



Technological and economical analysis of flare recovery methods, and comparison of different steam and power generation systems

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Abstract

One of the most important environmental issues in the oil, gas, and petrochemical industries is the appropriate disposal of waste hydrocarbon gases in industrial units. The most commonly employed method for the safe disposal of these gases is burning them in flare stacks followed by releasing them in the environment. To date, various methods and procedures, preponderantly focusing on the modification of the units which generates the gases directed to flare stacks, have been introduced to reduce and/or recover these gases. These methods face with a number of issues, such as the lack of economic justification, high systemic risks, and operational limitations. In this research, four methods for flare gas recovery have been introduced, namely high-pressure steam generation, steam turbine, electricity and heat generation, and combined cycle, and they have been simulated using Aspen HYSYS software. According to the results, producing electric power from flaring gases in the last three methods was 7.323×10^5 , 4.350×10^5 , and 1.442×10^6 kW, respectively, and it caused less pollution and saved energy. In order to assess the economic justification of the proposed methods, the economic assessment was conducted for each method, and economic return was calculated. The rate of investment return for the four processes of the high-pressure steam generation, steam turbine, electricity and heat cogeneration, and combined cycle was 18.66, 19.76, 25.79, and 31.97, respectively, reflecting the high economic return of the combined cycle method.

Keywords Flare gas recovery · High-pressure steam · Steam turbine · Electricity and heat · Combined cycle · Economic consideration

List of symbols

LP	Low pressure
HP	High pressure
VHP	Very high pressure
P	Pressure (Pa)
T	Temperature (K)
GBR	Gibbs reactor

Introduction

Increasing the cost of energy carriers has drawn considerable attention to unconventional sources of energy. By possessing a high thermal value and remarkable abundance, flare, currently burnt as a waste of oil production, has a great potential for use [1–5]. It is of utmost

importance to address the flare from two general viewpoints. First, the gases directed to flare stacks are gases with economic value, and second, it is the destructive environmental impact of the combustion of these gases. Flare gas recovery systems result in the removal or reduction in the combustion of flare gas in the oil and gas production facilities and refineries. This method saves gas consumption and reduces greenhouse gas emissions. The visible torch is considered a symbol of wasting sources and pollution. In the case of using this system, the torch will shut off in normal operation of the system. The energy potential of flare is remarkable, and according to studies, 70–80% of the flare gas is economically recoverable [4–7]. One of these methods is to apply gas recovery techniques instead of burning them and to convert them into valuable products such as electricity. According to the World Bank, more than 121 billion m^3 of flare gases are burned annually. Such flaring produces 411 billion tons of CO_2 . However, this amount of gas can be used for other purposes, including energy production [8].

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Due to large amounts of energy dissipation in large industries, especially oil, gas, and petrochemical industries, through the flaring system, as well as environmental requirements that are becoming more and more rigorous day by day, more extensive research has been conducted on the reduction and recovery of gases directed to flare stacks over the past 10 years. The American firm of John Zink introduced the flare gas recycle system for the first time, one of the most successful flare recovery systems [9, 10]. Afshar et al. [11] presented the recovery of gases directed to the petrochemical torch and related solutions based on the inspections performed. Darpashi et al. [12] investigated the feasibility of a flare gas recovery system and reduction in the flaring process. Rahimpour et al. [13, 14] suggested three different methods to recover torch gas instead of burning in the gas processing firms of Farashband and Assalouyeh.

Zolfaghari et al. [6] investigated the role of flare gas recovery on thermal efficiency and optimizing process, which was followed by economic analyses of GTE, GTG, and GTL processes.

The technology of high-pressure steam generation from gas

Steam is a valuable fluid, mostly used as a utility. Steam takes four forms: very high pressure steam (VHP), high-pressure steam (HP), medium-pressure steam (MP), and low-pressure steam (LP). Based on operational data, in most industrial units, steam with pressures of 10,000, 4237, 1500, and 600 kPa is, respectively, classified as VHP, HP, MP, and LP with various thermodynamics properties and these can affect steam turbine and related power generation unit [15].

The steam is responsible for preparing heat, controlling pressure, mechanical motion, and water supply to different processes. Since most of the heat of steam is in latent form, a large amount of heat can be transferred efficiently in a constant temperature. While it is applied to control pressure and temperature in many processes, in some cases, steam is also used directly. In industrial plants, more than 60% of the thermal energy (mainly in the form of steam), on average, is used for process warming [16]. High-temperature and high-pressure steam is utilized to start up steam turbines. Another feature of water steam is that it can transfer a large amount of heat and be converted to a superheated steam. This steam has many advantages in industries, especially in starting up the turbines.

Krane [17] applied the second law of thermodynamics based on the minimum production of entropy to find out the optimum design for thermal energy storage systems. Arpaci [18] estimated the produced entropy during the heat transfer through radiation. Bejan [19] discussed how to

optimize thermodynamic conditions for designing different steam-generating systems.

The technology of electricity generation using steam turbines

Three generators of the gas turbine, steam turbine, and internal combustion engines could be used for electricity generation [20, 21]. Luo et al. [22] studied a mathematical method accompanied by a turbine simulation to achieve proper heat. Shang et al. [23] investigated the useful properties of the steam turbine model to optimize the system. Cui et al. [24] introduced a model to estimate the lifetime of components of the steam turbine system.

Technology of electricity and heat cogeneration

In recent years, the technology of heat and electricity cogeneration, which has proved its high productivity in energy consumption, has been expanded into other power generators (mechanical or electrical) [25]. In other words, today, with achieved progress, any power generation system of any size and application can be designed as a cogeneration unit. In this way, in addition to the electrical or mechanical power generation by the unit, there is also the possibility of producing heat. As expected, these systems possess a high power-to-heat ratios and a high electrical efficiency [26]. In these methods, the required electricity and heat are usually generated by steam turbine and heat is provided by the combustion of fuels in boilers and heating equipment [27].

