Kinetic Modeling, Economic and Environmental Feasibility Study of Mitigation of Flaring Gas in Oil Fields to Produce Methanol

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Abstract

Increased global flaring is a major source for greenhouse gas emission and airborne pollutants that have been proven difficult to mitigate. A promising way of reducing the flare is to convert it into a useful product or generate electricity. In this work, the feasibility study of converting flare gas to methanol is discussed. Aspen Hysys is incorporated to simulate a methanol plant with the help of feed stock data obtained from two oil fields. Economic Analysis is performed over the data to determine the total cost involved for production. Payback period and net present value (NPV) are appraised according to different scenarios (1) Without considering an environmental tax and (2) With considering the environmental tax. A sensitivity analysis is deployed over economic and technical data. The results show that the flow rate and the methane percentage of input gas have a great influence on profitability of the plant. Increase in feed gas flow rate will increase the methanol production. This novel method reduces flare gas emission into the atmosphere. In addition, by considering environmental taxes the possibility of getting feasible economics becomes more realistic.

Keywords
Flare Gas Mitigation; Environmental Taxes; Methanol Production; Process Simulation; Payback Period; Internal Rate Return.

1. Introduction

The flare gas or flare stack is the flammable waste gas which is liberated as the result of unplanned over pressurizing of plant equipment in petroleum refineries, chemical plants, and natural gas processing facilities [1]. These gases are vented out through a pressure relief valve [2]. Flaring of gas is vulnerable to human health as well as ecosystem near the flaring sites [3]. Flare gas contains oxides of nitrogen (NOx), oxides of sulfur (SOx), greenhouse gases (CH4 and CO2), volatile organic compounds, H2, and dangerous particulate matter which are released directly into the atmosphere [4]. Gas flaring contributes to about 1.2% of the global CO2 emissions [5]. The most recent data reported by the Energy Information Administration (EIA) indicated that approximately 3.4×1012 cubic feet of natural gas are flared annually, which was about 2.7 percent of all natural gas production in the world [6, 7]. Figure 1 depicts the earth observation satellite data of the top ten gas flaring nations.

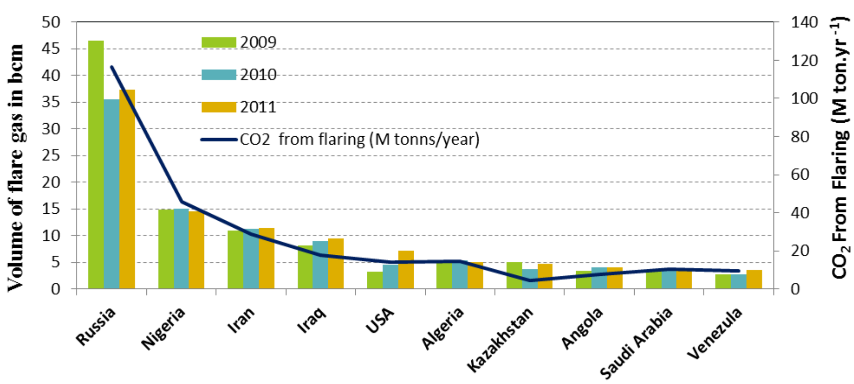


Figure 1. Satellite data of top 10 gas flaring nations (2009-2011) and Annual CO2 emission [7].

Although flaring at refineries is generally limited and closely regulated in developed countries, gas flare reduction in the oil production and refinery industry is still of great interest due to the environmental regulations and economic benefits. Opportunities to eliminate continuous flaring of associated gas at oil production sites in some parts of the world have enabled several projects to be implemented that have achieved significant reduction in greenhouse gas (GHG) emission by Clean Development Mechanism (CDM) provisions of the Kyoto Protocol [5,8]. To illustrate, the recovery of gas flaring for methanol production was implemented in Equatorial Guinea and Nigeria [9, 10].

The best possible way to mitigate flare gas is recovery. Recovering of flare gas can be done by different methods, namely, liquid fuel or petrochemical production, electricity generation, and compression and injection into the pipelines [11]. Electricity generation in the distributed manner becomes popular due to the less transmission losses. Flare gas is a favorable source of energy for distributed electricity generation thanks to the cheaper price. Therefore, the ability of flare gas to generate electricity is promising and it can contribute to the national income. Moreover, flare gas can be effectively utilized in combined heat and power systems (CHP) to multi-generate energy and materials, such as, electricity, heat, and hydrogen, simultaneously. Direct natural gas conversion through solid oxide fuel cells or dehydroaromatization is another method of using flare gas [12]. Moreover, flare gas can also be used in producing petrochemical products. Different methods of flare gas recovery were compared through a multi criteria decision making approach in Ref. [12].

