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Integration of vertical ground-coupled heat pump into a conventional natural gas pressure drop station: Energy, economic and CO_2 emission assessment

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A B S T R A C T

City gate stations receive high pressure natural gas and decrease the pressure by throttle valves. Concurrent with the natural gas pressure reduction, the temperature also drops. Thus, to prevent blocking of the downstream pipeline by the liquid and solid particles, natural gas must be preheated before pressure reduction. Heaters utilized for preheating task, have a low thermal efficiency and consume a large amount of fuel. In addition to the high fuel consumption, they release a huge amount of CO_2 into the atmosphere. Therefore, the present study proposes a new system for in-situ fuel consumption elimination at these stations. It utilizes vertical ground-coupled heat pump system as a renewable source of energy to preheat natural gas stream. The system performance was studied at two different climatic conditions of Iran which have also two different natural gas compositions. Results show that the system is completely capable to eliminate in-situ fuel consumption of city gate stations; however, by considering indirect fuel consumption of electrical heat pumps, the system fuel consumption reduction potential was calculated over 65%. It is also able to reduce CO_2 emission up to 79%. The discounted payback period is computed around two years, which proves the suitability of offered system.

1. Introduction

Natural gas (NG) has become the primary energy source in Iran after the change in country's energy consumption policy from oil to gas over the past 25 years. Currently, Iran is the second largest producer of NG in the world with a yearly amount of 166.6 billion cubic meters (bcm), 4.9% share of the world, and one of the largest consumers of NG in the world with a yearly amount of 162.2 bcm, 4.8% share of the world. The most of extracted NG is consumed at the domestic and industrial sectors [1]. Furthermore, the share of NG in Iran's CO_2 emission is 53%. Over 295 million ton CO_2 annually is released to the atmosphere by burning the NG. Therefore, to promote sustainable development and reduce energy consumption, improving thermal efficiency of equipment or finding an alternative energy sources are essential. NG pressure drop stations, known as CGSs (City Gate Stations) have attracted more attention due to considerable amount of fuel consumption and utilizing renewable energy sources could decrease fuel consumption and CO_2 emission.

Delivering NG to end consumer is an energy consuming process as well as cost consuming. Iran's NG pipeline delivery network has been expanded over 34,000 km. NG is transported from a production point via pipeline with pressure as high as 5–7 MPa. The pressure must be reduced in several steps to make it usable for end consumers. One major pressure drop occurs in CGSs. The pressure is reduced through a throttling valve placed in CGSs to the 1.5–2 MPa. As the pressure reduces via throttling process, the temperature is also reduced (Joule-Thomson phenomena). After pressure drop process, low temperature and high pressure state of NG, cause gas hydrates (ice like compounds) appear in downstream. The undesirable gas hydrate formation may damage NG transmission pipeline [2]. For avoiding the gas hydrate formation, the inlet NG must be heated up. Indirect water bath heaters (line heaters) are used to preheat NG stream in Iran, which utilize the available NG at the station as fuel source. The standard temperature of preheated gas is in the range of 30–55 °C [3]. The exact value depends on the inlet pressure and the NG compositions. A schematic of a typical line heater is also shown in Fig. 1. Heat is produced

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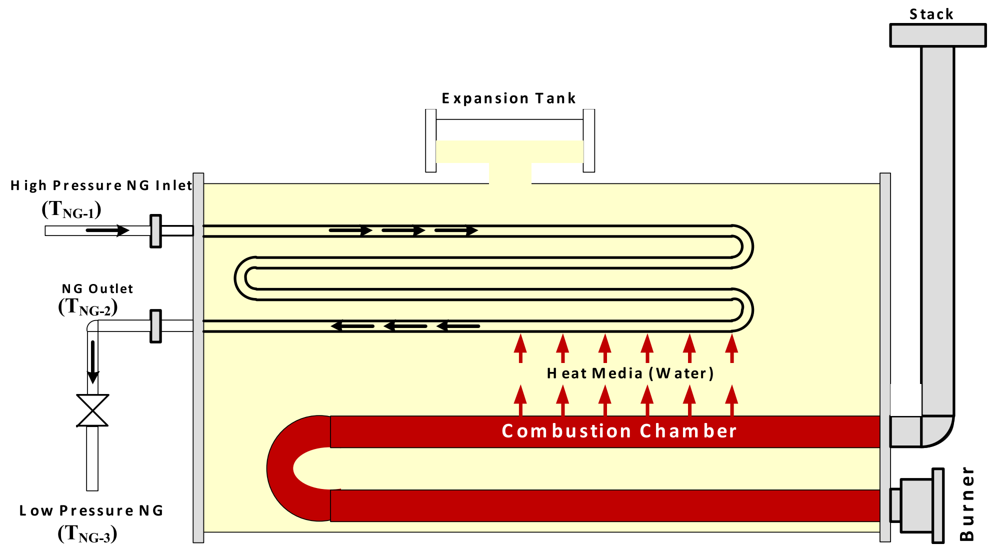

Fig. 1. A schematic of NG pressure drop station.

by burning NG in fire tube, and then it is transferred to heat transfer medium fluid (water). Finally, heat is delivered to NG passing through the line heater.

To reduce energy consumption in CGSs, a few studies have been conducted. Farzaneh-Gord and Kargaran [4] proposed the possibility of using vortex tube instead of throttling valves in CGSs. They have studied vortex tube performance with low pressure NG stream experimentally. Farzaneh-Gord et al. [3] proposed a solar system to provide a part of heat demand in the Akand CGS. The study was carried out by assuming an uncontrolled line heater. Economic analysis shown the system net benefit is coming back after 11 years. Recent study by Farzaneh-Gord et al. [5] revealed that using solar heat with controllable heater at the Akand CGS gives annual benefit of 27,011 USD with capital cost equal to 144,000 USD. The simple and discounted payback period were also determined to be 5.5 and 8 years respectively. Lately, in another work, Farzaneh-Gord et al. [6] proposed and studied using of vertical ground heat exchangers in CGSs to reduce fuel consumption in Gonbad Kavoos CGS. Comprehensive thermo-economic analysis showed that a system comprising 8 boreholes with 150 m depth and 0.15 m diameter each is the most efficient configuration for Gonbad Kavoos station. The discounted payback period and IRR of the system was computed to be about 5 years and 15.5% respectively. In comparison to utilizing solar systems, the offered system showed good economic performance. Ghezelbash et al. [7] investigated employing GCHP (Ground-Coupled Heat Pump) system in the modern type of NG pressure drop station which uses turbo-expander instead of throttle valve. In the proposed system, initially, the vertical GCHP system preheats the NG stream up to medium temperatures, then; gas stream passes through station heater and reaches the desired temperature. They concluded the fuel saving potential of the system is 45.80% annually. Economically, the discounted payback period was also calculated about 6 years. In the recent study by Ghezelbash et al. [8], they offered a new system based on vortex tube and vertical ground heat exchangers in order to minimize energy consumption. The proposed system reduced energy consumption up to 88%, and the discounted payback period was always less than 4.5 years.

For this purpose, heat pumps are connected to the ground heat exchangers, which are installed either vertically or horizontally, and heat or cool the building space. Compared to Horizontal GCHP, vertical GCHP uses less land area [9] and less pumping energy. Moreover, heat exchange rate per unit length of the straight horizontal heat exchanger pipe is mainly lower than those obtained from vertical GHXs [10]. Although the installation cost of the vertical GCHP is higher than the horizontal one, it has attracted more attentions due to mentioned advantages [11–16]. It uses relatively constant temperature of earth for heating and cooling purposes [17,18] which is approximately constant below the 15 m depth [19]. It also has proved better thermal performance than other conventional heating and cooling devices such as air source heat pumps [20–24].

Utilization of free geothermal heat for providing process heat in industrial applications is not common, especially for low temperature cases. It may be due to available low temperature waste heat in most big industries. However, for industrial sectors or places with no waste heat, the utilization of geothermal energy has the potential for substantial economization of primary energy resources. As low temperature NG stream (less than 55 °C) required at CGS, it has the good opportunity of using geothermal heat at CGSs.

The NG price is high and consequently its export could enhance the earnings of Iran. Thus, wasting this reliable energy source in the CGSs is undesirable. Moreover, utilizing of NG as a heat source especially in low thermal efficiency heaters could release considerable amount of CO_2 into atmosphere. Consequently, in the present study an innovative system based on vertical GCHP is proposed to be integrated into the line heater of the conventional CGS in order to eliminate in-situ fuel consumption of the medium flow and partly high flow CGSs. The system capability in eliminating in-situ fuel consumption is studied. The energy and economic performance is studied as well as the CO_2 emission reduction potential of the proposed system. In order to show the possibility of using geothermal heat pump at different climatic condition of the Iran, two mega cities at north of the Iran is selected as case studies. The cities experience cold days in winter and have different undisturbed ground temperature and NG chemical composition. The mentioned parameters directly or indirectly affect the viability of the proposed system.

2. Description of proposed system

The proposed system employs the vertical GCHP for transferring the ground heat to a pressurized NG in a pipeline before the pressure reduction process. As it was claimed, the proposed system takes advantage of geothermal heat pump to provide the whole (or part) of the required heat in the CGSs. The system comprises of water to water heat pump, vertical GHXs, fluid circulating pump, throttling valve and line heater. The throttle valve and the line heater of the conventional CGS will be utilized in the proposed system and no extra costs will be paid for them. It is worth noticing that the burner within line heater in the proposed system could be set off. In such case, the line heater is actually working as a bath type heat exchanger.

The proposed system involves multiple vertical boreholes. These boreholes have a diameter about 15 cm and 100–150 m long (see Table 1). The heat pump is connected to the ground via a u-tube inserted into the boreholes then antifreeze solution circulates through closed loop and absorbs ground heat. The collected geothermal energy by the heat exchangers is used by the heat pump to warm the incoming water from the line heater. The water is warmed up via heat pump and enters the line heater to give its thermal energy to the incoming NG stream passing through the line heater. Then the NG enters into the throttle valve. The temperature of the NG is maintained high enough to avoid any low temperature issues after the throttling process. As Fig. 2 shows, if the inlet NG temperature is above the specific temperature (T_{NG2}), it goes through a bypass line without being warmed up. Otherwise, it should pass a preheating process through the proposed system. Energy to operate the system equipment, i.e. heat pump compressor and fluid circulating pump, is provided by the electricity grid.

Iran has only one commercial company which supplies GCHPs in country. The minimum and maximum source side fluid temperature has been proposed by the manufacture is −7 °C and 44 °C. By knowing that the heat pump will always operate in heating mode, the possibility of fluid temperature falling below 0 °C is high. Thus, antifreeze solution must be used as a heat carrier fluid in source side of the heat pump, i.e. ground loop, to protect against freezing of water.

