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Application of Turbo-Expander to Greenhouse Gas and Air Pollutant Emissions Reduction Using Exergy and Economical Analysis

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ABSTRACT

The effects of greenhouse gases (GHG) on the growth of global warming and increase of GHG and air pollutant emissions for energy production have prompted the need of energy recovery, which is normally wasted in industrial plants. The present research is focused on the GHG and air pollutant emissions reduction employing pressure waste energy recovery. Break-down pressure via Joule-Thomson valve is a neat potential for waste energy recovery in gas refineries, which may also be provided using a turbo-expander instead of commercial valves. Based on this ground, an exergy analysis is carried out for Joule-Thomson valve. The results showed that the exergy loss is higher than 6.5 MW, and it is possible to recover about 1.9 MW of exergy loss. On the other hand, it was found that about 16900MWh of electrical energy can be produced by recovering the energy of waste pressure, which may lead to less consumption of the load and gas in refinery power unit. Consequently, the gas consumption reduction, 12056 ton CO2e of GHG and 54.6 ton of air pollutant emissions, is reduced annually. Economical evaluation of utilizing a turbo-expander, instead of a valve, proved that an alternative scenario is deductible and practical. Economical indexes, namely IRR and NPV, are found to be equal to 25.51 % and 929571 US$, respectively. Moreover, sensitivity analysis conducted on each specific state certified the obtained results.

1. Introduction

In recent decades, there has been a growing concern about global warming due to the large emission level of greenhouse gases (GHGs). Earlier, the Intergovernmental Panel on Climate Change (IPCC) has published a report, concluding that human activities result in the production of four major types of gases, namely carbon dioxide, methane, chlorofluorocarbon, and nitrous oxide, which all significantly contribute to global warming [1]. The mentioned crisis caused by the increase of these gases emissions is one of the most serious environmental problems. Among these four gases, CO_2 has the greatest amount. Hence, the reduction of CO_2 emissions from

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the fossil fuel's energy systems is considered to be the most urgent so as to slow down the global warming trend. Generally, CO_2 accounts for a majority of recent increases in the heat trapping capacity of the atmosphere, with worldwide atmospheric concentrations of CO_2 increasing at about 0.5 % annually [2].

Recently, in order to prevent the global warming, several countries have signed the Kyoto Protocol and promised to decrease their emission levels. This, in turn, calls for a clear identification of the sources of CO_2 emissions [3]. Different strategies have been proposed to reduce the emission of CO_2 into the atmosphere. These strategies include fuel alternative, energy conservation, and improving power generation efficiencies. However, their implementation may still affect CO_2 emission reduction.

Concerning the alternative of supplied fuel sources, Delarue and D'haeseleer [4] investigated the possibilities of switching coal-fired plants to gas-fired ones considering different load levels (for the latter case). They considered fixed allowance cost and variable natural gas price, and found that with an allowance cost following the switch level of a 50 % efficient gas-fired plant and a 40 % efficient coal-fired plant in the summer season, the global GHG emission reduction (in the electricity-generating sector) could be about 19 % [4]. Masoumi et al. [5] studied removal of carbon dioxide by aqueous amino acid salts. They showed that PG has a better performance when it comes to the absorption of CO_2 in comparison to MDEA, DEA, and PS at relatively high CO_2 partial pressures. Lee et al. [6] studied CO_2 sequestration technology through mineral carbonation as a potential method of controlling greenhouse gas emissions. In their experiment, calcium ion was extracted from blast furnace slag, granulated slag, and air-cooled slag; calcium carbonate was then synthesized from the extracted calcium and reacted with CO_2. Based on the results, the feasibility of reducing CO_2 emissions in this manner was demonstrated. Wei-hua et al. [7] discussed a case study of straw cogeneration project in Laixi city, Shandong province of China, for CO_2 emission reduction and energy recovery from straw cogeneration. They came up with a hypothesis stating that the project capacity will reduce emissions of about 4.418 million tons of CO_2e over the next 21-year lifetime by combined combustion and flaring, and at the same time, 126,720 MWh electricity and 908,000 GJ heat will be produced per year. Maruoka et al. [8] examined the possibility of developing a new heat recovery system from various hot wastes generated by the steel-making industry and utilizing the endothermic heat of reaction instead of sensible heat. Their results showed that the exergy loss in the proposed system was only 15 % from the total exergy losses in the conventional systems. Therefore, various technologies have also been tested to reduce, remove, and recover CO_2.

One line of research in ecological economics points to the consumed production of electricity which makes a significant contribution to the overall GHG balances of various products and processes. These specific properties make the assessment of GHG emissions associated with the individual process of consuming or conserving grid electricity a complex and challenging procedure. However, such particular information is highly relevant to and required for almost any environmental impact assessment in one form or another. GHG emissions associated with electricity consumption have been considered in an extensive number of studies related to the cost externalities of electricity consumption.

There are a range of other potential emissions reduction opportunities that have been identified by businesses. Emissions reduction from the direct combustion of fuels in the industry could be achieved by reducing fuel use or improving the efficiency of industrial processes. For example, a project consists of the installation of a turbo-expander on which waste gases can be expanded in order to generate electricity. The equipment is installed in the URFCC (Residual Fluid Catalytic Cracking Unit) of the refinery, which is a new addition of production capacity to the industrial facility. As mentioned before, energy recovery as one of the energy conservation fields, is in fact one of the strategies that can be used for GHG emission reduction [9].

