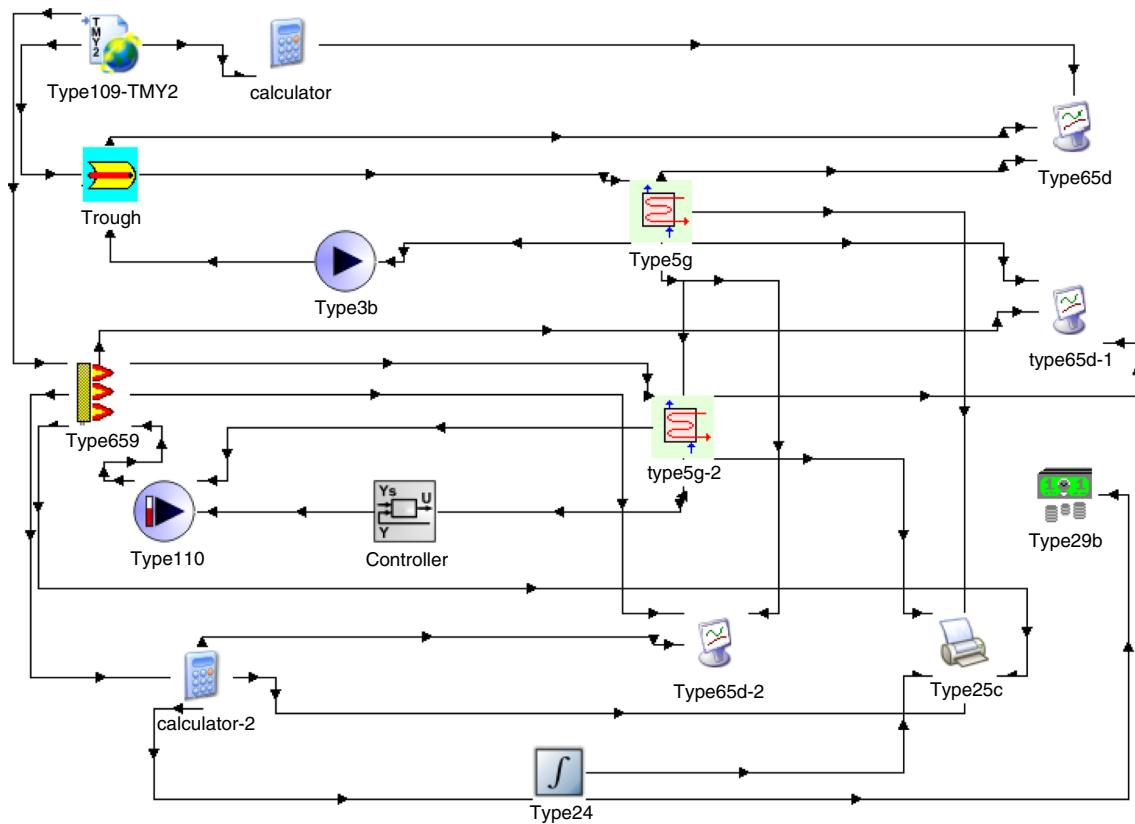


Fig. 7 Modeling of the indirect furnace and preheating solar system in TRNSYS environment

$$K = \cos(I_a) - 0.0003512(I_a) - 0.00003137(I_a)^2 \quad (4)$$

Because of the high thermal load, thermal converters in the solar farm and furnace both are of the crust type and pipe type 5 g. It should be noted that the type of the furnace unit 400 converter available in the Parsian Refinery is of type crust and pipe. Type 659 is used for modeling unit furnace 400 that presents a constant output in different flow rates of HTF. The flow rate of HTF in the solar farm and its thermal transfer is circulated through pump (type 3d) with a fixed flow rate, while the flow rate of HTF between the furnace and the thermal transfer between the furnace and its associated thermal convertor might vary according to the signal that the pump (type 110) receives during the day from the controller (type 22). Therefore, the type of the pumps in the solar farm and the furnace are fixed speed and variable speed types respectively. Finally, type 29b is used for economic analysis calculations that have been dealt with in “Economic analysis” section, economic analysis.

In the proposed model, the reduction of reflection of trough area as a result of the pollution in its surface is ignored. In addition, the tubes conveying fluids between different parts are assumed completely insulated. Thermal energy loss of pumps and heat exchangers is also ignored.

Results

Validation

For evaluation of the modeling of the solar farm with parabolic trough collectors in TRNSYS software, the empirical data obtained from the solar farm constructed in Mojave Desert in California are used. A large number of solar power plants have been built in this desert, one of which is SEGS VI power plant. The empirical data of this power plant are used for the evaluation of the solar power plant in a sunny day on July 18, 1991. The solar farm of the solar power plant SEGS VI consists of parabolic trough collector in an area of 188 thousand square meters. The type of HTF in the solar farm is the artificial oil Therminol VP-1 [31]. Figure 8 demonstrates the profile of temperature, wind speed and DNI for the mentioned evaluation of the farm on the mentioned date.

Figure 9 compares the exiting HTF temperature from the solar farm for the empirical case and the presented model in this research. As can be shown in the diagram, the difference is insignificant and the mean value of the relative difference between the empirical case and the modeling is about 6% that indicates a very good and accepted match.

