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The impact of a zero-flaring system on gas plants, environment, and health

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Abstract

Continuous natural gas flaring wastes significant energy resources and increases greenhouse gas emissions, contributing to global warming. Our work provides an overview of a technique to recover flare gas and reduce CO_2 emissions to a minimum level. There are two methods to recover flare gas: the recovery of natural gas liquids and sales gas production by existing LPG unit and the production of liquid fuels by mini-GTL unit (gas to liquid). This study was conducted using real data from the field. All cases were simulated using Aspen HYSYS software. The mini-GTL unit is modeled using an autothermal reforming method. CO_2 emissions will be reduced by 107.68 tonne/day in both methods. Economic analyses revealed that the NGL and sales gas product has a net present value (NPV) of 77.03 MMUSD, while the mini-GTL product has an NPV of 73.7 MMUSD. The study showed that we could extract natural gas liquids (NGLs), including propane, LPG, and sales gas, from the flare gas or convert it to liquid products, including gasoline and diesel. The expected internal rate of return (IRR) and payout time (POT) for NGL and sales gas method are 150.73% and 0.27 years, respectively. The mini-GTL method is recommended due to Egypt's petroleum fuel shortage and the best solution without an entry point to the Egyptian national gas grid in the plant. However, the IRR and POT for the mini-GTL method are 30.09% and 1.19 years, respectively, and it needs more CAPEX than the NGL and sales gas method.

Highlights

- A model has been developed to recover stranded associated gas through a flare gas recovery system (FGRS).
- Natural gas liquids are recovered in addition to sales gas production.
- Mini-GTL unit (gas to liquid) is studied as an option for flare gas recovery.
- Financial modeling parameters and what-if analysis techniques are reported.

Keywords: Flare gas utilization, GTL simulation, Liquified petroleum gas recovery, Economic indicators

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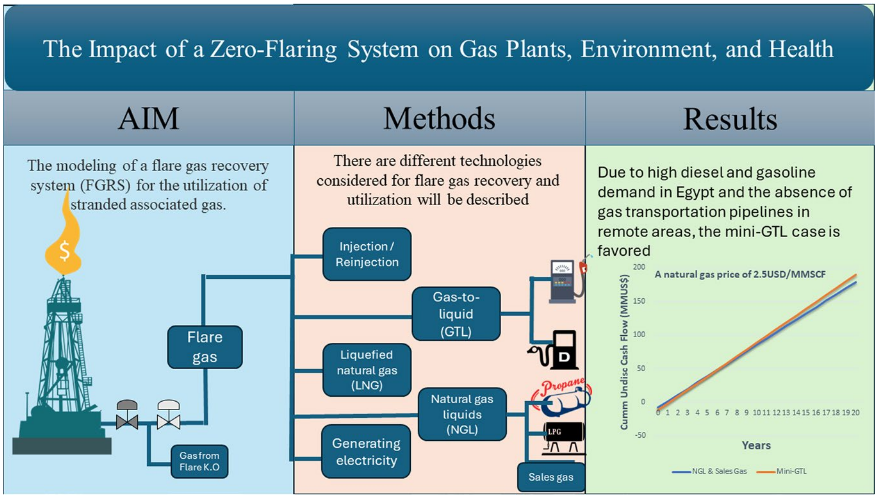
Graphical Abstract



The Impact of a Zero-Flaring System on Gas Plants, Environment, and Health

AIM

The modeling of a flare gas recovery system (FGRS) for the utilization of stranded associated gas.

Methods

There are different technologies considered for flare gas recovery and utilization will be described

Results

Due to high diesel and gasoline demand in Egypt and the absence of gas transportation pipelines in remote areas, the mini-GTL case is favored

Introduction

Global gas flaring is estimated to be more than 144 BCM in 2021 [1]. Egypt contributes 1.45% of this amount (2.1 BCM) [2]. In 2015, the World Bank launched the "Zero Routine Flaring by 2030" project. Egypt signed it in Dec. 2017. This event unites governments and oil and gas companies, who acknowledge that flaring is unsustainable and agree to participate in eliminating routine flaring by no later than 2030. Nowadays, the world is confronting global warming as one of its fundamental issues, and this problem can be caused by a rise in CO_2, CH_4, and other greenhouse gas (GHG) outflows within the atmosphere. CO_2 is the main greenhouse gas, accounting for approximately three-quarters of emissions. Climate change is the term researchers use to describe the complex changes caused by greenhouse gas concentrations that now impact our planet's climate and weather frameworks. Climate change involves rising average temperatures, which we call global warming, extraordinary meteorological phenomena, displacement of wild-life populations and habitats, higher seas, and various other impacts [3].

The recovery system also prevents CO and H_2S from going into the atmosphere. Door level of CO, greater than 800 parts per million (ppm), harms human health because it causes tissue hypoxia, including weakness, nausea, vomiting, vertigo, and passing. Because of CO poisoning, tissue hypoxia reduces the capacity of hemoglobin (Hb) to bind to O_2. It can also negatively impact animals, such as changes in the hormonal framework, changes in fetal growth, reduced productivity, and immune framework suppression [4]. H_2S may irritate the eyes, nose, or throat, causing trouble breathing in people with asthma or respiratory distress. Long-term exposure to gas may cause weak mainspring memory and motor function, coordinating headaches, tiredness, balance diseases, and loss of awareness [5]. Egypt hosted the 27th climate conference meeting (COP 27) from 6 to 18 November to the UNFCCC [6].