Concerning the natural gas industry, in order to reduce gas temperature, the gas pressure may be reduced by Joule-Thomson process. The pressure of gas in the entrance of this process is normally in the range of 92-98 bars. It is necessary to reduce this pressure to lower level. Usually, the pressure reduction is accomplished by mechanical valves where a large amount of latent energy of high-pressure gas is wasted during the pressure reduction process [10]. Turbo-expander can be installed in parallel with this regulating valve in order to recover this energy. Besides, it can reduce gas pressure for downstream as well as mechanical valves. Moreover, the power extracted by turbo-expanders can drive electrical generators or other loads. In brief, if there is a Joule-Thomson process, it is possible to recover huge amounts of energy to produce electricity. Thus, similar to the energy recovery, the amount of GHG and Air pollutant emissions may be reduced.

Recently, several researchers have investigated the problem of turbo-expander modeling for power system applications. Jesse et al. [11] introduced turbo-expander for energy recovery in the electrical form, and presented some operational topologies of turbo-expander and electrical generators. The basic rule of recoverable energy and variable efficiency of turbo expander due to changes in inlet flow rate and pressure was studied in this paper. Babaei and Rastegar [12, 13] employed the same model for turbo-expander coupled with a synchronous generator to study the mechanical oscillations of shaft and power quality issues of the generated power.

The above literature survey shows that earlier research works, generally, are focused on the heat recovery, fuel consumption, CO_2 capturing, and process efficiency, whereas none of them has fully considered a combination of pre-mentioned parameters yet. In the present work, the relationship among income, energy recovery of waste pressure, and carbon emissions reduction is investigated utilizing exergy analysis and economical evaluation. For these purposes, the exergy losses of gas as well as the Joule-Thomson process parameters are calculated. In order to generate electricity, energy recovery derived from waste pressure via turbo-expander is recommended.

2. Process description

Water and heavy molecules of natural gas must be removed before being transferred through pipelines, because the water molecules present in gas in both vaporized and liquid states form a hydrate causing flow restrictions and pressure drops, as well as lowering the heating value of gas, corrosion in pipelines, and other equipment. Moreover, the state of heavy components changes to liquid at low temperatures causing much more difficulties. In some of the gas refineries, low temperature separation method is implemented to dry the natural gas [10, 14]. Hence, the Joule-Thomson process (breaking down pressure to decreases temperature via a valve) is usually applied. Figure 1(a) indicates the Joule-Thomson process. As the figure shows, pressure breakdown occurs across the valve, and the resulting refrigeration effect depends on the temperature of the upstream side of the choke, the pressure differential across the choke, and the amount of liquid formed. In order to achieve maximum removal rate of liquids from the gas stream for a given pressure differential and sales-gas pressure, the lowest possible temperature within reasonable limits should be attained in the separator. Consequently, gas becomes cold due to Joule-Thomson effect. A separator is also installed immediately after the downstream of the valve. The stream flows through the low temperature separator and then to the inlet separator where liquid is separated from the gas. The major product outgoing the separator is the dry gas which is now ready to be delivered into the pipeline (Fig. 1(a)). Note that the liquids coming from low temperature separator are dumped to obtain some form of stabilization before going to storage.