For heating dominant applications, boreholes with open configuration such as L-shaped and U-shaped are suggested [25]. L-Shaped configuration has more open space than others. Therefore, L-Shaped configuration for boreholes is selected here.

Fig. 3 shows the proposed layout for the boreholes at the CGS in an L shape configuration with a regular distance of 0.08 H between the boreholes. Naturally, the selection of the appropriate number of the boreholes depends on the amount of required energy. Therefore, the number of boreholes (consequently the distance between adjacent boreholes, a number of the heat pump unit) should be determined on a basis of a thermo economic analysis. Eventually, Table 1 details the information about the proposed system which is used here for the analysis.

Table 1
The proposed geothermal system details for the considered NG pressure drop station.

Diameter of Each Borehole	0.15 m
Depth of Each Borehole (H)	100 m–150 m
Distance Between the Boreholes (B)	0.08 × H
Operating Fluid	25% ethylene glycol (mass basis)
Operating Fluid Mass Flow Rate	0.2456 kg/s
Operating Fluid Velocity	0.634 m/s
Pipe Material	High Density Polyethylene
Pipe Thermal Conductivity Coefficient	0.42 W/mK
Pipe Inner Diameter	0.0218 m
Pipe Outer Diameter	0.0267 m
Grout Thermal Conductivity Coefficient	0.75 W/mK
Undisturbed ground Temperature (°C)	Tabriz (11.3), Mashhad (16.7)
Ground's Thermal Conductivity Coefficient	2 W/mK
Ground's Thermal Diffusion Coefficient	0.1178 m^2/day

3. Mathematical modeling

3.1. Line heater

Considering the schematic diagram of the NG pressure drop station, Fig. 1, one could accomplish a thorough thermal and energy analysis of the conventional configuration. According to Fig. 1, the NG temperature at the line heater exit should have the value given by the following equation to prevent hydrate formation:

$$T_{NG2} = T_{hyd} + T_c + \Delta T_{tv} \tag{1}$$

In which, T_c and ΔT_{tv} represent the confidence value and the temperature reduction value due to pressure drop through the throttling valve. T_{hyd} also refers to the hydrate forming temperature of the NG stream. The NG pressure and temperature at the station inlet is usually known. Once, the NG temperature and pressure at the heater exit are known, the rate of required energy of the NG stream for being warmed up could be calculated as below:

$$\dot{Q}_{NG} = \dot{m}_{NG} \cdot C_{p,NG}(T_{NG2} - T_{NG3}) \tag{2}$$

Where, $\dot{m}_{NG}$ and $C_{p,NG}$ are the NG mass flow rate and thermal capacity, respectively. As the NG flows through a buried pipeline at a depth of 1.2 m, the gas temperature in the pipeline is the same as the soil surround the pipeline which could be calculated as a function of ambient temperature as follow [3]:

$$T_{NG1} = T_{soil} = 0.0084T_0^2 + 0.3182T_0 + 11.403 \tag{3}$$

The heating duty of the heater is provided by burning NG as fuel. Considering the thermal efficiency of the heater, η_h, the fuel mass flow rate, $\dot{m}_{fuel}$, could be calculated as below:

$$\dot{m}_{fuel} = \frac{\dot{Q}_{NG} + \frac{m_w C_w \left(T_w^{i+1} - T_w^i\right)}{3600}}{\eta_h \cdot LHV} \tag{4}$$

$$\dot{Q}_H = \dot{Q}_{NG} + \frac{m_w C_w \left(T_w^{i+1} - T_w^i\right)}{3600} \tag{5}$$

In which, LHV, m_w and C_w are the lower heating value of the fuel, the in heater water mass and thermal capacity, respectively. η_h is the thermal efficiency of the heater, which is in the range of 35%–50% [3]. In this work, the thermal efficiency of the heater was assumed to be 40%. Also the subscripts (i) and $(i+1)$ stand for the period number.

T_w also refers to the heater water temperature. The immersed coil in water bath could be considered as a pipe in a constant temperature environment, based on the correlation presented by Incropera and Dewitt [26], T_w could be calculated from:

$$\frac{T_w - T_{NG2}}{T_w - T_{NG1}} = \exp(Y), \quad Y = \frac{-\pi D_{oc} L_c U_c}{\dot{m}_{NG} \cdot C_{p,NG}} \tag{6}$$

Where, D_{oc}, U_c and L_c are the external diameter, length and overall heat transfer coefficient of the coil, respectively. Rearranging the above equation and solving for T_w, the following equation could be derived:

$$T_w = \frac{T_{NG2} - T_{NG1} \cdot \exp(Y)}{1 - \exp(Y)} \tag{7}$$

The previous studies suggest that the line heaters are so designed that have $U_c = 568$ W/m^2 K [3]. Employing the formulation presented above, the detailed energy analysis of the NG pressure drop station would be possible.

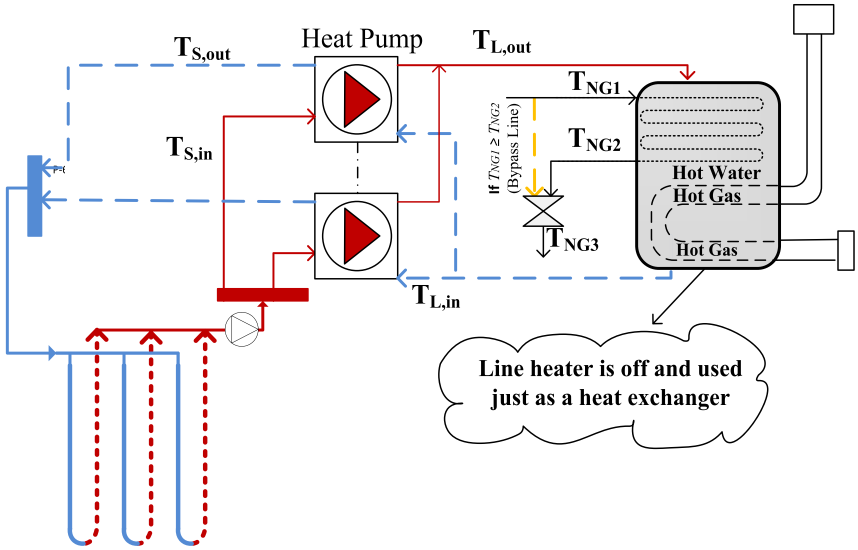

Fig. 2. Schematic of the proposed system.

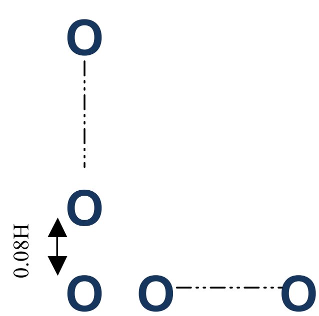

Fig. 3. The proposed layout for arranging the boreholes.

3.2. Vertical GCHP

In this study, heat transfer modeling inside and outside of boreholes modeled separately with the borehole wall acting as the interface. The model for the borehole interior uses steady state heat transfer [27], but the outside model must take care of the thermal phenomenon from the borehole wall to the surrounding soil and the other boreholes. One could use analytical and numerical models to study heat transfer outside the borehole. Compared to numerical models, analytical models [28–33] have a low computational time and are flexible in programming. Therefore it is a best choice for feasibility studies such as present study. Analytical models are based on ILS (infinite line heat source) [31], CS (cylindrical heat source) [27] and FLS (finite line source) [30].

The ILS and CS were generally used to model heat transfer around the boreholes. The both methods offer a 1D solution to heat transfer from a heat source and neglect axial heat transfer which cause to overestimation of borehole wall temperature for times greater than 3 years [34]. On the other hand, FLS solution can predict 2D heat transfer from a finite length source positioned in a semi-infinite medium and subjected to a constant heat transfer rate. Eskilson [35] proposed the analytical solution of the FLS. Zeng et al. [30] presented a new methodology to evaluate the temperature in a bore field using the FLS. Contrary to Eskilson work which the temperature was calculated at mid-height of the source, they used the integral mean temperature over the borehole height and it showed better results. Lamarche and Beauchamp [36] simplified the double integral into a single integral in the FLS solution which led to reducing considerably the time required to calculate the integral mean temperature over the borehole height. Claesson and Javed [33] obtained a correlation to predict integral mean temperature of geothermal bore field where boreholes are buried at a distance D from the ground surface. In contrast to Zeng et al. [30] and Lamarche and Beauchamp [36], the FLS was defined by point heat source integral which was initially integrated in space. Then after, the obtained solution is given in the form of an integral in the time domain.

As the FLS method gives more accurate solution in long time, (Claesson and Javed [33]) the FLS method is utilized in this study. The method also provides a simpler formulation comparing to ILS and CS.

3.2.1. Computing the fluid temperature into the vertical GHXs

The mean temperature of circulating fluid can be obtained by the concept of thermal resistance:

$$T_f(t) = T_{bw}(t) + q(t)\cdot R_b \tag{8}$$

$$T_{S,out}(t) = T_f(t) - \frac{q(t)\cdot H}{2\dot{m}_f c_f} \tag{9}$$

$$T_{S,in}(t) = T_f(t) + \frac{q(t)\cdot H}{2\dot{m}_f c_f} \tag{10}$$

T_f is the average temperature of the circulating fluid into the vertical GHX. $T_{S,in}$ and $T_{S,out}$ are the inlet and outlet fluid temperature to the heat pump source side or respectively. T_{bw} is a borehole wall temperature and R_b is a borehole thermal resistance. In heat extraction mode the sign of the heat flux, q, is negative.

