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Environmental study of waste energy recovery by using exergy and economic analysis in a fluid catalytic cracking unit

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ABSTRACT

An increase in fossil fuel consumption has significantly increased the concentration of greenhouse gases (GHGs). Waste energy recovery can reduce GHGs by reducing fossil fuel consumption. In the FCC unit in refineries, the catalyst is continuously regenerated by burning off the deposited coke with air and a large flux of waste gas with high temperature is generated which is vented into the atmosphere. The purpose of this study was to investigate the effect of waste heat/pressure recovery of the waste gas on the reduction of GHGs and air pollutant emissions. Based on this objective, exergy and economic analysis were carried out for two scenarios (S-1 and S-2). The S-1 scenario involved the installation of a Heat Recovery Steam Generator (HRSG), while S-2 applied the simultaneous usage of HRSG and a turbo-expander to evaluate electricity production using waste gas pressure. The exergy of waste gas was formulated and an in-house code was developed for solving the equations via a trial and error method. The results showed that exergy loss of the waste gas was higher than 660 MW and it was possible to recover about 64 MW and 75 MW in the S-1 and S-2, respectively. The amount of steam and the electrical energy produced were found to be about 88 ton/h and 8323 MWh/month, respectively. The results also showed that S-1 can reduce 72227 tCO2e of GHGs and 327 ton of air pollutant and S-2 can reduce 143464 tCO2e of GHGs and 649 ton of air pollutant annually. The economic indexes were evaluated and the results indicated that the internal rates of return (IRR) were found to be 33.18% and 36.76% for S-1 and S-2, respectively. This showed that the two scenarios were economically feasible, but from an environmental, economic and energy recovery standpoint, S-2 was the best scenario and the economic analysis on S-2 certified that there was no economic risk.

1. Introduction

Energy demand has increased all over the world due to the rapid developments in chemical and manufacturing industries. The global demand of energy was estimated to be 13.371 billion tonnes of oil equivalent (btoe) in 2012 by the International Energy Agency and is predicted to grow to around 18.30 btoe by 2035 under current policies. This represents an increase of 1.37%. Currently, about 65% of the world energy demand is supplied with gaseous and liquid fossil fuels because of their widespread availability and convenience of use. By 2050, the global demand for energy is estimated to double or triple [1]. The extensive consumption of these fuels has produced an excessive volume of greenhouse gases (GHGs) in the atmosphere; this issue is a cause for concern due to the harmful effects of

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GHGs on the environment. Industrial flue gas emissions include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons particulate matter and sulfur dioxide (SO_2), which have an adverse impact on human health, plant species, various ecosystems and the overall environment. GHGs also play a vital role in global warming. Among GHGs, CO_2 is the most widely produced gas that is directly involved in climate change, and greenhouse gases emissions contain about 77% of CO_2 [2]. According to recent studies, around 56% of CO_2 emissions are generated by fossil fuel combustion in the industrial sector [3]. Recent IPCC reports show that the atmospheric CO_2 concentration is now close to 400 ppm and it is continuously increasing. However, most comprehensive studies recommend its safe level to be below 350 ppm [4]. Therefore, it is vital to find acceptable strategies for reducing the amounts of CO_2 in the atmosphere. Recently, several countries have signed the Kyoto Protocol to fight global warming by reducing their emission levels. Consequently, several mitigation strategies have been developed, including improving the energy efficiency of industrial processes, reducing fossil fuel consumptions by using alternative energy such as clean and renewable fuels, energy conservation, and CO_2 capture and storage. The first two options call for efficient use of energy and the examination of low carbon-intensive energy (e.g., natural gas) or renewable energy (e.g., biogas, H_2, solar and wind power), while the third option suggests the development of new energy efficient technologies for CCS [5]. This involves the capture of CO_2 directly from industrial or utility plants which is then stored in a secure medium [6]. However, the development and utilization of CCS technology suffers from many uncertainties and knowledge gaps in terms of costs, storage capacity and permanent storage, lifecycle effects, but researchers are trying to find ways to solve these problems [7]. Due to the limitations of carbon capture storage facilities, it is necessary to find technologies that can use captured carbon in sustainable ways [2]. For example, hydrogen is a high energy feedstock that can react with carbon dioxide. The CO_2 needed for this reaction can come from various sources including the captured CO_2 [8]. In this field, Matzen et al. [9] proposed a method of producing methanol from renewably derived H_2 and CO_2. In recent years, renewable energy technologies have attracted considerable attention and several renewable energy sources have been presented and investigated [10]. Renewable energy is any energy resource that is naturally regenerated over a short time scale and results directly or indirectly from the sun such as photochemical and hydropower, or from other natural movements and mechanisms of the environment such as geothermal energy. [11]. Technologies for energy production from renewable sources have been developed over time [12] in the past two decades, crude oil usage has increased by nearly 32%, natural gas by 63%, and coal consumption by a striking 78%. In terms of absolute numbers, the total renewable energy consumption of 316 MTOE (million ton oil equivalent) in 2014 stands a little forlorn when compared with the increase in two decades of nearly 4000 MTOE in the yearly consumption of fossil fuels [13]. The growing use of fossil fuels illustrates that there is a clear need to continue efforts to develop more efficient and cost-effective methods as well as utilizing fossil fuels more efficiently and in environmentally sensitive manners. Emissions reductions from the direct combustion of fossil fuels in industries could be attained by decreasing fuel usage or improving the efficiency of industrialized processes. In this area, William et al. [14] employed an aggregated notional refinery model (NRM) to study efficiency improvement measures applicable to refining, and they quantified the potential cost of conserved energy for these measures. They found that roughly 1500 petajoules per year of plant fuel savings and 650 GWh per year of electricity savings were potentially cost-effective. This equates to a potential 85 Mt-CO_2/yr reduction. Pressure reduction in natural gas transmission systems and the natural gas industry is usually achieved by mechanical valves which waste a great amount of latent energy of high pressure gas. The exergy evaluation of the natural gas stream through the pressure reduction process has been of interest for many years. In this area, Pozivil [15] investigated the possibility of utilizing turbo expanders in the natural gas pressure reduction stations (CGS) using HYSIS software. He evaluated the special effects of the isentropic efficiency of these turbines on the temperature and pressure drop of the NG as well as electricity generation. Farzaneh-Gord and Magrebi [16] studied waste exergy in Iran's CGSs and showed that a total of 4200 MW electricity can be generated in these stations. Jesse et al. [17] quantified the energy that can be extracted from various pressure reduction facilities using an expander coupled to an electric generator. They created a model to analyze the problem with seasonal variations of the gas flow rate entering the facility. Their results revealed if the coupled technologies operate at their assumed peak efficiencies, then electricity can be extracted from the pressure reduction with 75% exergetic efficiency. In another work, Arabkoohsar et al. [18] studied the feasibility of replacing the throttling valve with a turbo expander in order to utilize the NG stream exergy in a natural gas pressure reduction station (CGS). They also investigated using a solar heating system aimed at reducing the heater fuel consumption for preheating NG. The net present value (NPV) method was employed to analyze the proposed system's economic effectiveness. Sharma and Singh [19] carried out an exergy analysis of a dual pressure (DP) heat recovery steam generator (HRSG). Results were obtained for the exergy loss and exergy efficiency with varying dead state temperatures for different HP and LP steam generation states in different sections of the HRSG. The exergy analysis for the chosen conditions/parameters was implemented to locate the particular sections of the HRSG having maximum exergy loss. Their results were useful in finding the thermodynamic states that will help in reducing the exergy destruction for enhancing HRSG performance which eventually improves the efficiency of combined cycle power plants. Li et al. [20] proposed a novel once-through HRSG which could be used for low temperature heat resource recovery. Experiments were carried out in a cement plant under different conditions to study its thermal performance. They performed exergetic and economic analyses of the HRSG and built a mathematical model based on the energy and mass balance equations. Moreover, a flash tank was employed in their study and optimized researches were carried out to find the best exergy efficiency of the HRSG. Their results showed that the HRSG was highly efficient in recovering energy from a low temperature heat source. The above literature review illustrates that previous research mostly focused on fuel consumption, CO_2 capturing, and process efficiency, while none of them have yet fully considered a combination of the pre-mentioned factors (environmental, amount of energy recovery and economic). In the present study, the relation between waste pressure/heat recovery, income and carbon emissions reduction was investigated for a waste gas stream using exergy analysis and economical evaluation. For this purpose, the exergy losses of gas flow were determined and a HRSG and a turbo-expander were used to generate steam and electricity using waste energy.