1.1 Global impact of CO2, SOx, NOx, and VOC

The increasing level of CO2 causes alarming impact over human and ecological systems [15]. The present atmospheric concentration of CO2 is 395 ppm which is 30% higher than pre-industrial level and it is anticipated to rise up to 440-480 by the year 2025. Due to this surmounting problem of CO2 emission, government is imposing stringent policies towards oil production and refinery plants to mitigate the CO2 exposure into the atmosphere. The traditional way of mitigating CO2 is capturing of carbon and storing it. The chemical reduction of CO2 is considered to be the most effective way of extenuating CO2 concentration from the atmosphere [16]. Catalytic hydrogenation of CO2 is one among the chemical reduction methods which produces low grade hydrocarbon. The harmful pollutants which are discharged in the atmosphere along with CO2 are NOx, SOx, and volatile organic compounds (VOC). NOx instantaneously reacts with organic chemicals and even with ozone to form compounds like nitroarenes, and nitrosamines which have the tendency to cause cancer [17]. From the atmospheric observation it is found that about 5 percent increase in aerosol which includes NOx and SOx in the stratosphere, twenty- three tons of SOx are generated from burning 46 tons of natural gas [18]. The amount of SOx released to the atmosphere is increasing every year. SOx along with NOx have the ability to form acid rain.

1.2 Flare gas recovery systems

Flaring of gas in oil fields and refineries is a serious problem which should be reduced and used effectively to mitigate the environmental hazards. Flare gas recovery system is an important method of reducing the flare gas emission into the atmosphere. In this system the flare gas is captured and used to produce valuable feed stocks and products. Many refinery plants have understood the importance of this system and started to include it in their operations. The three main flare gas recovery systems which are discussed next are widely used in many refinery industries.

1.2.1 Gas to Liquid technology

An advent solution for reduction of gas flaring is Gas to Liquid (GTL) technology. It is an innovative method deployed for transportation of gases in the form of fluids. The vicinity of natural gas is not abundant and so transportation of gas to a longer distance is an expensive and difficult task. Hence, GTL technology is introduced where the gaseous form of natural gas is converted to liquid state and then transported to the refinery plants. GTL process is encouraged in most of the refinery plants as it can reduce the loss of natural gas through transportation. GTL products are environmentally friendly when compared with products that are produced traditionally, namely, petroleum byproducts. Due to the stringent government policies and increasing awareness of environmental impact, this environmentally friendly technique is employed to reduce the flaring of gas. Among the various techniques which are suggested in reduction of flare gas, GTL technology is increasing in researcher's interest due to the viability of producing Ultra-clean fuels for transportation [19-21].

1.2.2 Generating electricity from flare gas

Flaring of gas can be effectively used to generate electricity by operating the gas turbine which is coupled with a generator. This type of power generation is increasing in popularity due to its high efficiency and low emission. It works under a simple principle of Brayton cycle which is an effective thermodynamic cycle that describes the working of a constant pressure heat engine [22]. A flare gas passes through the compressor. Compressed hot gas enters the combustion chamber where methane is oxidized to form CO2 and H2O [23]. The gas from the chamber then enters the gas turbine where it expands to atmospheric pressure and the heat energy from the gas is converted to mechanical energy by operating the turbine and it is then converted to electrical energy via generator which is coupled with the turbine.

1.2.3 Compression and injection into pipeline

Compression and injection into pipeline is an important method in reducing and reusing of flare gas. This method produces high pressure gas [24]. A compressor consists of a piston which is connected to a crankshaft with connecting rod that is constantly set into motion. Air is drawn into the intake valve of the compressor during down stroke process. From the intake valve the air is compressed constantly and forced out of the pressure valve. The process is carried out in single or multiple cylinders depending on the stages. A multiple stage compressor is used to produce high pressure gas. Low pressure gas can also be produced by using a single stage single cylinder compressor. An intermediate cooling system is essential in a multi-stage compressor to reduce the temperature of the gas from one stage to another [25].