Sun et al. [28] recovered about 41% of the waste heat from a vapor turbine by adding heat exchanger injectors in heat recovery process. Lin et al. [29] studied a new heat exchanging unit for increasing heat supply capacity. Lund et al. [30] indicated that lower temperature in heat recovery is one of the major characteristics of heat and electricity conversion.

Technology of combined cycle

These power plants are often used as the base load system with an operation of more than 6000 h per year [31]. In combined cycles, two power cycles are applied together, one is the Brayton cycle, for the gas turbine, and the other is the auxiliary Rankine cycle, for the steam turbine [32]. In this way, the gas turbine in the Brayton cycle and the steam turbine in the Rankine cycle separately generate energy. The idea of combined cycles was proposed to improve the efficiency of the simple Brayton cycle using the exhaust gases of gas turbine [33].

Sanchez et al. [34] analyzed the performance of a combined cycle power plant worked by synthesis gas. The

ratio of high pressure to low temperature of fuel in the inlet of the gas turbine plays an important role in the engine power capacity. Esmalei et al. [35] conducted various optimization approaches to achieve the optimal configuration of a dual-pressure heat recovery steam generator. The reduction in gas pressure drop and a reduction in steam production cost were considered as the first optimization approach. Ozgener et al. [36] studied the operation of a combined cycle based on the first law of thermodynamics using data collected from the control room of a power plant. The results demonstrated that the energy efficiency was about 56%. Kaviri et al. [37] investigated the effects of mass flow rate and gas inlet temperature to the heat recovery system on the cycle efficiency. They observed that increasing the temperature of the exhaust gas entering the steam heat recovery process up to 650 °C led to an increase in thermal efficiency while the temperatures higher than that would reduce the efficiency. Ganjehkaviri et al. [38] studied the effect of the quality of the steam turbine exhaust on the output energy. Franco et al. [39] investigated the effect of heat recovery units' performance on the efficiency enhancement of a combined cycle. Sanjay [40] assessed the effect of different parameters on cycle efficiency. Rahman et al. [41] studied the optimization of a gas turbine for improving cycle performance.

Procedure and methods

Modeling and evaluating economic processes

Owing to the increasing growth of chemical and oil, gas, and petrochemical processing industries, the use of engineering software to design and evaluate these units is inevitable. For the conceptual design of a unit, economic estimations, and conduction of all stages of basic and detailed designs, it is necessary to apply reliable simulating software such as Aspen HYSYS. This software is one of the most powerful simulating tools in engineering, most commonly used in chemical and petrochemical engineering. Here, Aspen HYSYS v10 was applied to simulate processes, and after simulating, the results were directed to Aspen Capital Cost Estimator (ACCE or Icarus), which is one of the most complete and unique software in factory design, economic estimation of chemical engineering projects, preparation of technical reports, economic evaluation, and feasibility study, to perform economic analysis. The ACCE is used to estimate the investment requirements of capital cost of projects. The pricing basis for this release has been updated from qualified databases and libraries. These economic and design results were obtained by running a general benchmark projects containing a

representative mix of equipment found in a processing plant. In addition to model enhancements, pricing changes and defect corrections have affected overall percentage differences. This software performs a cursory review of wage rates and productivities, code of account definition and allocation, material and man-hour indexing, equipment rental, and project execution schedule. Therefore, many economic equations and quantities have been involved in calculations.

The information about investigated flare gas in this paper was obtained from Assaluyeh refinery. In all the four methods of recovery, the composition of percentages and conditions of input gas were equal, and information and conditions are shown in Table 1 and Table 2, respectively.

Processes description

Steam generation process

The feed of high-pressure steam-generating unit is the gas collected from the burner system of the refinery. As shown in Fig. 1, the steam-generating unit consists of a compressor and a reactor. The pressure and temperature of the air, taken from the environment, are 1 atm and 25 °C, respectively. The composition of air is considered as 21% of O₂ and 79% of N₂, as major components. The compressed air and outlet gas from the compressors enter a Gibbs reactor (GBR100). They are combined and react in the reactor. The detailed reaction of the reactor is CH₄ + H₂O ⇌ 3H₂ + CO. The conditions of inlet air to the compressor are presented in Table 2.

Electricity generation process by a steam turbine

In an electricity generation system by a steam turbine, at first the gas and air are compressed by a compressor, and then, the compressed mixture enters the combustion chamber. In the combustion chamber, the compressed mixture is heated by burning fuel. As steam crosses through the boiler and water is injected into the boiler, the

Table 1 Composition of gathered flare gas

Component	Mole fractions
Methane	0.8729
Ethane	0.0557
Propane	0.0205
Nitrogen	0.0365
i-Butane	0.0038
n Butane	0.0059
i-Pentane	0.0019
n-Pentane	0.0017
H ₂ O	0.0012

Table 2 Conditions of gathered flare gas

Conditions	Value (air to compressor)	Value (flare gas entrance)
Temperature/°C	25	34.98
Pressure/kPa	100	100
Molar flow/kgmol h ⁻¹	191,900	17,450
Mass flow/kg h ⁻¹	5,537,000	321,900
Molar enthalpy/kJ kgmol ⁻¹	- 8.092	- 73,950
Molar entropy/kJ kgmol ⁻¹ °C	187.151.8	187.9
Heat flow/kJ h ⁻¹	- 1.553e+006	- 1.291e+009