Fig. 8 Mojave Desert weather condition, located in California, registered on July 18, 1991 [31]

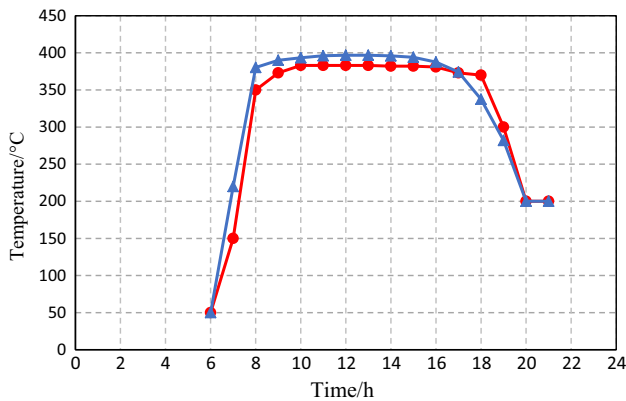
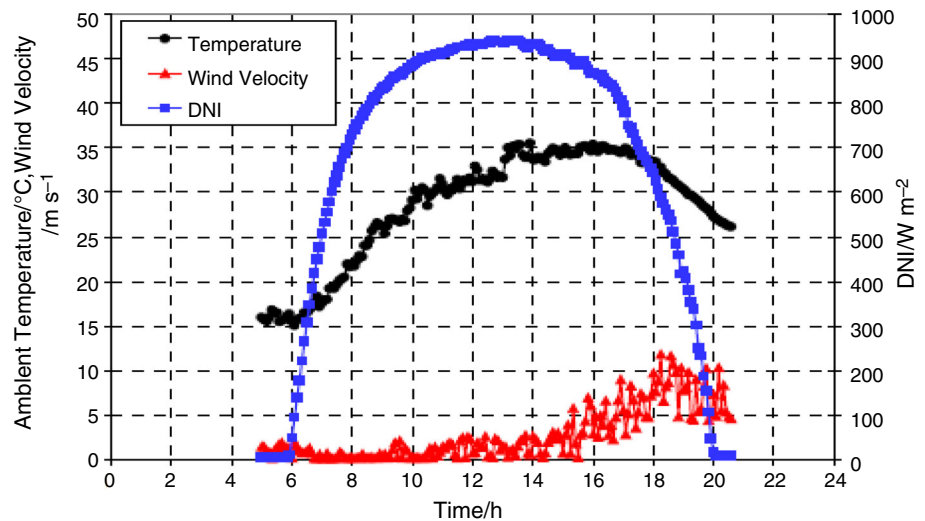


Fig. 9 HTF temperature leaving the solar farm—comparing experimental data (the red curve) and numerical simulation results (the blue curve). (Color figure online)

Modeling results

First, for a better understanding of the thermodynamic operation of the solar farm with furnace, the modeling for the solar farm with ten rows of 12 collectors for 2 days, sunny day and partially cloudy day is carried out. Figure 10 shows the input and output temperature of the solar farm along with DNI and the total radiation flow in a 24-h period in a sunny day. As demonstrated in the diagram, DNI is smoother as compared with the total radiation flow during the day. Since the parabolic collectors only reflect the DNI on the absorbing pipe, the temperature of the input HTF to the thermal transfer (temperature of the exiting HTF from the solar farm) is almost smooth during sunshine and is proportional to DNI. The output process fluid from the thermal convertor of the solar farm enters the thermal transfer of the furnace in order to increase to a certain temperature. Figure 11 shows the input and output temperatures for this thermal convertor as well as the HTF flow

rate as circulating between the thermal convertor and furnace. As shown in the diagram, the temperature of the input HTF to the thermal convertor of the furnace (the exiting HTF from the furnace) is the constant value of 300 °C and the temperature of the output process fluid from the thermal convertor of the furnace is also constant at the value of 280 °C. The flow rate of GTF in the furnace is decreased with an increase in the temperature of the process fluid to the thermal convertor of the furnace, in order to control the temperature of the process fluid. As the temperature of the output HTF from the furnace is constant, the energy consumption of the furnace decreases in proportion to the decreased flow rate of HTF in the furnace (Fig. 12).

In some days of the year, as the sky becomes cloudy in some hours of the day, the solar radiation decreases, which leads to a decrease in the preheating of the process fluid in the solar thermal convertor through the solar farm or it is totally eliminated (Fig. 13). As a result, the changes in the flow rate of HTF and the reduction in the fuel consumption of the furnace will be insignificant or zero (Figs. 14, 15).

According to the changes of weather in different months of the year, the energy obtained from the solar farm will be different. In Fig. 16, the temperature of the outgoing HTF from the solar farm during a 1-year period is shown. The interruption in some hours of the day is due to the lack of direct solar radiation caused by the cloudiness. Figure 17 demonstrates the input and output temperatures from the furnace thermal convertor during the year with an attempt to hold the temperature of the outgoing process fluid fixed. Some fluctuations with a very low amplitude in the temperature of the outgoing process fluid and HTF are due to controller error. This error is insignificant because of the chosen time step 0.01 s for calculations. Figure 18 demonstrates the changes in the fuel consumption of the furnace with the temperature of the input process fluid to

Fig. 10 Input and output temperatures of the solar collector, total radiation on a horizontal surface and DNI, on a sunny day