1.2.4 Methanol

Flare gas can be a baseline feedstock to produce synthesis gas (syngas) which is the starting material for methanol production. Methanol (MeOH) is a popular raw material which is deployed to produce different value added chemicals namely formaldehyde (HCHO), Single cell Proteins (SCP), Methyl amines and other organic chemicals. It is primarily used to synthesize MTBE (methyl tert-butyl ether), and as an additive to gasoline which increases the octane number for better engine efficiency. Many countries use gasoline with an additive MTBE for fuel, the demand for MeOH has continuously increased over time. It is the main feedstock for DMFC (direct methanol fuel cell) which is projected to be used as a substitution for gasoline and diesel [26]. DME (Dimethyl ether) is also produced by consuming methanol which can be easily liquefied at ambient temperature. Liquefied product of methanol possess similar physical properties to LPG, hence it can be used as a substitution for LPG or can be used as an engine fuel after mixing with LPG. Methanol synthesis is an emerging process which has a humongous scope in the energy sector. The process is very simple and cost effective when compared with the conventional reforming of oil [27].

1.3 Objectives

Gas flaring is increasing in an alarming rate and it can be reduced by converting it into synthesis gas via steam reforming. Flare gas has a very high potential of producing syngas which is the feedstock for methanol synthesis process. A steam reformer is used to convert the methane and CO2 which is present in the flare gas to produce syngas. Flare gas recovery is gaining its attention due to the environmental regulations and amount of resources that are lost. So an alternative way of reducing flare gas emission needs to be implemented. In this paper, feasibility of methanol synthesis from flare gas is studied. A methanol plant is simulated with help of the data obtained from two actual oil fields of Marun and Siri [28,29]. The plant economics are determined with the help of various parameters such as pay back, net present value, internal rate of return, operational and production cost. A comparison was made between the two plants to determine the profitability index. Two scenarios are considered, 1) Cost calculation considering environmental taxes, and 2) Cost calculations without considering environmental taxes to determine the capital cost. In summary, the main contributions of this paper are:

(1) A novel method for methanol synthesis from flare gas is developed with the help of suitable kinetics. Aspen Hysys is the platform used to simulate the data of gas flared obtained from the actual oil fields.
(2) A comparative study is made between two flared gas input case studies (Marun and Siri) to determine the solvency of the plants. Two scenarios were considered to obtain the total cost involved for methanol production.
(3) Sensitivity analysis is performed to address the relationship between methanol production and economic and technical parameters.
(4) A list of appended results and future progress of this work are explained at the conclusion of this paper.

2. Literature Review

Figure 2 represents the general outline of methanol production from flare gas. The process can be divided into three general major steps (1) syngas production, (2) methanol synthesis, and (3) purification of methanol. The sulfur content in flare gas accelerates corrosion of the equipment. In order to minimize this effect, a desulphurization unit is deployed. Wet scrubbing is a popular method used to remove sulfur. SO_x is an acid gas so a suitable alkaline sorbent is employed. $CaCO_3$ is the most preferred sorbent which reacts with SO_x to produces CO_2 and a solid component. The CO_2 from desulphurization unit enters the reformer [30].

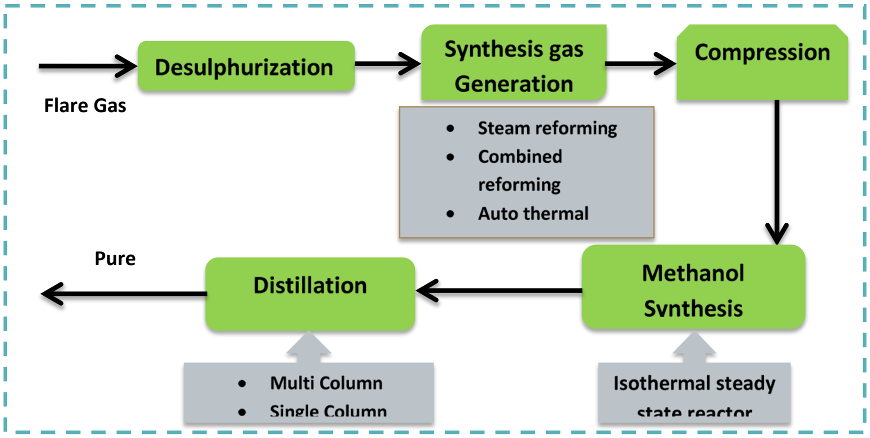


Figure 2. General outline of Methanol production from Flare gas [30]

2.1 Reforming of flare gas

The flare gas obtained from natural gas can be effectively reformed to produce syngas. There are three main types of reforming available in commercial scale including, Steam reforming, OX reforming, and CO_2 reforming. Steam reforming is also called steam methane reforming (SMR) and is an effective way of producing syngas. Its reaction and the enthalpy change are described in Table 1. The important problem in reforming is capturing and storage of CO_2 which is highly feasible in steam reforming. This is the most preferred method of producing synthesis gas as it is a cost effective process [27, 31]. The syngas produced from steam reforming has the synthetic ratio (H_2/ CO) of as high as 3 (CO_2 is not recycled) or 4-6 (when CO_2 is recycled) [32]. For methanol production, a synthetic ratio equal to 2 or slightly above is required; the synthetic ratio can be adjusted by lowering the hydrogen concentration through CO_2 injection to the system [20]. Steam reforming requires high temperature and hence it takes time to instigate the synthesis. The operating condition of reformer depends on many factors such as Equilibrium conversion of steam reforming of methane and syngas ratio.