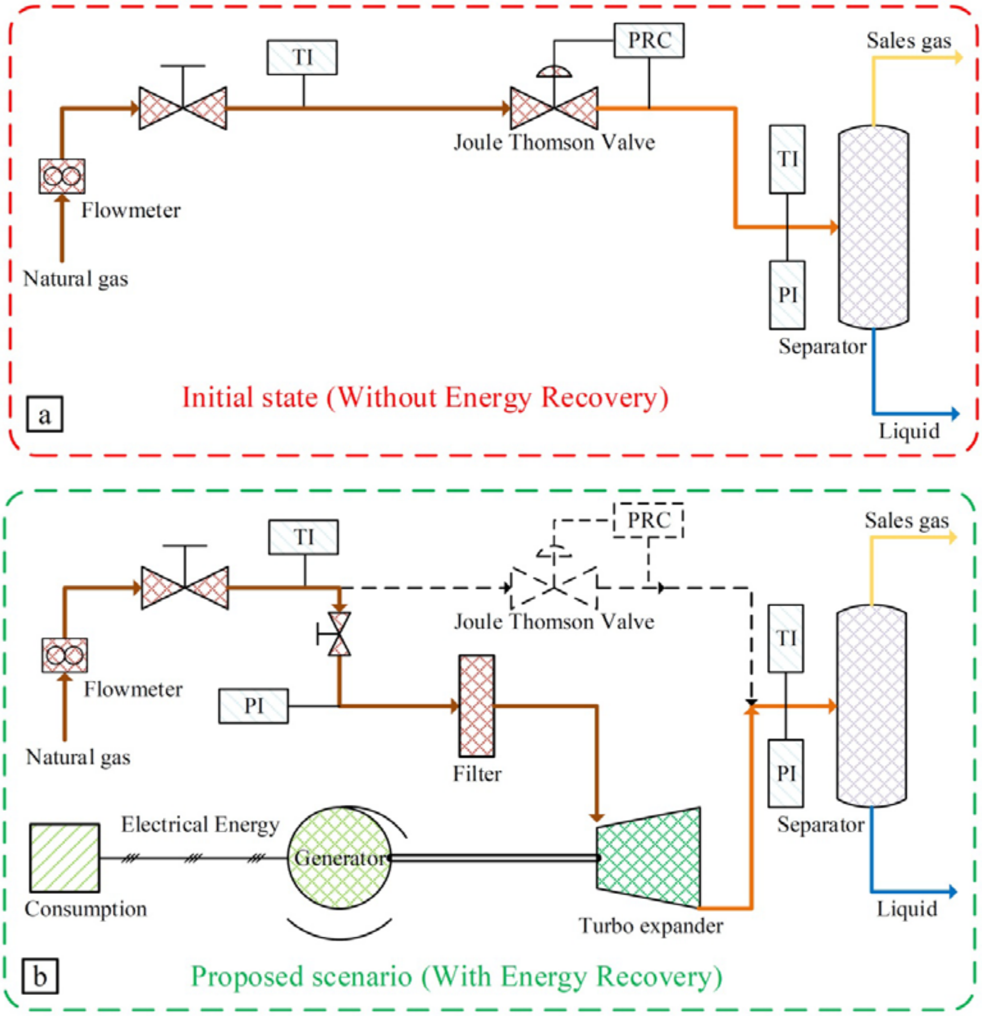

Figure 1. Schematic view for pressure break-down process via (a) Joule-Thomson valve (without energy recovery), (b) Turbo-expander system (with energy recovery).

Regarding the recent fairly developments in gas processing, turbo expander is one of the simplest and operable options in waste pressure recovery. The favorable operating characteristics allow the plant to run unattended through long periods, and its simplicity and relatively low investment cost make it an attractive option. Turbo-expander system and JT-valve are different in that the turbine turns a shaft from which a work is extracted. The gas stream flows to the expander where the pressure is reduced and low temperature is achieved. The gas and liquid mixture leaves the expander and flow to the separator. The gas, frequently, is expanded below sales-gas pressure, and then recompressed to make use of the work that must be extracted from the shaft of the turbine [14]. In the present work, as depicted in Fig. 1(b), a turbo-expander is recommended to be installed in parallel with a Joule-Thomson valve in order to provide the waste pressure energy recovery. The valve could be used during start-up as well as O&M sessions of the turbo expander. Both of the systems might also operate in parallel if there is high amount of feed gas for the expander.

3. Methodology

Turbo-expander is a mechanical device that produces work by expanding the feed gas stream from its initial high pressure to a lower pressure level. As mechanical work produces, the enthalpy of the gas decreases. In reality, the expansion cannot completely approach the isentropic case, but produce a high percentage of the ideally possible works. In a pressure break-down process, the gas is allowed to be expanded and, consequently, a certain temperature drop occurs while the enthalpy of the gas stream decreases. This enthalpy variation possesses the potential for work generation whose loss can be evaluated via exergy analysis.

3.1. Exergy analysis

Exergy or availability of a system at a given state represents its maximum work potential. Therefore, the exergy loss provides a very important criterion to evaluate the thermodynamic performance of a system. By analyzing the energy recovery of the system, it can be observed if the cycle is suitable or economically right for investment. The exergy loss is calculated by making exergy balance for each component of the system. In the present study, a steady-state operation, an adiabatic process, constant gas stream component are considered as the main assumptions.

Concerning the exergy loss computations, some equations have been derived for the case of a Joule-Thomson valve [15-17]. The percentage of the exergy loss in each component can be calculated and expressed as the ratio of the partial exergy loss to the total exergy loss [18]. The total exergy equation can be expressed as follows:

$$\mathrm{Ex} = \mathrm{Ex_k} + \mathrm{Ex_P} + \mathrm{Ex_{Ph}} + \mathrm{Ex_{Che}} \qquad (1)$$

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

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

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

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

Next, the enthalpy and entropy terms must be calculated. Defining the enthalpy in terms of T and P, i.e., h = h (T, P), it can be evaluated from the following equation:

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

Using the Maxwell relations, the following equations can be derived:

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

$$\mathrm{Tds} = \mathrm{dh} - \mathrm{vdP} \quad (6)$$

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

Employing the so-called equation of state, Pv=ZRT, the following equation is obtained:

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

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:

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

The physical exergy term can be calculated from the following equation:

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

The specific heat at constant pressure can be calculated via Eqs. (11) and (12).

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

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

3.2. Solution procedure

Pressure breakdown process by Joule-Thomson valve is a constant enthalpy process, but when a gas expands from pressure P_1 to P_2 adiabatically by turbo expander, the isentropic process occurs. Herein, the enthalpy variation can be expressed as follows:

$$\mathrm{H_{2s}} - \mathrm{H_1} = \mathrm{Q} - \mathrm{W_s} \quad (13)$$

Typically, turbo-expander equipment is insulated, and the pressure break-down process is a very quick phenomenon. Therefore, Q is zero and $\mathrm{W_{Real}} = \eta \mathrm{W_s}$, where η denotes the turbo-expander's efficiency. The isentropic temperature ratio after the process is given by the following formula:

$$\frac{\mathrm{T_{2S}}}{\mathrm{T_1}} = \left(\frac{\mathrm{P_2}}{\mathrm{P_1}}\right)^{\frac{\gamma-1}{\gamma}} \quad (14)$$