3.2.2. Borehole wall temperature at a variable heat flux

For a time varying heat flux, $q(t)$, borehole wall temperature is predicted by temporal superposition principle from $Z = D$ to $Z = D + H$ [37].

$$T_{bw}(t) - T_g = \Delta T(t) = \sum_{j=1}^{n_t} \frac{q_j - q_{j-1}}{4\pi k} \cdot \int_{\frac{1}{\sqrt{4\alpha(t-t_{j-1})}}}^{\infty} I_e \cdot \frac{I_{ls}(Hs,\ Ds)}{Hs^2} \cdot ds \tag{11}$$

In which T_g is the undisturbed ground temperature, $q(t)$ is the ground heat load, k is the ground thermal conductivity, α, H and D are ground thermal diffusivity, borehole active length and borehole inactive length respectively. j is the time step index and n_t is the number of time steps before time t.

$$I_e(s) = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{N} \exp\left(- r_{i,j}^2 s^2 \right) \tag{12}$$

$r_{i,j}$ denotes the radial distance between borehole i and j (i ≠ j). The contribution of the own heat source of the borehole i is obtained for the radial distance r_b.

$$r_{i,j} = \sqrt{(x_i - x_j)^2 + \left(y_i - y_j\right)^2} \quad i \neq j \tag{13}$$

$$I_{ls}(h,d) = 2 \cdot ierf(h) + 2 \cdot ierf(h+2d) - ierf(2h+2d) - ierf(2d) \tag{14}$$

n_t Eq. (11) could be rewritten as a convolution product [38]:

$$\Delta T(t) = \sum_{j=1}^{n_t} h(t_j) \cdot f(t - t_{j-1}) = (h*f)(t) \tag{15}$$

Where the h(t_j) is the incremental heat flux function:

$$h(t_j) = q(t_j) - q(t_{j-1}) \tag{16}$$

$$f(t - t_{j-1}) = \frac{1}{4\pi k} \cdot \int_{\frac{1}{\sqrt{4\alpha(t-t_{j-1})}}}^{\infty} I_e \cdot \frac{I_{ls}(Hs,\ Ds)}{Hs^2} \cdot ds \tag{17}$$

Marcotte and Pasquier [38] showed that Eq. (15) could be computed with a spectral approach using discrete Fourier approach:

$$\Delta T(t) = \mathcal{F}^{-1}(\mathcal{F}(h) \cdot \mathcal{F}(f)) \tag{18}$$

3.2.3. Borehole interior thermal resistance

Since the thermal capacitance of the borehole is relatively small compared to adjacent ground, it is generally considered that heat transfer form borehole wall to fluid is in a steady state [27]. Thermal resistance inside the borehole includes the thermal resistance of fluid convection, and that of solid conduction in the pipe and grout. Conduction Thermal resistance of pipe and the convection thermal resistance of fluid into the pipe are obtained by Eqs. (20) and (21) respectively:

$$R_b = \frac{1}{2}(R_{conv} + R_{cond}) + R_{grout} \tag{19}$$

$$R_{cond} = \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi k_{pipe}} \tag{20}$$

$$R_{conv} = \frac{1}{\pi d_{in} h} \tag{21}$$

h is a function of the Nusselt number (Nu). Nu is determined according to the flow regime. By increasing the turbulence of flow, thermal convection resistance decreases and consequently heat transfer between soil and VGHX enhances.

$$\begin{cases} Nu = 0.023\, Re^{0.8} Pr^{0.4}, & Re > 10^4 \\ Nu = 4.36, & Re < 2300 \\ Nu = \dfrac{\left(\frac{f}{8}\right) \times Re \times Pr}{1.07 + 12.7\left(\frac{f}{8}\right)^{0.5} \times \left(Pr^{0.67} - 1\right)}, & 2300 < Re < 10^4 \end{cases} \tag{22}$$

To calculate the grout thermal resistance, Paul's model [39] is used. Paul used the so-called shape factor correlations, which were created by the experimental data and simulation results.

$$R_{grout} = \frac{1}{k_{grout} \beta_0 \left(\frac{d_b}{d_o}\right)^{\beta_1}} \tag{23}$$

Where, β_0 and β_1 are dimensionless equation fit coefficients. d_b and d_o are diameter of borehole and outer diameter of pipe, respectively. Values of β_0 and β_1 are variable depending on the position of the tube in the grout. In this study typical values of $\beta_0 = 20.100377$ and $\beta_1 = -0.94467$ are considered [40].

3.2.4. Coupling vertical GHXs with heat pumps

For coupling vertical GHXs with heat pump COP, power consumption and heat delivered by the heat pump are required. The only variables that affect the modeled water to water heat pump performance are source and load side inlet fluid temperatures, providing the source and load side fluid mass flow rates are constant. The heat pump model permits the characteristics to alter pursuant to both temperatures and mass flow rates; however, since the manufacturer's data only accessible for single design flow rate, the model can be defined solely in terms of source and load side inlet temperatures. As a result the governing equations for the heating mode are simplified and can be identified as follows [41,42]:

$$\frac{\dot{Q}_{HP}}{Q_{h,ref}} = A1 + A2\left[\frac{T_{L,in}}{T_{ref}}\right] + A3\left[\frac{T_{S,in}}{T_{ref}}\right] \tag{24}$$

$$\frac{\dot{W}_{HP}}{P_{h,ref}} = B1 + B2\left[\frac{T_{L,in}}{T_{ref}}\right] + B3\left[\frac{T_{S,in}}{T_{ref}}\right] \tag{25}$$

$A1-B3$ are equation coefficients for the heating mode which are obtained based on data published in the manufacturer's catalog. T_{ref} is the reference temperature, equal to 283 K. $T_{L,in}$ and $T_{S,in}$ are the load and source side inlet temperature in Kelvin respectively. $\dot{Q}_{HP}$ and $\dot{W}_{HP}$ are load side heat transfer rate and power consumption of the heat pump respectively. Ultimately, the $Q_{h,ref}$ and $P_{h,ref}$ are the reference source side heat transfer rate and power input at the condition as the heat pump operates at the highest heating capacity.

The model coefficients have been derived from manufacturer's data for WWG240 water to water heat pump, with a rated heating capacity of 76 kW. Table 2 shows the derived heat pump coefficients.

By knowing the required equations to simulate the heat pump performance, one could obtain the hourly heat flux absorbed from the ground:

$$q(t) = \frac{n_{HP}(t)\cdot \dot{Q}_{HP}(T_{L,in}, T_{S,in})}{N_b \cdot H} \times \left(1 - \frac{1}{COP(T_{L,in}, T_{S,in})}\right) \tag{26}$$

$$n_{HP}(t) = \frac{\dot{Q}_H(t)}{\dot{Q}_{HP}(T_{L,in}, T_{S,in})} \tag{27}$$

N_b is the total number of boreholes. $\dot{Q}_{HP}$ is the amount of energy which is delivered by the one heat pump unit. $\dot{Q}_H$ is a required thermal energy which must be delivered to the NG. n_{HP} is the number of heat pumps. The COP and $\dot{Q}_{HP}$ are given as follows:

$$COP(T_{L,in}, T_{S,in}) = \frac{\dot{Q}_{HP}(T_{L,in}, T_{S,in})}{\dot{W}_{HP}(T_{L,in}, T_{S,in})} \tag{28}$$

For a given borehole configuration in simulation step, first the antifreeze solution temperature is guessed, $T_{S,in}$, and the amount of heat flux is determined, $q(t)$, then by using a FFT command in MATLAB, Eq. (18), the new inlet fluid temperature to the heat pump source side is estimated in the whole life of the proposed system by using Eq. (10). If the difference between the old and new temperature is greater than the specified value of 0.001 °C simulation process repeated with the new fluid temperature. The simulation is assumed to converge when temperature difference is lower than 0.001 °C.

3.3. Pumping power

Antifreeze solution pump consuming power could be estimated by theoretical formulas, however due to simplification of real condition, it underestimates the power consumption. Thus, for establishing a condition near to reality, the pumping power is assumed to be 2.5% of heat load supplied by heat pumps (mediate grade pump) [43].

3.4. CO_2 emission

The line heater has a low thermal efficiency and expected to release significant amount of CO_2 into atmosphere. Here, CO_2 emission factor of NG, 53.9 kg CO_2/Gj NG [44], is used for calculation of the produced amount of CO_2 by the heater.

The proposed systems also produce CO_2 due to utilizing electricity for operation of heat pump and fluid circulating pump. It is assumed that electricity is purchased from the local gas turbine (GT) power plant or combined cycle (CC) power plant. In Iran the use of 1 kWh GT and CC power plant electricity corresponds to release of 0.8498 kg CO_2 and 0.4831 kg CO_2 respectively [45]. Finally the total annual CO_2 produced by the conventional CGSs and the proposed system is compared in a 25 year lifetime of the system.

Table 2
Heat pump coefficients.

A1	−3.6354	B1	−6.3759
A2	−0.3590	B2	6.1975
A3	4.8172	B3	0.6545

3.5. NG consumption by the local thermal power plants

As mentioned power consumption by the proposed system lead to thermal power plants located in the region consume fuel. The average NG consumption per unit of electricity generation by the Iranian GT and CC power plants are 0.2910 m^3/kWh and 0.2019 m^3/kWh respectively [46]. Thus the reduction in NG consumption could be given by:

$$RC_{NG} = \frac{\left|\left(\dot{W}_{P,T} + \dot{W}_{HP,T}\right) \times PF - \dot{V}_{f,T}\right|}{\dot{V}_{f,T}} \times 100 \tag{29}$$

$(\dot{W}_{P,T} + \dot{W}_{HP,T}) \times PF$ and $\dot{V}_{f,T}$ are the total annual NG consumption of thermal power plant and conventional CGS.

4. Economic considerations

The employed method of economic analysis for selecting the most efficient layout of the geothermal system is explained thoroughly in the conclusion section. The selected configuration will also be assessed economically by the internal rate of return (IRR) as a very reliable and authentic technical method. The IRR is the rate of return used to measure and compare the profitability of an investment. The term internal refers to the fact that its calculation does not incorporate environmental factors such as the interest rate or inflation. Based on the definition, the IRR on a project is the rate of return that makes the net present value (NPV) of all cash flows from a particular investment equal to zero.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} = 0 \tag{30}$$

Where, n, C_n and r refer to the number of years, cash flow in the project in the corresponding year and IRR respectively. Overall, the higher a configuration's IRR, the more desirable it is to undertake the project [47]. The critical parameter for calculating the IRR of a project is the number of years (discounted payback period) in which NPV should be equal to zero. This totally depends on the investor of the project; however, for such industrial projects the duration of 8 years seems to be a good choice.

For such systems that take advantage of geothermal energy, there are numbers of important issues to be defined in the simulation step such as the number, the depth and the diameter of boreholes, the distance between the boreholes, the operating fluid flow rate passing through each borehole. The depth and number of the boreholes are determined via economic analysis. In order to choose the borehole depth, it is allowed to vary in the range of 100–150 m. About the distance of boreholes, it is recommended that the value of the BH factor should be selected from 0.05 to 0.2 [48]. BH is defined as the ratio of distances between the boreholes to the depth of each borehole. The value of BH adopted for this work is 0.08. Finally, by considering typical head loss of 0.4 kPa/m in the ground loop [49], mass flow rate in each borehole is given. The capital cost of the system equipment presented as follows.

4.1. Heat pump cost

The heat pump model used in the present study is WWG240 made in a commercial company of Iran. Purchase cost of this model is 17,000 $.