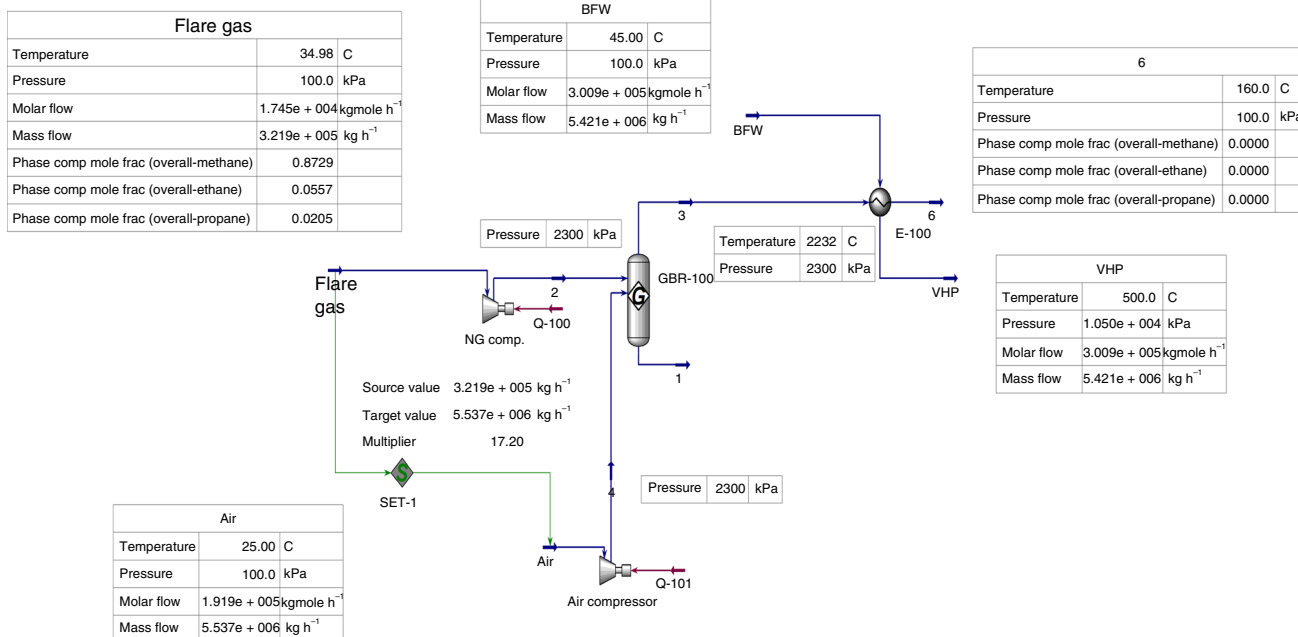


Fig. 1 Process flow diagram of very high pressure vapor production unit

pressure of the fluid increases up to 105 bar, and it becomes a fluid with a high kinetic energy. This fluid drives the steam turbine blades, converting gas energy into mechanical energy and after that electricity. The information about steam turbine used in this simulation process is provided in Table 3. Figure 2 illustrates a scheme of the simulation of the steam turbine process.

Electricity and steam cogeneration process in a steam turbine

In simulating this method, similar to the generation of electricity from a steam turbine, flare gas and air enter the boiler after crossing through the compressor and reacting in the reactor. The exhaust gas from the boiler with a temperature of 500 °C and a pressure of 105 bar passes through a tee and is divided into two equal streams. The first stream is converted into a high-pressure steam with a significant mass flow while the second stream enters the steam turbine and generates high-power electricity. The

characteristics of the turbine are listed in Table 3. Figure 3 depicts a scheme of the process simulation.

Electricity and steam generation process in a combined cycle

The gas turbine comprises three components: a compressor, a combustion unit, and a power generation unit. In the compressor, the air required for the process is compressed. A part of this air, along with the gas flow, enters the combustion unit to generate electricity. The resulting combustion gas loses an amount of its mechanical energy in order to rotate the gas turbine. The outlet stream of this unit enters the turbine and generates electricity. Hot outlet gas from the gas turbine passes through the boiler and produced steam and then is directed to the atmosphere. The steam produced in the boiler expands in the steam turbine, generating another part of mechanical power required to generate electrical energy in the generator. In this method, the consumed water is reduced by converting the outlet

Table 3 The characteristics of gas and steam turbine

	Steam turbine to produce electricity	Steam turbine in electricity and vapor production unit	Gas turbine in combined cycle	Steam turbine in combined cycle
Duty/kWh day ⁻¹	1.757e+007	1.059e+007	2.496e+007	9.630e+006
Adiabatic efficiency	50	50	50	50
Polytropic efficiency	42.23	53	44.9	42.23
Pressure decrease/kPa	10,390	10,400	2000	10,390
Pressure ratio	0.01048	0.0095	0.1304	0.01048
Capacity [ACT-m ³ /h]	1.681e+005	8..321e+004	1.919e+006	9.211e+004