2. Process Description

The fluid catalytic cracking (FCC) process is one of the most important conversion processes used in petroleum refineries. It is used to convert the raw material including high-boiling, high-molecular weight hydrocarbon fractions of petroleum crude oils into more valuable gasoline, olefinic gases, and other products. The cracking reaction is driven by the presence of a catalyst and takes place in an ascendant reactor (RISER). The coke is generated as a by-product of the cracking reaction and settles all over the catalyst surface, diminishing its performance. Regeneration of the catalyst must be continuously carried out to maintain catalytic activity and extend the catalyst's life. The exhausted catalyst is sent to a regenerator where coke is removed from the catalyst's surface by burning it with air (oxidation). As a result, a flux of waste gas is generated and released into the atmosphere. The operating temperature and pressure of the regenerator are about 678 °C and 2.71 bar, respectively. This stream of waste gas with high temperature and pressure has significant energy that can be recovered and used in other sections of the refinery. Figure 1 shows a simple diagram of a FCC unit. It should be noted that there are two limitations for the pressure and temperature of waste gas after energy recovery. Its pressure must be higher than atmospheric pressure (P_{WG} after energy recovery 1.013 bar); otherwise, it cannot be released to atmosphere. Also, its temperature must be higher than the dew point of the waste gas in this pressure (dew point of waste gas is lower than 93 C°).

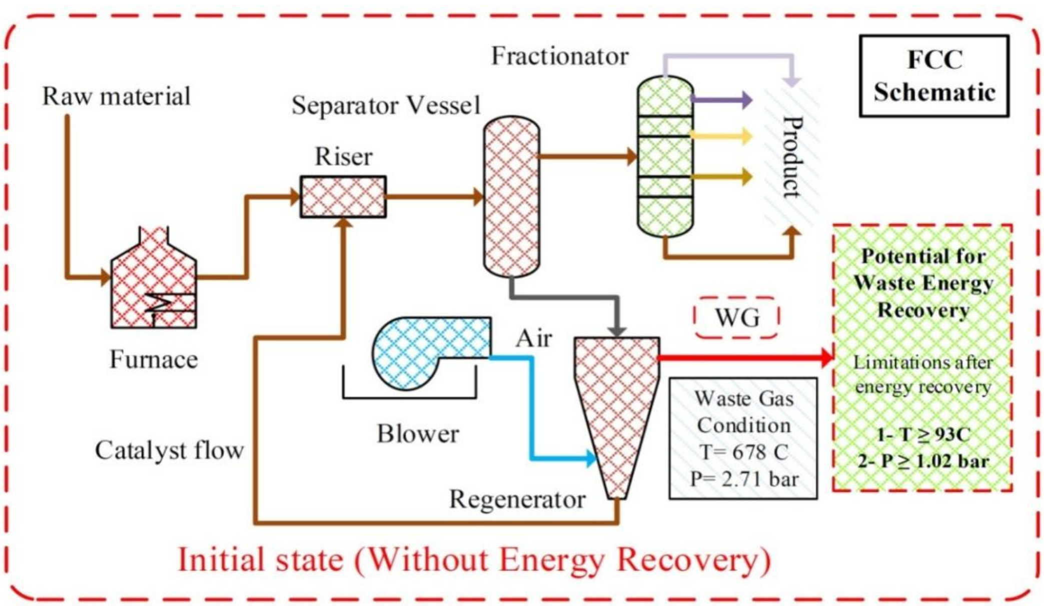

Fig. 1. Schematic of Fluid Catalytic Cracking (FCC) process, without energy recovery

3. Methodology

The main objectives of this work were to analyze the maximum waste energy recovery of the waste gas and GHGs emissions reduction as well as to show whether it was economically feasible. In fact, the idea involved an alternative use of waste heat/pressure energy that would not have been used in the absence of the proposed idea.

For this purpose, two scenarios were proposed. The first scenario consisted of the installation of a HRSG in which the waste gas flows into to provide the waste heat energy recovery and produce steam (section a of Figure 2). In the second scenario, a turbo expander was installed exactly after the HRSG was added to the previous system where the waste pressure energy was used. There is a synchronous generator connected to the turbo expander to generate electricity (sections a and b of Figure 2). A heat recovery steam generator (HRSG) is a heat exchanger designed to recover waste heat from a hot gas stream. The recovered heat is used to generate steam that can be used to in a process such as cogeneration or used to drive a steam turbine to generate more electricity. Also, a turbo-expander is a mechanical device through which a high pressure gas is expanded to a lower pressure level to produce work. As the mechanical work is produced, the enthalpy of the gas decreases. Although in reality, the expansion do not occur in an isentropic state, but it can produce a high percentage of the ideally possible work. In a pressure break-down process, the gas is allowed to expand and consequently, a certain temperature drop occurs while the enthalpy of the gas stream decreases. This enthalpy variation possesses the potential for work generation which its loss can be evaluated via exergy analysis.