4.2. The cost of drilling, backfilling, pipe and piping

Inquiry of local deep drilling boreholes corporates revealed that the cost of drilling cost varies in the range of 10–25 USD/m which the amount of 15 USD/m was chosen. By considering the cost of preparing grout with thermal conductivity of 0.75 W/mK and the cost of pipe and piping [50], the total cost of vertical GHX is estimated to be 20 USD/m.

4.3. Pump cost

The following equation is used to calculate the pump cost [50]:

$$C = 271.64 \times \dot{m}_f + 1094.7\ (\$) \tag{31}$$

4.4. Electricity and NG prices

Purchase cost of electricity per 1 kwh considered to be 0.11 USD. The NG price also considered to be 0.44 USD/m^3.

5. Case study

The proposed system is employed to study the thermal, economical and the CO_2 emission reduction performance of the stations located in the two largest central provinces of Iran. Tabriz and Mashhad cities are located at the northwest and northeast of Iran, respectively. These two cities are selected due to different climate zone and different NG compositions. Tabriz is one of the coldest climates of Iran and Mashhad has a milder climate in comparison with Tabriz. Climate zone affects the inlet NG temperature and undisturbed ground temperature. Table 3 and Table 4 show the NG composition and properties of the both stations, respectively.

In order to study the performance of the proposed system at the worst condition, the station inlet and outlet pressure for both cities were considered 67 bar (maximum inlet pressure in Iran) and 17 bar respectively. Inlet NG temperature to the stations were determined based on hourly ambient temperature. Based on thermodynamic relations, the hydrate temperature at the station exit for Tabriz and Mashhad was 7 °C and −5.27 °C respectively. Depending upon the gas hydrate formation temperature and the climate zones which has a significant effect on outlet temperature of a station, outlet gas temperature of Tabriz and Mashhad stations considered to be 15 °C and 10 °C respectively. Paying attention to Fig. 4 which shows monthly averaged ground surface temperature, one could conclude that the NG temperature at the exit of Tabriz station should be higher than Mashhad one (due to low ground temperature). By considering the temperature fall due to pressure drop through the throttling valve, inlet gas temperature (T_{NG2}) to the throttle valve is computed to be 39 °C and 33 °C for Tabriz and Mashhad stations. T_{NG2} and T_{NG3} are kept constant all time at the mentioned values. To keep T_{NG2} constant, the water temperature within the heater has to be higher than T_{NG2} regardless of the time.

The performance of station is investigated for two constant yearly average NG mass flow rates. The first mass flow rate is assumed to be 1.8 kg/s (M1) which is representative of the medium flow CGSs and the second one is representative of the partly high flow CGSs with the mass flow rate of 3 kg/s (M2) based on divisions of the CGSs by Farzaneh-Gord et al. [51].

Table 3
Chemical NG composition of Tabriz and Mashhad stations.

Composition	Mole fraction (%)	
	Tabriz (NG1)	Mashhad (NG2)
CH_4	88.553	98.548
C_2H_6	3.50	0.647
C_3H_8	0.95	0.069
n-C_4H_{10}	0.2502	0.039
i-C_4H_{10}	0.2301	0.018
n-C_5H_{12}	0.10	0.021
i-C_5H_{12}	0.09	0.018
C_6H_{14}	0.10	0.14
N_2	4.00	0.50
CO_2	0.20	0
H_2S	2.0267	0

Table 4
NG properties of Tabriz and Mashhad stations.

Properties	NG1	NG2
LHV (Mj/kg)	45.01	49.52
ρ_{NG} (kg/m^3)	0.7572	0.6845
$C_{p,NG}$ (j/kg.k)	2534	2700
T_{hyd} (°C)	7	−5.27

6. Results and discussion

In this section, the energy status of considered CGSs are discussed, then based on economical analysis the most beneficial proposed system is selected for each station at the both considered NG mass flow rates. Finally, the energy, economic and the CO_2 emission performance of the selected systems are investigated.

Fig. 5 illustrates monthly averaged NG inlet temperature at Tabriz and Mashhad CGS. The temperature of NG at the CGS inlet is a direct function of ambient temperature. As expected the least entrance temperatures belongs to January and the highest temperature has been recorded in July. Yearly average NG inlet temperature of Tabriz and Mashhad CGS are 17.4 °C and 18.2 °C respectively. By comparing Mashhad and Tabriz climate, it is obvious Tabriz experiences colder fall and winter.

Currently, the heaters are not equipped with automatic control systems. Thus, they should be manually adjusted to meet the heating demands. As a result, fuel consumption of heaters stays constant for a certain time, even when heating demand is low, in this study we assumed the heater is controlled with automatic systems. Fig. 6 and Fig. 7 show the hourly heating duty of Tabriz and Mashhad CGSs. Fig. 6 shows a case in which inlet NG mass flow rate of the stations across the year is constant and equals to 1.8 kg/s. As can be seen, heating duty of Tabriz heater is always higher than Mashhad station. The major reason of this high energy consumption of the heater in Tabriz CGS is the higher NG temperature (39 °C) after the heater compared to Mashhad one (33 °C). The highest heating duty value of heater occurs in almost three coldest months of the year (i.e. from December to February) and the lowest values are seen from June to August. As the inlet NG mass flow rate of the stations increases to the constant amount of 3 kg/s across the year, Fig. 7, the energy consumption by the heaters also goes up. The yearly average heating duty value of heater for Tabriz increases from 98.5 kW to 164.2 kW. This value for Mashhad rises from 71.8 kW to 119.6 kW. The peak heating value of the heater is also important since it would increase or decrease the required total borehole length of the proposed system which has a great influence on the economic viability of the system due to high installing cost of the GHXs. The peak heating value for Tabriz and Mashhad CGSs corresponding to 1.8 kg/s inlet NG mass flow rate are 138.7 kW and 118 kW respectively, and for 3 kg/s NG mass flow rate the corresponding values are 231.1 kW and 196.6 kW.

Another important parameter which gives valuable information on heater condition is fuel consumption rate. Figs. 8 and 9 depict the hourly fuel consumption rate of the stations for inlet NG mass flow rate of 1.8 kg/s and 3 kg/s respectively. For NG mass flow rate of

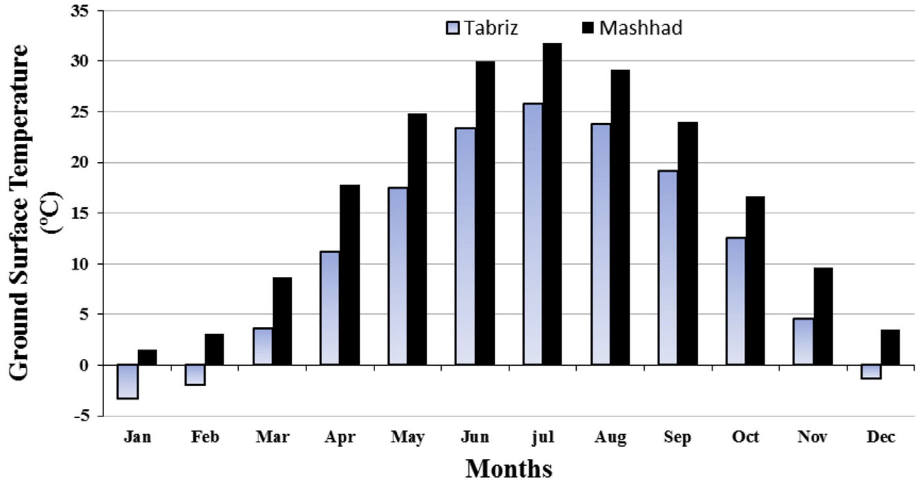

Fig. 4. Monthly averaged ground surface temperature at Tabriz and Mashhad cities [45].

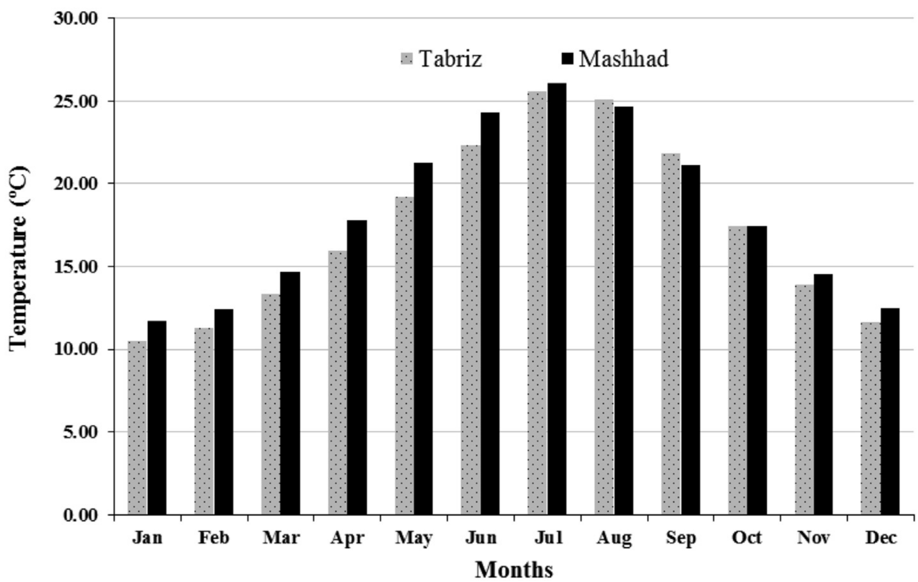

Fig. 5. Monthly average temperature of inlet NG to Tabriz and Mashhad CGS.

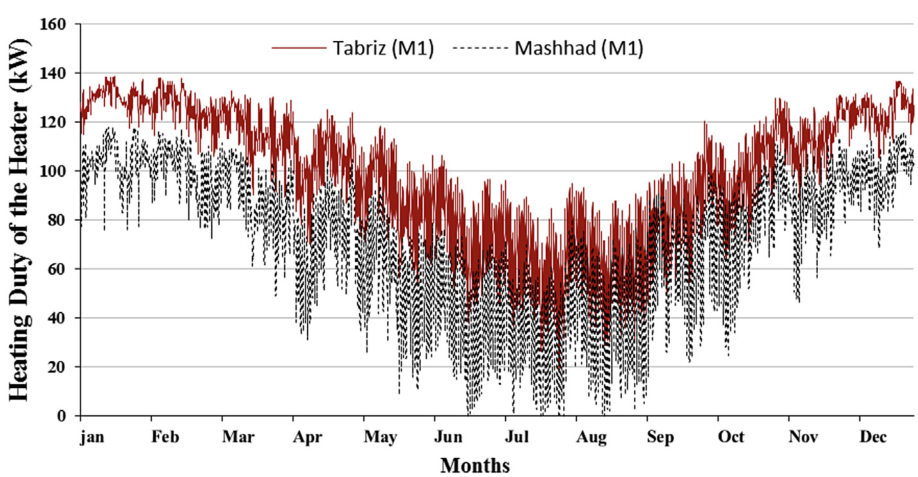

Fig. 6. Heating Duty of Tabriz and Mashhad CGS in NG mass flow rate of 1.8 kg/s.