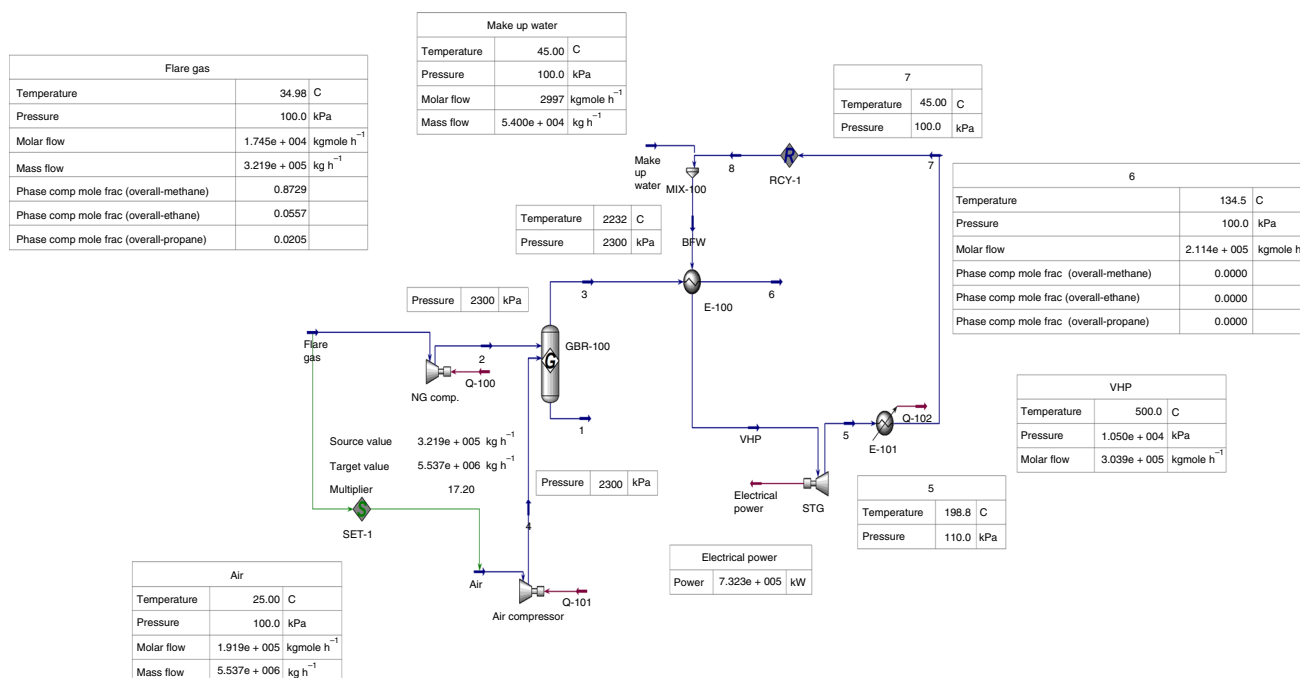


Fig. 2 Process flow diagram of STG unit

steam of the turbine to the water and returning it to the system. The characteristics of the gas and steam turbine are presented in Table 3. Figure 4 illustrates the simulation of the combined cycle process.

Results and discussion

The simulation of processes was performed using the Aspen HYSYS software. At first, the results of four simulated processes, as well as the economic evaluation using Icarus software of each method, are presented. Finally, comparative models are illustrated and discussed based on the rates of return (ROR) to increase capacity and costs.

Unit converting gas to electricity

The simulation result of the software is a high-pressure steam. This steam has a temperature of 500 °C, a pressure of 105 bar, and a mass flow rate of 521,000 kg h⁻¹. This steam has numerous applications, including process heating, jack jets, electricity production, and space heating. In industries, more than half of the thermal energy of steam is used for heating. The information of the outlet gas of the process is presented in Table 4. The cost of a unit that feeds on flare gas is less than the same unit which uses natural gas as feed. The calculated costs and investments by Icarus software obtained for the steam generation method are reported in general and detailed in Tables 5 and 6, respectively.