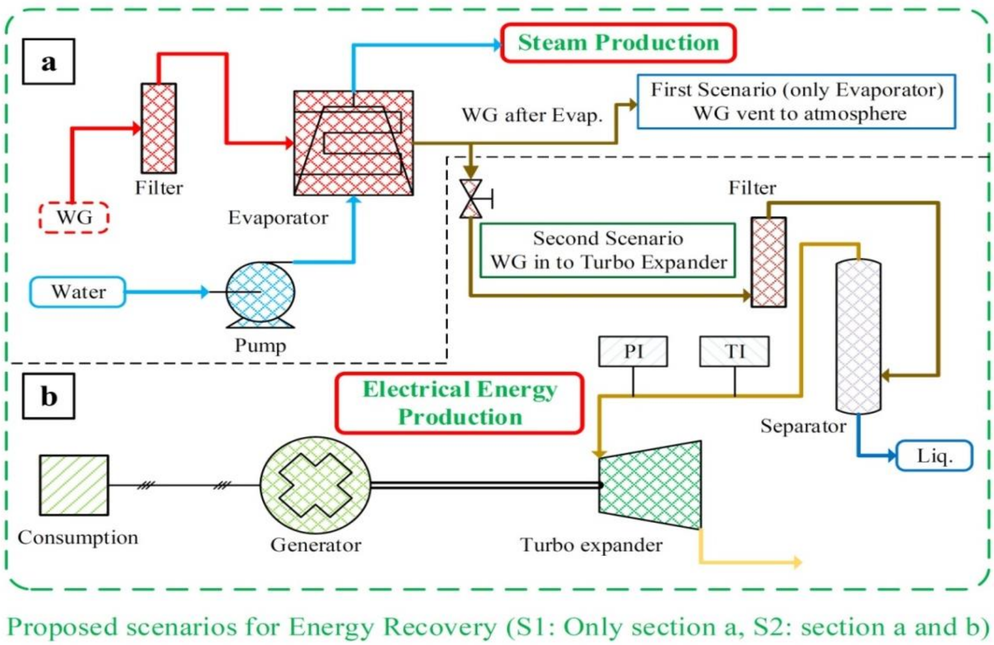

Fig. 2. Schematic of energy recovery with two scenarios (S1-only steam production, S2- steam and Electrical energy production)

There is both pressure and thermal energy in this process and due to that, the exergy must be calculated to compute the amount of energy recovery. The first scenario includes the installation of a single HRSG and the second scenario involves the simultaneous installation of a HRSG and turbo expander.

3.1. Exergy analysis

Exergy of a system at a certain thermodynamic state is defined as the maximum useful work that can be obtained when the system moves from that particular state to a state of equilibrium with the surroundings. Therefore, the exergy loss provides a very important criterion to evaluate the thermodynamic performance of a system. Energy exists in many different forms and each form has a different exergy or quality. Energy recovery analysis of the system makes it known just how the cycle is suitable or economically feasible for investment. The exergy loss is measured by making an exergy balance for each component of the system. In this study, the main assumptions include an adiabatic process, a steady state operation, and constant gas stream component. The percentage of the exergy loss in each component of a system can be calculated and expressed as the ratio of the partial exergy loss to the total exergy loss [21]. The total exergy equation can be expressed as follows:

$$\mathrm{Ex} = \mathrm{Ex_k} + \mathrm{Ex_P} + \mathrm{Ex_{Ph}} + \mathrm{Ex_{Che}} \tag{1}$$

In the above equation, $Ex_k = \frac{v_e^2}{2}$ and $Ex_p = \mathrm{gz}$ are kinetic and potential exergy, respectively. Chemical exergy, Ex_{Che}, is defined as follows:

$$Ex_{Che} = T_0 R \sum_{i=1}^{n} y_i \ln\left(\frac{y_i}{y_{i0}}\right) \tag{2}$$

Ex_{ph}, the physical exergy, can be determined with the enthalpy and entropy values of the gas stream (characterized by its composition) at the generic state, and the environmental state temperatures and pressures. The thermodynamic exergy can be defined as

$$\mathrm{Ex_{ph}} = (\mathrm{h} - \mathrm{h_0}) - \mathrm{T_0}(\mathrm{S} - \mathrm{S_0}) \tag{3}$$

To calculate the enthalpy term, it is defined as a function of *T* and *P*, i.e. *h = h (T, P)*, and can be evaluated from the following equation:

$$dh = \left(\frac{\partial h}{\partial T}\right)_p dT + \left(\frac{\partial h}{\partial P}\right)_T dP \quad (4)$$

The following equations are derived by using the Maxwell relations:

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p \quad (5)$$

$$Tds = dh - vdP \quad (6)$$

$$h - h_0 = \int_{T_0}^{T_1} C_p dT + \int_{P_0}^{P_1} \left[v - T\left(\frac{\partial v}{\partial T}\right)_p\right] dP \quad (7)$$

By employing the so-called equation of state, *Pv=ZRT*, the following equation is attained:

$$h - h_0 = C_P(T_1 - T_0) - RT_1^2 \left(\frac{\partial Z}{\partial T}\right)_P \ln\frac{P_1}{P_0} \quad (8)$$

Using Maxwell relations and equation of state *PV=ZmRT*, the entropy in terms of *T* and *P* (s= s (T, P)) can be obtained as follows:

$$s - s_0 = C_P \ln\frac{T_1}{T_0} - ZR\ln\frac{P_1}{P_0} - \left(\frac{\partial Z}{\partial T}\right)_P RT_1 \ln\frac{P_1}{P_0} \quad (9)$$

The physical exergy term can be calculated from Eq. (10).

$$\begin{aligned} Ex_{ph} = C_P(T_1 - T_0) - C_P T_0 \ln\frac{T_1}{T_0} + ZRT_0 \ln\frac{P_1}{P_0} \\ + RT_1T_0\left(\frac{\partial Z}{\partial T}\right)_P \ln\frac{P_1}{P_0} \\ - RT_1^2\left(\frac{\partial Z}{\partial T}\right)_P \ln\frac{P_1}{P_0} \end{aligned} \quad (10)$$

Eq. (11) and (12) are used to calculate the specific heat at constant pressure.

$$C_{Pi} = a_i + b_iT + c_iT^2 + d_iT^3 \quad (11)$$

$$C_P = \sum_{i=1}^{n} y_i C_{pi} \quad (12)$$

3.2. Solution procedure

A gas with high temperature can be used for steam production. For this purpose, the hot gas flows into an evaporator and after increasing the temperature of water to its boiling point, converts it into steam and this is an energy recovery. The right side of relation (13) presents the heat required for increasing of water temperature, latent heat of vaporization, and the heat required for superheating the steam.

$$\dot{m}_{WG}C_{PWG}(T_{WG} - T_1) = \dot{m}_W C_{PW}(T_{Win} - T_{sat}) + \dot{m}_W\lambda_W + \dot{m}_S C_{PS}(T_{SSuper\,heat} - T_{Ssat}) \quad (13)$$