On the other hand, flared gas is comparable to natural gas. It is a cleaner energy source than other commercial fossil fuels, so its recovery is very profitable. There are a variety of methods for reducing and recovering flared gas, which are summarized as follows: gathering, compression, injection/reinjection, liquefied natural gas (LNG), gas-to-liquid technology (GTL) to produce gasoline and diesel [7], and NGL recovery that gave LPG and propane in addition to sales gas and generating electricity [8]. Our study provides an overview and simulation of two methods of flared gas recovery: an NGL recovery plant and a mini-GTL unit. The NGL recovery plant consists mainly of gas purification from mercury and water, de-ethanizer, de-propanizer, and LPG tower [9].

This study compares the economic potential of using the NGL recovery method with small-scale GTL plants to recover and utilize associated stranded gas in Egypt [10]. Net present value (NPV), internal rate of return (IRR) [11], payout time (POT), and profit per dollar invested (P/$) are the investment evaluation techniques used to evaluate which project is a better return [12].

In 2015, [13] introduced a technique for utilizing flare gas as fuel after treatment in Egypt. This method's technical challenges include safety and operational considerations and power consumption, and unit suppliers [14] compare three solutions to recover flare gas: LPG/condensate extraction, recycling, or power generation. They declare that the profit differs from one investor to another, and national oil companies prefer power generation. Elhagar et al. [15] increase flare gas recovery by manipulating separator operating conditions. In the current study, five flare gas recovery technologies have been investigated; we will focus on two.

The practical significance of employing the gas-to-liquids (GTL) technology for recovering flare gas is as follows:

a. *Utilizing wasted resources*: Flare gas, typically wasted, can be transformed into valuable liquid hydrocarbons like diesel and gasoline through GTL technology, allowing companies to capitalize on an otherwise squandered resource [16].
b. *Environmental friendliness*: GTL fuels offer cleaner combustion than traditional fuels from crude oil, thereby reducing harmful emissions such as sulfur oxides and particulate matter, contributing positively to environmental sustainability efforts [17].
c. *Enhancing energy security*: Particularly beneficial in regions abundant in natural gas but lacking in crude oil reserves, GTL technology allows for the domestic production of liquid fuels, reducing dependence on imported crude oil and bolstering energy security [18].
d. *Applicability in remote areas*: GTL systems can be deployed in remote regions with limited gas transportation infrastructure. By converting flare gas into liquid fuels locally, GTL facilitates easier distribution of fuels to remote areas, supporting various industrial activities, power generation, and local communities [19].
e. *Production of high-value products*: GTL technology yields high-value, clean-burning liquid fuels with superior properties to conventional crude oil-derived fuels. These premium-quality products can fetch higher prices in the market, offering economic benefits to stakeholders investing in GTL facilities [20].

f. *Technological advancements*: Ongoing advancements in GTL technology continually improve its efficiency, scalability, and cost-effectiveness. As the technology evolves, it becomes increasingly viable for a broader range of applications and geographic locations, further enhancing its practical value for flare gas recovery [21].

GTL technology for flare gas recovery offers opportunities to monetize waste gas, mitigate environmental impact, bolster energy security, facilitate fuel distribution in remote areas, produce high-value products, and capitalize on technological advancements.

Literature review

This section outlines various technologies evaluated for the recovery and utilization of flare gas.

Compression injection/reinjection

Compression is used to send the flare gas back to the production facilities. The compressed gas is used as fuel in the downstream plants, such as refineries, while reinjected into oil reservoirs in the upstream plants. Gas reinjection is commonly used to increase oil recovery and gas storage or to protect the environment from highly contaminated gases, where there is no gain from the sulfur removal process and low operational cost [22]. The main parameters of the gas reinjection process are reservoir engineering considerations and the price of the compressors and spare parts. The disadvantages of this method include reservoir heterogeneity, the potential for gas channeling, and high capital and operational costs [23].

Liquefied natural gas (LNG)

Liquefied natural gas (LNG) is the liquefied form of natural gas. The process of deep refrigeration is cooled to minus 162 °C for liquefaction. LNG takes up only about one-six-hundredth of the volume of natural gas that could be stored more safely and cheaply. LNG has 2.4 times the capacity of compressed natural gas (CNG) once liquefied. This technology is available both onshore and offshore by tank trucks and railway tank containers in addition to mass storage in tanks [24]. Once converted back to its gaseous form at the destination, the gas can only be utilized in its liquid state. There are different types of LNG technologies according to the type of refrigerant: mixed refrigerants, pure refrigerants, and hybrid [25]. Large-scale LNG facilities do not suit flare gas recovery. Innovations in mini/small-scale LNG facilities offer new opportunities to recover smaller volumes of flare gases. LNG is environmentally friendly, has safe storage and transportation, and provides a stable and long-term supply. The disadvantages of this method include production risks, as direct contact can cause freezing of the contact point and fluctuation of NGL price.

Gas-to-liquid technology (GTL)

The gas-to-liquids (GTL) method produces synthetic fuels [26]. It can provide an alternative to conventional transportation fuels. The GTL process is based on the Fischer–Tropsch reaction [27]. During the 1920s and 1930s, this method was used in Germany with coal as the feedstock [28]. The main process entails reforming natural gas to produce synthesis gas, converted via the Fischer–Tropsch reaction into long-chained hydrocarbons [29]. In an upgrading unit, the long-chained hydrocarbons are finally broken into products with the desired chain length [30]. The products can be used as chemical and petrochemical feed materials. High cetane numbers [31], reduced or no sulfur, NO_x, particulates, and aromatics [32] are all characteristics of the fuels generated using the GTL method. Its flexibility in blending with conventional fuel and used in current fuel frameworks is another significant benefit [33]. This technology has several challenges, including substantial complexity, high cost, high water consumption, and, in some cases, oxygen production units [21].