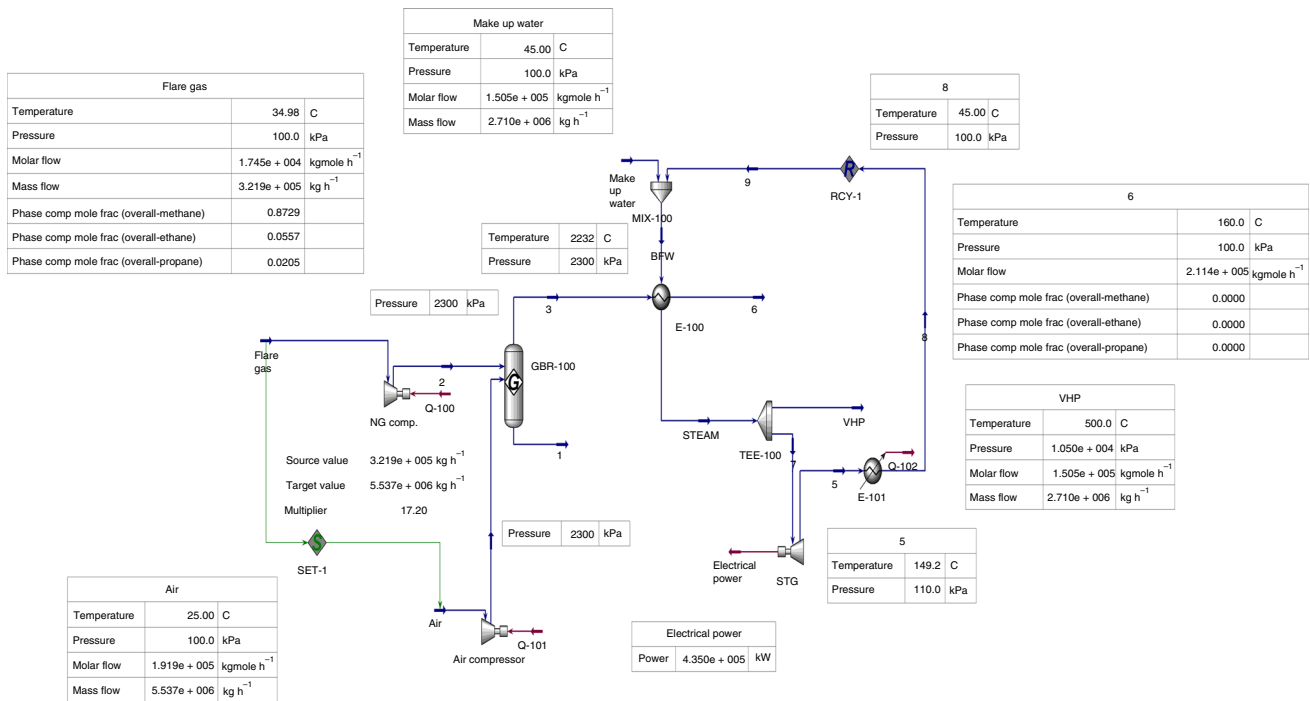


Fig. 3 Process flow diagram of electricity and vapor production unit

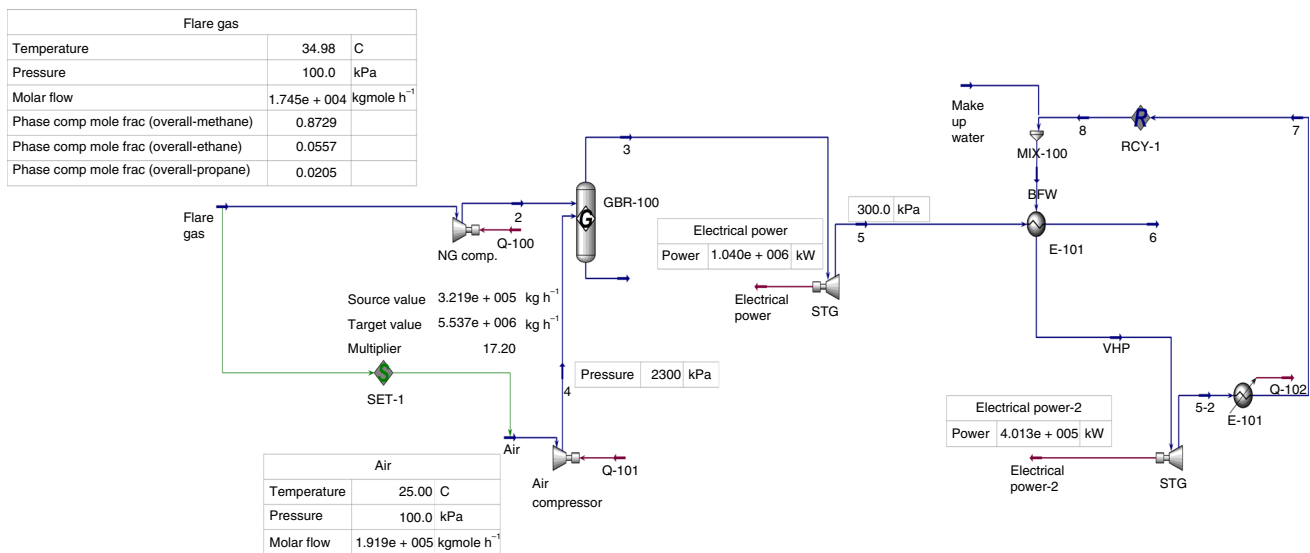


Fig. 4 Process flow diagram of a combined cycle

Electricity generation unit using the steam turbine

According to the simulation of the electricity generation process using the steam turbine, the power of 7.323 e+005 kW electricity has been generated by the turbine. Regarding the critical conditions of electrical energy in the world, producing this amount of electricity from gas using the steam turbine can be a way to address these problems.

To optimize the process and reduce the water consumption of the boiler, the amount of 3.900 e+005 kg h⁻¹ of turbine outlet water is returned into the system, so the amount of water added to the boiler's inlet flow reduced to its minimum amount of 5.400 e+004 kg h⁻¹. The conditions of exhaust gas from the turbine are provided in Table 7. Only a small amount of carbon dioxide, nitrogen, and steam have remained. The economic justification of this project plays an important role in its success, and producing electricity from flare gas is only possible if the economic advantage is

Table 4 Conditions of vapor output

Conditions	Value
Temperature/°C	500
Pressure/kPa	10,500
Motor flow/kgmol h ⁻¹	500,900
Mass flow/kg h ⁻¹	5,421,000
Molar enthalpy/kJ kgmol ⁻¹	- 2.272e+005
Molar entropy/kJ kgmol ⁻¹ °C	166.5
Heat flow/kJ h ⁻¹	6.838e+10

guaranteed. The results of the economic analysis are presented in Tables 8 and 9.

Electricity and steam cogeneration unit

As a new method, the electricity and steam cogenerating system should have advantages over the current systems to

be successful in attracting customers, marketing, and replacing other systems. In this simulation, the ratio of gas flow to generated electricity and high-pressure steam was equal, considered to be 0.5. So, the direct outlet flow of the tee produced 2.710 e+006 kg h⁻¹ of steam at a temperature of 500 °C and a pressure of 105 bar, and the gas flow passing through the turbine generated 4.350 e+005 kW electricity. Table 7 presents the characteristics of the produced high-pressure steam and the outlet steam of the turbine. The economic interpretation of the results is provided in Tables 10 and 11 (all prices in dollars).

Electricity generation unit using the combined cycle

The combined cycle power plants consist of gas and steam units, and by combining these two cycles, the performance of the system increases up to 50%. Results of the

Table 5 VHP project cost

Contract number and description	Design eng' and procurement K-USD	Construction				Contract handling and misc K-USD	Amount K-USD	Percent of base total
		Material K-USD	Man-hours	Manpower K-USD	Indirects K-USD			
Main	1380.4	121,324.1	79,028	3178.5	3775.4	0.0	129,658.4	100.0
Base total	1380.4	121,324.1	79,028	3178.5	3775.4	0.0	129,658.4	100.0
Contingencies	138.0	12,132.4	-	317.9	377.5	0.0	12,965.8	10.0
TOTAL	1518.5	133,456.5	-	3496.4	4153.0	0.0	142,624.2	110.0

Table 6 VHP project detailed cost

Account	Key Qty	Unit MH	MH	Wage rate	Labor cost	Unit matl	Matl cost	Total cost
(2) Equipment	3 Item (S)	3580.7	10,742	38.11	409,355	37,328.6	111,985,996	112,395,351
(3) AG pipe	312 M	136.0	42,398	38.03	1612,196	5.987	1,866,595	3478,793
(4) Concrete	1213 M3	8.7	10,500	30.10	316,099	264.01	320,236	636,335
(4) Grout	1.7 M3	146.3	252	28.65	7208	3972	6832	14,040
(6) Instrumentation	87 EACH	24.9	2163	37.90	81,970	4.868	423,519	505,489
(7) UG electrical	267 M	1.3	336	33.38	11,202	24.84	6636	17,838
(7) AG electrical	13,806 M	0.61	8409	36.66	308,262	56.31	777,417	1085,630
(8) Pipe insulation	373 M	1.7	652	28.36	18,505	62.49	23,318	41,823
(8) Equip insulation	966 M2	2.2	2171	28.26	61,350	53.43	51,623	112,972
(9) Paint	2601 M2	0.54	1403	27.90	39,152	7.13	18,550	57,702
Direct totals			79,028		2865,301		115,430,721	118,346,022
Const equip and indirect								2251,600
Const Mgt. Staff, Supv			11,160					1151,800
Engineering			9007					1116,100
Other project costs			1479					6792,869
Contingency								12,965,341
Indirect totals			21,646					24,278,210
Project totals			100,674		2865,301		115,480,721	142,624,232