In relation (14), γ is heat capacity ratio which is temperature-dependent. The variations of enthalpy and entropy can be calculated based on the following equations:

$$\Delta\mathrm{h} = \mathrm{C_P}(\mathrm{T_2}-\mathrm{T_1}) - \mathrm{RT_2^2}\left(\frac{\partial \mathrm{Z}}{\partial \mathrm{T}}\right)_{\mathrm{P_2}} \ln\frac{\mathrm{P_2}}{\mathrm{P_0}} + \mathrm{RT_1^2}\left(\frac{\partial \mathrm{Z}}{\partial \mathrm{T}}\right)_{\mathrm{P_1}} \ln\frac{\mathrm{P_1}}{\mathrm{P_0}} \quad (15)$$

$$\Delta\mathrm{s} = \mathrm{C_P}\ln\frac{\mathrm{T_2}}{\mathrm{T_1}} - \mathrm{ZR}\ln\frac{\mathrm{P_2}}{\mathrm{P_1}} - \left(\frac{\partial \mathrm{Z}}{\partial \mathrm{T}}\right)_{\mathrm{P_2}} \mathrm{RT_2}\ln\frac{\mathrm{P_2}}{\mathrm{P_0}} + \left(\frac{\partial \mathrm{Z}}{\partial \mathrm{T}}\right)_{\mathrm{P_1}} \mathrm{RT_1}\ln\frac{\mathrm{P_1}}{\mathrm{P_0}} \quad (16)$$

In the present work, in order to calculate the turbo-expander energy recovery, an iterative algorithm is defined based on the above formulations (Fig. 2). Following the algorithm, an in-house code for calculating the exergy of pressure break-down is developed. The code calculates the energy recovery gained by turbo-expander. It should be noted that in relation to the quantity of the energy recovery (electrical energy is generated by generator), the amount of the combustion GHG emissions reduces in a power plant.

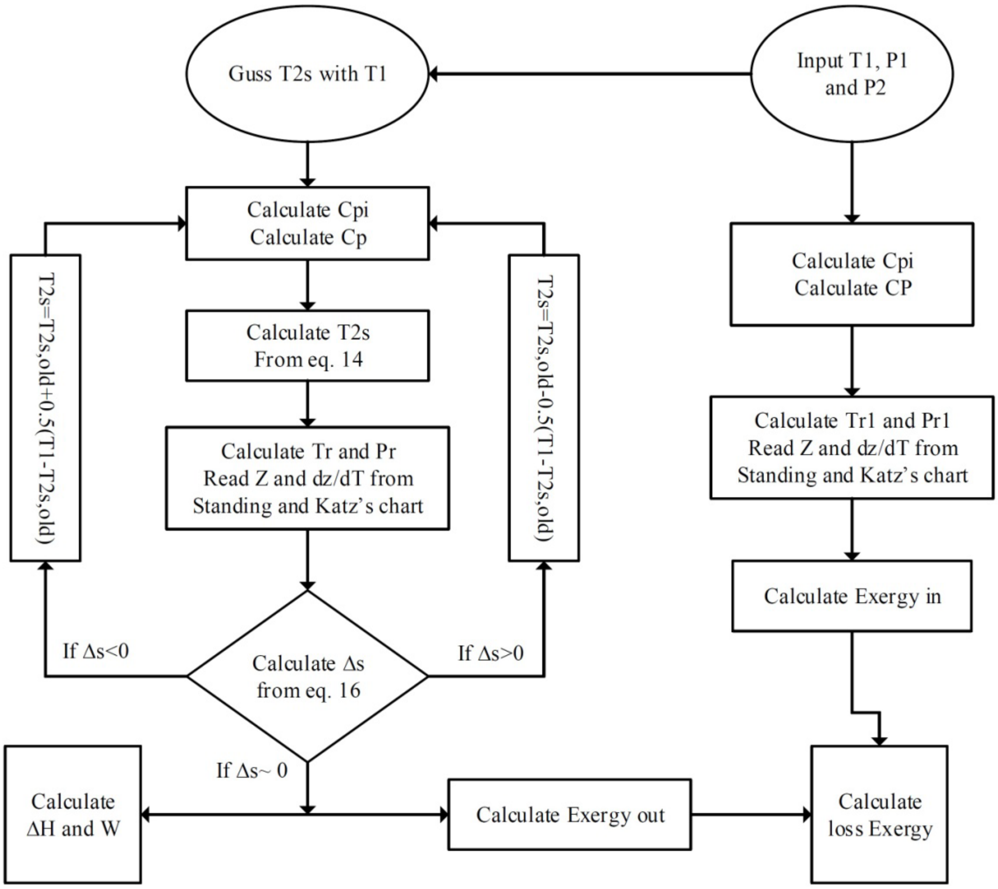

Figure 2. Algorithm for exergy and energy recovery calculation.

