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Simulation and Economic Evaluation of Polygeneration System for Coproduction of Power, Steam, CH_3OH, H_2, and CO_2 from Flare Gas

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Highlights

- The polygeneration system has been used for converting flare gas to energy and various products such as power, steam, methanol, H_2, and CO_2;
- A polygeneration system has lower raw material cost, utility cost, and operating cost than the corresponding single-product processes;
- The total capital cost and the operating profit of the polygeneration system are $71 million and $115 million per year respectively, and the payback period is 1.5 years.

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Abstract

Today, one of the challenging issues all over the world is the appropriate use of flare gases in oil, gas, and petrochemical industries. Burning flare gases having high heating value results in economic losses and the pollution of the environment. There are several methods to use flare gases; the heat and power generation, the production of valuable fuels, or the separation of more precious components are examples of these methods. In this study, a polygeneration system is designed and simulated for the coproduction of power, steam, methanol, H_2, and CO_2 from the flare gases in South Pars and Assaluyeh gas fields. The polygeneration system has advantages such as reducing greenhouse gases and the coproduction and sales of energy-related products. The polygeneration system for converting flare gases to energy and various products includes an acid gas removal unit, a synthesis gas production unit, a methanol synthesis unit, a hydrogen purification unit, a combined heat and power generation unit, and a CO_2 capture unit. The purpose of this study is to conduct an economic evaluation of the polygeneration system and obtain the total capital cost, the operating profit, and the payback period of this process. The simulation results show that using 9690 kg/h of flare gases produces 8133 kg/h methanol, 653.7 kg/h hydrogen, 46950 kg/h nitrogen, 9103 kg/h CO_2, 109850 kg/h medium-pressure steam, and 3.7 MW power. The economic evaluation results show that in the polygeneration system, the total raw material cost and the total utilities consumption cost are $193.8 and $1859.5 per hour respectively, and the total product sales and the total utility sales are $12941.8 and $2243.5 per hour respectively; also, the operating profit is $13132 per hour. Also, the equipment cost, the installation cost, the total capital cost, and the total operating cost are $29.7 million per year, $39.2 million per year, $71 million per year, and $27.9 million per year respectively; finally, the payback period is 1.5 years.

Keywords: Flare Gas, Polygeneration, Simulation, Total Capital Cost, Payback Period

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1. Introduction

It is well known that flaring is used to consume waste gases, including gases rich in acidic components and gases burned during emergencies. It is used usually to expel incendiary gases that are either unusable or cannot be recovered (Zadakbar et al., 2015). Burning valuable flare gases will release large amounts of CO_2, SO_x, NO_x, and other greenhouse gases (GHG) into the atmosphere (Mesbah et al., 2017). It is obvious that flare flameout often releases toxic components to the atmosphere. The toxic components released may have serious effects on the surrounding environment (Zadakbar et al., 2011). This has caused two major challenges in the world: global warming and environmental pollution (Ziyarati et al., 2019). Flare gases have great economic value, and their use can lead to increased energy efficiency. In 2018, Iran was ranked third in flare gas production and burning and has produced 17.3×10^9 m^3 of flare gas. The total amount of flare gas produced in the world has been 145×10^9 m^3 (Fisher et al., 2019). Therefore, the conversion of flare gases to energy or valuable products has been considered by National Iranian Oil Company (Zoeir et al., 2019). Flare gas recovery (FGR) is considered as an effective method to decrease the emissions of greenhouse gases and prevent the wastage of valuable hydrocarbons. There are a number of methods, including heat (or cold) and power generation (Dwiyantoro et al., 2019), power and desalinated water generation (Chen et al., 2016), enhanced oil recovery (Calderón et al., 2020), compression and injection into the pipeline (Hoo et al., 2018), gasoline production (Jafari et al., 2018), liquefied petroleum gas (LPG) production (Fallah et al., 2019), and hydrogen production (Saidi et al., 2018) to reduce flare gases. The choice of these methods depends on the flare gas conditions such as the composition, volume flow rate, profit of product sales, lack of environmental degradation, and market needs. One of the challenges of using flare gases continuously in different scenarios is controlling the volume flow rate and composition of flare gases (Snytnikov et al., 2018). To control the volume flow rate and composition of flare gas, natural gas or part of the treated flare gases can be returned to the flare gas as a makeup stream.

Zadakbar et al. (2008) studied the FGR system in oil and gas refineries and presented the results of two case studies of recovering and reusing flare gases of Tabriz Petroleum Refinery and Shahid Hashemi-Nejad Natural Gas Refinery. The design considerations, the economics of the process, and the system operation were studied. Their results showed that flare gas recovery decreases the sound and thermal pollution, the operating and maintenance costs, air pollution and emissions, and fuel gas and steam consumption. Rahimpour et al. (2012) presented a comparative study of three different methods for recovering burner gas in Assaluyeh gas refinery and three methods for recycling gases sent to the burner tower instead of the usual combustion in the gas refinery. Their proposed methods include 1) gas to liquid (GTL) production, 2) power generation, and 3) compression and injection in refinery pipelines. Their simulation results showed that 48056 barrels per day of GTL valuable products are produced by the first method. The second and the third methods provide 2130 MW of power and compressed natural gas at a pressure of 129 bar respectively for the injection into the refinery pipelines. Their results showed that for 337600 kg/h of flare gas from Assaluyeh gas refinery, the GTL production provides the highest rate of return on investment. However, GTL production has the highest investment cost. The third method, i.e. gas compression, also has the highest rate of return on investment and is the best choice for Assaluyeh gas refinery due to its low investment cost. Zolfaghari et al. (2017) performed simulation and economic analysis of the recovery of flare gas at a mass flow of 337600 kg/h in different gas-processing plants. In their study, three methods, including GTL production, power generation, and gas to ethylene conversion were introduced and compared with the best process. Meanwhile, the estimation of the capital and the operating costs and the evaluation of the processes involved were conducted using Aspen One. The results showed that the production of power from flare gases is one of the most economical methods. Power generation method, with an annual profit of about \$480 million, has a greater rate of return (RoR). Hajizadeh et al. (2018) performed the simulation and economic evaluation of the recovery of flare gas in a giant gas refinery by including gas compression units and LPG production. In their study, the feasibility of three methods for FGR is evaluated in a giant gas refinery in Iran. The first two methods considered liquefaction and LPG production by using flare gases as the feed for an existing LPG unit. The third studied option used a three-stage compression unit to compress the flare gases. The economic results showed that the rate of return of the liquefaction unit and the LPG production unit was more than 200% for different scenarios and was higher than that of the compression unit. In another work, Fallah et al. (2019) studied and simulated the potential of the flare gases produced in oil and gas producing companies for power generation. Olga software was utilized to study the possibility of transporting the flare gas in the same pipeline that carries oil and water. In order to survey the process feasibility, technical, economic, and environmental assessments were performed. Their results showed that the process of removing flare gases presented a net present value of about \$408315 and a payback period of 3.2 years. Shafiee et al. (2020) studied the economic value of flare gases in the South Pars gas (phase 12) refinery. The economy of the process itself has been examined from two perspectives. The first method was the conversion of flare gases to power. In the second method, the volume of the flare gases was equivalent to the amount of gas consumed in industries, households, and exports. Their results showed that the gross profit of the conversion of flare gases to power was \$123,125 per year. Shayan et al. (2020) conducted the simulation and economic evaluation of flare gas recovery methods and the comparison of different steam and power generation systems. In their study, four methods for FGR, namely high-pressure (HP) steam generation, steam turbine, heat and power generation, and a combined cycle power plant, were introduced and simulated using Aspen HYSYS. The results showed that the rate of investment return of the four processes of the high-pressure steam generation, steam turbine, heat and power generation, and the combined cycle was 18.66, 19.76, 25.79, and 31.97 respectively. The results showed that the rate of investment return of the combined cycle power plant method is higher than that of the other methods. Hamidzadeh et al. (2020) also studied a multi-objective decision-making model to recover flare gases in a zone with multiple flare gases and reviewed different technologies, including natural gas liquids (NGL), injection in pipelines, liquefied natural gas (LNG), GTL, natural gas hydrate (NGH), compressed natural gas (CNG), enhanced oil recovery (EOR), and power and water generation used for the enhancement of flare gas recovery in south of Iran. Then, a complete investigation and modeling of all the technologies for FGR were developed. Finally, the optimal combination for using these technologies was considered with the objective function of minimizing the payback period of the capital costs (the economical aspect) and maximizing the reduction of CO_2 by using the genetic algorithm and decision-making methods. By the technical, economic evaluation and modeling of the FGR technologies in MATLAB software, the final results showed that the outlet gas of the NGL plant (100% of flare gases) should be dedicated to EOR (70% of the dry gas), the gas turbine (4% of the dry gas), the combined cycle power plant (26% of the dry gas), and water generation (80% of the gas turbine flue gases) technologies. Using the selected technologies in this model will decrease 966000 tons/year of CO_2 production in oil wells, and the total capital costs of such a process will be \$410.8 million with a payback period of 1 year.