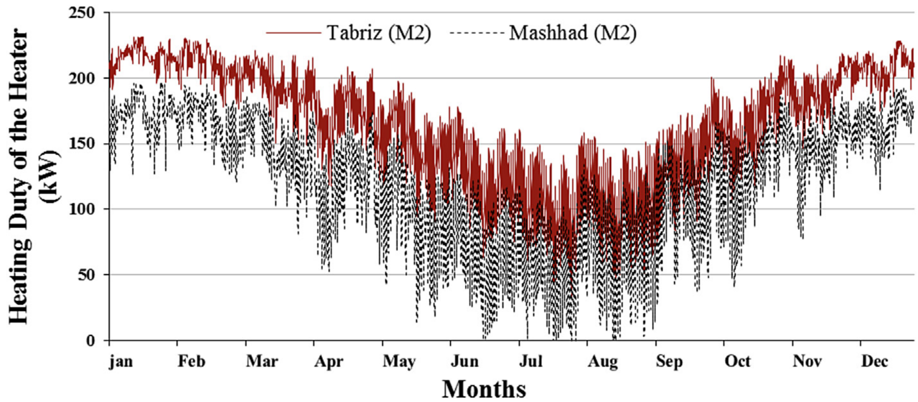

Fig. 7. Heating Duty of Tabriz and Mashhad CGS in NG mass flow rate of 3 kg/s.

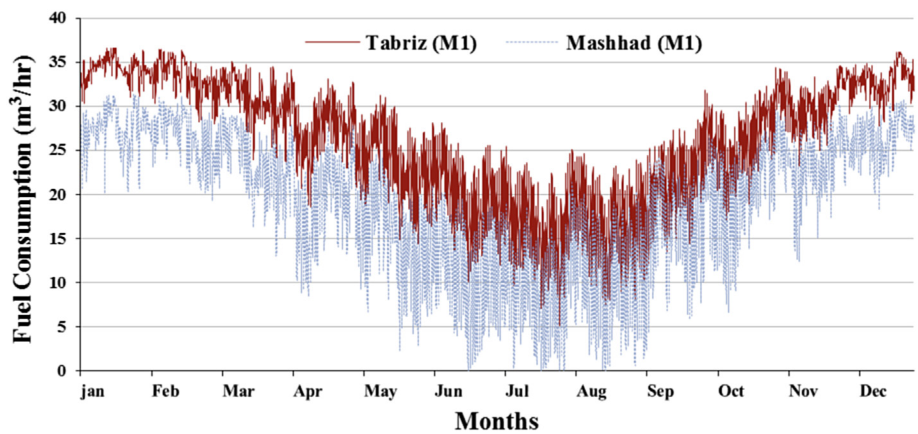

Fig. 8. The hourly fuel consumption rate of the stations without utilizing the proposed system in NG mass flow rate of 1.8 kg/s.

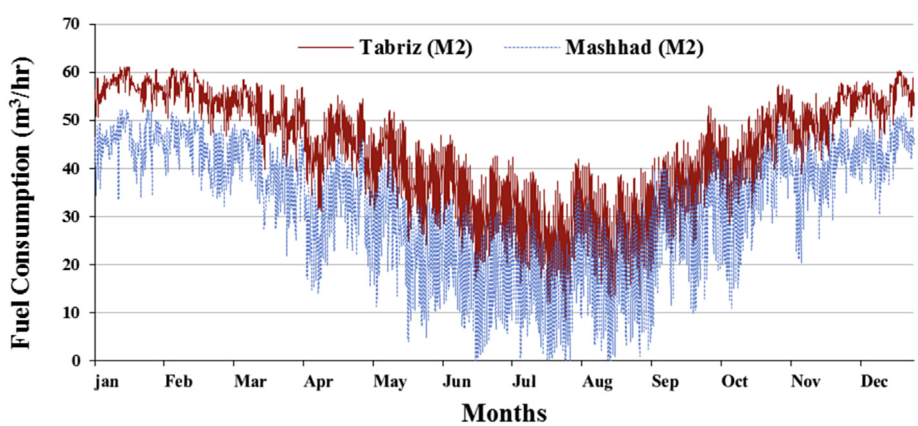

Fig. 9. The hourly fuel consumption rate of the stations without utilizing the proposed system in NG mass flow rate of 3 kg/s.

1.8 kg/s, maximum fuel consumption by the heaters located in Tabriz and Mashhad will be 36.6 m^3/hr and 31.3 m^3/hr respectively. At the inlet NG mass flow rate of 3 kg/s corresponding values are 61 m^3/hr and 52.2 m^3/hr. Total annual fuel consumption of the stations which must be eliminated by employing the vertical GCHP, are determined to be 227,908 m^3 and 166,943 m^3 for Tabriz and Mashhad at inlet NG mass flow rate of 1.8 kg/s respectively, and with the NG mass flow rate of 3 kg/s the corresponding values are 379,848 m^3 and 278,238 m^3.

6.1. *Identifying a high benefit system based on economic analysis*

Fig. 10 displays the selecting procedure of a proposed system for each station based on IRR method. Since the borehole length and distance between adjacent boreholes have a considerable impact on profitability of the proposed system (number of purchased heat pumps, drilling costs, operational cost, i.e. cost of electricity used by the heat pump) the best profitable system for each station is selected based on borehole length. To this aim, the proposed

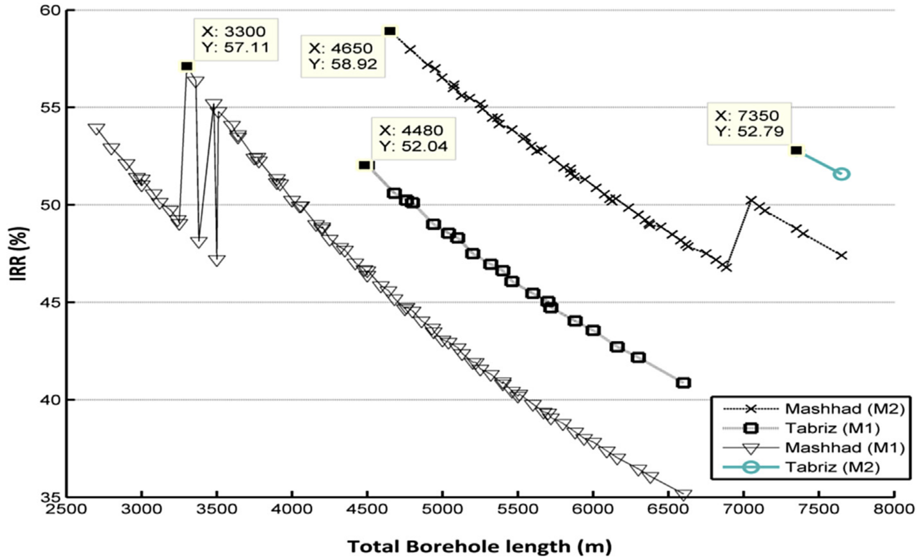

Fig. 10. Procedure of selecting a high benefit system.

system was simulated with different number of boreholes and depth range of 100–150 m. The distances between adjacent boreholes are also allowed to be 0.8H to decrease the thermal interaction between boreholes in long time operation of GCHP. Some configurations which had a low borehole length and were not able to deliver fluid in temperatures bigger than the minimum temperature allowed by the heat pump manufacturer (−7 °C) automatically were deleted in the simulation process. The simulation was accomplished for both Tabriz and Mashhad stations with two inlet NG mass flow rate of 1.8 kg/s and 3 kg/s. The details of the selected systems have been listed in Table 5.

Based on the tabulated results, Table 5, the IRR value of the four considered cases are more than 50%. The best IRR value belongs to the Mashhad station as the inlet NG mass flow is 3 kg/s. On the other hand the smallest value belongs to the Tabriz station with inlet NG mass flow rate of 1.8 kg/s. Compared to Mashhad stations, at the same NG mass flow rate, Tabriz stations have higher borehole length and they need one additional heat pump unit. Furthermore, due to high thermal load extracted by the GCHP units, the proposed system operates at temperatures near to the minimum allowable value (−7 °C) on the source side of heat pump (see the $T_{S,in,min}$ in Table 5).

6.2. Energy performance of the selected systems

Fig. 11 shows the total annual thermal energy absorbed from the ground by the vertical GCHP system in the stations. The descending behavior of the extracted heat from the ground over the 25 year simulation period is completely obvious. Since the vertical GCHP only extract ground heat (heating mode) and there is no heat delivering to the ground (cooling mode) to be able to recover its heat, boreholes environment gets colder and colder little by little

Table 5
Details of the selected systems.

	$T_{s,in,min}$ (°C)	H_{tot} (m)	H (m)	N_b	N_x	N_y	n_{HP}	IRR (%)
Tabriz (M1)	−6.75	4480	140	32	16	16	3	52.04
Mashhad (M1)	−3.33	3300	150	22	11	11	2	57.11
Mashhad (M2)	−6.5	4650	150	31	15	16	4	58.92
Tabriz (M2)	−6.57	7350	150	49	24	25	5	52.8

and year by year. The maximum and minimum heat extraction rate occurs in the 1st and 25th year respectively. Based on the total borehole length, stations with high borehole length absorb more free thermal energy from the ground. Consequently selected systems for Tabriz and Mashhad for NG mass flow rate of 3 kg/s and 1.8 kg/s are in the rank of 1–4.

By dropping the ground heating potential over the upcoming years, heat pump must consume more electricity power year by year to provide a constant heat load for the NG passing through the station. The increasing trend of the total annual electricity power consumption of the proposed system is clearly obvious in Fig. 12. The total power consumption of the proposed system is equal to power consumption by the circulating fluid pump and heat pump. Since the total annual pump power is constant; the ascending behavior of the total annual power consumption is due to the increase in heat pump power consumption. For the same inlet NG mass flow rate, Tabriz stations consume more power than Mashhad stations.