Natural gas liquids (NGL) recovery

NGL technology employs compression and cooling techniques to separate natural gas's lighter and heavier fractions with the heavier hydrocarbons known as natural gas liquids (NGL) [34]. This process mainly feeds petrochemical complexes and prepares the gas for GTL and LNG plants. Different integrated processes have been developed to compare capital and operating costs and energy and separation efficiency. Flare gas must be treated before entering the processing unit. The treatment unit includes mercury removal, gas sweetening, and gas dehydration [35]. Many NGL recovery processes include turbo-expanders, liquid sub-cooled process, and gas sub-cooled processes [36]. Within this study, the expander shaft revolves during gas expansion and is coupled with the compressor shaft to leverage the expansion work while also generating a cooling effect [37]. The processing unit also includes a de-ethanizer, debutanizer, and LPG tower.

Generating electricity

Generating electricity from flare gas is also known as gas to power. This technology proves advantageous in remote oil and gas fields because it is simpler to transmit electricity over extended distances than natural gas. Different technologies are available, including gas turbines, gas engines, combined cycles, and solid oxide fuel cells [38]. The drawbacks of this approach include the long distance between the power plant and consumer, the complexity of managing the gas supply, and the flare gas must be purified from oil and water in addition to CO_2 and H_2S removal [39].

Methods

The plant has three oil separators where we treat the oil of sister companies, and its associated gases flare up during normal operation. The plant also contains a gas-treating unit. This unit includes a sweetening unit with methyl di-ethanol amine (MDEA) and a dehydration unit with tri-ethylene glycol (TEG) of 10 MMSCFD capacity. The treated gas is compressed to a sister company to produce propane, LPG, and sales gas. The analysis and conditions of the associated feed gases are illustrated in Table 1.

Technical implementation

The extraction and processing of the gas go through several steps as part of the study's technical implementation. Three key phases are used for this study as follows:

Table 1 Flared gas sources and compositions

Component/mole fraction	Feed-01	Feed-02	Feed-03
C_1	69.3	74.15	59.7
C_2	13.4	12.15	15.4
C_3	7.5	6.5	11.5
i-C_4	1.4	1	1.3
n-C_4	2.4	2.6	3
i-C_5	0.9	0.7	0.8
n-C_5	0.5	0.6	0.8
C_{6+}	1.6	0.8	0.7
N_2	1.2	1.2	0.3
CO_2	1.1	0.3	6.4
H_2S	0.7	0	0.1
Q (MMSCFD)	1.8	1	0.5

Gas recovery and compression

This paper originally focused on flared gas. Using appropriate techniques to recover this gas from the flare line is vital. The conventional flare package consists of a knockout drum to remove free liquids, a water seal drum, and a flare stack. Conventionally, all the associated gas is flared. The gas recovery reduces nearly 107 tonne/day of CO_2 emissions going to the atmosphere, according to HYSYS simulation. Recovery occurs by diverting the gas from the flare knockout drum to the processing units. Figure 1 shows this process. The proposed compressor is used to raise the recovered gas pressure to compression unit pressure.