The waste gas also has pressure energy and it is possible to use this energy too. When a gas flow expands from pressure P1 to P2 adiabatically by turbo expander, an isentropic process occurred. Here, the enthalpy variation can be expressed as:

$$H_{2s} - H_1 = Q - W_s \quad (14)$$

Because the break-pressure process is a very quick phenomenon, then *Q* is zero which indicates the turbo expander efficiency. The isentropic temperature ratio after the process is specified by the following formula:

$$\frac{T_{2S}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad (15)$$

In above relation, γ is the heat capacity ratio which is temperature dependent. The variations of enthalpy and entropy can be calculated using Equations (16) and (15):

$$\begin{aligned} \Delta h = C_P(T_2 - T_1) - RT_2^2\left(\frac{\partial Z}{\partial T}\right)_{P_2} \ln\frac{P_2}{P_0} \\ + RT_1^2\left(\frac{\partial Z}{\partial T}\right)_{P_1} \ln\frac{P_1}{P_0} \end{aligned} \quad (16)$$

$$\begin{aligned} \Delta s = C_P \ln\frac{T_2}{T_1} - ZR\ln\frac{P_2}{P_1} - \left(\frac{\partial Z}{\partial T}\right)_{P_2} RT_2 \ln\frac{P_2}{P_0} \\ + \left(\frac{\partial Z}{\partial T}\right)_{P_1} RT_1 \ln\frac{P_1}{P_0} \end{aligned} \quad (17)$$

In this study, an iterative algorithm based on the above formulations is used to calculate the HRSG and turbo expander energy recovery (Figure 3). Following the algorithm, an in-house code is developed to calculate the exergy of temperature reduction and pressure break. The code calculates the energy recovery gained by the HRSG and the turbo expander too. It should be noted that proportional to the quantity of the energy recovery (steam and electrical energy production), the amount of the GHGs emissions will be reduced.

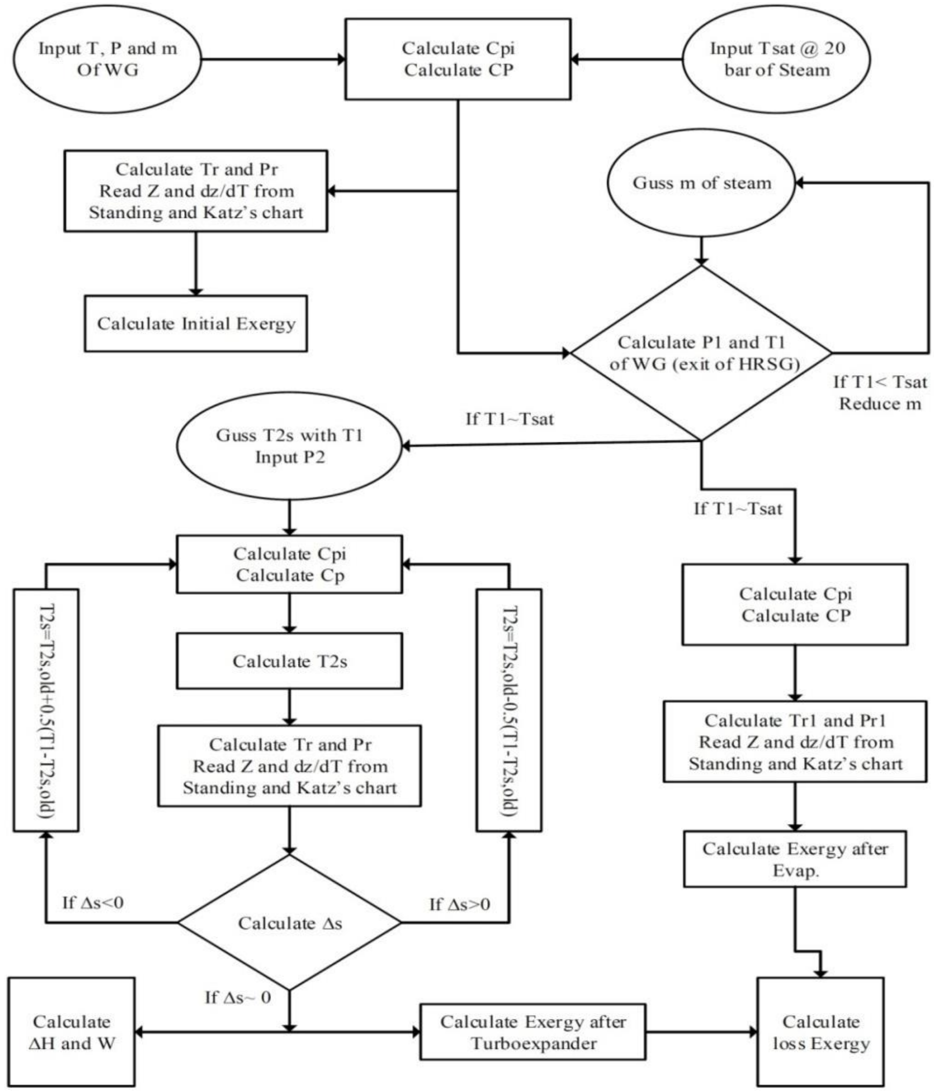

Fig. 3. Algorithm for exergy and energy recovery calculation

3.3. Combustion GHG emissions estimation

As noted previously, the fuel combustion of power plants and refineries release GHGs emissions. This section presents a standard method for the emissions estimation of the major greenhouse gases from fuel combustion. A combustion process may produce carbon dioxide, CH_4, and N_2O. A material balance approach based on fuel carbon analyses and fuel usage data is one of the most reliable techniques for estimating the emissions from stationary combustion sources. It can be applied to the combustion of any fuel, granted fuel carbon analyses are likely more readily available for produced or purchased gas streams than for refinery gas, liquid or solid fuels. Assuming a complete combustion, the combustion of hydrocarbons may be presented by the following general reaction [22]

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2}\right) O_2 \rightarrow (x)CO_2 + \left(\frac{y}{2}\right) H_2O \quad (18)$$

CO_2 emissions are calculated using a mass balance approach. The equations are slightly different and depend on whether the fuel combusted is a gas, liquid, or solid. The CO_2 emissions of gaseous fuels combustion can be calculated using the following equation, assuming 100% oxidation.

$$E_{CO_2} = FC \times \frac{1}{molar\ volume\ conversion} \times MW_{Mixture} \times Wt\%C_{Mixture} \times \frac{44}{12} \quad (19)$$

The carbon content of a fuel mixture is the weighted average of the specific component carbon contents that can be calculated using the following equation.

$$\mathrm{Wt\%C_{Mixture}} = \frac{1}{100}\sum_{i=1}^{\#components}(\mathrm{Wt\%_i} \times \mathrm{Wt\%C_i}) \quad (20)$$

In addition, emissions of CH_4, N_2O, and air pollutants are calculated using emission factors [22].