Considering the potential of flare gases for the production of various products and preventing environmental pollution, this work attempts to design and simulate a special system using conventional processes. In this special system, energy consumption and emissions of pollutants into the atmosphere are very low. In view of the fact that most of the flare gas recovery equipment has poor efficiency, high energy consumption, and secondary pollution, the products, heat, and power coproduction process scheme are presented in this study. Thus, a plan is proposed to use the huge resources of flare gases of South Pars gas field and Assaluyeh region for the coproduction of CH_3OH, H_2, CO_2, power, and medium-pressure (MP) steam in a polygeneration system. Processes based on the concept of polygeneration can use a number of energy sources (renewable and nonrenewable), providing a number of energy forms (heating, cooling, and power) and several products. Overall efficiency increases if the polygeneration system design and the integration between the subsystems are performed effectively. In this method, the impurity and GHG emissions are also reduced (Luqman et al., 2020). Therefore, CO_2 production is performed mostly because no gases are released into the atmosphere, that is, zero-carbon emissions; further, the income from CO_2 sales is also considered. Also, CO_2 can be returned to the synthesis gas unit to increase the production of synthesis gas, CH_3OH, and H_2 (Jafari et al., 2018). Therefore, CO_2 capturing can be very efficient. In the polygeneration system, a combined heat and power (CHP) generation unit is required. The CHP unit is designed to be able to provide all the power of the polygeneration system. The reduction of the total capital cost, energy consumption, and payback period are the most important reasons for investors, and using green technologies is the most important reason for the government to invest in flare gas recovery in Iran. Therefore, in this study, both objectives have been considered. The following describes the processes of the coproduction of the products from flare gases in the polygeneration system. The simulation, economic evaluation, and calculation of the total capital cost, the operating profit, the payback period, the equipment cost, and the installation cost of the polygeneration system by Aspen HYSYS v.11 software are some of the innovations of this research, which have not been reported in the related literature.

2. Materials and methods

South Pars in Assaluyeh region is one of the largest sources of the production of flare gases in Iran. The flare gases in Assaluyeh mainly contain CH_4 (Rahimpour et al., 2012). The other constituents of the flare gases in this region include C_2–C_6 hydrocarbons, N_2, H_2S, and CO_2. The specifications of sample flare gases in South Pars gas field are listed in Table 1. Aspen HYSYS v. 11 was used for this simulation of the flare gas recovery. The fluid package used in this simulation is Peng–Robinson–Stryjek–Vera (PRSV), but some units require a separate fluid package to reach a very high degree of accuracy (Jafari et al., 2018). The fluid package used in various units are:

- Amine unit and CO_2 separation unit: acid gas chemical solvents (Nourmohamadi et al., 2018);
- Synthesis gas production unit: PRSV (Behroozsarand et al., 2017);
- Methanol synthesis unit: UNIQUAC (Jafari et al., 2018);
- Hydrogen production unit, power generation unit: Peng–Robinson (Unlu et al., 2020).

There are two methods for the economic evaluation: first, using manual reference books and economic evaluation manuals, which in principle results in up to 30% error (Peters et al., 1968). Second, using Aspen Process Economic Evaluation (APEA) software which has become common (Al-Malah, 2016). APEA v.11 has been used for economic evaluations and has been updated in 2019. APEA is a cost estimating software that provides the estimates for the capital expenditure and operating expenses so as to compare and screen multiple process schemes. Aspen HYSYS along with the APEA tool can quickly create first approximations of process sizing and costs. This is very useful when attempting to compare a number of process designs so as to decide which design will have the best potential to be profitable.

Table 1

Specifications of sample flare gases sent to the polygeneration system (Jafari et al., 2018).

Condition	Values
Mass flow rate	9690 kg/h
Temperature	30 °C
Pressure	100 kPa
Composition	**Mole fraction**
Methane	0.8458
Ethane	0.0518
propane	0.0191
n-butane	0.0055
i-butane	0.0036
n-pentane	0.0016
i-pentane	0.0017
C_6^+	0.0101
CO_2	0.0202
N_2	0.0354
H_2S	0.0052

3. Polygeneration system description

Figure 1 represents a block flow diagram (BFD) of the conversion of flare gases into products in a polygeneration system consisting of six units: 1) acid gas removal unit (amine unit); 2) synthesis gas production unit; 3) conversion of synthesis gas to methanol; 4) hydrogen purification unit; 5) combined heat and power (CHP) generation unit; 6) CO_2 capture unit.

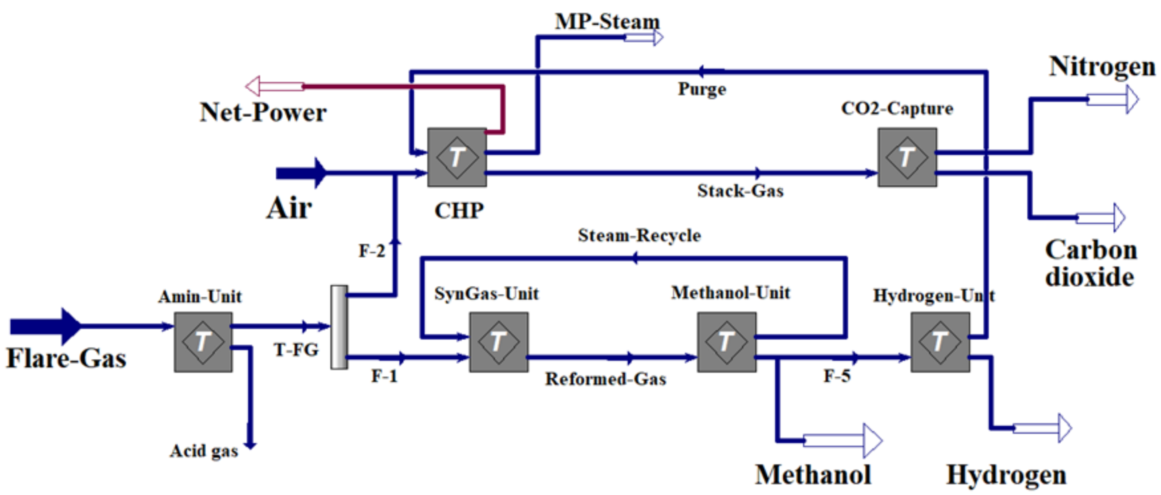

Figure 1

The BFD of the conversion of flare gas into products in a polygeneration system.