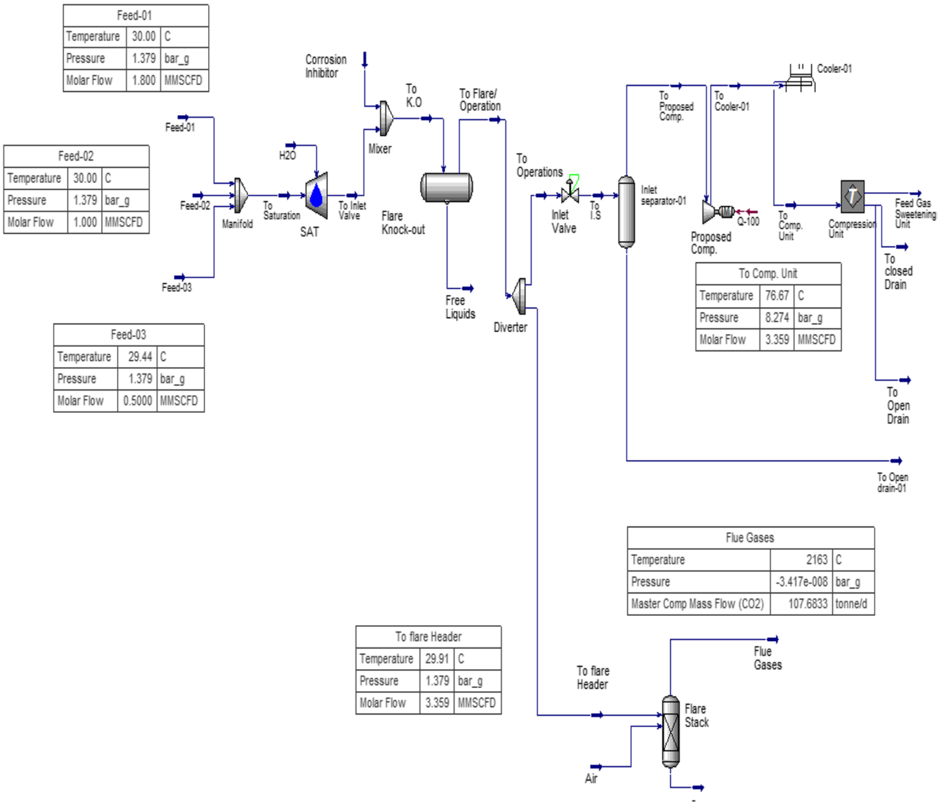
Gas treatment

The entrained impurities must be removed to make the recovered gas suitable for the next processing units. The performance and efficiency of downstream processes might be negatively impacted by inappropriate treatment of the recovered gas. Either NGL recovery and sales gas production or GTL unit conversion to liquid gasoline and diesel is involved in this work. Treatment is done to remove corrosive gases (CO_2 and H_2S), mercury, nitrogen, and water vapor. The required downstream utilization determines the treatment intensity. A total of 3.359 MMSCFD of gas from the flare knockout drum with a condition of 37.78 °C and 44.82 bar-g is fed into the amine unit. The sweetening medium is a methyl diethanolamine (MDEA) solution with 50% water. The sweet gas is fed into the dehydration unit using tri-ethylene glycol as the absorbing medium.

The two case studies

The work has two cases: case A is the NGL recovery and sales gas, and case B focuses on producing gasoline and diesel using a mini-GTL unit.

A. Simulation of NGL recovery and sales gas production After gas sweetening and dehydration, the gas is sent to the treating unit to remove mercury and water vapor by the molecular sieve. It passes through a warm gas/gas ex and reflux exchanger (DSR Ex)



Feed-01		
Temperature	30.00	C
Pressure	1.379	bar_g
Molar Flow	1.800	MMSCFD

Feed-02		
Temperature	30.00	C
Pressure	1.379	bar_g
Molar Flow	1.000	MMSCFD

Feed-03		
Temperature	29.44	C
Pressure	1.379	bar_g
Molar Flow	0.5000	MMSCFD

To Comp. Unit		
Temperature	76.67	C
Pressure	8.274	bar_g
Molar Flow	3.359	MMSCFD

Flue Gases		
Temperature	2163	C
Pressure	-3.417e-008	bar_g
Master Comp Mass Flow (CO2)	107.6833	tonne/d

To flare Header		
Temperature	29.91	C
Pressure	1.379	bar_g
Molar Flow	3.359	MMSCFD

Fig. 1 The flare gas recovery system simulation in HYSYS. **a** Gas recovery and compression. **b** Gas treatment/processing. **c** NGL recovery/conversion to GTL

to cool it down. Gas and condensate are separated in the cold separator. The expander reduced the gas temperature to nearly − 34 °C by lowering the pressure to 18 bar-g, resulting in the condensation of heavy hydrocarbons. The operator sent the gas and condensate to the de-ethanizer, recovering the overhead gas as a sales gas after heating it with warm gas/gas ex. as shown in Fig. 2. Liquid hydrocarbons from the bottom of the de-ethanizer are fed into the de-propanizer at 71 °C and 21.5 bar-g. The overhead product is recovered as high-purity propane with a purity of more than 95% and a quantity of 6.474 tonne/day. Liquid hydrocarbons from the bottom of the de-propanizer are fed into the LPG tower at 119 °C and 19.5 bar-g. The top product is 12.96 tonne/day LPG, and the bottom is 44.86 bbl/day condensate. The hydrate formation tool in HYSYS shows that hydrates will not form under operating conditions.

B. Case B: Simulation of the mini-GTL unit HYSYS V.11 was used in the simulation of the mini-GTL unit. The model configuration made use of the Peng-Robinson fluid property package. All components were added as straight-chain paraffin, and $C_{21} \rightarrow \infty$ was added as C_{21+} because they have the same properties. The reactions in the pre-reformer and the reformer were set as equilibrium reactions. At first, the operator heated the recovered gas from 3 to 455 °C with heater-01. The pre-reformer has two feed streams: 155 Kmol/h of heated recovered gas and 550 Kmol/h of steam. The outlet stream from the pre-reformer is reheated and goes to the autothermal reactor (ATR) with 153

Kmol/h of oxygen. The C.W.01 heat exchanger was used to cool the synthesis gas down to 38 °C, and the condensed water was collected in Separator-01 before the Fischer reactor. Heater-03 is used to raise the reactor inlet temperature to 210 °C.

A plug-flow reactor (PFR) was used to simulate the Fischer-Tropsch reactor (FTR). Gaseous and liquid end products are produced by the multi-tubular fixed-bed reactor (MTFB). Cool gaseous products to 38 °C in the C.W.02 heat exchanger before entering three-way separator-3 with liquid stream (from sep-2). The steam from the reactor is separated as water in the separator. The liquid stream (to upgrading unit) is sent to the upgrading unit, including towers UUT-01 and UUT-02. The final product of the mini-GTL unit includes 12.98 tonne/day of gasoline and 20.81 tonne/day of diesel. Figure 3 illustrates the process simulation in HYSYS.

Project financial implementing

The financial evaluation is performed for the sales gas and NGL recovery and mini-GTL products cases. The project's financial indicators are listed below.

a) The recovered gas rate was 3.359 MMSCFD.
b) The yield of the mini-GTL unit was 33.79 tonne/day, comprising 20.81 tonne/day diesel and 12.98 tonne/day gasoline.
c) Considering the capital expenses (CAPEX) of 12 million dollars for the mini-GTL unit
d) The yield of the NGL unit was 12.69 tonne/day LPG, 6.474 tonne/day propane, 44.86 bbl/day condensates, and 2.727 MMSCFD sales gas.
e) Considering the capital expenses (CAPEX) of 2.5 million dollars for NGL recovery and sales gas recovery case
f) The flared gas price is 2.5 USD/MMSCF since gas has no usage.
g) Considering operating expenses (OPEX) of 2% of CAPEX (without feed gas price)
h) The designed project's operating time is 20 years.
i) The designed plant's operating days are 350 days per year.
j) The GTL product's prices are 210 USD/bbl for diesel and 154 USD/bbl for gasoline.
k) We are using the straight-line depreciation method.
l) We are using a salvage value of zero.
m) We are using a 35% base income tax case.
n) We are using 100% owners' equity.