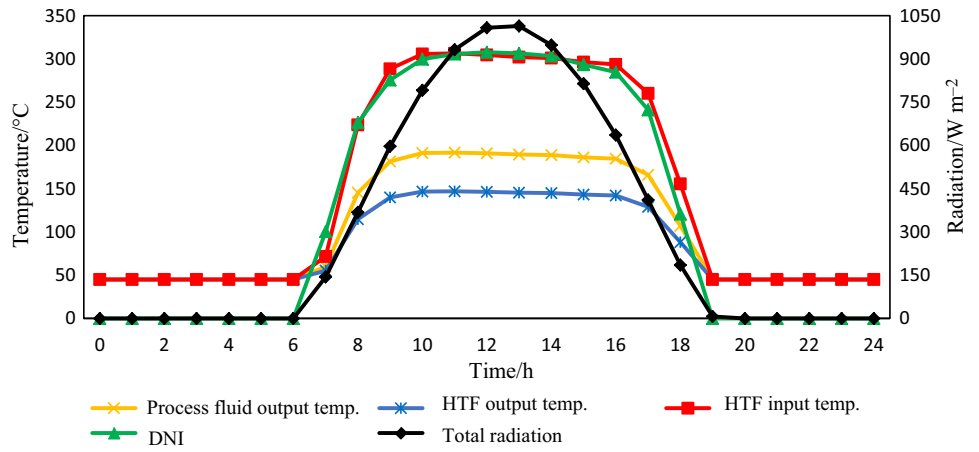


Fig. 11 Input and output temperatures of the furnace heat exchanger, HTF input and output temperatures and flow rate, on a sunny day

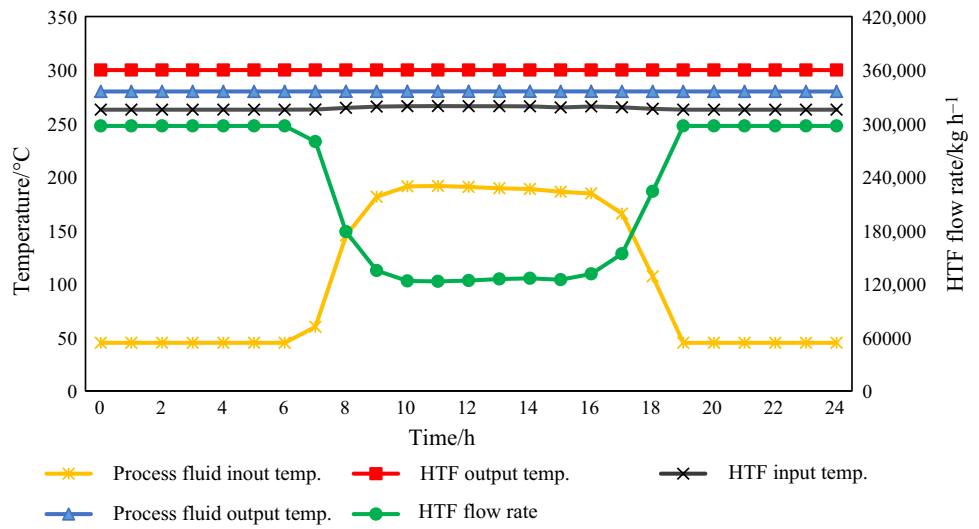
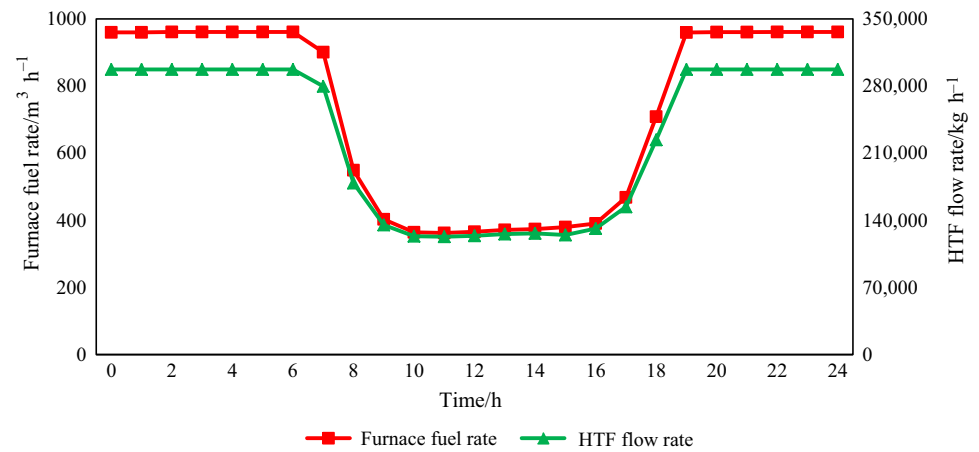


Fig. 12 Influence of reducing HTF flow rate on furnace fuel rate, on a sunny day



the thermal convertor of the furnace in different times of the year. The higher the temperature of the input fluid to the thermal convertor, the higher the decrease in the fuel consumption of the furnace.

One of the most important parameters in the evaluation of the performance of the solar farm with parabolic trough collector is its thermal efficiency. The thermal efficiency of the collector is defined as the proportion of the absorbed thermal energy by the HTF to the direct radiation flow

Fig. 13 Input and output temperatures of solar farm, total radiation on a horizontal surface and DNI, on a partly cloudy day