3.3. Combustion GHG emissions estimation

As noted earlier, GHG emissions are released from the fuel combustion in power plants and refineries. This section provides a standard method for emissions estimation of the main greenhouse gases from combustion. Carbon dioxide, CH_4, and N_2O may be produced or emitted as a result of combustion. A material balance approach, based on fuel usage data and fuel carbon analyses, is one of the most reliable methods for estimating emissions from stationary combustion sources. This approach applies to the combustion of any fuel, though fuel carbon analyses are likely to be more readily available for produced or purchased gas streams than for refinery gas, liquid or solid fuels. Combustion of hydrocarbons can be represented by the following general reaction, assuming a complete combustion [19]:

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2}\right) O_2 \rightarrow (x)CO_2 + \left(\frac{y}{2}\right) H_2O \qquad (17)$$

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

$$E_{CO_2} = FC \times \frac{1}{\text{molar volume conversion}} \times MW_{Mixture} \times Wt\ \%C_{Mixture} \times \frac{44}{12} \tag{18}$$

The carbon content of a fuel mixture is a weighted average of the individual component carbon contents. The carbon content of the fuel mixture can then be calculated by the following equation:

$$Wt\ \%C_{Mixture} = \frac{1}{100} \sum_{i=1}^{\#components} (Wt\ \%_i \times Wt\ \%C_i) \tag{19}$$

In addition, emissions of CH_4, N_2O, and air pollutants are calculated using emission factors [19, 20].

4. Results and discussion

4.1. Electrical-specific emission factor

In the present study, the electrical energy is produced by 3 turbines (UGT-2600), one of which is in the standby mode. The methodology for power plant's specific emission factors involves calculating the total emissions resulting from the generation of electricity within a power plant and dividing them by the total amount of electricity produced. Based on an operating data sample, average fuel consumption and electrical energy productions in 3 years are equal to 82.5 $MMNm^3$ and 161732 MW.h, respectively. The values of fuel gas share are presented in Table 1.

Table 1
Fuel consumption components.

Component		%
CH_4	Methane	88.09
C_2H_6	Ethane	3.42
C_3H_8	Propane	1.27
C_4H_{10}	i-Butane	0.29
C_4H_{10}	n-Butane	0.66
C_6H_{14}	Hexane	0.09
N_2	Nitrogen	5.75
CO_2	Carbon dioxide	0.53

Global Warming Potential (GWP) of each gas is used to convert the effects of the gases into equivalent amounts of CO_2. These ratios are based on a standard ratio, which describes its total warming impact relative to CO_2 over a set period, which is usually a hundred years. Over this time frame, according to the standard data, methane scores 25 and nitrous oxide comes in at 298, which is shown in table 2 [19].

Table 2
Global Warming Potential (GWP) and carbon dioxide equivalent (CO_{2e}) [19].

Item	Gas	GWP	CO_{2e}
1	CO_2	1	1 ton CO_2=1 ton CO_{2e}
2	CH_4	25	1 ton CH_4=25 ton CO_{2e}
3	N_2O	298	1 ton N_2O =298 ton CO_{2e}

Employing the above-mentioned methodology, total emissions are calculated and the results are tabulated in Table 3. This table reports the amounts of CH_4 and N_2O versus that of CO_{2e}.

4.2. Exergy balance

In the present study, all terms of exergy before and after the pressure break-down process are equal, except the physical exergy. The physical exergy balance is shown in figure (3). This figure shows that 84 % of input exergy remained with natural gas stream and 16 % is lost. 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. Results show that it is possible to recover 33 % of the exergy loss or 5 % of the total exergy.

Table 3

Power plant's specific emission factors.

Greenhouse gas (ton)						Air pollutant (ton)			
CO_2	CH_4		N_2O		Sum				
CO_2	CH_4	CO_2e	N_2O	CO_2e	CO_2e	NOx	CO	PM	VOCs
114.3	8.1	0.2	2.9	849.5	115354.4	407.4	104.4	5.98	2.7
Emission factor (kg/MWh)									
706.74	50.17	1.25	17.63	5.25	713.25	2.52	0.65	0.04	0.02

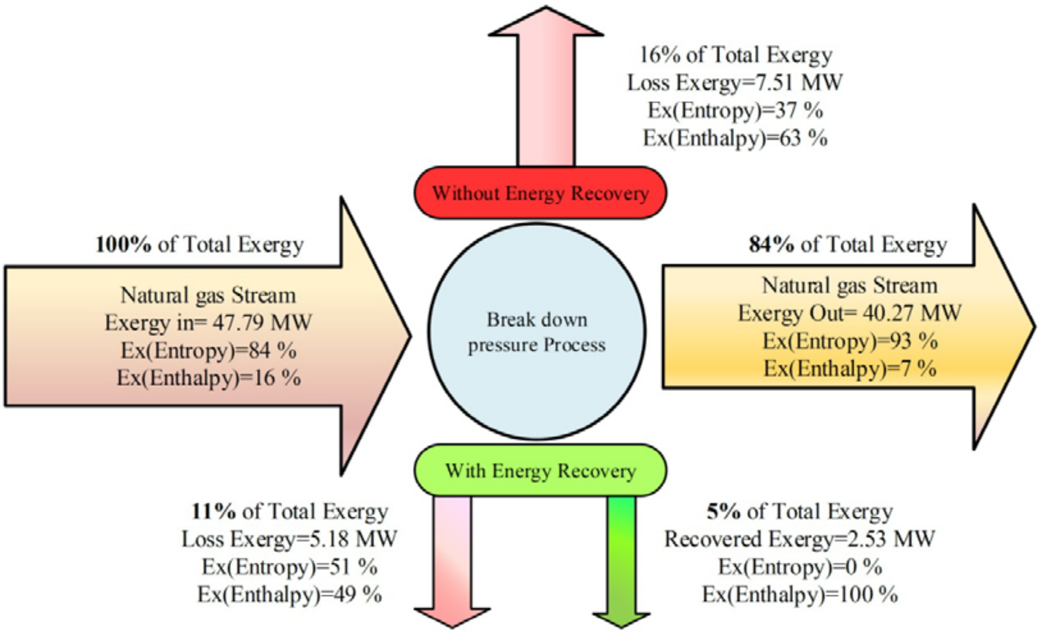

Figure 3. Physical exergy balance for pressure break-down process with and without energy recovery.