The study outlines a project focused on recovering and processing stranded gas from a plant's oil separators, treating it, and converting it into valuable products such as sales gas, propane, LPG, gasoline, and diesel. The project involves technical implementation, including gas recovery and compression, gas treatment, and two case studies: NGL recovery and sales gas production and mini-GTL unit simulation. In the gas recovery and compression phase, gas is diverted from the flare knockout drum to processing units to reduce CO_2 emissions. Gas treatment involves removing impurities like CO_2, H_2S, mercury, nitrogen, and water vapor to prepare the gas for downstream processes.

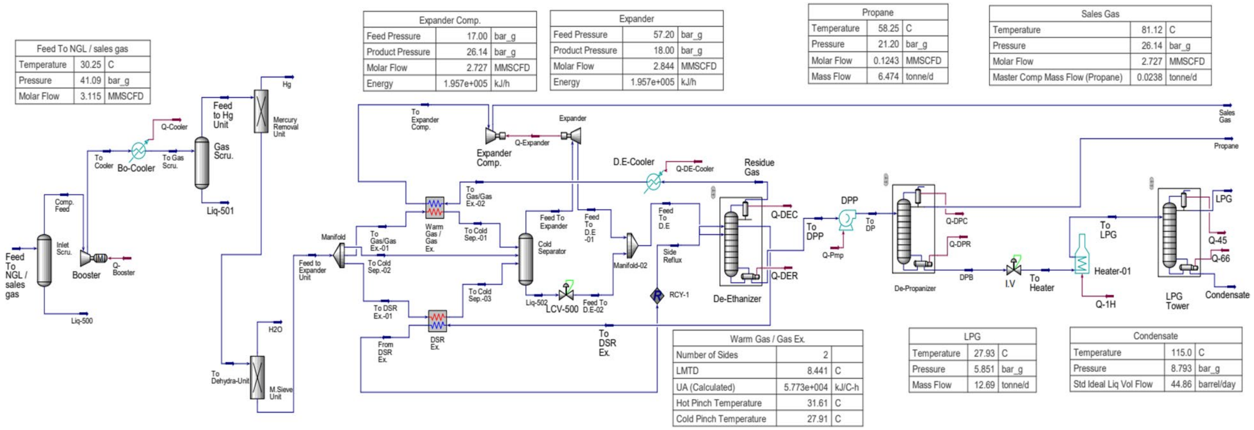


Fig. 2 The NGL/sales gas processing unit (PFD) in HYSYS

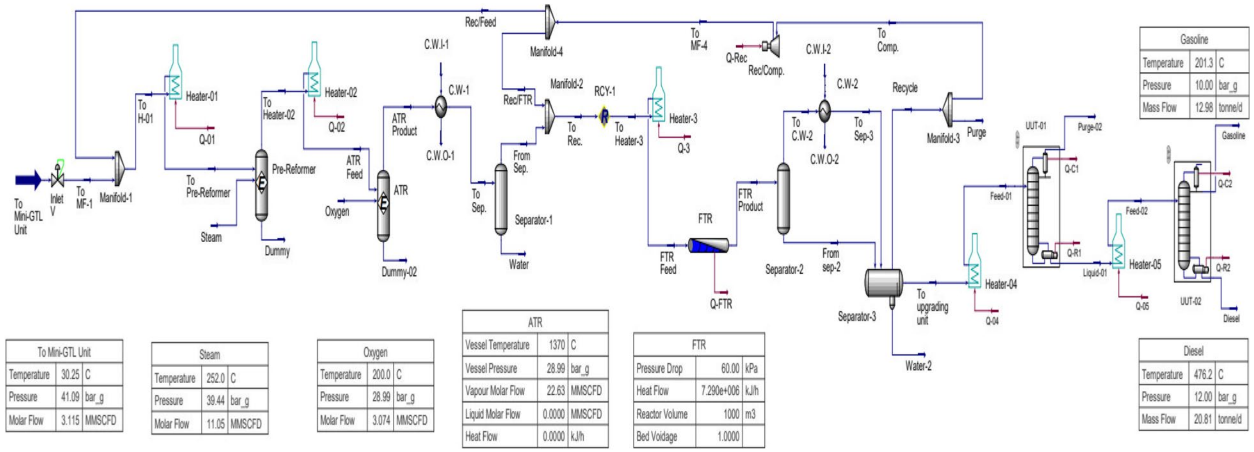


Fig. 3 The mini-GTL unit simulation diagram

Case A focuses on NGL recovery and sales gas production, where after treatment, the gas undergoes further processing to produce propane, LPG, and sales gas. Case B simulates a mini-GTL unit where recovered gas is converted into gasoline and diesel through various processes, including pre-reforming, autothermal reforming, Fischer–Tropsch synthesis, and upgrading.

Financial evaluation is performed for both cases, considering capital expenses, operating expenses, project lifespan, tax rates, and product prices. The project aims to maximize the economic value of recovered gas by converting it into valuable products while minimizing environmental impact and optimizing financial returns. The project involves recovering and processing stranded gas to produce valuable products, with a financial evaluation conducted to assess the economic feasibility and returns over 20 years.