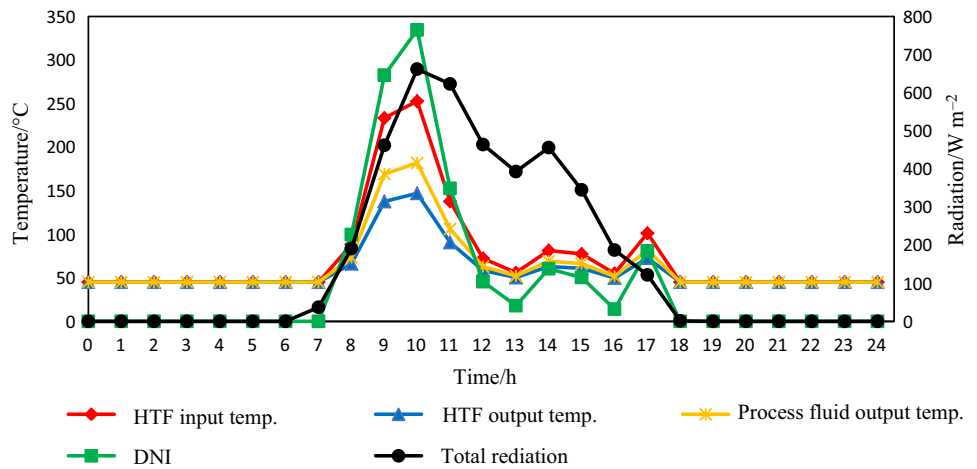


Fig. 14 Input and output temperatures of furnace and HTF flow rate, on a partly cloudy day

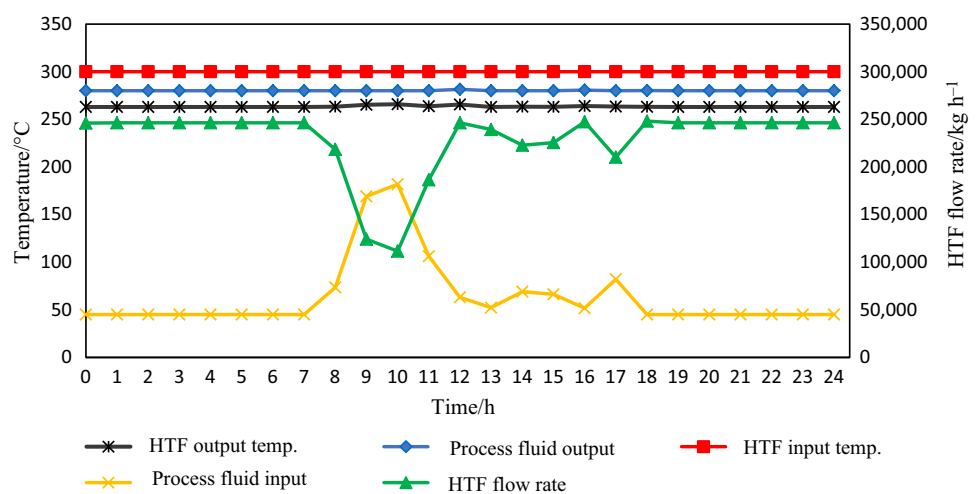
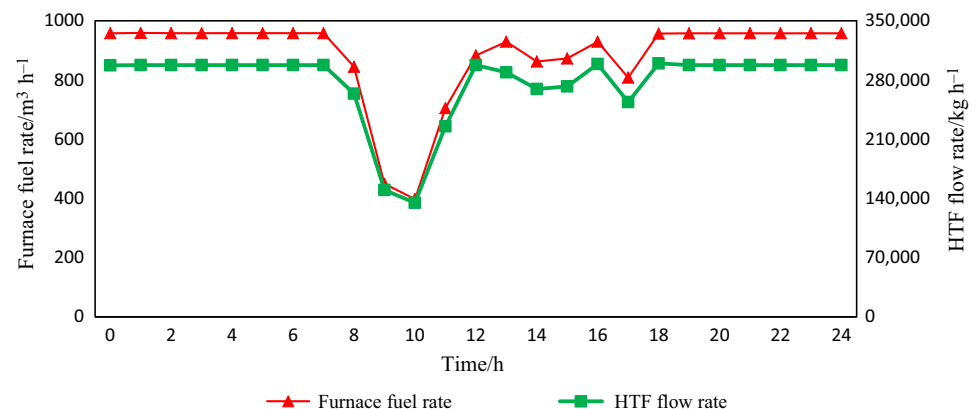


Fig. 15 Influence of reducing HTF flow rate on furnace fuel rate, on a partly cloudy day



reached the collector that depends on factors such as the structure of the collector, the temperature of HTF in circulation and air temperature. Figure 19 shows the thermal efficiency of the solar farm for different hours of the year. Moreover, as the angle of the height of the sun in the sky

decreases, at the end part of the collector, the radiation flow reflected by the reflector will not be reflected on the absorbing pipe (end effect) that reduces the efficiency of the collector. Since the length of the rows of collectors is not high, the losses due to end effect in this study are not