3.1. Acid gas removal (amine) unit

Since flare gases contain H_2S components, they are sent to the acid gas removal unit using an amine solvent. Absorption by alkanolamine solvents is widely used for acid gas removal in gas sweetening plant (Nourmohamadi et al., 2018). The specifications of the flare gas are presented in Table 1. Flare gas with a mass flow rate of 9690 kg/h, a temperature of 30 °C, and a pressure of 100 kPa is pressurized to a pressure of 2500 kPa, while reducing the temperature to 40 °C, and then enters the absorption tower (T-100) to remove its acid gases by methyl diethanolamine (MDEA) solvent (Abd et al., 2019). The mass flow rate of the MDEA stream is 29,000 kg/h at a concentration of 45% water-soluble mass (Seidi et al., 2019). The pressure of the absorption tower is 2500 kPa, and it has 20 real stages. The diameter and the height of the absorption tower (T-100) are 1.5 and 14 m respectively. The flare gases after purification (treated flare gas), containing a very small amount of H_2S (less than 4 ppm), exits from the top of the absorption tower and is sent to the synthesis gas production unit. To recover the enriched amine, it must be warmed and restored in a regeneration tower (T-101). In this tower, the acid-rich amine enters the regenerator tower, and, as its temperature rises by the reboiler, it is discharged and returned to the acid gas removal unit. The number of regenerator tower trays is 20, and the top and bottom pressure of the tower is 160 and 180 kPa respectively (Radzuan et al., 2019). The diameter and the height of the regeneration tower (T-101) are 0.8 and 12 m respectively. Figure 2 illustrates a process flow diagram (PFD) of the acid gas removal unit in Aspen HYSYS environment.

3.2. Synthesis gas production unit

As shown in Figure 1, the treated flare gas is divided into two parts: 65% of the treated flare gas enters the synthesis gas (H_2 + CO) production unit, and 35% enters the combined heat and power generation unit. With this ratio, all the power required for the polygeneration system will be supported. The production of the synthesis gas is of the steam methane reforming (SMR) type (Roohollahi et al., 2019), and two reactors, namely pre-reformer and reformer, are used; the reactions are listed in Table 2. Steam is required to perform synthesis gas reactions, and approximately 52% of this steam is provided by the methanol synthesis unit. Figure 3 provides a PFD of the synthesis gas production unit in Aspen HYSYS environment.

Table 2

Types of pre-reforming and reforming reactions (Amran et al., 2017).

Pre-reforming conversion reactions	Stoichiometry of reactions (100% conversion)
Ethane reforming	$C_2H_6 + 2H_2O \rightarrow 2CO + 5H_2$
propane reforming	$C_3H_8 + 3H_2O \rightarrow 3CO + 7H_2$
n-butane reforming	$i{-}C_4H_{10} + 4H_2O \rightarrow 4CO + 9H_2$
i-butane reforming	$n{-}C_4H_{10} + 4H_2O \rightarrow 4CO + 9H_2$
n-pentane reforming	$i{-}C_5H_{12} + 5H_2O \rightarrow 5CO + 11H_2$
i-pentane reforming	$n{-}C_5H_{12} + 5H_2O \rightarrow 5CO + 11H_2$
Reforming equilibrium reactions	Stoichiometry of Reactions
Steam methane reforming	$CO + 2H_2 \leftrightarrow CH_4 + H_2O$
Water gas shift	$CO_2 + H_2 \leftrightarrow CO + H_2O$

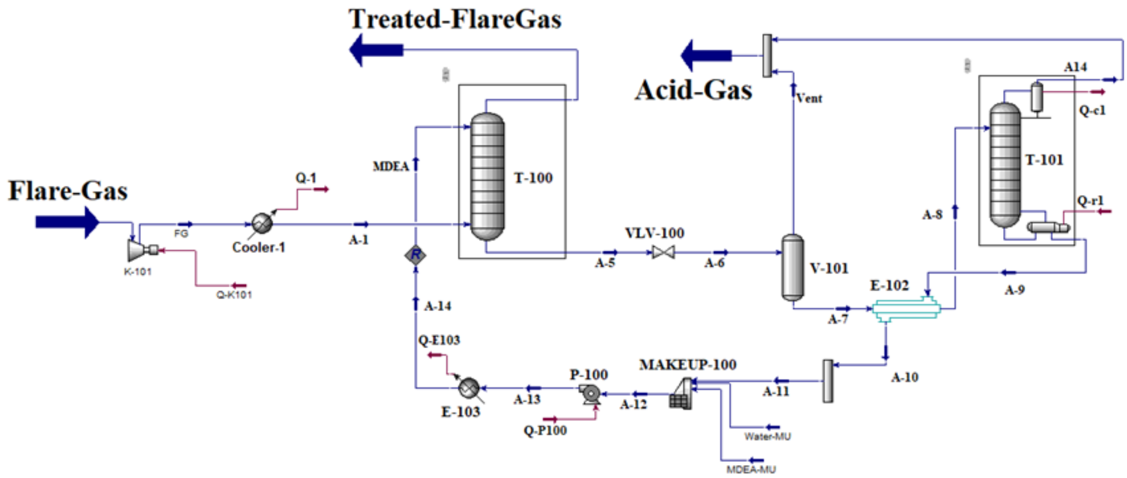

Figure 2

PFD of acid gas removal unit as configured in Aspen HYSYS v.11 environment (Sharif Dashti et al., 2015).

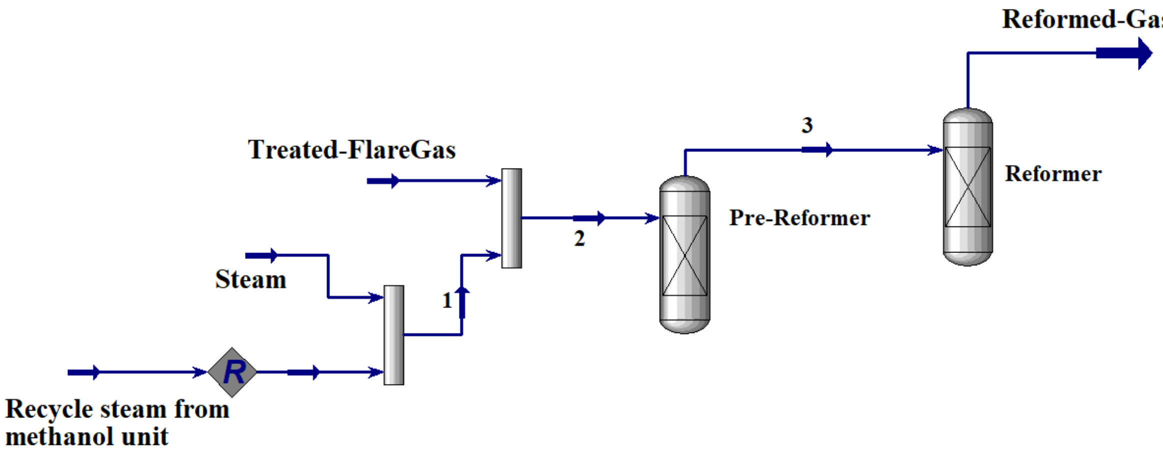

Figure 3

PFD of synthesis gas production unit as configured in Aspen HYSYS v.11 environment (Jafari et al., 2018).