Results and discussion

The outcomes for the two scenarios are illustrated in this section. Technical and economic parameters will be evaluated.

HYSYS simulation product results

According to HYSYS simulation for the NGL and sales gas case, the yield from 3.359 MMSCFD of recovered gas is 2.727 MMSCFD of sales gas in addition to 12.69 tonne/day LPG, 6.474 tonne/day propane, and 44.86 bbl/day condensate, while the yield for the mini-GTL case is 20.81 tonne/day of diesel and 12.98 tonne/day of gasoline.

NGL and sales gas case technical parameters

Figure 4 shows a relation between pressure and temperature of the gas. Hydrate will not form in operating or transportation conditions. The sales gas follows the Egyptian natural gas specifications for transmission network code, as shown in Table 2.

Mini-GTL case technical parameters

From the simulation process, the H_2/CO ratio is 2.43, which is suitable for the FT reactor in this study. The carbon efficiency is 67%. The thermal efficiency is 62.75%, while the optimum percentage is 60% or less. Therefore, the process is efficient. The product yield is 20.81 tonne/day (159.5 bbl/day) of diesel and 12.98 tonne/day (116.3 bbl/d) of gasoline. The total yield is 33.79 tonne/day (275.8 bbl/day). Compared to other alternatives for gas recovery, this unit is competitive in cost and efficiency.

Economic results

In this work, the investment decision is based on comparing two alternatives, as mentioned before. After simulating the two case processes via the HYSYS simulation software, an economic assessment of each process is evaluated. The profitability of each method is analyzed using the net present value, the internal rate of return, and the payout period.

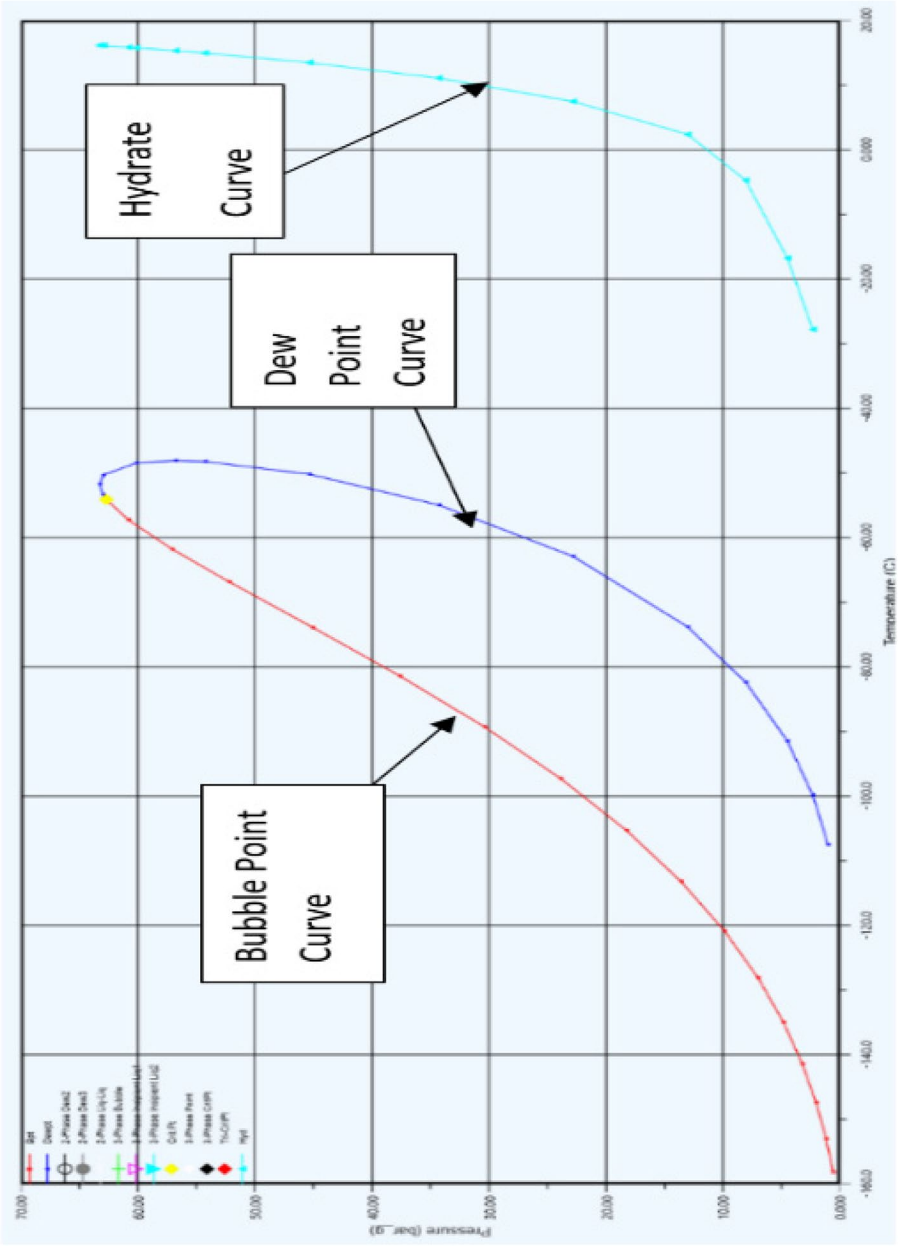


Fig. 4 The hydrate formation conditions

Table 2 Sales gas specifications

Properties	Value
Water dew point > 0 °C	-
HC dew point > 5 °C	-60.2
H_2S content (PPM) > 4	0.008
CO_2 content % > 3	0.34
LHV vol. basis (BTU/ft^3)	1008
Molar flow (MMSCFD)	2.727
Temperature (°C)	81.12
Pressure (bar)	27.15