Fig. 16 HTF output temperature of solar farm during a year

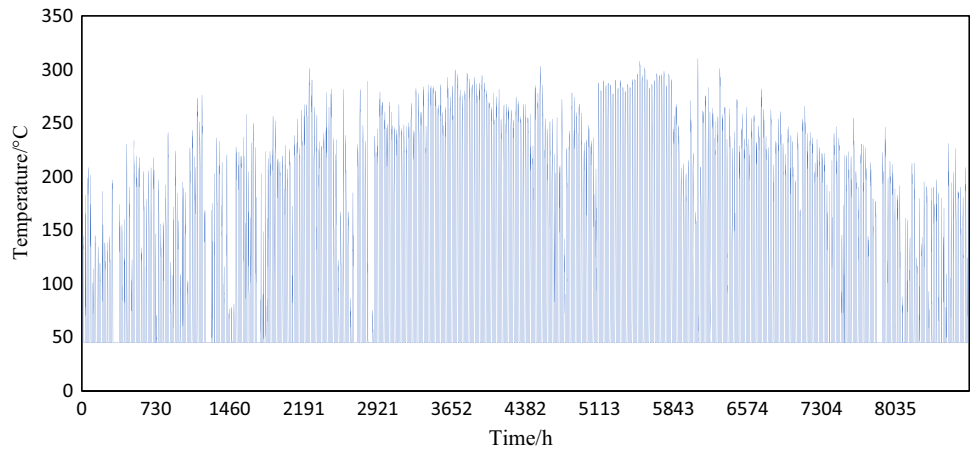


Fig. 17 Input and output temperatures of furnace heat exchanger during a year

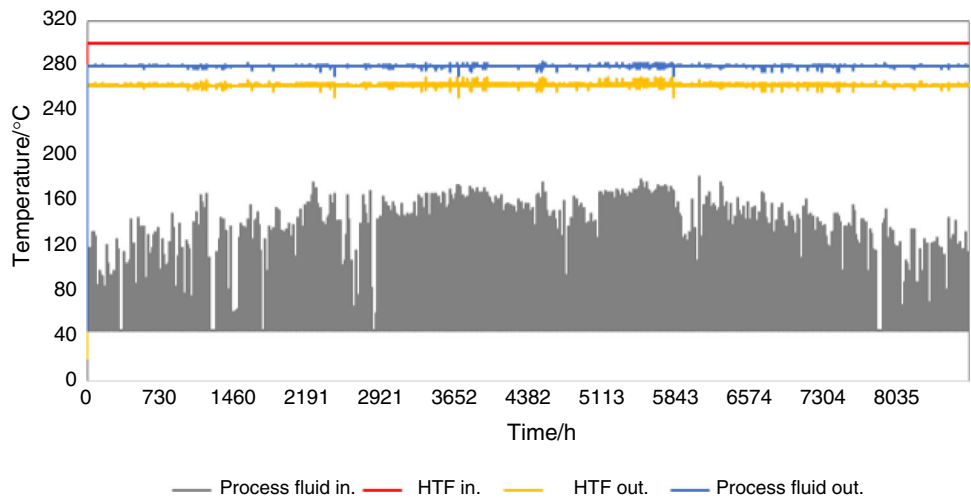
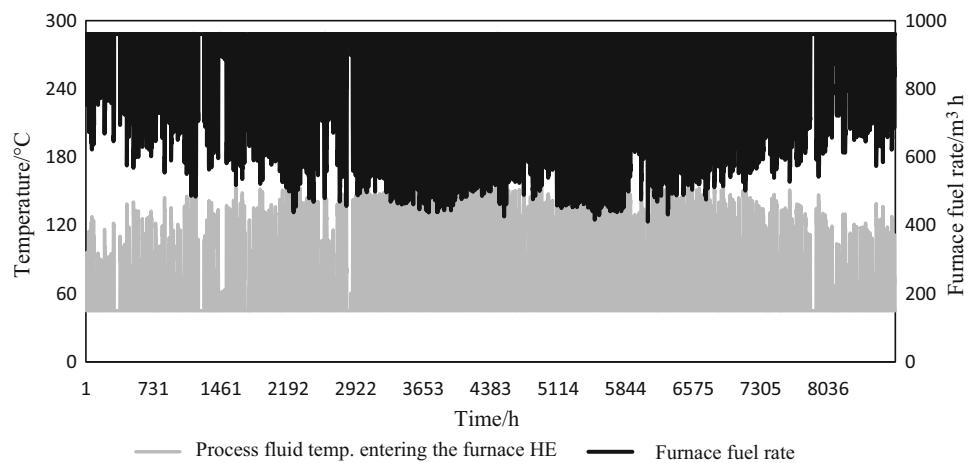


Fig. 18 Variations of furnace fuel rate with process fluid temperature entering its heat exchanger

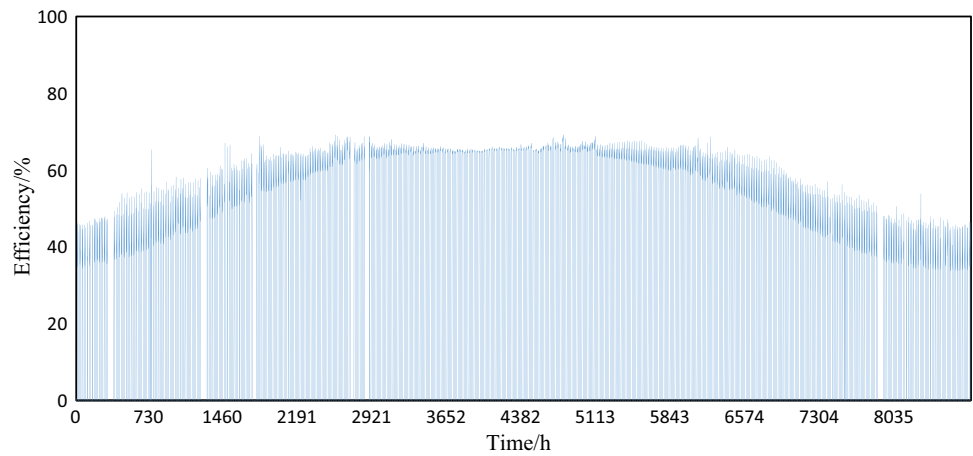


significant. In general, an increase in the temperature of the outgoing HTF from the solar farm or a decrease in air temperature reduces the thermal efficiency of the collector. This loss of efficiency is due to a higher thermal loss between the absorbing pipe and the ambient air.