3.3. Methanol synthesis unit

Reformed gas (synthesis gas) is sent to the methanol synthesis unit. In this unit, the methanol synthesis cycle is used to maximize the methanol production. The methanol synthesis cycle includes synthesis reactors, coolants, methanol separators, and heat exchangers (Liu et al., 2019). According to Figure 4, the produced synthesis gas after being cooled down to 35 °C enters the separator. In this separator, steam is separated from the synthesis gas and enters the compressor to increase its pressure to 3360 kPa. The separated steam is then recycled to the synthesis gas production unit to supply part of the required steam. The synthesis gas stream is then sent to the methanol synthesis reactor (PFR reactor).

The tube length, the tube number, and the tube diameter of the PFR reactor are 8, 1500, 0.040 m respectively, and the catalyst porosity coefficient is 0.45 (Jafari et al., 2018). The methanol synthesis reactions and catalyst kinetics of the Langmuir–Hinshelwood state are presented in Table 3. The purity percentage of the produced methanol is about 96% to 99%. The methanol purification tower has 20 equilibrium stages and 2 feed trays; the top and bottom pressure of the tower is 304 and 204 kPa respectively. The diameter and the height of the methanol purification tower (T-102) are 1.8 and 15 m respectively. Also, the M-25 stream, which is rich in H_2, is sent to the hydrogen purification unit. Figure 4 depicts a PFD of the methanol synthesis unit in Aspen HYSYS environment.

3.4. Hydrogen purification unit

Light off-gases (F-5 stream) from the methanol unit are rich in H_2 and contain components such as CH_4 (Liu et al., 2019). Off-gases stream (F-5) enters the H_2 purification unit at a temperature of 40 °C and a pressure of 4700 kPa. In this unit, two stages of the silica membrane are used in series; the properties of this membrane are presented in Table 4. Since Aspen HYSYS software does not perform membrane simulation, another simulator tool is required. Since PRO/II software is capable of simulating a membrane system (Ghasemzadeh et al., 2017), this membrane system is first simulated in PRO/II; then, using the output of PRO/II software, this membrane system is functionally implemented in Aspen HYSYS software (Figure 5) by Component Splitter. Considering the properties of the silica membrane and the pressure gradient crossings, the first stage used 130 m^2 of silica membrane, and the second stage used 40 m^2 (Jafari et al., 2018).

Table 3

Catalytic reactions and kinetics of methanol synthesis (Wilkinson et al., 2016).

Methanol synthesis reaction		$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O + \text{heat}$	
The gas-water shift reaction		$CO_2 + H_2 \leftrightarrow CO + H_2O - \text{heat}$	
$r_1 = \dfrac{k_1 P_{CO_2} P_{H_2} - k_1' P_{CH_3OH} P_{H_2O} P_{H_2}^{-2}}{[1 + K_1 P_{H_2}^{0.5} + K_2 P_{H_2} + K_3 {P_{H_2O}}/{P_{H_2}}]^3}$		$[r] = \dfrac{Kmole}{m^3.s}$ $[P_i] = bar$	
$r_2 = \dfrac{k_2 P_{CO_2} - k_2' P_{CO} P_{H_2O} P_{H_2}^{-1}}{[1 + K_1 P_{H_2}^{0.5} + K_2 P_{H_2} + K_3 {P_{H_2O}}/{P_{H_2}}]}$		$[r] = \dfrac{Kmole}{m^3.s}$ $[P_i] = bar$	
k_1	1.2	E_2'	55200 J/mol
E_1	–36450 J/mol	K_1	0.449
k_1'	4.2238×10^{-10}	E_{Ad1}	–17197 J/mol
E_1'	21670 J/mol	K_2	6.62×10^{-11}
k_2	$1.23 \times 10^{+10}$	E_{Ad2}	-1.2412×10^{-5} J/mol
E_2	94850 J/mol	K_3	3454.4
k_2'	1.1521×10^{-8}	E_{Ad3}	0.000

Table 4

Specifications of the silica membrane (Gallucci et al., 2013).

Specifications	Values
Stream pressure (kPa)	1300
Pressure gradient (kPa)	1200
Permeance of H_2 $\frac{m^3}{m^2.hr.pa}$	0.0003225
Permeance of CH_4 $\frac{m^3}{m^2.hr.pa}$	6.45×10^{-8}
Permeance of C_2H_6 $\frac{m^3}{m^2.hr.pa}$	8×10^{-8}
Permeance of C^{+}_{2} $\frac{m^3}{m^2.hr.pa}$	5×10^{-9}

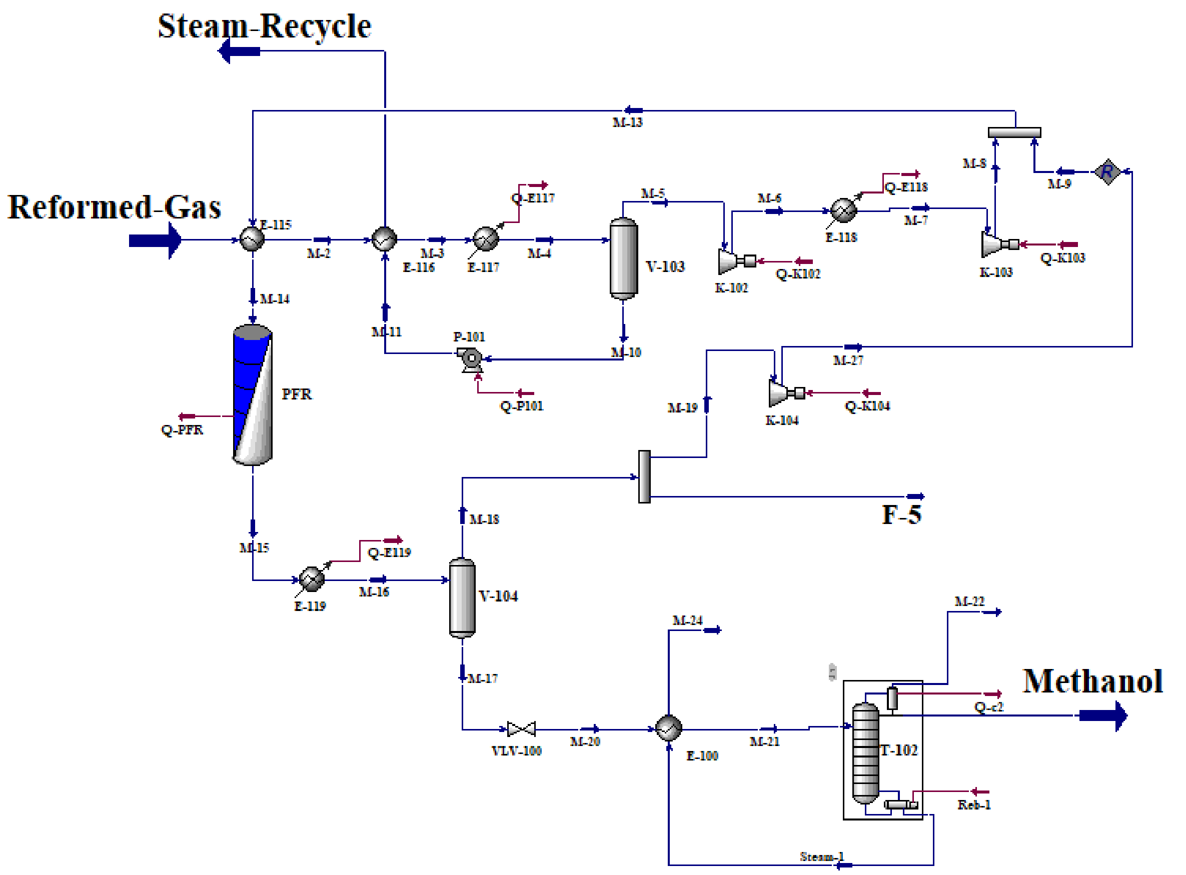

Figure 4

The PFD of the methanol synthesis unit as configured in Aspen HYSYS v.11 environment (Jafari et al., 2018).