Table 3 Cash flow analysis for the two scenarios under review

	Volume (BBD)	Price/unit USD/bbl	Daily revenue (USD)	Annual revenue (MMUSD)
NGL and sales gas				
Product				
Propane	81.35	52.5 [40]	4270.875	1.49
LPG	147.8	132	19,509.6	6.83
Natural gasoline	44.86	120 [41]	5383.2	1.88
Sales gas	2.727	7.2	19,634.4	6.87
Total				17.08
Mini-GTL products				
C2 +	15.6	25	390	0.14
Gasoline	116.3	154	17,910.2	6.27
Diesel	159.5	210 [42]	33,495	11.72
Total	291.4			18.13

Cash flow calculation

The cash flow for both scenarios is illustrated in Table 3. From Table 3, the NGL and sales gas case has a yearly cash flow of 17.08 MMUSD. The mini-GTL case has an annual cash flow of 18.13 MMUSD. The cash flow from mini-GTL fuels is greater than that from NGL and sales gas products.

Operating expenses

The NGL and sales gas case has a yearly OPEX of 2.78 MMUSD, while that for the mini-GTL case is 2.97 MMUSD. The OPEX for mini-GTL products is greater than that for NGL and sales gas, as illustrated in Table 4.

Financial modeling parameters

Table 5 presents the financial modeling parameters for both cases. It shows that in the NGL and sales gas case, the NPV at a 10% bank rate, the net cash recovery, the internal rate of return, and the profit per dollar invested are higher than in the mini-GTL case. The payout time for the NGL and sales gas case is lower than that for the mini-GTL. From Fig. 5, the NGL and sales gas case has a lower payout time than the mini-GTL case

Table 4 Operating expenses for both scenarios

	Q MMSCFD	Price	Daily expenses	Annual expenses (MMUSD)
1: NGL and sales gas				
Variable				
Feed gas	3.115	2.5 USD/MMSCF	7.7875	2.73
Additional OPEX		2% of CAPEX	0.05	0.05
Total				2.78
2: Mini-GTL products				
Feed	3.115	2.5 USD/MMSCF	7.7875	2.73
Variable OPEX		2% of CAPEX	0.24	0.24
Total				2.97

Table 5 Economic indicators' presentation

	Value	
Parameter	Case 1: NGL & sales gas	Case 2: Mini-GTL
NPV at 10% (MMUSD)	77.03	73.7
POT (years)	0.27	1.19
IRR (%)	150.73	30.09
NCR (MMUSD)	9.34	10.07
P/$	73.73	15.78

for the same cumulative undiscounted cash flow. The two lines intersect at a POT of 6 years with a cumulative undiscounted cash flow of 48 MMUSD.

What-if analysis

What-if analysis is a technique used in financial modeling to examine the effects of different values of a group of independent variables on a certain dependent variable under certain conditions. It tests the model against a wide set of possibilities, as follows:

1) Bank rates of 10%, 15%, and 20% and gas costs of 2.5 USD/MMSCF and 3 USD/MMSCF.
2) 2% and 2.5% change in total operating expenses, excluding raw materials.
3) Changes in CAPEX according to a product by a barrel of liquid a day of 35,000 USD/PBLD and 50,000 USD/PBLD.
4) The natural gas prices are 2.5 USD/MMSCF and 3.0 USD/MMSCF.

The what-if analysis is used to study the effect of natural gas prices of 2.5 USD/MMSCF and 3.0 USD/MMSCF, as well as for different bank rates, OPEX, and CAPEX on the net present value as a function of a product by a barrel of liquid a day (PBLD). The NPV drops when CAPEX and OPEX rise (especially CAPEX), as illustrated in Table 6. The financial outcomes at the natural gas price of 3 USD/MMSCF are shown in Table 7. Any increase in the price of natural gas lowers the NPV for every parameter considered, as illustrated in Tables 6 and 7. As the gas price decreases, the net present value increases at the same bank

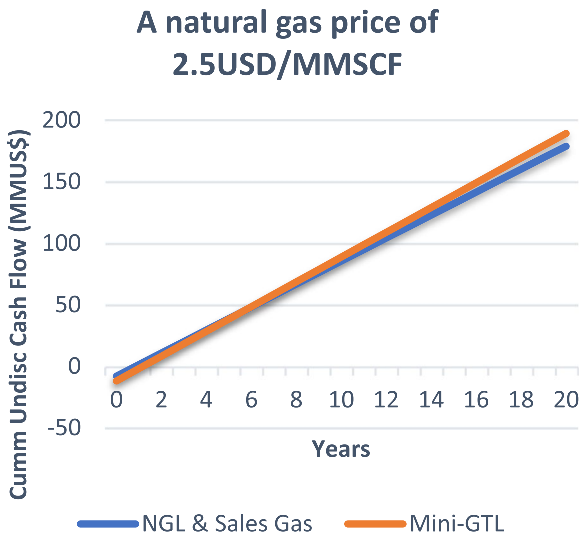


Fig. 5 The payout time for a natural gas price of 2.5 USD/MMSCF

Table 6 Financial results of mini-GTL sales for the natural gas price of 2.5 USD/MMSCF