Effect of the size of solar farm on furnace fuel rate

In this section, the effect of different area sizes of the solar farm on the reduction of fuel consumption of the furnace and reduction of the carbon dioxide released to the

Fig. 19 Variations of the efficiency of the solar farm with parabolic trough solar collectors, during a year



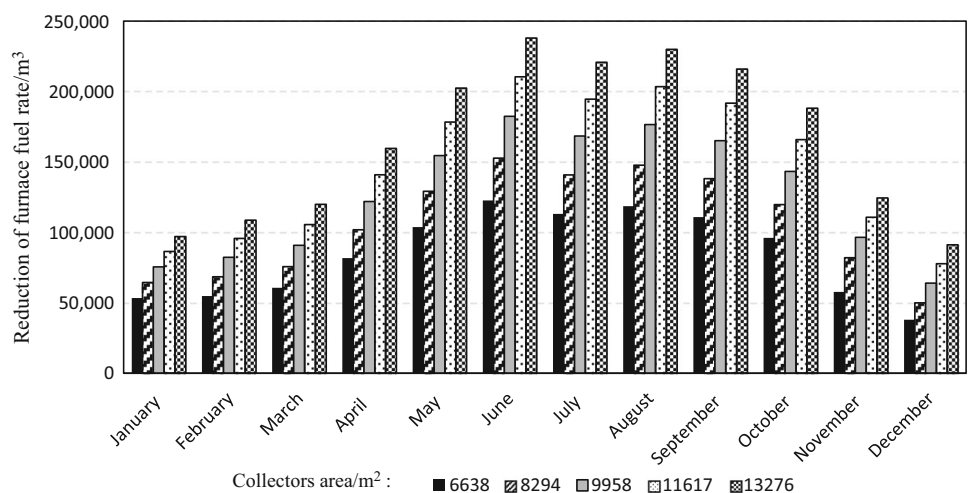
environment will be considered. As mentioned in earlier sections, for a reduction of the controller costs, and the collector actuators for sun tracking, collector modules need to be cascaded in 12 collectors in a row and attached at the ends to form a ring. As a result, the change in the solar farm area is carried out by a change in the number of the collector rings. Data and results of different area modeling for the solar farm for a 1-year period are given in Table 3. In the optimum case, the maximum collector area is

13,276 m² since at areas surpassing this, at some hours in different days in the year, the extra energy required for preheating of the fluid is generated by the solar farm. Therefore, in order to utilize higher areas, a system for storing the thermal energy is needed that has not been addressed here. Figure 20 demonstrates the saving in fuel consumption of the furnace for different areas of collector in different times of year. For all area sizes of the solar farm, the maximum and minimum amount of the saving in

Table 3 Data and modeling results of investigating solar farms of different sizes

Reduction of carbon dioxide emissions/ton	Reduction of furnace fuel rate/m ³	Size of the solar farm/m ²	Collectors area/m ²	Number of modules	Number of loops
1816	1,019,000	19,800	6638	96	4
2264	1,271,000	24,750	8294	120	5
2711	1,521,000	29,700	9958	144	6
3140	1,762,000	35,650	11,617	168	7
3558	1,996,000	39,600	13,276	192	8

Fig. 20 Reduction of furnace fuel rate with changes in collector area, in different months of the year



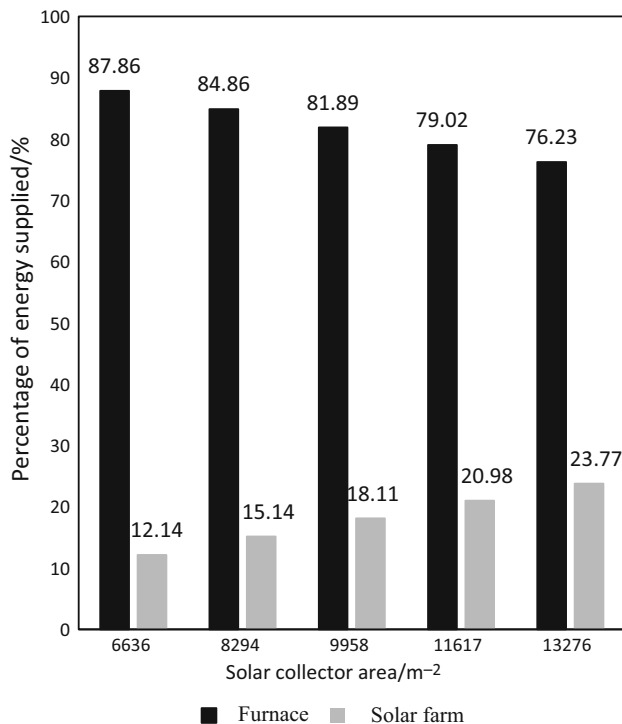


Fig. 21 Percentage of energy supplied by furnace and solar farm for heating the process fluid, considering different values of solar collector area, in a year

the fuel consumption happens for months of June and January, respectively. The reason for a high saving of energy in June in comparison with other months is the angle of solar radiation when in June the solar radiation flow is higher.

Figure 21 shows the percentage of the provided energy by the solar farm and the furnace in different area sizes for the collector for a period of 1 year. By increasing the area of the solar farm, the energy provided by it also increases and the percentage of the energy provided by the furnace is

reduced. By doubling the size of the area of the solar farm, the percentage of the energy provided by it is not doubled, because an increase in the area of the solar farm increases the HTF in circulation of the solar farm and the thermal loss between the absorbing pipe and the surrounding air increases.

Economic analysis

In previous sections, the operation and the effect of the thermal convertor of the solar preheat on the consumption of the furnace were studied. In this section, based on the results obtained from previous sections, the costs and the economic analysis of the project are taken into account. TRNSYS software is used for the calculation of the economic analysis.