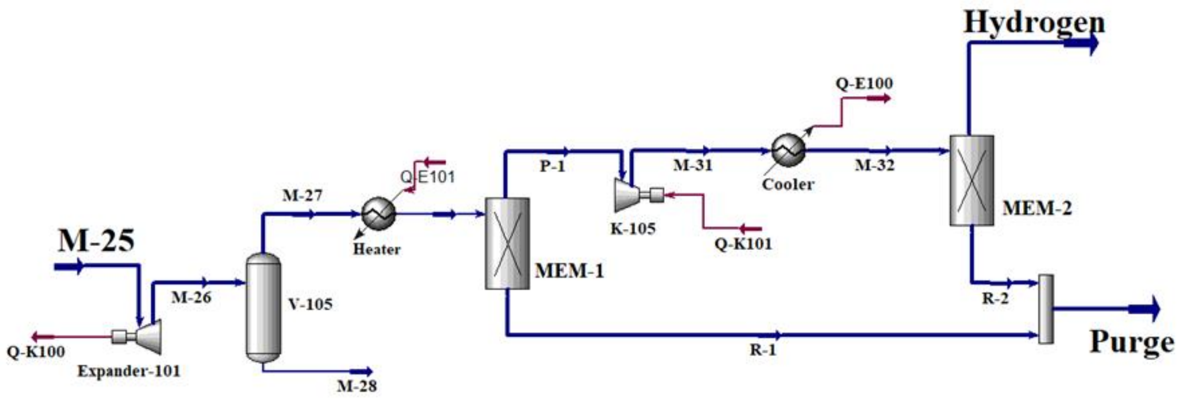

Figure 5

The PFD of the hydrogen purification unit as configured in Aspen HYSYS v.11 environment (Jafari et al., 2018).

3.5. CHP generation unit

As mentioned, 35% of the treated flare gas with gases separated from the hydrogen purification unit (Purge stream), which is rich in methane, enters the CHP unit to co-generate heat and power. The mass flow rates of the purified gas sent to the flare and hydrogen-free gas sent to the CHP unit equal 3308 and 1646 kg/h respectively. Air with a molar discharge of 10 times the amount of the purified gases sent to flare enters the air compressor at a temperature of 25 °C and a pressure of 100 kPa to reach a pressure of 1500 kPa; it then enters the furnace or combustion chamber (Kang et al., 2014). In this furnace, methane undergoes complete combustion and generates a lot of energy. It is assumed that all the reactions reach a conversion of 100% in the furnace. Also, in the furnace, the hydrocarbons are completely burned and converted to carbon dioxide and water. The outflow of the furnace mainly contains carbon dioxide, water, and nitrogen at a high pressure and temperature. In order to generate power, the stream enters a gas turbine and its pressure is reduced to 50 kPa. Then, the turbine output stream enters the heat recovery steam generator (HRSG) for heat generation (Khademi et al., 2019). Figure 6 displays the PFD of the CHP unit in Aspen HYSYS environment.

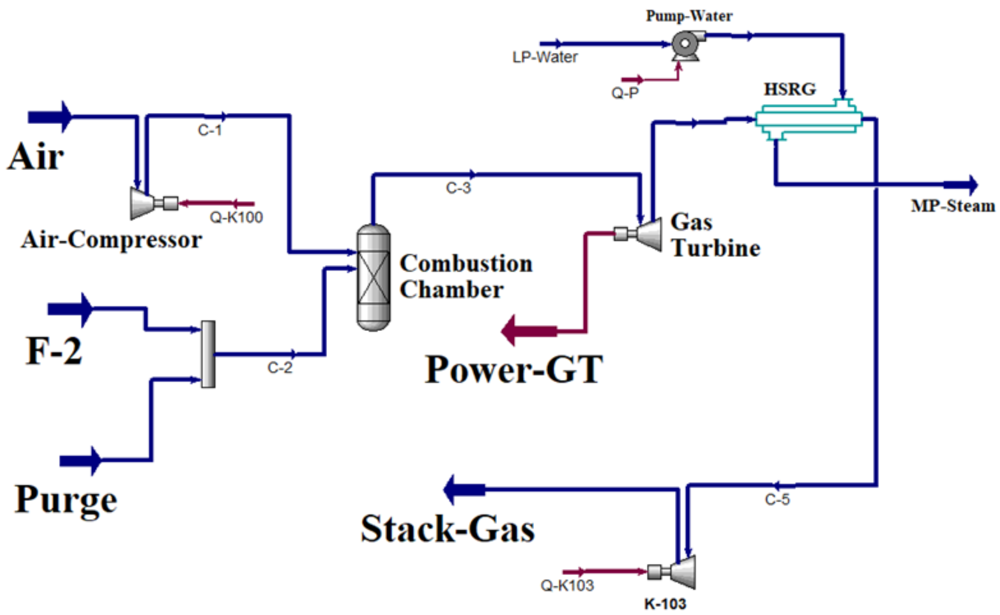

Figure 6

The PFD of the CHP generation unit as configured in Aspen HYSYS v.11 environment (Zolfaghari et al., 2017).

3.6. CO_2 capture unit

Due to increasing global warming and greenhouse gas emissions from the combustion of fossil fuels in recent years, CO_2 capture units have received great attention in terms of environmental and economic benefits (Rahmandoost et al., 2014). In this work, the combustion gases created by the power and heat generation plant of the polygeneration enter the CO_2 capture unit. Then, the combustion gas at a mass flow rate of 65500 kg/h (71% mass fraction of N_2, 13% mass fraction of CO_2, and the remainder as H_2O) after being cooled down to a temperature of 40 °C enters the absorption tower (T-103) to purify its nitrogen by an amine solvent, i.e. monoethanolamine (MEA), (Jafari et al., 2019). The mass flow rate of MEA is 150,000 kg/h, and its concentration is 28% water-soluble mass (Roh, 2018). The top and bottom pressure of the absorption tower is 2900 and 2800 kPa respectively. The diameter and the height of the absorption tower (T-103) are 1.3 and 14 m respectively. For the recovery of the amine solvent, as well as for the removal of carbon dioxide, the solvent rich in carbon dioxide enters the tower (T-104) to remove its carbon dioxide. The tower (T-104) has 20 trays, and the top and bottom pressure of the tower is 340 and 360 kPa respectively (Jafari et al., 2019). The diameter and the height of the regeneration tower (T-104) are 2.2 and 14 m respectively. Figure 7 depicts the PFD of the CO_2 capture unit in Aspen HYSYS environment.