Table 7 Conditions of gas out put

Conditions	Electricity	Electricity and vapor production unit		Combined cycle	
	Gas front steam turbine	High-pressure gas	Gas front steam turbine	Gas from gas turbine	Gas front steam turbine
Temperature/°C	198.8	500	149.2	1851	198.8
Pressure/kPa	110	10,500	110	300	110
Mass flow/kg h ⁻¹	5.475e+006	2.710e+006	2.710e+006	5.859e+006	3.000e+006
Molar enthalpy/ kJ kgmol ⁻¹	- 2.359e+005	- 2.272e+005	- 2.377e+005	- 7546	- 2.359e+005
Heat flow/kJ h ⁻¹	- 7.170e+010	- 3.419e+010	- 3.576e+010	- 1.595e+009	- 3.929e+010

Table 8 STG project cost summary

Contract number and description	Design eng' and procurement K-USD	Construction				Contract handling and misc K-USD	Amount K-USD	Percent of base total
		Material K-USD	Man-hours	Manpower K-USD	Indirects K-USD			
Main	4297.7	293,138.4	333,347	12,139.1	13,439.4	0.0	323,014.7	100.0
Base total	4297.7	293,138.4	333,347	12,139.1	13,439.4	0.0	323,014.7	100.0
Contingencies	429.7	29,313.8	-	1213.1	1343.4	0.0	32,301.5	10.0
TOTAL	4727.5	322,452.3	-	13,353.0	14,783.3	0.0	355,316.1	110.0

Table 9 STG project detailed cost data

Account	Key Qty	Unit MH	MH	Wage rate	Labor cost	Unit matl	Matl cost	Total cost
(2) Equipment	83 Item(S)	454.8	37,747	38.06	1436,497	3181,74	264,084,696	265,521,193
(3) AG pipe	2775 M	24.3	67,363	37.78	2544,708	1744	4838,188	7382,896
(4) Concrete	19,202 M3	8.2	157,003	30.14	4731,475	258,48	4963,255	9694,730
(4) Grout	102.2 M3	122.3	12,466	28.65	357,119	3952	402,936	760,055
(6) Instrumentation	1007 Each	32.5	32,750	37.87	1240,129	3148	3442,299	4682,428
(7) UG electrical	507 M	0.84	428	33.65	14,407	16.71	8475	22,882
(7) AG electrical	13,806 M	0.61	8409	33.66	308,262	56.31	777,417	1085,680
(8) Pipe insulation	5494 M	1.8	9623	28.36	272,936	71.37	392,110	665,046
(8) Equip insulation	1165 M	3.1	3590	28.26	101,441	57.29	66,712	168,153
(9) Paint	6944 M2	0.57	3967	28.09	111,420	6.33	43,981	155,401
Direct totals			333,347		11,118,396		279,020,068	290,138,463
Const equip and indirect								8796,302
Const Mgt. Staff, Supv			33,851					3513,101
Engineering			28,953					3586,101
Other project costs			4228					16,980,672
Contingency								32,301,458
Indirect totals			67,032					65,177,634
Project totals			400,379		11,118,396		279,020,068	355,316,097

simulation demonstrated that 1.040e+006 kW electricity was generated from the gas turbine; in the meanwhile, the wasted heat from the gas turbine (through combustion

products) was applied for production of steam required for the steam turbine and generated 4.013e+005 kW electricity. Table 7 reports the characteristics for the exhausted gas

Table 10 Electricity and vapor production unit project cost summary

Contract number and description	Design eng' and procurement K-USD	Construction				Contract handling and misc K-USD	Amount K-USD	Percent of base total
		Material K-USD	Man-hours	Manpower K-USD	Indirects K-USD			
Main	2981.6	207,223.6	206,239	7678.7	8462.1	0.0	226,346.0	100.0
Base total	2981.6	207,223.6	206,239	7678.7	8462.1	0.0	226,346.0	100.0
Contingencies	298.2	20,722.4	–	767.9	846.2	0.0	22,634.6	10.0
TOTAL	3279.7	227,946.0	–	8446.6	9308.3	0.0	248,980.7	110.0

Table 11 Electricity and vapor production unit project detailed cost data

Account	Key Qty	Unit MH	MH	Wage rate	Labor cost	Unit matl	Matl cost	Total cost
(2) Equipment	23 Item(S)	1054.1	24,245	38.07	922,926	8175,45	188,035,396	188,958,322
(3) AG pipe	1543 M	35.6	54,881	37.87	2078,453	2172	3352,391	5430,844
(4) Concrete	10,207 M3	8.2	83,774	30.13	2524,394	258,81	2641,746	5166,139
(4) Grout	51.8 M3	122.7	6359	28.65	182,164	3952	204,884	387,047
(6) Instrumentation	547 Each	32.0	17,486	37.87	662,106	3520	1925,562	2587,667
(7) UG electrical	387 M	0.99	382	33.53	12,805	19.52	7556	20,360
(7) AG electrical	13,806 M	0.61	8409	36.66	308,262	56.31	777,417	1085,680
(8) Pipe insulation	2933 M	1.8	5138	28.36	145,720	70.81	207,714	353,434
(8) Equip insulation	1065 M2	2.7	2881	28.26	81,396	55.54	59,167	140,563
(9) Paint	4773 M2	0.56	2685	28.04	75,286	6.55	31,265	106,551
Direct totals			206,239		6993,512		197,243,097	204,236,609
Const equip and indirect								5522,400
Const Mgt, Staff, Supv			20,959					2184,600
Engineering			20,592					2549,800
Other project costs			2273					11,852,625
Contingency								22,634,606
Indirect totals			43,824					44,744,031
Project totals			250,063		6993,512		197,243,097	248,980,640