Cost analysis

One of the most important steps in the economic analysis of projects is the identification of the costs and the equipment costs. In this project, the costs can be categorized into two types: initial costs and annual costs. Initial costs can further be divided into direct and indirect costs. Direct costs include collector costs, HTF system and ground preparation costs. As mentioned earlier, the collector type intended for this project is those made by Gaia Solar Company. The determined price by this company for each module is 19,800\$, and the price of one set of controlling system that can be applied to 12 modules is 15,000\$. Due to the area of the modules and their placement in 12 cascades, the cost per square meter of the collectors is 304.5\$. Considering the lack of a valid reference for the costs of HTF system and ground preparation, such costs are determined by Bakos and Parsa as a percentage of the collector

Table 4 Initial investment costs of the proposal per area of solar collector

	Price per unit	
	\$/m ²	%
<i>Direct costs</i>		
Collector costs	304.5	68.1
HTF system costs (14.28% of collector costs)	43.48	9.7
Land preparation costs (5.7% of collector costs)	17.35	3.9
Potential costs (10% of total costs of collector, HTF system and land preparation)	36.53	8.2
Total direct costs	401.86	89.9
<i>Indirect costs</i>		
Engineering, procurement and construction (EPC) costs (10% of direct costs)	40.18	9.0
Project management costs (1.2% of direct costs)	4.82	1.1
Total indirect costs	45	10.1
Total initial investment costs	446.86	100

Table 5 Assumptions and values of parameters for the economic analysis [34]

Parameters	Value
Inflation rate/%	10
Discount rate/%	13
Project lifetime/year	20
Mortgage rate/%	70 and 0
Shares of the shareholders/%	30 and 100
Interest rates on mortgage/%	16
Mortgage payment period/year	10
Rate of increase of fuel cost/%	3

Table 6 Initial investment costs for different sizes of solar collectors

Solar collector area/m ²	Initial investment cost/\$
6638	2,966,190
9958	4,449,732
13,276	5,932,380

cost. For this study, the costs of HTF system and ground preparation are 14/28 and 5.7% of the collector cost, respectively.

Indirect costs in the project can be evaluated as the engineering, procurement and construction costs (EPC), as well as the project lifecycle management costs (PLM) which are considered 10 and 1.2% of direct cost,

respectively [32]. Table 4 demonstrates a summary of initial investment cost per one square meter of collector.

Some costs are mandatory that are paid during the life cycle of the project annually, such as the costs of maintenance, taxes and insurance. The annual costs are not fixed so that according to the inflation rate, an amount is added to them per year. In this project, since the system itself does not have a separate output and also the saving in the fuel consumption is part of the cycle of the refinery production, the costs related to taxes and insurance are not considered [23] and only the maintenance and repair costs are considered 2.5% of initial costs, which increase due to the inflation annually. The lifetime of the project is proportional to the lifetime of the collector, which has been estimated by the vendor at 20 years. General parameters and assumptions used in the economic analysis are demonstrated in Table 5. In this project, the income resource for investment comes from the saving in fuel consumption by the furnace. As mentioned in earlier sections, the consumed fuel of the furnace is natural gas. Clear data do not exist presently about the price of exported gas from Iran by officials. In November 2014, the then Petroleum Ministry announced the price of the exported gas to Turkey as 50 cents, in a contract with Pakistan as 55 cents and in contract with Iraq as 43 or 44 cents [33]. In the following, the economic analysis of the project with the different price of the exported gas will be presented. In addition, the minimum price possible for an economically justifiable project will be considered.

Table 7 Economic analysis results for different sizes of solar farm, different values of solar costs and mortgage rate of 70%

Fuel cost/\$ m ⁻²	Collector area/m ²								
	6638			9958			13,276		
	IRR/%	NPV/\$	PP/year	IRR/%	NPV/\$	PP/year	IRR/%	NPV/\$	PP/year
0.3	1.9	- 1,165,798	20	1.7	- 1,785,740	20	1.3	- 2,441,821	20
0.45	14.2	121,556	12	13.9	136,532	12	13.4	147,652	12
0.55	23	980,910	7	22.7	1,434,089	7	21.9	1,764,498	7

Table 8 Economic analysis results for different sizes of solar farm, different values of solar costs and mortgage rate of 0%

Fuel cost/\$ m ⁻²	Collector area/m ²								
	6638			9958			13,276		
	IRR/%	NPV/\$	PP/year	IRR/%	NPV/\$	PP/year	IRR/%	NPV/\$	PP/year
0.3	7	- 936,412	11	6.9	- 1,439,780	11	6.7	- 1,980,762	12
0.45	15	352,671	7	14.8	484,220	7	14.6	543,531	7
0.55	19.5	1,212,411	6	19.5	1,781,358	6	19	2,227,121	6

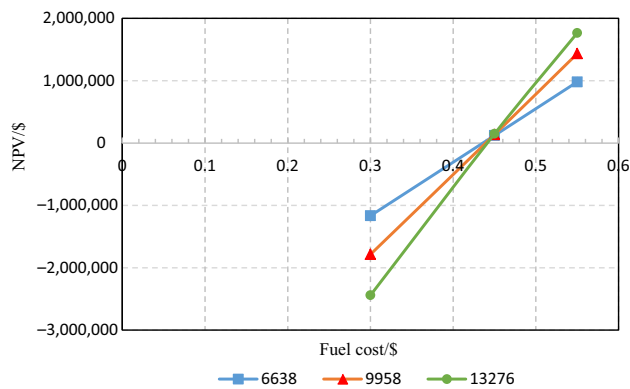


Fig. 22 Variations of NPV with fuel cost for different sizes of solar collectors and mortgage rate of 70%