4. Results and discussion

4.1. Calculation of the fuel consumption in boiler for steam generation

In order to estimate emissions reduction by means of HRSG, the amount of fuel that is used by the boiler to generate steam must be calculated. The enthalpy of inlet water and outlet steam can be used to determine the fuel consumption. It can be represented by the following equation.

$$E_b = \frac{\dot{m}_s(h_s - h_w)}{\dot{m}_f(\mathrm{HHV})} \times 100 \quad (21)$$

where $\dot{m}_s$ and $\dot{m}_f$ are the rates of steam production and gas fuel consumption, respectively, h_s and h_W are the enthalpy of steam and water, HHV is the higher heating value, and E_b is boiler efficiency.

4.2. Electrical-specific emission factor

The methodology for power plant specific emission factors involves calculating the total emissions from the generation of electricity within a power plant and dividing it by the total amount of electricity produced. Based on sample operating data, the average fuel consumption and electrical energy productions in 3 years are equal to 82.5 $MMNm^3$ and 161732 MW.hr, respectively. Global warming potential (GWP) is a relative measure of how much a particular gas contributes to global warming. The GWP of each gas is used to convert the effect of the gas into equivalent amounts of CO_2. This ratio is based on standard ratio over a set period of time, which is usually a hundred years. Over this time frame, CO_2 as the reference gas scores one, methane scores 25, and nitrous oxide comes in at 298 [22]. Employing the above mentioned approach, total emissions were calculated.

4.3. Exergy balance

In the present study, all the terms of exergy before and after the HRSG and turbo-expander are equal except the physical exergy. The physical exergy balance is shown in Figure 4. This figure shows that 100% of input exergy is lost without energy recovery. On the other hand, an energy recovery of 31% and a 21% of input exergy remain with waste gas stream and lose in S-1 and S-2, respectively. The exergy of a system at a certain thermodynamic state is the maximum amount of work that can be obtained when the system moves from that particular state to a state of equilibrium with the surroundings. The exergy balance in Figure 4 shows the delta exergy (differential exergy) in the equipment. As can be seen from this figure, it is possible to recover 64 and 11 MW of the exergy loss by the HRSG and turbo-expander, respectively.

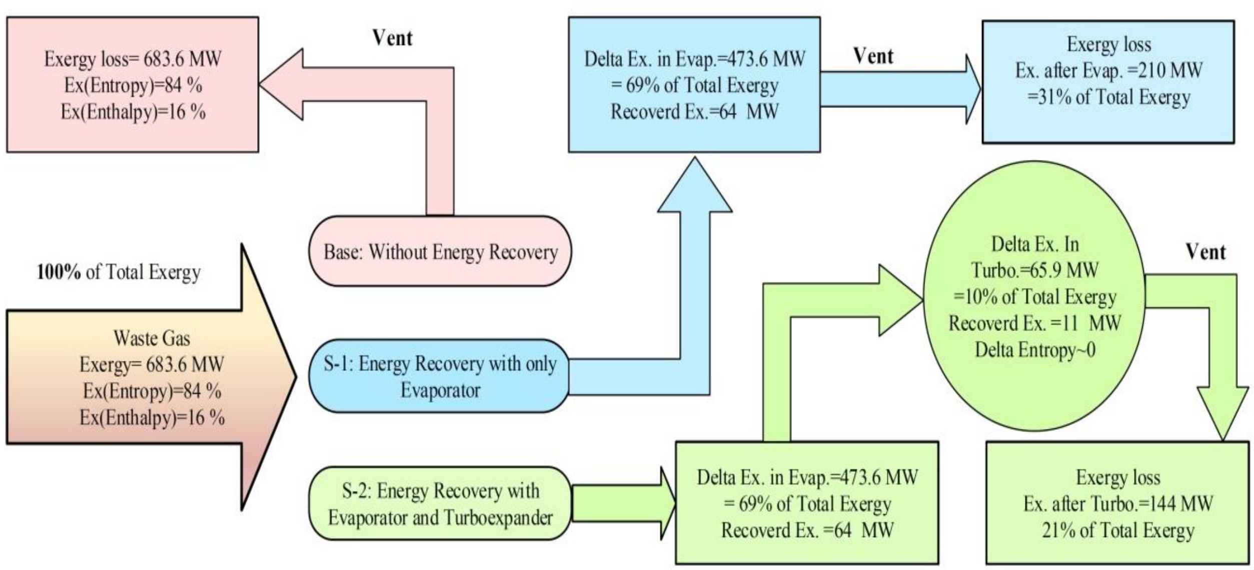

Fig. 4. Physical exergy balance for break down pressure process with and without energy recovery

When the waste gas is vented to the atmosphere, the total amount of its exergy is lost. Table 1 exhibits the conditions of the waste gas stream and its loss exergy during a year for various seasons. As Table 1 shows, there is a sensible dependence between the waste gas temperature and the surrounding temperature, and its flow rate generally depends on seasonal variations.

Table 1. Waste gas stream conditions and its loss exergy.

Month	T (K)	P (bar)	m (ton/h)	Loss exergy (MW)
1	946.7	2.69	406023.4	669.3
2	949.0	2.67	403659.4	660.8
3	950.4	2.66	410751.5	677.1
4	951.2	2.65	417252.6	684.5
5	951.0	2.65	417252.6	684.5
6	950.1	2.66	412524.5	675.7
7	948.6	2.66	407205.4	666.9
8	946.4	2.70	416661.6	683.5
9	944.2	2.70	443257	712.3
10	943.5	2.71	441484	712.6
11	943.7	2.71	439119.9	707.6
12	945.1	2.69	403659.4	668.3

Utilizing a computer CODE based on Eqs. (10) – (17), the exergy analysis that corresponded to input exergy, output exergy, and loss exergy is performed. Figure 5 shows the results of this exergy analysis. The initial exergy and output exergy values for the two scenarios previously mentioned are presented in this figure. As can be seen from the figure, the amount of initial exergy is significant during the whole of a year and changes slightly in different months because of the variable flow rate of the waste gas.