This gas along with CO_2 and CH_4 is employed as a feedstock for the methanol synthesis process through the heterogeneous reactor after pretreatment.

Table 1. Reactions inside the reformer [32]

reaction	ΔH_0 (298 k) $kJ.mol^{-1}$
$CH_4 + H_2O \rightarrow CO + 3H_2$	-206
$CO + H_2O \leftrightarrow CO_2 + H_2$	41
$\mathrm{CnHm} + \mathrm{nH2O} \leftrightarrow \mathrm{nCO} + (\frac{m}{2} + \mathrm{n})\mathrm{H2}$	-

Flare gas which is free from heavy hydrocarbons like propane, butane, and Pentane along with steam is fed into the mixer MIX-100 which is operated at 140°C and 520 kPa. The mixed feed is sent to the heater where the temperature is raised to 760°C and enters the reformer E which is operated at 760°C, 440 kPa and Steam/C ratio range of 2.5-3. Moreover, the maximum allowable H_2S concentration of reactor feed should be 0.25ppmv [30]. The syngas which is produced in the reformer (Table 1) advances to the cooler with subsequent drop in the temperature. The waste heat is collected by waste heat recovery unit which is used to preheat the feed. The product enters the Separator V-100 which is operated at 40°C and 440 kPa. The syngas and CO_2 which is discerned from the separator enters the Compressor unit [33].

2.2 Modeling and simulation of methanol synthesis

Synthesis gas and sequestrated CO_2 which are obtained from the reformer are the feed stock for methanol synthesis. The methanol synthesis process is operated at a low temperature of 220-300ºC and high pressure of 5000-8000 kPa [34]. As hydrogenation of CO and CO_2 are exothermic in nature, the reaction rate increases with temperature, but only up to a certain value. At higher temperature, the net rate decreases with an increase in temperature as thermodynamic equilibrium constant decreases. The reactor is operated at 250ºC and 5000 kPa to obtain the maximum achievable yield of methanol. Conversion is further improved by recycling the vent gas from the separator. A split ratio of 0.9 gives 95% conversion [35]. SO_x and NO_x which is present in the feedstock poisons the catalyst and affects the methanol conversion and hence various researches are made to produce catalyst which is highly stable and has a long deactivation time.

Since the targeted product is produced at high temperature (~800 C) and high pressure (~5000 kPa), Peng-Robinson equation can be applied as a thermodynamic package model for methanol production processes in Aspen Hysys. The CO and CO2 of Syngas subsequently react with hydrogen to form methanol and H_2O (Table 2). Methanol synthesis involves two major reactions, namely; hydrogenation of CO_2 and Water gas shift reaction.

Table 2. Reactions inside the isothermal reactor for methanol production

reaction	ΔH_0 (298 k) $kJ.mol^{-1}$
$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$	-49.43
$CO_2 + H_2 \leftrightarrow CO + H_2O$	41.12
$CO + 2H_2 \rightarrow CH_3OH$	-91

In this study, the kinetic equations proposed by Vanden Bussche and Froment [36] are used as shown in Equations 1 to 3. Table 3 presents the parameters which are used in the above equations. The parameter values of Rate constant for steady-state kinetic model are given in Table 4.