When the natural gas stream flows through Joule-Thomson process, the amount of exergy varies. Table 3 exhibits the properties of natural gas upstream and downstream of the pressure break-down process. As Table 4 shows, there is sensible interconnectedness between the inlet temperature and the surrounding temperature, while the flow, generally, depends on seasonal variations.

The exergy analysis corresponds to exergy input and output; exergy loss is carried out utilizing a computer CODE based on Eqs. (10) – (16). Figures 4 and 5 show the appropriate results of exergy analysis. As the figures indicate, the exergy values during a whole year are considerable where they are more significant in summer and winter as compared to those of spring and autumn. This is due to the fact that the energy demand increases in summer and winter in relation to the surrounding temperature.

Table 4

Gas stream conditions before and after the pressure break-down process.

Month	T_{in} (K)	T_{out} (K)	P_{in} (bar)	m_{in} (ton/h)	*Loss exergy of Valve (MW)*	*Loss exergy of Turbo E. (MW)*
1	308.9	258.1	96.7	312	7.14	4.80
2	311.0	258.2	96.1	308	6.89	4.25
3	312.3	258.4	95.8	320	7.37	4.35
4	313.0	258.3	95.5	331	7.59	4.30
5	312.9	258.3	95.5	331	7.59	4.32
6	312.0	258.3	95.6	323	7.33	4.33
7	310.6	258.1	95.7	314	7.07	4.40
8	308.6	258.0	97.0	330	7.56	5.11
9	306.6	258.0	97.0	375	8.41	6.12
10	305.9	258.0	97.5	372	8.42	6.31
11	306.1	257.9	97.4	368	8.27	6.13
12	307.4	258.1	96.8	308	7.11	5.07

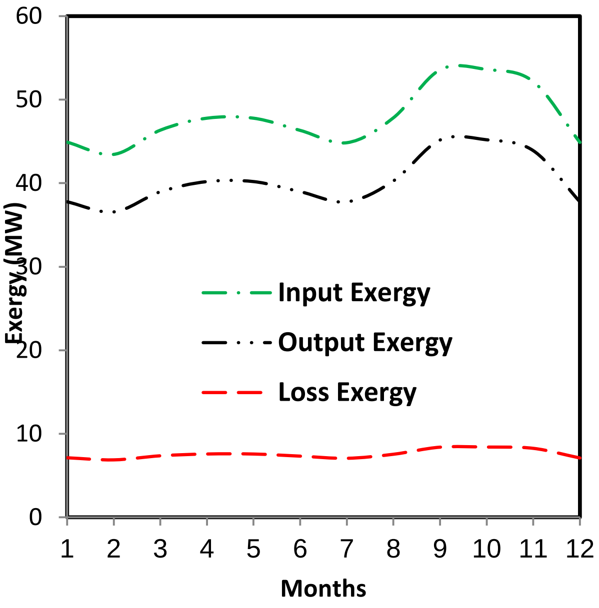

Figure 4. Input, output and loss exergies through pressure-break process.

Moreover, in hot seasons, the electrical energy consumption increases, and the power plants' demand on natural gas levels up; however, residential sections consume more natural gas in winter. On the other hand, the pressure and temperature output conditions fluctuate, while the temperature of input gas increases in summer. Therefore, the input and output exergy's dependence on natural gas flow increases in summer and winter.

Different energy forms have different quality rates (or different amounts of exergy) in the sense that they have different capabilities to generate work.

Figure 5 demonstrates the annual variations in exergy loss and energy recovery for different months. Based on the figure, comparing the values of exergy loss and energy recovery, it can be found that the total amount of the exergy loss is not recoverable; however, the maximum amount of recovery, which can be obtained by turbo-expander, is equal to the so-called energy recovery (Fig. 5). Moreover, it can be observed from the figure that, due to the instantaneous variation of domestic consumptions, weather temperature, and other effective parameters, mass flow rate of turbo-expander varies in each month. Consequently, the extracted power smoothly varies with time. It should be noted that at the higher values of pressure, temperature, and gas-flow, more exergy and energy recovery can be achieved.