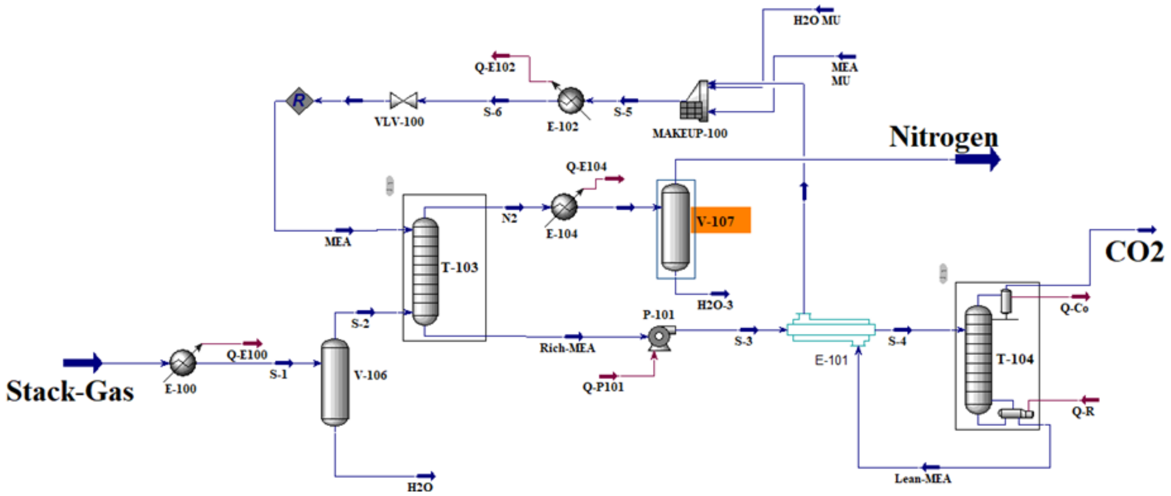

Figure 7

The PFD of the CO_2 capture unit as configured in Aspen HYSYS v.11 environment (Younessi Sinaki et al., 2019).

4. Economic evaluation

The following section evaluates whether the production of the desired energy and products from the flare gases is economically profitable or not. Since the design of the polygeneration system is innovative, the system should be carefully evaluated in terms of optimization and economic evaluation. The following is a list of some terminologies commonly used in economic evaluation with their description (Jafari et al., 2019).

- **Equipment cost** represents the bare equipment cost associated with the project components.
- **Installation cost** represents the total direct material and labor costs associated with the project component. Due to the items that are included in the installation cost, in APEA software, the installation cost is more than the equipment cost.
- **Total utilities cost** refers to the annual consumption of cooling water, steam, power, etc.

- **Operating cost** indicates, by period, the total expenditure on the following items necessary to keep the facility operating: raw materials, operating labor cost, maintenance cost, utilities, operating charges, plant overhead, etc.
- **Payback period** refers to the amount of time required to recover the total capital cost.
- **Total capital cost** includes:
  - ✓ Direct costs: equipment and setting, piping, civil, structural steel, instrumentation and controls, electrical equipment and materials, insulation, paint;
  - ✓ Indirect field costs: engineering and supervision, start-up and commissioning, construction expenses-fringe benefits, burdens, insurance, equipment rental, field services, temporary constructions, etc.
  - ✓ Indirect non-field costs: freight, taxes and permits, engineering, and material procurement, contingency, allowances for unpredictable events, other project costs, etc.

The right decisions made during the economic evaluation operations such as choosing the right type of equipment and the type of utility have a major impact on the correct economic evaluation. At the beginning of the work, the stream price of feed and products are input to determine if the unit design is profitable or not. Table 5 tabulates the stream price of the flare gas, the products, and the utility.

Table 5

Stream price of the flare gas, the products, and the utility.

Stream	Price	Unit	Reference
Flare gases	0.02	USD/m^3	(Shafiee et al., 2020, Hamidzadeh et al., 2020)
Methanol	400	USD/tonne	(Methanex posts regional contract methanol prices for North America, Europe, and Asia, 2020)
H_2	12000	USD/tonne	(Hydrogen Fuel Price, 2020)
N_2	40	USD/tonne	(Jafari et al., 2019)
CO_2	20	USD/tonne	(Poelhekke et al., 2019)
Cooling water	2.125×10^{-7}	USD/kJ	(Jafari et al., 2019)
High-pressure steam	2.5×10^{-6}	USD/kJ	(Jafari et al., 2019)
Medium-pressure steam	2.2×10^{-6}	USD/kJ	(Jafari et al., 2019)
Low-pressure (LP) steam	1.9×10^{-6}	USD/kJ	(Jafari et al., 2019)
Power	1.58×10^{-5}	USD/kJ	(Jafari et al., 2019)

The utility type of the equipment is selected after determining the stream price of the raw materials, products, and utilities; the utility type of the equipment of each unit is presented in Table 6. The operating profit of the polygeneration system is expressed by:

$$\begin{aligned} Operating\ Profit \\ &= (total\ product\ sales\ +\ total\ utilities\ sales) - (total\ raw\ materials\ cost \\ &+\ total\ utilities\ cost) \end{aligned}$$

Table 6

Type of utilities of the multifunctional process equipment for the production of flare gas products.

Equipment type	Utility type
Compressors, pumps, and turbines throughout the process	Power
Tower coolers and condensers throughout the process	Cooling water
Reboiler resuscitation tower in the sweetening unit	Low-pressure steam
Reboiler of tower in CO_2 separation units and methanol purification tower	Medium-pressure steam
Thermal load of the reactor reforming and over-reforming synthesis gas production unit	High-pressure steam

A key step in the economic evaluation in APEA software is the mapping of the unit operators. For example, a distillation column in Aspen HYSYS may be mapped into a number of items such as a trayed or packed tower, a kettle-type reboiler, an overhead condenser, a reflux pump, etc. The type of equipment and its unit operations are listed in Table 7. Sizing of the equipment is performed using the available simulation data and the default sizing procedure. The default material for the construction of all the equipment is carbon steel. However, the materials used in the construction of the equipment can be changed according to the conditions such as high temperature, high pressure, or corrosion. After mapping and sizing operations, the economic evaluation in APEA software is completed, and the results are reported.

Table 7

Equipment type and the unit operations of the mapping equipment.

Equipment type	Type of unit operation
Absorption and towers in the polygeneration system	Single drop-tower with tray
Pumps in the polygeneration system	Centrifugal single or multistage pump
Compressors in the polygeneration system	Centrifugal-integral gear
Coolers and condensers in the polygeneration system	TEMA standard shell and tube heat exchanger
Heaters and reboilers in the polygeneration system	TEMA standard shell and tube heat exchanger
Separators in the polygeneration system	Vertical tank
Air compressor in the CHP unit	Air compressor with engine
Gas turbine and furnace in the CHP unit	Gas turbine with combustion chamber
Ceramic membrane ($250 per square meter)	The price is input to the software
PFR reactor in the methanol unit	Packed tower

5. Results and discussions

Flare gas recovery can play an effective role in energy efficiency and can produce valuable products. Moreover, the use of these gases can play an important role in increasing Iran's energy efficiency and sustainable development. Flare gas recovery is also very effective in protecting the environment and preventing international penalties. In this study, flare gases of Assaluyeh, which has no flare gas recovery technology, were chosen. The total mass flow of the flare gases in the case study is 9690 kg/h, which, at a price of $0.02 per cubic meter, results in an economic loss of $1.7 million per year. Meanwhile, this is small part of the flare gases in the area selected as the case study. In order to prevent economic losses and reduce the GHG, it is necessary to use FGR technologies. Since various technologies can be used for FGR, the polygeneration system was developed in this paper.

The polygeneration system mainly has six units, including an acid gas removal unit, a synthesis gas production unit, a methanol unit, a hydrogen production unit, a heat and power generation unit, and a CO_2 capturing unit. This study performed the simulation and economic evaluation of a polygeneration system suggested for producing energy and various products such as power, CH_3OH, H_2, N_2, CO_2, and medium-pressure steam from flare gases. In the simulation of the polygeneration system, the connection between the streams in the main flowsheet and the sub flowsheets is well done. Table 8 tabulates the molar composition, mass flow rate, temperature, and pressure of the streams in the polygeneration system. The only stream that is not sold as a product in the polygeneration system is the acid gas extracted from the amine unit. The stream of the acid gas must be sent to the sulfur recovery unit (SRU). Table 9 lists the flow rate of the raw materials (flare gas), the power consumption, the cooling water, the low-pressure (LP) steam, the medium-pressure steam, and the high-pressure steam, and Table 10 presents the flow rate of CH_3OH, H_2, N_2, and CO_2; the power generation; and the medium-pressure steam generation.