Heat pump COP is affected by entering fluid temperature to source side (evaporator). By increasing the evaporator inlet temperature, the performance of the vertical GCHP goes up. It means that the heat pump needs smaller amounts of electricity for the compressor. So, it is important to investigate the temperature variations of heat transfer fluid. In the present study, continuously heat extraction from ground degrades its energy level. As can be seen in Figs. 13 and 14, the heat transfer fluid temperature decreases due to temperature drop around the boreholes. At the NG mass flow rate of 1.8 kg/s, the minimum and maximum antifreeze fluid temperature at the outlet of vertical GHXs for the Tabriz and Mashhad stations are (−6.75–8.17)°C and (−3.33–13.81) °C, respectively. These parameters are equal to (−6.58–8.23) °C and (−6.51–13.30) °C at the NG mass flow rate of 3 kg/s.

Fig. 15 shows the average COP of the vertical GCHP and overall system in the whole life of the proposed system. The overall system COP comprises power consumption by the circulating fluid pump as well as the heat pump power consumption. As it can be seen, Tabriz stations COP of the heat pump and the whole system are in the range of (3–4). The corresponding values for Mashhad stations are in the range of 4–5. The higher COP values obtained by Mashhad stations imply that the operational cost of the proposed system (purchased electrical power from electricity grid) is lower

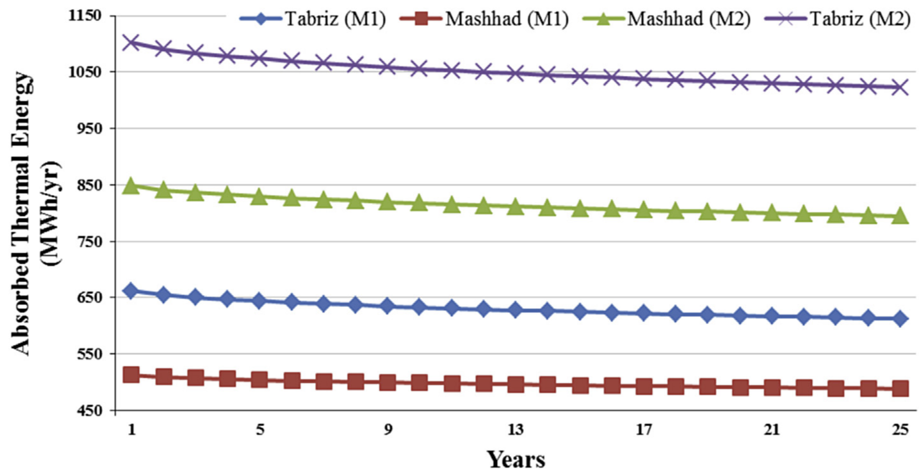

Fig. 11. Thermal energy absorbed from the ground by each of the selected systems.

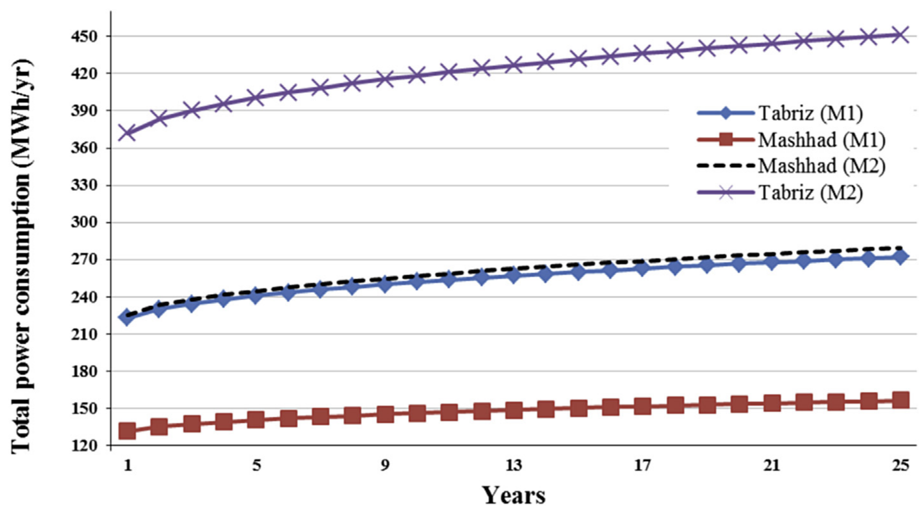

Fig. 12. The total electricity power consumption by the proposed system in the whole life of the system.

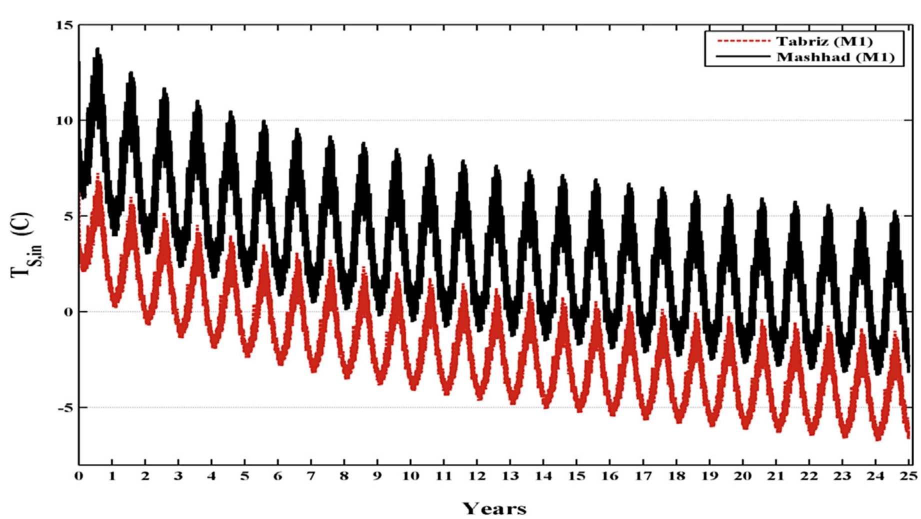

Fig. 13. Antifreeze fluid temperature at the outlet of vertical GHXs (NG mass flow rate of 1.8 kg/s).

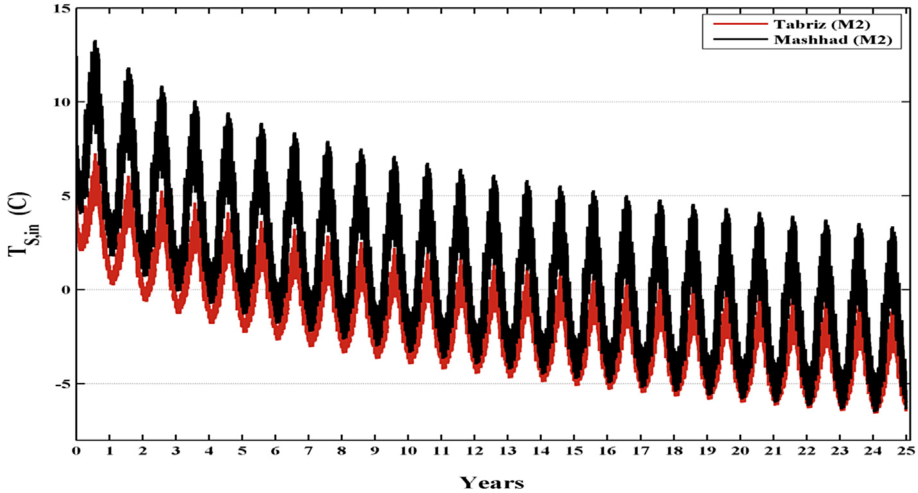

Fig. 14. Antifreeze fluid temperature at the outlet of vertical GHXs (NG mass flow rate of 3 kg/s).

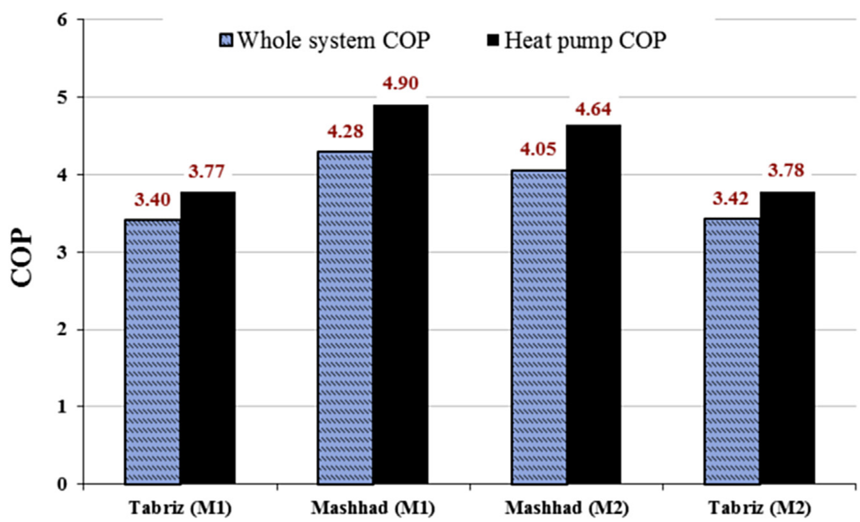

Fig. 15. The mean COP of the heat pump and whole system over the 25 years.

than Tabriz stations.

The proposed system is capable to eliminate the in situ fuel consumption of Tabriz and Mashhad CGSs; however the system indirectly consumes NG because of using electricity which is produced at a faraway thermal power plant. Fig. 16 shows the total annual NG consumption at a case which the local thermal power

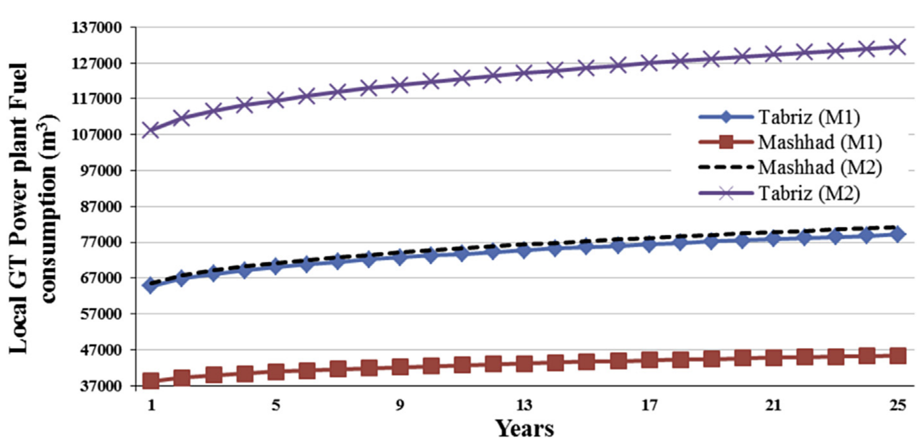

Fig. 16. The total annual NG consumption of gas turbine due to supplying required electrical power for the proposed system.

plant uses a gas turbine technology. According to the obtained results, the proposed system for the Tabriz station at the NG mass flow rate of 1.8 kg/s and 3 kg/s is able to save NG at an amount of (65.28–71.23) % and (65.41–71.52) % respectively. The corresponding values for the Mashhad stations are (72.79–77.13) % and (70.78–76.43) %.