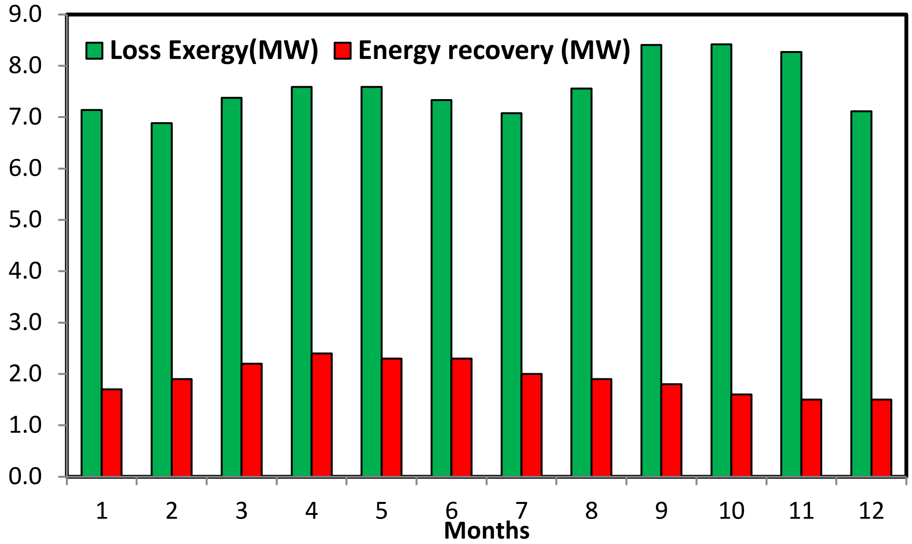

Figure 5. Amount of exergy loss and possibility electrical energy generation.

4.3. Environmental impact

The idea of the present research work persuades the use of energy efficiency in the reduction of GHG and air pollutant emissions by recovering waste pressure to generate electricity. The goal involves an alternative use of waste pressure that would not have been used in the absence of the proposed turbo-expander system. Its development brings about several benefits, such as reduction of global GHG emissions due to the displacement of energy generation sources from the power plant, less emission of air pollutants (CO, NO_x, PM, among others) due to the displacement of other generation sources, improvement of energy efficiency due to the good use of unused resources (waste gases) with the consequent contribution to lessen the dependency on fossil fuels, promotion of practices that bring about environmental benefits, paving the way for others to follow this trend. Herein, an assessment of the environmental impact, including the installation of the turbo-expander, is performed. It was found that no environmental effects exist with respect to a turbo-expander. Moreover, equal to the electricity produced by turbo-expander, the fuel consumption in power plant decreases, lowering the amount of emission.

The annual average emission per electrical energy is presented in Table 5 based on power plant emissions calculation. Considering electrical energy recovery and emission factors, emission reduction rate is calculated. The amounts of GHG and air pollutant emissions reductions are estimated to be 12056 tCO2e and 54.61 ton, respectively, for each year of a lifetime project.

4.4. Economical evolution

Economical evaluation is one of the major aims of the current work. This includes equipment (turbo-expander and synchronous generator), pipelines, commissioning, training of operators, and other costs [21-23], all of which are listed in Table 6. The turbo-expander is connected to a synchronous generator, which produces the power that will be used in the refinery. Power will be generated during a 4-year campaign, after which a period of maintenance will be required. The project income is provided by reduction of fuel gas consumption in power plant [24].

Table 5

GHG values and air pollutant emissions reduction.

	Electricity production	Greenhouse gas (ton CO_2e)				Air pollutant (ton)			
Month	(MWh)	CO_2	CH_4	N_2O	CO_2e	NOx	CO	PM	VOCs
1	1264.8	893.9	1.6	6.6	902.1	3.19	0.82	0.05	0.03
2	1413.6	999.1	1.8	7.4	1008.3	3.56	0.92	0.06	0.03
3	1636.8	1156.8	2.1	8.6	1167.5	4.12	1.06	0.07	0.03
4	1785.6	1262.0	2.2	9.4	1273.6	4.50	1.16	0.07	0.04
5	1711.2	1209.4	2.1	9.0	1220.5	4.31	1.11	0.07	0.03
6	1711.2	1209.4	2.1	9.0	1220.5	4.31	1.11	0.07	0.03
7	1440	1017.7	1.8	7.6	1027.1	3.63	0.94	0.06	0.03
8	1368	966.8	1.7	7.2	975.7	3.45	0.89	0.05	0.03
9	1296	915.9	1.6	6.8	924.4	3.27	0.84	0.05	0.03
10	1152	814.2	1.4	6.1	821.7	2.90	0.75	0.05	0.02
11	1080	763.3	1.4	5.7	770.3	2.72	0.70	0.04	0.02
12	1044	737.8	1.3	5.5	744.6	2.63	0.68	0.04	0.02
Sum	16903.2	11946.2	21.1	88.7	12056.2	42.60	10.99	0.68	0.34

Table 6

Relevant costs and revenues of a turbo-expander installation.

Cost	Unit	Value	Items	Unit	Value
Main equipment cost	USD	2772893	Total direct cost	USD	2814223
Instruments, controls and electrical		141231	Total indirect cost		203827
Piping		82707	Fixed capital investment		3339397
Installation cost		132770	Annual cost	USD/y	64340
Commissioning		5969	Annual benefit		967116

Genreally, in every project, operating and maintenance costs (O&M cost) are inescapable. Such costs imposed on the project are 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 of the most major financial indicators for this assessment. The discount rate is assumed to be 18 % which is an annual mean rate often used by refinery itself. It was found that NPV for the project development is 929571 USD regardless of environmental benefits, presented in Table 7.

Table 7
Financial indexes of a turbo-expander installation.