GTL: NG price	CAPEX: USD-PBLD	35,000	CAPEX: USD-PBLD	43,510	CAPEX: USD-PBLD	50,000
US $2.5 / MMSCF	**Operating expenses as a function of capital expenses**					
Bank rates	2%	2.50%	2%	2.50%	2%	2.50%
10%	75,952,502.91	75,685,413.26	73,695,418.91	73,363,389.93	71,973,995.67	71,592,439.02
15%	53,285,768.81	53,089,399.49	51,004,876.74	50,760,762.81	49,265,295.65	48,984,768.06
20%	39,311,550.66	39,158,780.98	37,015,980.72	36,826,067.11	35,265,205.19	35,046,962.8
NCR	10,055,190.25	10,023,818	10,065,751.75	10,026,751.75	10,073,806.75	10,028,989.25
IRR	45.16	45.14	33.23	33.21	32.59	32.57
POT	0.96	0.96	1.19	1.20	1.37	1.38
P/$	19.83	19.77	15.78	15.71	13.61	13.55

rate, when the other parameters are constant. Lower natural gas prices favor mini-GTL conversion processes' profitability.

- *Effect of natural gas prices*: The analysis considers two natural gas price scenarios: US $2.5/MMSCF and US $3.0/MMSCF. The results indicate that as the natural gas price increases, the net present value (NPV) of the GTL scenario decreases across different bank rates and CAPEX scenarios. The financial viability of the mini-GTL scenario increases with lower natural gas prices, leading to higher NPV.
- *Impact of bank rates*: Bank rates of 10%, 15%, and 20% are evaluated. Higher bank rates generally lead to lower NPV, indicating reduced profitability and potential returns on investment.
- *Changes in OPEX and CAPEX*: Operating expenses are expressed as a percentage of CAPEX, with 2% and 2.5% variations. Higher CAPEX and OPEX result in lower NPV, with CAPEX having a more significant impact on profitability, especially at higher discount rates.

Table 7 Financial results of mini-GTL sales for the natural gas price of 3 USD/MMSCF

GTL: NG price	**CAPEX: $-PBLD**	**35,000**	**CAPEX: $-PBLD**	**43,510**	**CAPEX: $PBLD**	**50,000**
US $3/ MMSCF	**OPEX (% of CAPEX)**					
Discount rates	2%	2.50%	2%	2.50%	2%	2.50%
10%	72,935,881.23	72,668,791.58	70,678,797.24	70,346,768.25	68,957,373.99	68,575,817.35
15%	51,067,892.06	50,871,522.75	48,786,999.99	48,542,886.06	47,047,418.91	46,766,891.32
20%	37,586,106.38	37,433,336.71	35,290,536.45	35,100,622.84	33,539,760.91	33,321,518.53
NCR	9,700,859	9,669,486.75	9,711,420.5	9,672,420.5	9,719,475.5	9,674,658
IRR	44.94	44.92	33.07	33.06	32.42	32.39
POT	1.00	1.00	1.24	1.24	1.42	1.43
P/$	19.10	19.03	15.19	15.12	13.10	13.03

- *Detailed financial metrics*: Additional financial metrics such as net cash return (NCR), internal rate of return (IRR), payback period (POT), and profit per dollar invested (P/$) provide further insights into the project's financial performance under different scenarios.

These metrics help stakeholders assess the project's feasibility, profitability, and risk exposure.

Conclusions

- *Environmental impact mitigation*: Recovering and treating flare gas prevent nearly 107 tonnes per day of CO_2, CO, and H_2S emissions from entering the atmosphere, significantly reducing environmental harm.
- *HYSYS software utility*: HYSYS software facilitated process simulation and optimization, enabling the development and modeling of recovered flare gas. MDEA and triethylene glycol were utilized for sweetening and dehydration, respectively, ensuring efficient gas treatment.
- *NGL recovery and sales gas production*: The NGL recovery process yielded 274.01 bbl/day of products, including propane, LPG, natural gasoline, and sales gas, meeting gas transmission network specifications and addressing transportation conditions.
- *Mini-GTL unit simulation*: The mini-GTL unit, employing steam reforming and non-catalytic partial oxidation, produced diesel and gasoline with superior energy density and environmental properties, meeting high demand in Egypt.
- *Financial comparison*: Financial analysis revealed that while the NGL and sales gas case had higher NPV, IRR, and profit-per-dollar metrics, the mini-GTL case had a longer payout time. The choice between the two depends on factors such as treating unit availability, gas transmission network access, and regional demand dynamics.

- *Market dynamics*: The growth of GTL is contingent upon crude oil prices, as GTL products directly compete with those from crude oil refining. In regions like Egypt, where demand for diesel and gasoline is high, the absence of gas transportation pipelines in remote areas favors the mini-GTL approach.
- In conclusion, the research highlights the effectiveness of both NGL recovery and mini-GTL approaches in utilizing recovered flare gas, each with advantages based on environmental impact, technical feasibility, and financial considerations.

Abbreviations

FGRS	Flare gas recovery system
LPG	Liquified petroleum gas
NGL	Natural gas liquids
GTL	Gas to liquids
BCM	Billion cubic meters
GHG	Greenhouse gas
COP	Conference of parties
UNFCCC	United Nations Framework Convention on Climate Change
FT	Fischer Tropsch
PFR	Plug flow reactor
MTFB	Multi-tubular fixed bed
LHV	Low heating value
BBL/D	Barrel per day
CAPEX	Capital expenses
OPEX	Operating expenses
NPV	Net present value
NCR	The net cash recovery
POT	The pay-out time
IRR	The internal rate of return
P/$	The profit per dollar
PBLD	Product by barrel of liquid a day

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Declarations

Competing interests
The authors declare that they have no competing interests.

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