Fig. 17 displays NG consumption at a case which local combined cycle power plant is responsible to provide electrical power for the proposed system. In comparison with the gas turbine power plant, combined cycle one consumes less fuel. Therefore, it is expected that the amount of NG saving will be considerable in this case. The NG saving at the Tabriz station with inlet NG mass flow rate of 1.8 kg/s and 3 kg/s are (75.91–80.27) % and (76–80.24) % respectively. The corresponding values for Mashhad station are (81.12–84.13) % and (79.73–83.65) %. As a result, the geothermal system is able to save a considerable amount of NG as a primary energy resource. In summary, Table 6 clearly presents the fuel consumption before and after the proposed system. In the presented table, first and final year fuel consumption of the proposed system have been included.

All in all, from point view of energy performance, COP of Mashhad CGS is approximately one unit higher than Tabriz CGS. Mashhad station has less borehole length and heat pump. In both stations, by increasing NG mass flow rate from 1.8 kg/s to 3 kg/s, 1.67 times rise, average absorbed thermal energy form ground is also increased 1.67 times, however, total borehole length for Mashhad and Tabriz increases 1.4 and 1.64 times, respectively. It could be concluded from presented results that for high NG mass flow rates, eliminating in situ fuel consumption by the proposed system is not possible because of high energy demand of NG stream and limited space of CGSs. For example by a rule of thumb, at NG mass flow rate of 15 kg/s, total borehole length in Mashhad station must be 23,100 m. In these cases, even decreasing distance between boreholes could not decrease required VGHX installation area (see Table 7). For such NG mass flow rates, the offered system could provide part of heat demand and the rest of heat demand could be provided by line heater or other renewable energy sources like solar energy.

One interesting parameter which has significant impact on performance of the proposed system is distance between boreholes. In the present study, it is assumed to be 0.08H, for instance, it is equal to 12 m for Mashhad station when NG mass flow rate is 1.8 kg/s. Mashhad station was selected to show this parameter effect on borehole number, length and occupied area, Table 7. For each borehole distance, the procedure of selecting high benefit borehole configuration was carried out. As it could be seen form Table 7, when B is 6 m, 50% decrease in distance between boreholes, total borehole length and occupied area by VGHXs increases by 40% and 100%. Therefore, it is concluded that decreasing borehole distance lead to increase in occupied area and if CGS capacity is high and there is limited area for installing VGHXs, installing the proposed system could be impossible and beside the offered system, another energy sources must be utilized. It is obvious that by decreasing borehole distance, borehole length is lowered, for parameter B equal to 6 m it is 105 m, and number of boreholes increases, it is because of lowering the thermal interaction between boreholes.

6.3. *Environmental performance of the selected systems: CO_2 emission*

CO_2 emissions of the proposed system and the conventional system are illustrated in Figs. 18 and 19 respectively. Fig. 18 shows a minimum (1st year) and maximum (25th year) CO_2 emissions of the proposed system against the conventional system emissions in a case of utilizing the electrical power from the gas turbine power plant. The maximum CO_2 emissions, 697.8 *ton CO_2/year*, belongs to the conventional CGS of Tabriz at the NG mass flow rate of the 3 kg/s. By employing the vertical GCHP system the maximum emissions of the system (at 25th year) drops to 383.7 ton *CO_2/year* (45% reduction in CO_2 emission). For the same inlet NG mass flow rate, CO_2 emission reduction of Mashhad station is in the range of (53.3–62.3) %. The corresponding values at the inlet NG mass flow rate of 1.8 kg/s were determined to be (44.8–54.8) % and (56.5–63.4) % for Tabriz and Mashhad stations respectively.

Fig. 19 shows CO_2 emissions for each station where the combined cycle power plant is employed for generating electricity. In this case, by employing the proposed system, reduction potential of CO_2 emission is determined to be (68.7–74.3) % and (73.4–78.6) % for Tabriz and Mashhad stations at the inlet NG mass flow rate of 3 kg/s respectively. At the inlet NG mass flow rate of 1.8 kg/s the corresponding values for both stations are in the range of (68.6–74.3) % and (75.3–79.2) %.

In a case of using combined cycle power plant electricity, the CO_2 emission reduction potential of the proposed system at Tabriz and Mashhad stations is over 68% and 73% respectively. In a case of gas turbine the corresponding values are over 45% and 53%. The obtained results prove that the innovative system is able to prevent

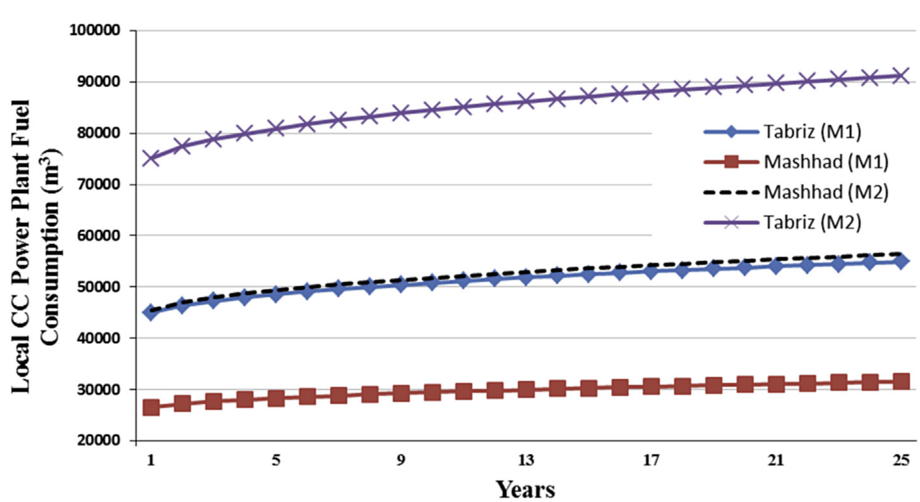

Fig. 17. The total annual NG consumption of combined cycle power plant due to supplying required electrical power for the proposed system.

Table 6
Fuel consumption before and after of current proposed system.

Fuel consumption (nm^3)		Tabriz (M1)	Mashhad (M1)	Tabriz (M2)	Mashhad (M2)
After GCHP, (GT power plant)	1st year	64,817	38,185	108,195	65,578
	25th year	79,123	45,425	131,395	81,290
After GCHP, (CC power plant)	1st year	44,971	26,493	75,068	45,499
	25th year	54,897	31,517	91,164	56,400
Before GCHP		227,908	166,943	379,848	278,238

Table 7
Effect of distance between boreholes on borefield parameters.

Parameter	B [m]		
	6	8	10
N_y	22	18	16
N_x	23	19	17
H	105	110	110
H_T	4620	3960	3520
N_b	44	36	32
A	2904	2592	2560

of releasing a large amount of CO_2 into the earth's atmosphere.

6.4. Economic aspects of the selected systems

Fig. 20 illustrates the total annual obtainable benefit from the proposed system in the considered CGSs. For the first year, the annual benefit for Tabriz station at the NG flow rate of 1.8 kg/s and 3 kg/s is over 55,000 and 125,000 USD respectively. The corresponding values for Mashhad stations are over 75,000 and 95,000 USD. Although, the annual benefit of the system decreases over time, even after 25 years, the system still works impressively.

Based on the results presented above, for the proposed system

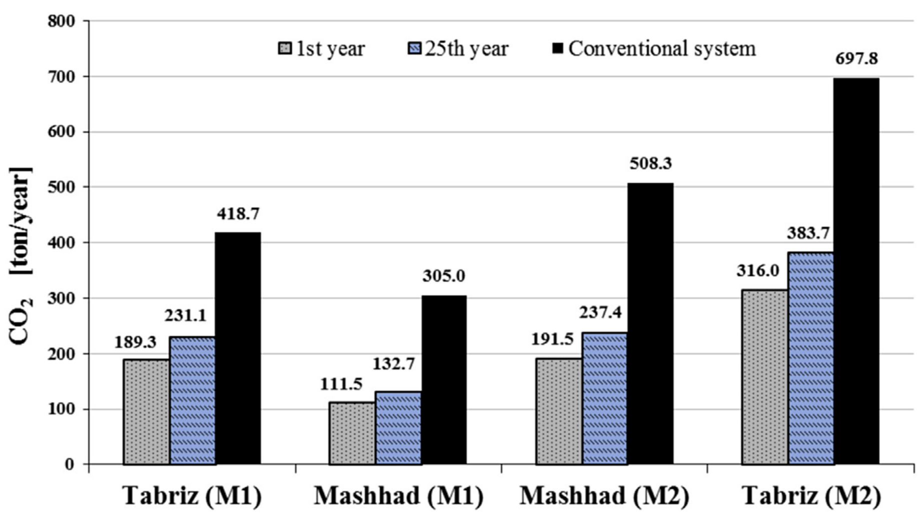

Fig. 18. CO_2 emission by the conventional and proposed system based on utilizing electricity of GT power plant.

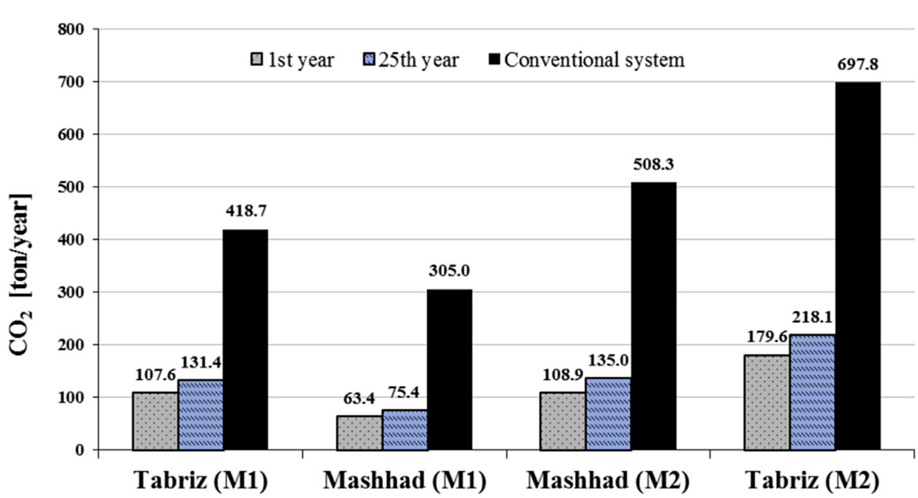

Fig. 19. CO_2 emission by the conventional and proposed system based on utilizing electricity of CC power plant.