Item	Discount rate	IRR (%)	NPV (USD)	Payback time (year)
Value	18	25.51	929571	4.5

Developing a project whose objective is to reduce greenhouse gas emissions provides a way to overcome some financial barriers such as price fluctuations and inflation growth. Therefore, sensitive analysis is required in order to approach a better understating of the subject and find whether a project is economically feasible or cost effective.

Figure 6 shows the sensitive analysis of a system with a turbo-expander considering the variations of IRR index for four generic factors, namely base condition, investment, revenue, and annual cost with a bounded level of ±20 %. As the figure demonstrates, all the conditions are over 18 % (interest rate), implying that the turbo-expander installation is feasible economically. In addition, according to Fig. 4, if one considers the possible variations of some parameters used in the economical calculation for the proposed project activity, the results exhibited in the figure may be obtained: if a maximum value of 20 % (though unreal) of the operating cost is applied, the IRR does not change consierably and continues to be more than the discount rate. If a variation of ±20 % be applied to the investment, revenue, and the annual cost, IRR would be more than the discount rate. So, the decision on implementing the project seems to be economically attractive. Moreover, it can be stated that the financial analysis is robust for reasonable variations in key factors. The sensitivity analysis clearly supports the financial attraction of the project activity.

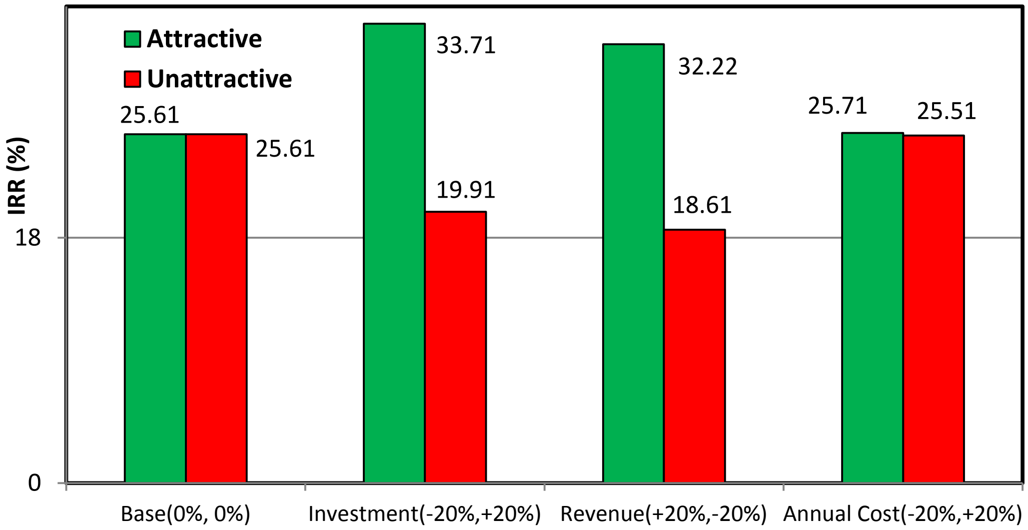

Figure 6. Economically sensitive analysisof installation the turbo-expander.

Moreover, according to the expected emission reductions, significant income is brought about due to environmental revenues helping mitigate the economic hurdles to the project activity and the technical problems that may arise during the implementation process. As a result, economic analysis clearly proves that the project is economically attractive.

5. Conclusions

Waste pressure recovery provides a potential for electrical energy generation and GHG and air pollutant emissions reduction by decreasing the load of power plant. For this purpose, a computational model based on the exergy analysis is presented for the case of pressure break-down in Joule-Thomson process. All the calculations are based upon real-world operation conditions. It was found that the pressure-break has strong effects on the exergy losses in the Joule-Thomson process. By investigating the use of a turbo-expander instead of a commercial valve, exergy analysis and economical evaluations have been carried out. The pressure break-down process was analyzed with initial pressure about 95 bars and final pressure 74 bars. The results showed that the exergy loss is higher than 35 MW in all months for the present case study, and it is possible to recover about 1.9 MW of energy loss. It was also found that about 16900MWh of electrical energy may be produced by recovering the energy of waste pressure, which decreases the load and gas consumption in the refinery power plant annually. Concerning the emission reduction, 12056 ton of CO2e of GHG and 54.6 ton of air pollutant emissions are reduced by the presented energy recovery. The IRR and NPV are estimated to be about 25.51 % and 929571 USD, respectively, in a ten-year period. Sensitive analysis on economical results of each state is conducted, and the results showed that installation of a turbo-expander, instead of a pressure-break valve, appears to be really effective. Finally, it is concluded that developing the proposed idea will promote the use of clean and highly efficient technologies to generate electricity, with low negative impact on the environment.

Nomenclature

C_P	specific heat [kj/kg.K].
h	enthalpy [J].
IRR	internal rate of return [%].
Ex	exergy [J].
m	mass flow [Kg/s].
NPV	net present value [$].
MW	molecular weight [gr/mol].
P	pressure [Pa].
Q	heat [J].
T	temperature [K].
v	volume [m^3].
ve	velocity [m/s].
W	work [J].
y	mole fraction [%].
subscription	
Che	chemical.
Di	diffusion.
Dh	physical.
e	equivalent.
i	component.
in	input.
0	initial.
out	output.
p	potential.
r	reduced.
s	isentropic.
k	kinetic.
Greek letters	
η	efficiency [%].
γ	heat capacity ratio

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