Table 12 Combined cycle project cost summary

Contract number and description	Design eng' and procurement K-USD	Construction				Contract handling and misc K-USD	Amount K-USD	Percent of base total
		Material K-USD	Man-hours	Manpower K-USD	Indirects K-USD			
Main	3923.5	483,232.7	404,134	14,592.3	16,030.9	0.0	51,7779.4	100.0
Base total	1921.5	483,232.7	404,134	14,592.3	16,030.9	0.0	517,779.4	100.0
Contingencies	392.3	48,323.3	–	1459.2	1603.1	0.0	51,777.9	10.0
TOTAL	4315.8	531,556.0	–	16,051.5	17,634.0	0.0	569,557.4	110.0

from the gas and steam turbines. In order to economically analyze this process, the simulation outputs were investigated. The results are listed in Tables 12 and 13.

Economic analysis of the processes

The structure and nature of oil and gas projects are generally long term in such a way that investors spend large

Table 13 Combined cycle project detailed cost

Account	Key Qty	Unit MH	MH	Wage rate	Labor cost	Unit Matl	Matl cost	Total cost
(2) Equipment	31 Item (9)	1264.3	39,193	38.06	1491,502	14,341.2	444,577,504	446,069,006
(3) AG pipe	1390 M	69,1	95,996	37,92	3640,522	3636	5054,487	8695,009
(4) Concrete	26,904 M3	8.1	218,616	30.15	6591,945	258.38	6951,312	135,432,577
(4) Grout	144.9 M3	109.9	15,923	82.65	456,145	3951	572,540	1028,685
(6) Instrumentation	467 Each	31.3	14,631	37.85	553,842	3638	1698,740	2252,582
(7) UG electrical	381 M	1.00	380	33.53	12,724	19.70	7510	20,234
(7) AG electrical	13,806 M	0.61	8409	36.66	308,262	56.31	777,417	1085,680
(8) Pipe insulation	2587 M	2.0	5301	28.36	150,355	87.95	227,497	377,852
(8) Equip insulation	1060 M2	2.7	2845	28.26	80,393	55.44	58,790	139,183
(9) Paint	5075 M2	0.56	2840	28.06	79,665	6.51	33,032	112,697
Direct totals			404,134		13,365,356		459,958,829	473,324,185
Const equip and indirect								10,761,702
Const Mgt, Staff, Supv			38,137				459,958,829	3921,301
Engineering			25,448					3133,001
Other project costs			5006					26,639,218
Contingency								51,777,932
Indirect totals			68,591					96,233,154
Project totals			472,725		13,365,356			569,557,339

amounts of money as capital costs in a short-term period for several years and make income and profit for a long period of time only by incurring operating costs. Because the flexibility of capital costs from one business activity to another is not easily achieved in this industry, at the beginning of the period and prior to the investment, it is necessary to make accurate estimations of the trend of variables affecting the project costs and to reach the final decision for investment. The most important factor affecting this decision at this stage is the expected economic returns of the project. The cost of investment is the costs considered in the contracting and includes the cost of the components of major equipment, construction and start-up, transportation, and contractual and probable costs. The major costs belong to equipment, 40 to 50% of total costs, on average. The project plan is prepared for project estimation based on the scope of work estimation. The plan includes the engineering design period, preparation and delivery of materials and equipment, and development and manufacturing. The plan is integrated with cost estimates to provide cost estimations, such as required equipment and monitoring the management and manufacturing. The scheduling techniques of a system, influenced by settings with engineer hours, performance, and weekly work instructions, are specified everywhere and used to create a plan summary. The project summary has been compiled to create a list of the materials quantities, material costs, required manpower, equipment, controlling, and installing

them. In this table, design engineering is all the work that a process or mechanic engineer performs to design a process, and procurement is the cost of purchasing goods, installing, and transporting. The construction is the construction cost that consists of materials, individual per hour, manpower, and miscellaneous costs. The project cost summary by contractor includes more precise costs and, in general, an overview of project costs.

Tables of information are prepared based on the contractor's estimate report and are applied in calculation of the return on investment. The first stage of the economic analysis is a determination of the total investment and variable and fixed operating costs. By calculating the installation cost, and the making assumption for indirect costs and working capital, the fixed investment cost and the total investment cost can be calculated. Diversification in design, installation, and costs may affect the economic analysis.

Economic consideration

Equations 1 to 7 have been used to calculate the return on investment [6]:

$$\text{Total investment} = \text{Fix capital} + \text{Working capital} + \text{startup cost} \quad (1)$$

$$\text{Startup cost} = 0.1 (\text{fix investment}) \quad (2)$$

$$\text{Working capital} = 0.15409 (\text{Total investment}) \quad (3)$$

$$\text{Fixed capital} = \text{direct cost} + \text{indirect cost} \quad (4)$$

$$\begin{aligned} \text{Total product cost} &= 1.3 (\text{cost of utility} \\ &\quad + \text{cost of raw materials}) \\ &\quad + 2.13 (\text{labor cost}) \\ &\quad + 0.103 (\text{fix capital cost}) \\ &\quad + 0.025 (\text{income}) \end{aligned} \quad (5)$$

$$\text{Profit before tax} = \text{Revenue} - \text{Total product cost} \quad (6)$$

$$\%ROR = \frac{\text{Annual profit}}{\text{Cap. Inv}} \quad (7)$$

According to calculations, Figs. 5–8 are presented to compare economic costs, investment, and return on investment between four methods. Figure 5 demonstrates that the total cost of a project, including direct and indirect costs, is much higher in the combined cycle method than in the other methods, and these costs have a direct effect on the total investment. Figure 6 indicates that the economic differences arise from the investment point of view. The method of electricity generation using the combined cycle of steam and gas turbines needs the highest investment, and production of high-pressure steam requires the lowest investment. Figure 7 depicts the rate of return on investment, in which the highest rate corresponds to the

generating electricity using the combined cycle; hence, given its high return rate, this method is more economical than the others. After the combined cycle, three other methods of electricity generation using a steam turbine, steam and electricity cogeneration, and steam production, respectively, have the highest return on investment. Figure 8 indicates that in the steam production unit, it takes five years for the initial investment cost to be equal with revenue.