Table 8

Material balance of the polygeneration system.

Steam name	**Flare Gas**	**Acid Gas**	**T-FG**	**F-1 and F-2**	**Recycle-Steam**
Mass flow rate (kg/h)	9690	631.3	9189	5881 and 3308	5379
Temperature (°C)	30	90	55	55	450
Pressure (kPa)	100	150	2400	2400	2290
Composition	Molar fraction	Molar fraction	Molar fraction	Molar fraction	Molar fraction
Methane	0.846	0.040	0.861	0.861	0.000
Ethane	0.052	0.005	0.053	0.053	0.000
C_2^+	0.042	0.084	0.040	0.040	0.000
CO_2	0.020	0.467	0.005	0.005	0.000
N_2	0.035	0.001	0.036	0.036	0.000
H_2S	0.005	0.157	0.000	0.000	0.000
H_2O	0.000	0.247	0.006	0.006	1.000
Steam name	**Steam**	**Reformed-Gas**	**F-5**	**Methanol**	**Hydrogen**
Mass flow rate (kg/h)	4844	16104	2346	8133	654
Temperature (°C)	220	900	40	57	40
Pressure (kPa)	2300	1800	4700	100	100
Composition	Molar fraction	Molar fraction	Molar fraction	Molar fraction	Molar fraction
Methane	0.000	0.032	0.116	0.000	0.000
CO_2	0.000	0.039	0.033	0.001	0.000
N_2	0.000	0.007	0.000	0.000	0.001

Steam name	Flare Gas	Acid Gas	T-FG	F-1 and F-2	Recycle-Steam
H_2O	1.000	0.200	0.000	0.023	0.000
H_2	0.000	0.573	0.816	0.000	0.997
CO	0.000	0.149	0.035	0.000	0.002
Methanol	0.000	0.000	0.000	0.976	0.000
Steam name	**Purge**	**Air**	**Stack-Gas**	**N_2**	**CO_2**
Mass flow rate (kg/h)	1692	60590	65540	46950	9104
Temperature (°C)	40	25	323	40	90
Pressure (kPa)	1400	100	300	280	340
Composition	Molar fraction	Molar fraction	Molar fraction	Molar fraction	Molar fraction
Methane	0.622	0.000	0.000	0.000	0.000
CO_2	0.181	0.000	0.139	0.001	0.990
O_2	0.000	0.210	0.000	0.000	0.000
N_2	0.000	0.790	0.720	0.991	0.002
H_2O	0.000	0.000	0.125	0.009	0.008
H_2	0.012	0.000	0.000	0.000	0.000
CO	0.185	0.000	0.016	0.000	0.000

Figure 8 displays the cost of raw materials (flare gases), the power consumption, the cooling water, the low-pressure steam, the medium-pressure steam, and the high-pressure steam; Figure 9 presents the sales of CH_3OH, H_2, N_2, and CO_2; the power generation, and the medium-pressure steam produced. These tables show that the production of hydrogen and methanol can be very profitable. The power generated by the CHP unit, in addition to supplying the entire process requirements, will be sold to the national grid, which can be very profitable. Furthermore, this process requires steam at various levels (LP, MP, and HP). In the CHP unit, the steam produced will be medium-pressure one, which, in addition to providing the total needs of the mentioned process, will also be sold. As can be seen in Figure 8, the cost of power and medium-pressure steam consumption is high, which indicates the need for a CHP unit in the polygeneration system. Also, the polygeneration system which has a CO_2 capturing unit produces large amounts of nitrogen gas. Nitrogen gas can be sold or used for other purposes such as adding an ammonia unit to the polygeneration system.

Table 9

The flow rate of the raw materials and the utility consumption.

Stream	Values	unit
Flare gas	9690	kg/h
Cooling water	12430000	kg/h
HP steam	54330	kg/h
MP steam	67550	kg/h
LP steam	4421	kg/h
Power	22.17	MW

Table 10

The flow rate of the products and the utility generation.

Stream	Values	unit
Methanol	8133	kg/h
Hydrogen	654	kg/h
Nitrogen	46950	kg/h
CO_2	9104	kg/h
MP steam	177410	kg/h
Power	25.87	MW

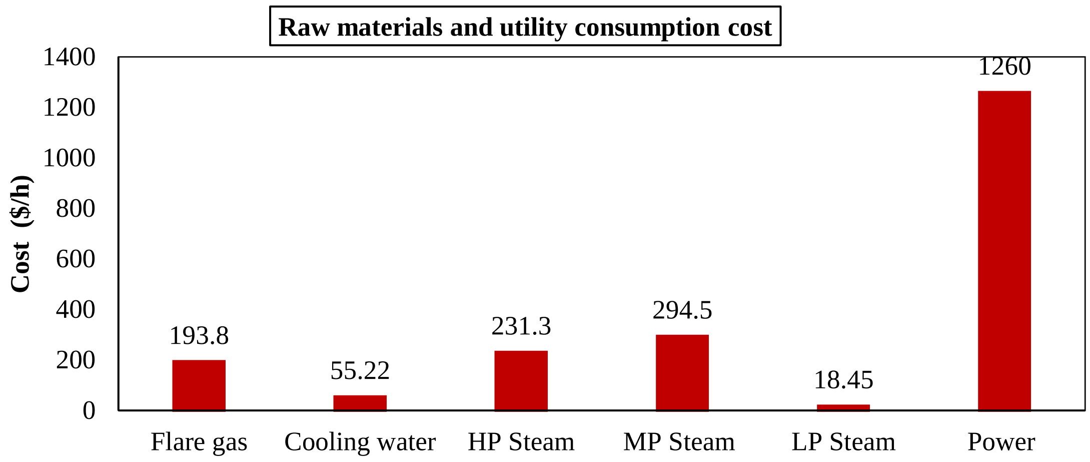

Figure 8

The raw materials and the utility consumption cost.

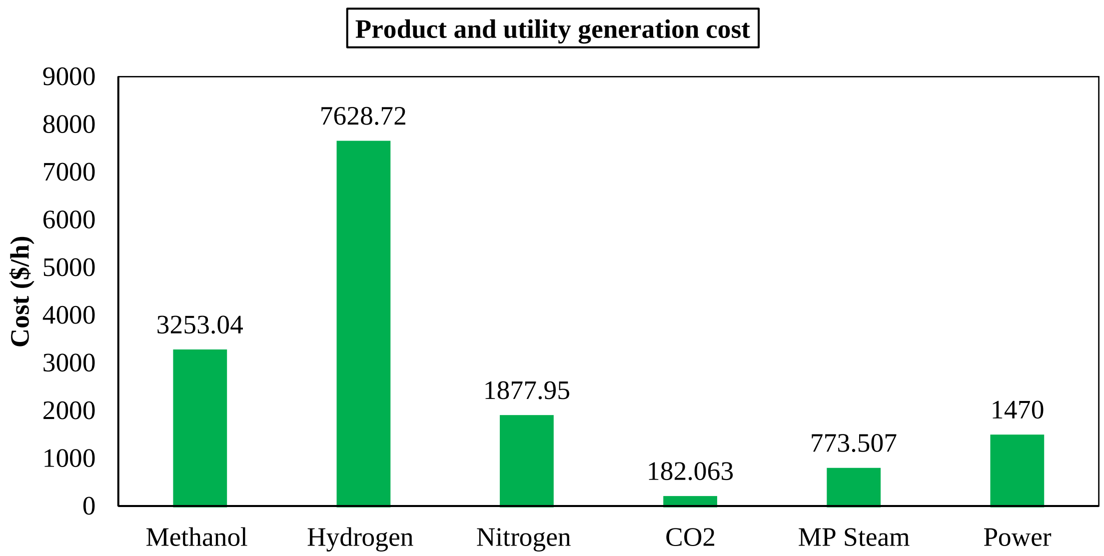

Figure 9

The products and the utility generation cost.