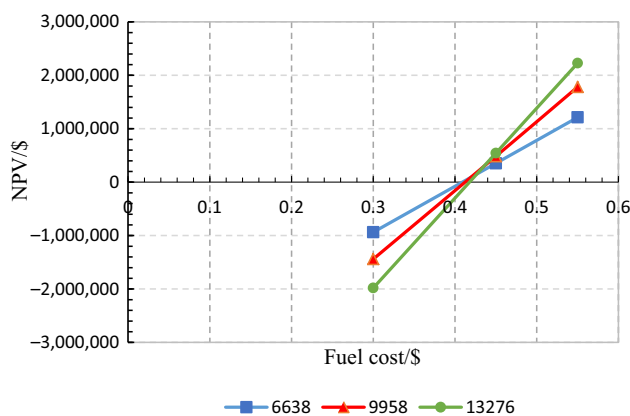


Fig. 23 Variations of NPV with fuel cost for different sizes of solar collectors and mortgage rate of 0%

Results of the economic analysis

One of the important criteria for the economic analysis of projects is the net present value (NPV), internal rate of return (IRR) and payback period (PP). In this section, the economic analysis for three different area sizes of the solar farm with parabolic trough collector is presented that was previously considered in terms of energy.

Table 6 shows the value of the initial capital for three different area sizes of the solar farm whose energy analysis was previously carried out. The results obtained for the economic analysis for different collector area sizes and different fuel prices for two different cases of 70% and 0% of mortgage rate are shown in Tables 7 and 8.

Due to the economic results, at a price of fuel equal to 30 cents per cubic meter, applying a solar preheat before the furnace is not economically affordable; however, at price of 45 cents, all area sizes the project is economically justifiable. In such cases, the investment with a mortgage rate of zero is more economically profitable. Because the internal rate of return is higher for this case. At the fuel

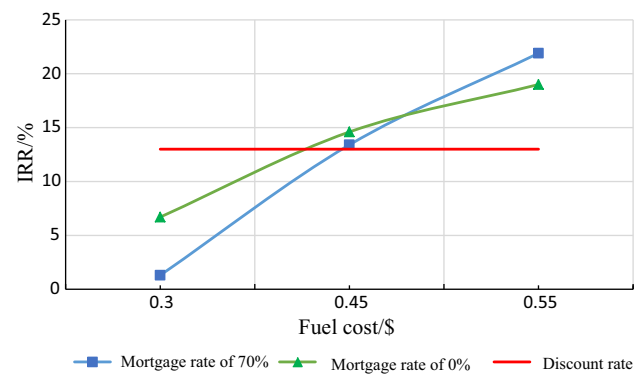


Fig. 24 Variations of IRR with fuel cost for two values of mortgage rate (0% and 70%) for collector area of 13,276 m²

price of 55 cents, the economic efficiency of the project rises significantly. In this case, the internal rate of return for the same collector size at the mortgage rate of 70% is higher as compared to rate 0%.

The net present value of investment in different fuel prices for three different collector sizes in diagrams is demonstrated in Figs. 22 and 23 for 70% and 0% mortgage rates, respectively. As shown in these two diagrams, for a 70% mortgage rate, the minimum price of fuel for an economically justifiable project is about 45 cents and for a 0% mortgage rate, this minimum price will be 41 cents that is due to the high rate of the bank interest as compared to the rate of discount. As shown in Fig. 24 for the collector area size of 13,276 m², from the fuel price of 48 cents per cubic meter upward, the investment with a mortgage percent rate of 70% as opposed to 0% mortgage leads to a higher internal rate of return.

Conclusions

In this study, one of the applications of the solar energy in the refining industry is presented. This method consists of utilization of a solar heating convertor with parabolic trough collectors in the path of the process fluid before heating the fluid in the furnace. The solar thermal convertor provides part of the required thermal energy for heating the process fluid at the time of solar radiation.

In this study, the furnace studied was the unit 400 furnace of the Parsian Gas Refinery and TRNSYS software was used for modeling. In the modeling presented in this study, for the optimum case, a maximum of 23.77% of the consumed energy of the furnace per year can be provided through solar energy. This leads to a reduction of the consumed fuel of the furnace up to 1996 million cubic meters and prevents the release of 3558 tons of carbon dioxide in a 1-year period for the unit 400 furnace. This amount of saving in the consumed fuel and reduction in the release of carbon dioxide is only for

one furnace of the refinery, which can be extended to other furnaces of the refinery. In such circumstances, the amount of saving of the energy and reduction of the carbon dioxide will be significant.

Due to international conventions against climate changes, this project is an efficient measure in reducing the spread of greenhouse gases and the consumption of fossil fuels in refinery industries, which are among high consumption industries with regard to fossil fuels. Moreover, this design as compared to other approaches to solar energy does not involve a peak in energy consumption and is constant at all times of the day.

The results from the economic analysis of the project for three prices of 30, 45 and 55 cents per cubic meter of exported natural gas show that from the price of 45 cents per cubic meter upward, the proposition of utilizing a solar thermal convertor for preheating before the furnace is economically affordable. Because of the increase in the price of the fossil fuels, this can become part of the investment. As the consumption of energy in refinery industries is high, utilization of solar energy in large scale will reduce most of the implementation costs as well as the maintenance costs of the solar farms as compared to small-scale programs and in addition presents high potentials for employments.

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