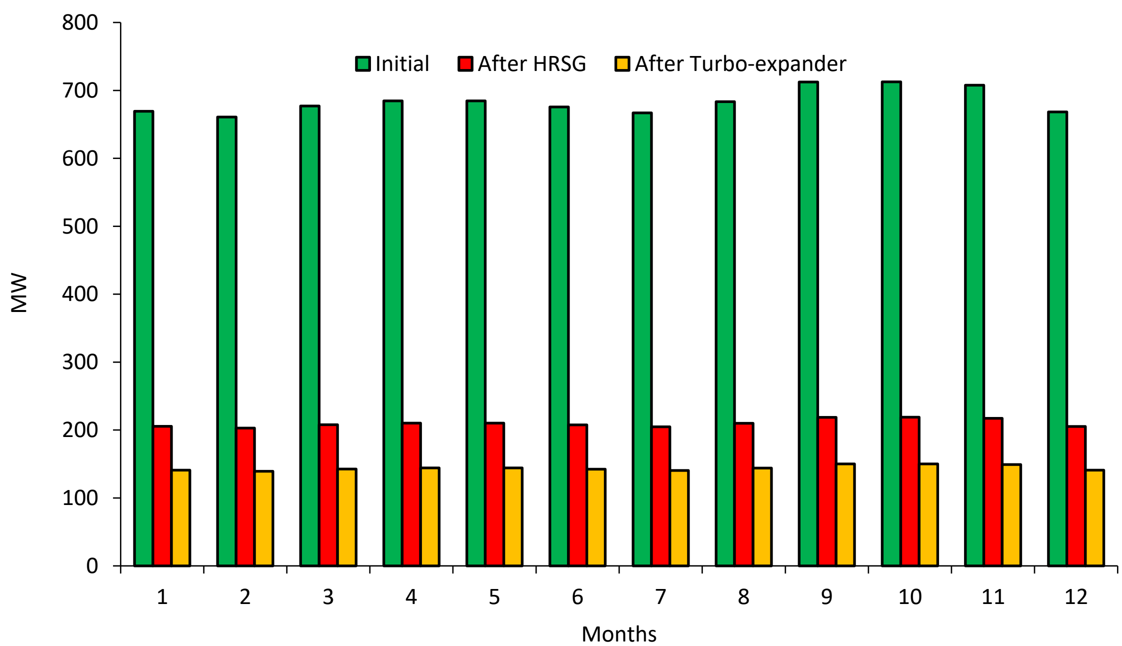

Fig. 5. Input, output and loss exergy for the HRSG and turbo-expander

In the first and second scenarios, the waste as flow is entering the HRSG and its heat is used to generate steam. Then, there will be a temperature drop to the waste gas. But its temperature cannot be reduced to less than about 220 Cº because the generated steam must be in super heat state with the pressure of 20 bar and the saturated temperature to this pressure is 212 Cº. Figure 6 and 7 represent the annual variations of loss exergy and energy recovery in different months for the HRSG and turbo-expander, respectively.