Table 11 lists the operating profit of the polygeneration system for converting flare gases into products. As shown in this table, the cost of the raw materials is very low, which provides an opportunity for domestic and foreign investors to make more profits by producing more valuable products, both for themselves and for Iran. Building a CHP unit along with the other units is a very good and profit-making idea because, in addition to supplying part of the desired utility, the surplus of the generated utility can be sold. As can be seen in Table 10, the sales of the utilities are more than the cost of the utilities, indicating the profitability of the CHP unit. As shown in Figure 8, the highest utility cost is related to the process of power supply.

Table 11

Total costs of the raw materials and the utilities and the sales of the products and operating profit.

Specification	Values	Unit
Total raw materials cost	193.8	USD/h
Total utilities cost	1859.47	USD/h
Total product sales	12941.773	USD/h
Total utilities sales	2243.507	USD/h
Operating profit	13132.01	USD/h

Figure 10 illustrates the economic evaluation of each unit separately and reports the equipment cost, the installation cost, the total operating cost, and the total capital cost in each unit. Also, Table 12 presents a summary of the various costs of the polygeneration system, including the equipment cost, the installation cost, the total utility cost per year, the total raw material cost per year, the total product sales per year, the total operating cost, the total capital cost, and the payback period. This process, with a payback period of only 1.5 years, appears to have the potential for a highly profitable investment. If the CHP unit was not in the polygeneration system, the operating profit would be smaller, and the payback period would be longer.

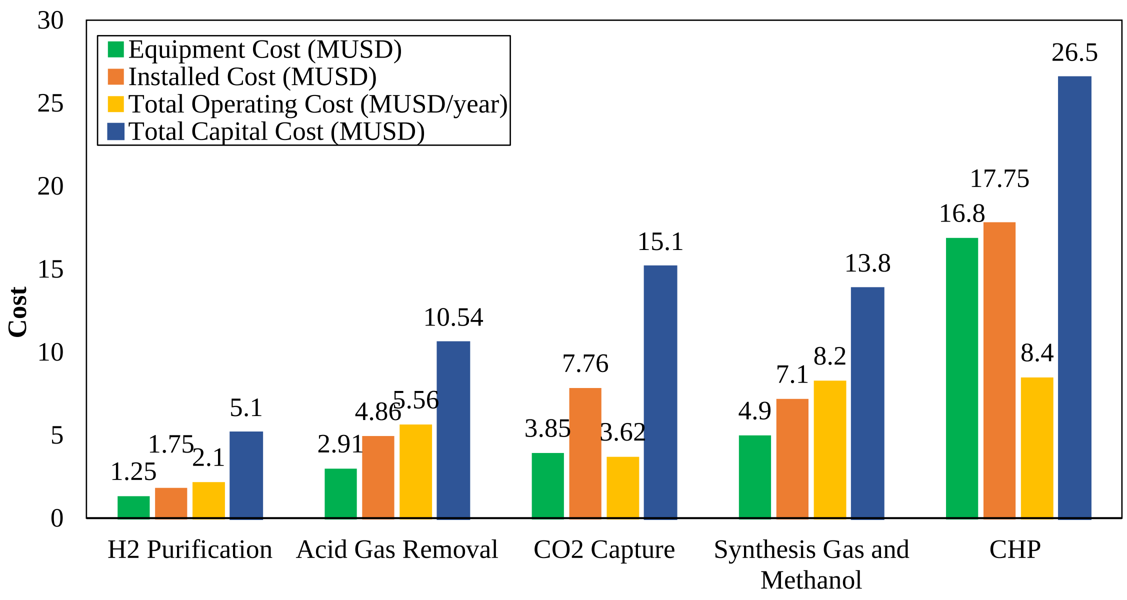

Figure 10

The equipment cost, the installation cost, the investment cost, and the operating cost for all the units.

An economic evaluation of the polygeneration system in APEA software was able to quickly create the first approximations of the process sizing and costs. This analysis will be very useful when we understand whether polygeneration systems for converting flare gases into energy and various products have the best potential for profitability. Because the polygeneration system has proven to be profitable at this level of economic evaluation and has a short payback period, in the following, for more complete and accurate results, this system is evaluated using more detailed cost analysis tools such as Aspen Capital Cost Estimator and Comfar software.

Table 12

Summary of the economic evaluation of the polygeneration system.

Economic evaluation summary	Values	Unit
Equipment cost	29.71	Million USD
Installation cost	39.22	Million USD
Total utilities cost	2.70	Million USD/year
Total raw materials cost	1.70	Million USD/year
Total products sales	113.36	Million USD/year
Extra power and MP steam sales	6.03	Million USD/year
Payback period	1.5	Year
Total operating cost	27.88	Million USD/year
Total Capital Cost	71.04	Million USD/year

6. Conclusions

The scope of this study was to perform the simulation and economic evaluation of converting part of flare gases of South Pars and Assaluyeh gas fields into energy (steam and power) and various products (CH_3OH, H_2, N_2, and CO_2) in a polygeneration system. The benefit of the polygeneration system is the production of various products (particularly power and fuels) with high efficiency and low GHG emissions. A polygeneration system has a lower raw material cost, utility cost, and operating cost than the corresponding single-product processes. After the simulation and economic evaluation of the polygeneration system, the following conclusions can be drawn:

- In the polygeneration system, flare gas with a mass flow rate of 9690 kg/h was used. After the H_2S removal of the flare gases in the acid gas removal unit, 35% of the treated flare gas was sent to the CHP unit and 65% of it to the synthesis gas production unit. The simulation results showed that 25.87 MW of power, 177400 kg/h of MP steam, 8133 kg/h of CH_3OH, 653.7 kg/h of H_2, 46950 kg/h of N_2, and 9103 kg/h of CO_2 were produced.
- Since the polygeneration system needs power, steam at various levels (LP, MP, and HP), etc., part of the power and MP steam produced will be consumed in the system itself. The polygeneration system requires 22.17 MW of power and 67550 kg/h of MP steam. Therefore, the remaining power and the remaining MP steam for sale will be 3.7 MW and 109850 kg/h respectively.
- The economic evaluation results show that the total cost of the raw materials and the total product sale are $1.7 million per year and $113.36 million per year respectively; the total utility cost (taking into account the supply of electricity and steam produced by the CHP unit) and the sale of the remining power and the remining MP steam are $2.70 million per year and $6.03 million per year respectively; the operating profit of this system is also $115 million per year. Further, the results demonstrate that the total operating cost and the total capital cost are $27.88 million per year and $71.04 million per year respectively; the payback period is 1.5 years.

Nomenclature

APEA	Aspen Process Economic Analyzer
BFD	Block flow diagram
CHP	Combined heat and power generation
FGR	Flare gases recovery
GHG	Greenhouse gases
GTL	Gas to liquids
HP	High pressure
HRSG	Heat recovery steam generator
LP	Low pressure
LPG	Liquefied petroleum gas
MDEA	Methyl diethanolamine
MEA	Mono ethanolamine
MP	Medium pressure
PFD	Process flow diagram
PRSV	Peng–Robinson–Stryjek–Vera
SMR	Steam methane reforming
TEMA	Tubular exchanger manufacturer association

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