Comparing the economics of power generation method with other processes

The researchers focus on both the recovery and sustainable aspect of flare gases with various gas processing and power generations. These procedures and industrial processes have been usually designed by incorporating conventional natural gas conversion processes [42–47]. The recent developments have shifted toward the introduction of power and electricity generation. The usage of chemical and power plants depends significantly on the technical performance, availability and reliability of recovery configuration and design as well as the economic consideration and rate of return of process plant [48–51]. In accordance with this research and their results, Rahimpour and coworkers claim that the development of flare gas recovery

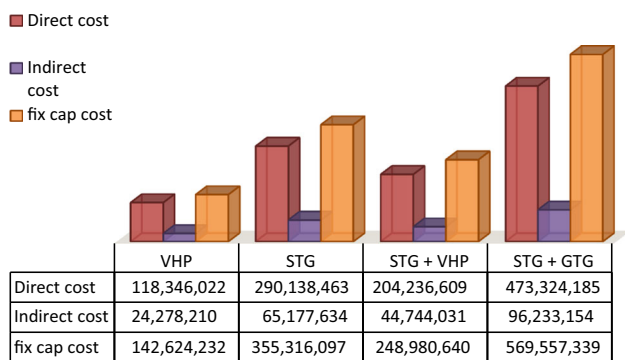


Fig. 5 A comparison between total cost of a project, involving: direct, indirect and fix capital costs (\$)

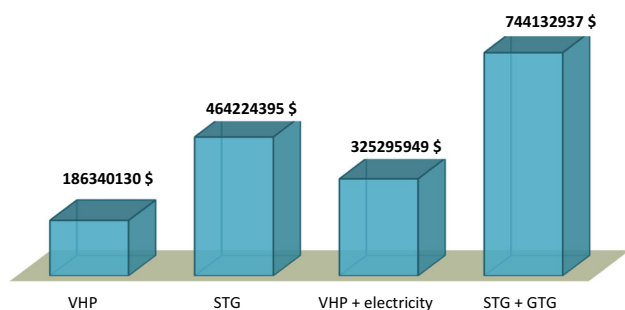


Fig. 6 A comparison between total investment (\$)

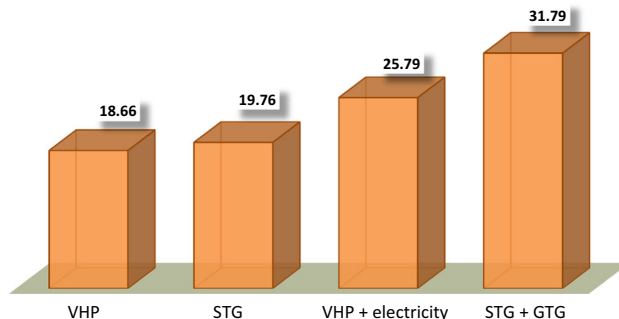


Fig. 7 A comparison between rates of return for capacity increment (%)

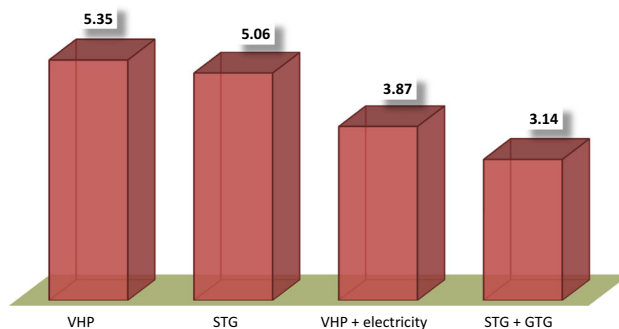


Fig. 8 A comparison between year of return for capacity increment

processes is financially feasible or impracticable. According to their simulation results, with the higher amount of flare gas, the rate of return for plants of GTL and power plants became more than other cases [13, 14]. Also, Iora et al. analyzed the potential energy recovery of the on-site electricity generation. They stated the power plant technologies may represent a cost-effective solution as an alternative to flare combustion. Various configurations were compared from both the economic and environmental aspects. They claimed that a scheme with non-derated internal combustion engines has the most cost-effective result, showing a rate of return of about 5 years and an internal rate of return (IRR) more than of 40% [51].

Conclusions

So far, methods and solutions that have been proposed to reduce or recycle the flare gases have mostly focused on the modification of units directing the produced gases to flare stacks. However, using the conducted studies and designing a proper system, the flaring amount of an industrial unit, like refinery or petrochemical plant, can dramatically be reduced, followed by a significant reduction in consequent pollutants.

Based on the presented diagrams and tables derived from the economic analysis and calculations, the following results are obtained:

- The electricity generation using the combined cycle of the gas and steam turbines is a more economical method than the others owing to its high rate of return on investment, of 31.79%.
- If the initial investment cost is not important and the only determining factor is the amount of generated electricity, the combined cycle, with a total production capacity of $1.442e+006$ kW electricity, can be the best option.
- The steam and electricity cogeneration is a better avenue compared to sole electricity generation in a steam turbine because its return on investment is greater than that of the steam turbine and requires less investment.
- Owing to its electricity generation of $7.323e+005$ kW and wide application in many industrial units, in addition to offsetting the shortage of energy production capacity and preventing waste of resources, the steam turbine can help to boost economic profits.
- Despite its low rate of return on investment, the production of high-pressure steam is a good option for recovery of flare gases because of requiring less investment than the other methods and its abundant applications in industry.

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