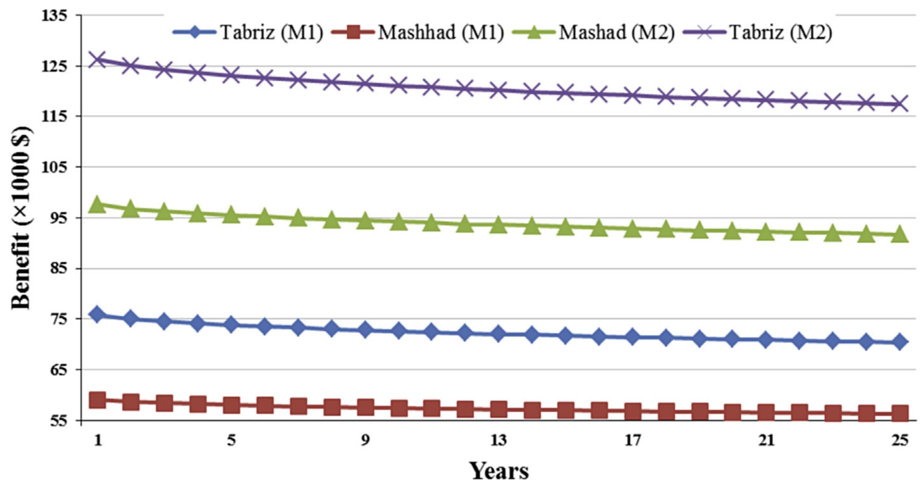

Fig. 20. The total benefit utilizing the proposed system in 25 years operation.

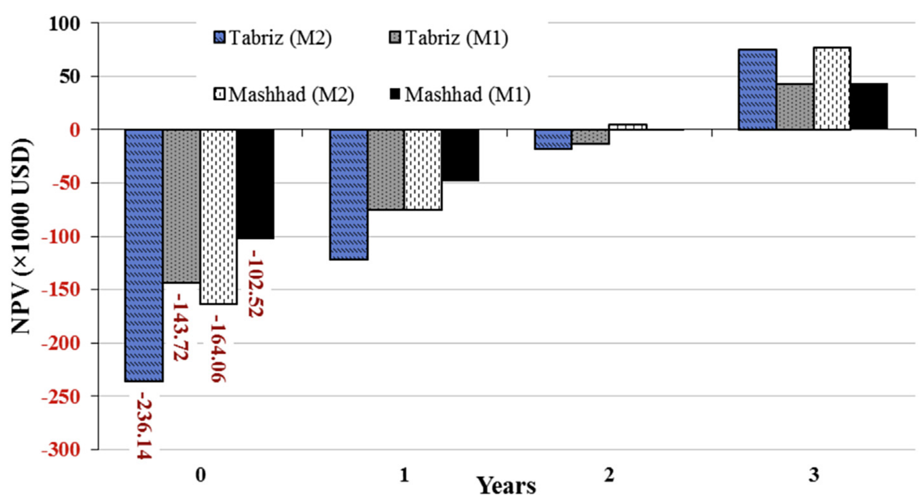

Fig. 21. NPV analysis of the system for assessment discounted payback period of the selected system.

in CGSs, Fig. 21 presents the discounted payback period of the system on a basis of the NPV method. In this assessment, the inflation rate has been considered 10% and the total annual O&M costs for the system has been considered 2% of the total capital cost. The analysis showed that, at the NG mass flow rate of 1.8 kg/s, the NPV of Tabriz and Mashhad stations are 521,391 USD and 421,727.1 USD respectively. Corresponding values at the NG mass flow rate of 3 kg/s are also 873,071.3 USD and 697,579.4 USD. The capital cost of the system is shown in Fig. 21.

Based on Fig. 21, the discounted payback period for Tabriz and Mashhad stations were determined to be 2.23 and 2 years at the NG flow rate of 1.8 kg/s respectively. Corresponding values at the NG flow rate of 3 kg/s were also determined to be 2.19 and 1.94 years.

According to obtained results, at the same NG mass flow rate, Tabriz stations need to high capital cost, (this is because of high energy demand and low undisturbed ground temperature), about 1.4 times of Mashhad stations however, the NPV of Tabriz stations are higher than Mashhad. The project DPP for the Tabriz stations is also higher than Mashhad, DPP difference of these two cities are negligible. Compared to Mashhad stations, IRR of the project for Tabriz stations are low. Results also express that by increasing NG mass flow rate DPP of the project decreases.

The previous economic analysis were based on NG price of 0.44 USD/m^3, VGHX cost of 20 USD/m, electricity price of 0.11 USD/kwh and discount/inflation rate of 10%, for better showing the economic performance of the system, the values of these 4 parameters were changed. Table 8 informs the impact of these parameters on the DPP and IRR of the system. Based on these results, NG price has a significant impact on economic viability of the project, for instance at the same condition, but in different NG prices, NG price of 0.03, DPP of the system is higher than 25 years and IRR is lower than assumed discount rate for NG price of 0.03, but, in NG price of 0.27, the project DPP is lower than7 years and IRR is more than 23%.

For better comparing, the effect of other parameters on economic performance of the offered system (distance between boreholes, parameter B) are also investigated. Consequently, parameter B allowed to vary as 6 m, 8 m and 10 m. Mashhad station with NG mass flow rate of 1.8 kg/s was selected as case study. Details of boreholes configurations could be seen in Table 7. As it could be viewed from Table 9, when distance decreases 50%, 6 m, capital cost rises 27%, NPV drops −6.5%, IRR decreases from 57.11% to 45%, 12% drop, and DPP increases from 2 years to 2.77 years. By increasing parameter B, capital cost and DPP decreases and NPV and IRR increase. In comparison to effect of NG price on DPP and IRR (see Table 8), effect of parameter B is negligible.

Table 8
Impact of some important parameters on DPP and IRR of the project.

NG price (USD/m^3)	VGHX cost (USD/m)	Electricity price (USD/kWh)	DR (%)	Tabriz (M1)		Mashhad (M1)		Tabriz (M2)		Mashhad (M2)	
				DPP (years)	IRR (%)	DPP (years)	IRR (%)	DPP (years)	IRR (%)	DPP (years)	IRR (%)
0.03	20	0.11	7	–	–	–	–	–	–	–	–
0.03	30	0.05	10	–	–	–	–	–	–	–	–
0.03	40	0.03	13	–	–	–	–	–	–	–	–
0.14	20	0.11	7	–	–	–	–	–	–	–	–
0.14	30	0.05	10	–	–	19	11	–	–	16.62	12
0.14	40	0.03	13	–	–	–	–	–	–	–	–
0.27	40	0.03	13	6.75	23	6.35	24	6.59	23	5.60	26
0.27	30	0.05	10	5.01	26	4.62	29	4.92	27	4.27	31
0.27	20	0.11	7	4.85	25	4.01	28	4.77	25	3.91	30
0.35	20	0.11	7	3.01	38	2.66	42	2.96	38	2.58	43
0.35	30	0.05	10	3.42	36	3.22	38	3.36	36	2.97	40
0.35	40	0.03	13	4.47	31	4.28	32	4.38	31	3.83	35

Table 9
Effect of distance between boreholes on economic parameters.

Parameter	B [m]		
	6	8	10
Capital cost (US$)	130,240	116,560	107,520
NPV (US$)	394,239.9	407,752.5	416,074.3
DPP (Years)	2.77	2.45	2.23
IRR (%)	45	50.3	54.14

7. Conclusion

The throttling valves are utilized in CGSs to reduce pressure of inlet natural gas. Concurrent with the natural gas pressure reduction, the temperature also drops. To prevent blocking of the downstream pipeline, NG must be preheated before pressure reduction. A large amount of natural gas as fuel is consumed for preheating task by CGS heaters. In addition to the high fuel consumption, the heaters release a huge amount of CO_2 into the atmosphere. The present study proposes a new system for in-situ fuel consumption elimination at these stations. It utilizes vertical GCHP system as a renewable source of energy to preheat NG stream. The system performance was studied at two different climatic conditions of Iran which have also two different natural gas compositions.

The proposed innovative system showed a great energy performance even at one of the coldest climate of Iran which has a lower undisturbed ground temperature between the other provinces. The proposed system is capable to eliminate in-situ fuel consumption of considered cases, however it needs electricity for running the GCHP. So in terms of fuel consumption reduction, the new system could reduce over 65% NG consumption.

The ability of the proposed system to reduce CO_2 emission is the other significant aspect of the studied system. It could reduce emissions over 45% and reach up to 79%. Economic analysis also showed the system IRR is always more than 50% and the discounted payback period is around the 2 years for all considered cases. One could conclude that the proposed system for eliminating the in-situ fuel consumption is a good solution with interesting emission reduction potential and economic viability, which could employ in CGS even for cold climates.

Nomenclature

q	Heat flux (W/m)
H	Active borehole length (m)
R	Thermal resistance
f	Friction coefficient
d	Diameter (m)
D	Inactive borehole length (m)
DR	Discount Rate
B	Borehole distance (m)
m_w	The line heater water mass (kg)
c_f	Antifreeze solution specific heat
T_f	Antifreeze average temperature at the ground heat exchanger (°C)
$T_{S,out}$	Antifreeze solution temperature at the ground heat exchanger inlet (°C)
$T_{S,in}$	Antifreeze solution temperature at the ground heat exchanger outlet (°C)
T_0	Ambient temperature
N_b	Number of boreholes
C_w	The line heater water thermal capacity
$C_{p,NG}$	Natural gas thermal capacity
$\dot{m}_f$	The mass flow rate of antifreeze solution (kg/s)
$\dot{m}_{NG}$	The mass flow rate of natural gas passing through the station (kg/s)
$\dot{Q}_{NG}$	Heat absorbed by the natural gas when passes through line heater (kW)
$\dot{Q}_{HP}$	Heat delivered to system with heat pump (kW)
$\dot{Q}_H$	Heating duty of line heater

Greek letters

η_h	Thermal efficiency of line heater
α	Soil thermal diffusivity
$\mathcal{F}$	Fast Fourier Transform

Subscripts

tv	Throttle valve
o	Outer
NG	Natural Gas
in	Inlet
i	Inner
hyd	Hydrate
g	Ground
Conv	Convection
Cond	Conduction
bw	Borehole wall
b	borehole

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