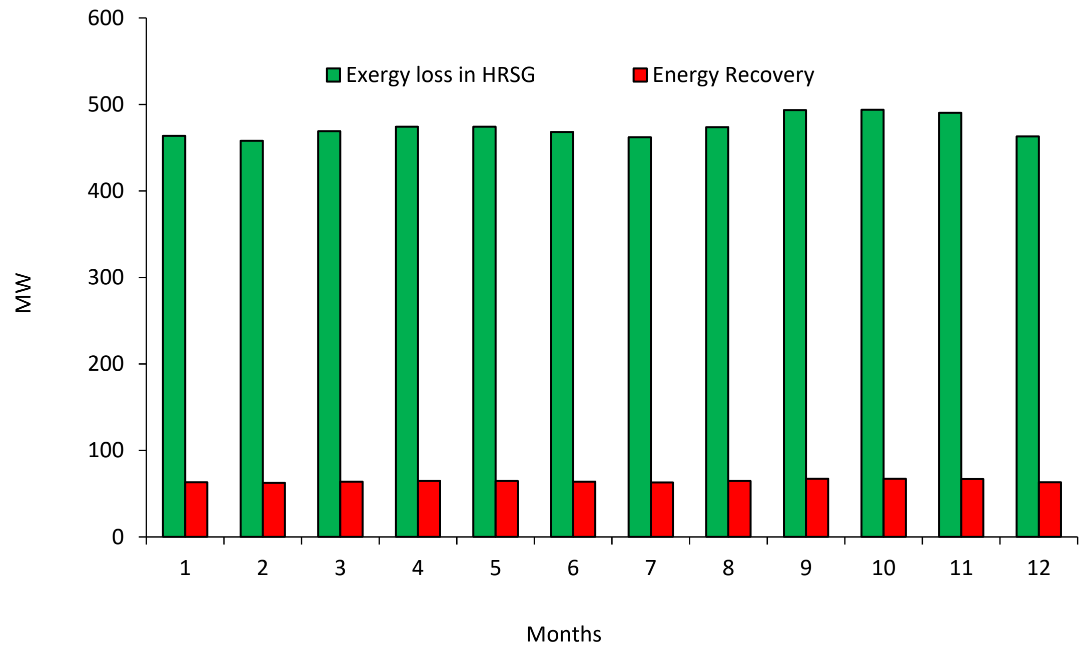

Fig. 6. Amount of loss exergy and possibility energy recovery by HRSG

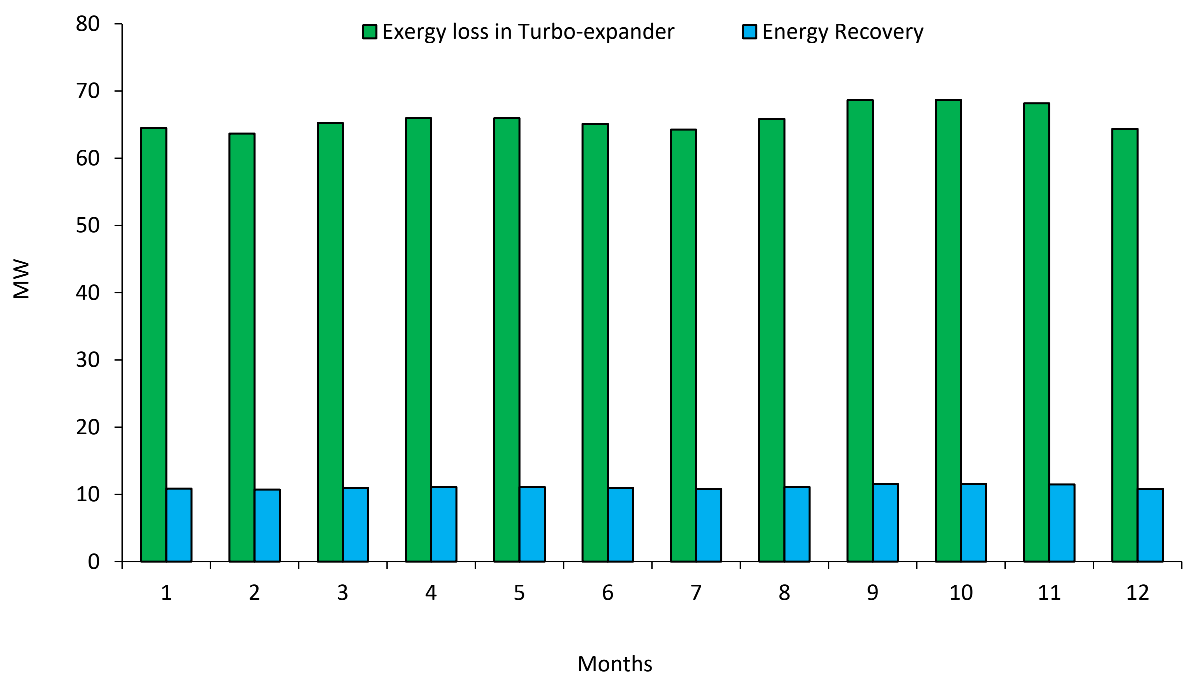

Fig. 7. Amount of loss exergy and possibility energy recovery by turbo-expander

By comparing the loss exergy and energy recovery values, it can be seen that the total amount of the loss exergy is not recoverable. However, the maximum amount of recovery which can be obtained by the HRSG and turbo-expander are equal to 64 and 11 MW, respectively, so-called energy recovery. As the Figures show, differential exergy around the HRSG is significantly more than the differential exergy around the turbo-expander; therefore, its energy recovery is more. The total energy recovery in the second state, by the HRSG and turbo-expander, is 75 MW which shows that the turbo-expander increases energy recovery by near 11 MW. The energy recovered from the HRSG and turbo-expander are 85% and 15% of the total energy recovery, respectively. Therefore, simultaneous use of the HRSG and turbo-expander may be a good method to recover the waste energy. Moreover, due to instantaneous variation of some effective parameters such as weather temperature, the mass flow-rate of the waste gas varies for each month. Consequently, the energy recovery varies a little with time. Also, it can be found that the higher values of pressure, temperature, and gas-flow result in more exergy and more energy recovery. It is clear that proportional to the amount of energy recovery, there will be a reduction in GHGs and air pollutant emissions that has been studied in the following section.

4.4. Environmental impact

One of the main targets of the present study is to reduce GHGs and air pollutant emissions by improving energy efficiency. For this purpose, the utilization of the HRSG and turbo-expander was proposed to recover the waste heat and pressure of the waste gas that would not have been used in the absence of the proposed project. The development of this project brings some benefits. Recovered energy reduces fossil fuel consumption in boilers and power plants for the production of steam and electrical energy, respectively; it also results in the reduction of GHGs emissions and air pollutants (CO, NO_x, PM, VOCs). In addition, it can reduce the dependency on fossil fuels and improve energy efficiency due to making good use of unused resources (waste gas). It should be noted that the HRSG and turbo expander have no environmental effects. Considering energy recovery and emission factors (base on natural gas as fuel), the reduced emissions are calculated. Table 2 shows the annual GHGs and air pollutant emissions reduction of the HRSG and turbo-expander. The amounts of GHGs and air pollutant emissions reductions are estimated to be 72227 tCO_2e and 327 ton for the first scenario, and 143464 tCO_2e and 649 ton for the second scenario for each year of project lifetime.

Table 2. GHG values and air pollutant emissions reduction

Greenhouse gas reduction (ton CO_2e)					
Equal Emission reduction of	CO_2	CH_4	N_2O	CO_2e	
HRSG installation (S-1)	71568.6	126.4	531.4	72227.6	
Turbo-expander installation	70586.4	124.8	524.3	71236.6	
HRSG and Turbo-expander In. (S-2)	142155.0	251.3	1055.7	143464.2	
Air pollutant reduction (ton)					
Equal Emission reduction of	NOx	CO	PM	VOCs	sum
HRSG installation (S-1)	255.2	65.8	4.1	2.0	327.1
Turbo-expander installation	251.7	64.9	4.0	2.0	322.6
HRSG and Turbo-expander In. (S-2)	506.9	130.8	8.1	4.0	649.8

Although about 85% of total energy recovery in the second scenario is achieved by means of HRSG, the results of emissions reduction show that emissions reduction of the turbo expander is 49% of the total emissions reduction. It is due to the high emission of electricity generated in respect to steam. In fact, the efficiency of gas turbines for electricity generation is about 30%, which is much less than the efficiency of boilers that is about 75%. Due to the results of energy recovery, especially the emissions reduction, this study proposes to use the second scenario that includes the simultaneous application of the turbo expander and HRSG. Since the economic factors are important keys that determine investment attractiveness for the installation of HRSG and the turbo-expander or only HRSG, they will be investigated in the following section.

4.4. Economical evaluation

Economical evaluation, which is one of the principal aims of this study, was carried out to evaluate the economic feasibility of S-1 and S-2. The investment evaluation is based on Clean Development Mechanism (CDM) projects that consists of the costs of the equipment package (HRSG, turbo-expander and synchronous generator), commissioning, pipelines, training of operators, and other costs [23-25]; these costs are listed in Table 3. The HRSG and turbo-expander have been installed to use waste energy. Steam and power will be generated during a 4-year campaign, after which a period of maintenance will be required [26]. The project income is generated by the savings resulting from the reduction of fuel gas consumption in the boiler and power plant.

Table 3. Relevant costs and revenues of installation of the HRSG and turbo-expander

Items	Unit	Scenario Cost		
		HRSG	Turbo-ex.	Total
Main equipment cost	USD	5893211	8117623	14010835
Instruments, Controls and Electrical	USD	471456	413452	884910
Piping	USD	671175	242124	913300
Installation Cost	USD	171520	388683	560204
Commissioning	USD	195190	17474	212666
Total Direct Cost	USD	7402557	8238617	15641175
Total Indirect Cost	USD	444152	596702	1040855
Fixed Capital investment	USD	7846710	9776060	17622770
Annual Cost	USD/y	419235	188355	607590

Generally, operating and maintenance costs (O&M cost) are inescapable parts of any project and assumed to be equal to 2% of the investment costs for each year of the project lifetime. The NPV (Net Present Value) and IRR (Internal Rate of Return) are the major financial indicators for this assessment. The discount rate is assumed to be 18% which is an annual mean rate often used by the refinery itself and based on the central bank of Iran. It was found that regardless of environmental benefits, the NPV for the project development are 4561641 USD and 12818289 USD for scenario one and two, respectively, which are presented in Table 4. As can be seen from Table 4, the IRR of the second scenario is about 36 and makes it more economical than the first scenario for energy recovery. Since the IRR for the installation of the single turbo-expander package is more than that of a single HRSG, the total IRR for the second scenario is greater than the first one. It should be noted that the installation of a single turbo expander has less energy recovery in respect to the installation of HRSG and therefore, there will be a lot of waste energy when HRSG is not employed.

Table 4. Financial indexes of HRSG and the turbo-expander package installation

Item	Unit	HRSG	Turbo-ex.	Total
Fixed Capital investment	USD	7846710	9776060	17622770
Annual Cost	USD/y	419235	188355	607590
Annual benefit	USD/y	3180274	4202196	7381171
Discount Rate	%		18	
IRR	%	33.18	39.58	36.76
NPV	USD	4561641	8256648	12818289
Payback time	year	2.8	2.4	2.6
Investment for 1 ton GHG reduction	USD/ton CO_{2e}	108.6	137.2	122.8

The development of a project whose objective is energy recovery and greenhouse gas emissions reduction provides a way to overcome some financial barriers such as price fluctuations and inflation growth. A sensitive analysis is required to get a better understanding on the subject and to find out whether the project is economically feasible, cost effective, or risk free. Figure 8 shows the result of the sensitive analysis for the best system (S-2) with the variations of the IRR index for four generic factors, namely, base condition, investment, revenue, and annual cost with a bounded level of ±20%.

As the figure demonstrates, the IRR for all conditions are approximately more than 18% (interest rate) for the proposed scenario 2; this implies that the installation of the HRSG and turbo-expander is economically feasible. In addition, if one considers the possible variations of some parameters used in the economical calculation for the proposed project, the results exhibited in Figure 8 may be obtained. Thus, if a maximum value of 20% (though unreal) of the operating cost is applied, the IRR does not change appreciably and it continues to be more than the discount rate. If a variation of ±20% is applied to the investment, revenue, and the annual cost, the IRR remains more than the discount rate. So, the decision to implement such a project seems to be economically attractive and risk free. Therefore, the financial attractiveness of the project is clearly supported by the sensitivity analysis.

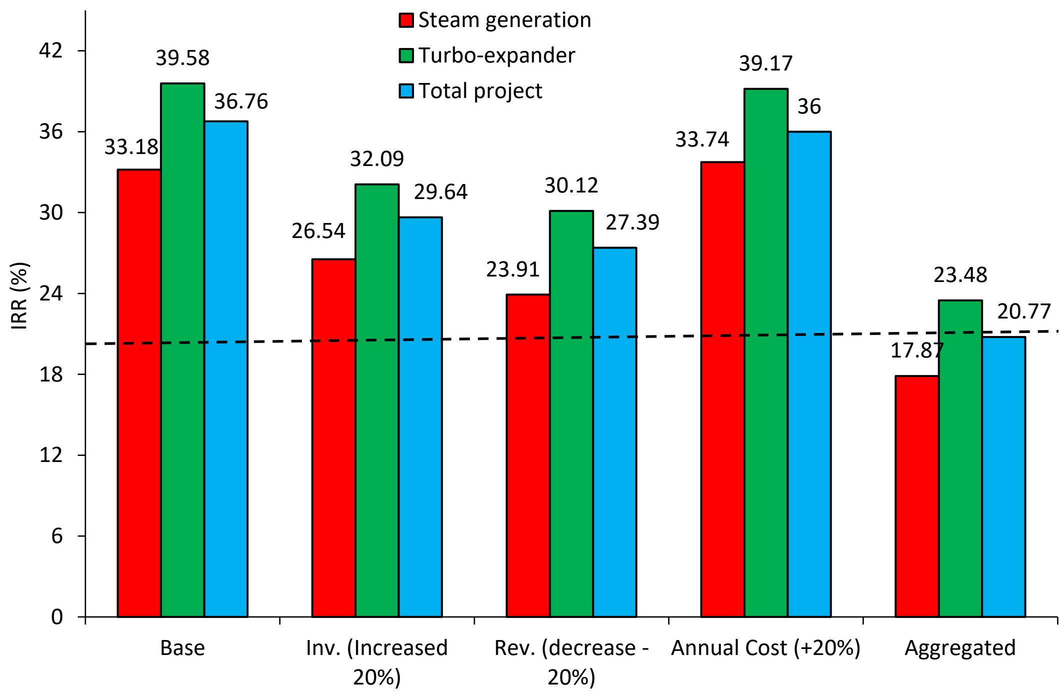

Fig. 8. Economically sensitive analysis of scenario 2 (HRSG and turbo-expander).

Moreover, according to the expected emission reductions, the projected income is significant enough to help mitigate the economic hurdles of the project and the technical problems that may arise during its implementation. As a result, the economic analysis clearly proves that the project is economically attractive and is not risky.

4. Conclusions

The waste heat/pressure recovery of the waste gas by installing the HRSG and turbo expander can reduce GHGs and air pollutant emissions. They generate steam and electrical energy, and thus decrease fossil fuel consumption in the boiler and power plant. For this purpose, a model based on exergy analysis was presented to calculate the energy recovery of the waste gas generated in the regenerator of the FFC unit in a refinery. All the calculations were based on actual operating conditions. It was found that the waste gas had a significant exergy. Two scenarios were proposed to use this exergy. In the first scenario, it is assumed that the HRSG has been installed at the output path of the waste gas to use its waste heat to generate steam. In the second case, in order to use the waste pressure of the gas, a turbo expander was added to the system. Then, the exergy analysis and economical evaluations were carried out. The results showed that the exergy loss is higher than 660 MW for all the months in the present case study in the absence of any energy recovery, and it is possible to recover about 64 MW of energy loss by means of the HRSG and 11 MW by using the turbo-expander. Therefore, it will be possible to recover about 75 MW energy by applying the second scenario. As well, the generation of steam and electrical energy was found to be about 88 ton/h and 8323 MWh/month, respectively. The result of this energy recovery was the reduction of fossil fuel consumption in the refinery and power plant. Also, the annual GHGs and air pollutant emissions reduction were estimated to be about 72227 tCO_2e and 327 ton for the first scenario and 143464 tCO_2e and 649 ton for the second scenario, respectively. The IRR and NPV were about 33.18% and 4561641 USD, respectively, for the first scenario and 36.76% and 12818289 USD for the second scenario for a period of ten years. The economic analysis showed both scenarios (S-1 and S-2) are attractive and economically feasible, but the second scenario is more effective because it will produce more emissions reduction and more energy recovery. In the end, the sensitive analysis on the economical results was carried out and the results showed that the installation of the HRSG on its own or simultaneous with a turbo-expander appears to be very effective and without risk. As well, it was concluded that the development of scenario 2 will result in more efficient use of energy, increased emissions reduction and significant economic gains as well as being risk-free.

Nomenclature		
symbol	*unit*	*description*
C_P	kj/kg.K	Specific heat capacity
h	J	Enthalpy
IRR	%	Internal rate of return
Ex	J	Exergy
m	Kg/s	mass flow
NPV	$	Net present value
MW	gr/mol	Molecular Weight
MTOE	*MTOE*	million ton oil equivalent
P	Pa	Pressure
Q	J	Heat
T	K	Temperature
v	m^3	volume
ve	m/s	velocity
W	J	work
y	%	mole fraction
subscription		
Che		chemical
Di		diffusion
Dh		physical
e		equivalent
f		fuel
i		component
in		input
k		kinetic
0		initial
out		output
p		potential
ph		physical
r		reduced
s		isentropic
sat		saturation
w		water
WS		Waste Gas
Greek symbol		
symbol	*unit*	*description*
λ	kj/kg	Latent heat
η	%	efficiency
γ		heat capacity ratio

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