$$r_{MeOH} = \frac{k'_{5a}k'_2\mathrm{k}_3\mathrm{k}_4k_{H_2}.p_{co_2}.p_{H_2}\left(1-\left(\frac{1}{k^*}\right).\left(\frac{p_{H_2O}\cdot p_{CH_3OH}}{p_{H_2}^3.p_{CO_2}}\right)\right)}{(1+\left(\frac{k_{H_2O}}{k_8k_9k_{H_2}}\right)\left(\frac{p_{H_2O}}{p_{H_2}}\right)+\sqrt{k_{H_2}.p_{H_2}}+k_{H_2O}.p_{H_2O})^3} \quad (1)$$

$$r_{WGS} = \frac{k'_1.p_{co_2}\left(1-(k_3^*).\left(\frac{p_{H_2}.p_{CO}}{p_{H_2}.p_{co_2}}\right)\right)}{(1+\left(\frac{k_{H_2O}}{k_8k_9k_{H_2}}\right)\left(\frac{p_{H_2O}}{p_{H_2}}\right)+\sqrt{k_{H_2}.p_{H_2}}+k_{H_2O}.p_{H_2O})} \quad (2)$$

$$k_j = A_j\exp\left(\frac{B_j}{RT}\right) \quad (3)$$

Table 3. Parameter values for steady-state kinetic model [36]

r_{MeOH}	Rate of methanol production
r_{WGS}	Rate of water gas shift reaction
$\boldsymbol{k^*}$,k_3^*	Equilibrium constants
k_j	Rate constant
A_j, B_j	Arrhenius constants
p_i	Partial pressure of i^{th} component

p	Total pressure
T	Temperature inside the reactor

Table 4. Parameter values for steady-state kinetic model [36]

Rate Constant	A_j	B_j
$\sqrt{k_{H_2}}$	0.499	0.499
k_{H_2O}	6.62*10^{-11}	124,119
$\left(\frac{k_{H_2O}}{k_8 k_9 k_{H_2}}\right)$	3,453.38	−
$k'_{5a}k'_2\mathrm{k}_3\mathrm{k}_4 k_{H_2}$	1.07	36,696
k'_1	1.22*10^{10}	-94,765

All the constants k_j follow the general Arrhenius model and equilibrium constants k^*, k_3^* were thermodynamically determined to be as presented below [37].

$$log k^* = \frac{3066}{T} - 10.592 \quad (4)$$

$$log \frac{1}{k_3^*} = \frac{-2073}{T} + 2.029 \quad (5)$$

The two methanol producing plants under consideration are operated at different flow rates. Based on input feed gas flow rate, the simulation model has been modified. Any change in the reactor flow rate will affect the reaction rate, this subsequently vary the methanol production.

3. Economic Evaluation

The profitability index of the plant is determined by accounting for the total cost and profits involved in the process. The balance sheets of the plants under consideration are obtained from the simulation results of the previous section.

3.1 Net present value (NPV)

Net present value (NPV) is a tool used to quantify the impact of time over the present and future value of money taking inflation and the rate of returns into consideration [41]. Net present value is also defined as consideration of the present value of future cash flows. This method is used to evaluate the present worth of the cash flows that occur during the life time of a project. For the project to be viable, the net present value should be positive or in the worst case 0. The higher value of NPV states that the project is economically stable. The net present value of the project considering of annual savings S(t), capital cost CC(t), and the rate of return(RR) is given by Equation 6. The following summation in this equation is over all time intervals of the life time of the project.

$$NPV = \sum_{t=1}^{n} S(t).RR(t) - CC\,(t) = \sum_{t=1}^{n} \frac{CF_t}{(1+RR)^t} \quad (6)$$

3.2 Internal Rate of return (IRR)

Internal rate of return (IRR) is the effective interest rate such that net present value becomes zero. Internal rate of return is a comparative tool which is inflicted to evaluate the stability of the company [41]. It is an indicator for the yield of investment. Higher internal rate of return implies higher solvency of a company. The IRR is obtained by solving the following Equation.

$$\sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} = 0 \quad (7)$$

Where, CF_t is the cash flow at period t.

3.3 Payback period (Y)

Payback period is defined as the time period required to recoup the investment or to reach the breakeven point. Payback period is determined to understand the time value of the money. It is a comparative tool used by economists to identify the better investment opportunities [41]. The rate of return to the investment should be less to reduce the operating cost. Solvency of a company is determined from the payback period. The payback period is calculated from the Equation 8.

$$Y = \frac{\sum_{t=1}^{n} CC(t)}{S(t)} \quad (8)$$

3.4 Assumptions

Several assumptions are adopted to conduct the economic and environmental analysis including:

(1) The size and capacity of the each equipment was calculated based on the optimum simulation flow rate results [42].
(2) The purchased costs of the equipment were estimated from these size parameters [42].
(3) Carbon steel was used as the main material of construction [42].
(4) The Chemical Engineering Plant Cost Index (CEPCI) is used so that the conversion of the cost from the base year to the study year of the project is possible [42].
(5) The lifetime of this system is supposed to be 20 years.
(6) The time duration of this system is around 7200 hours per year.
(7) All the data are calculated according to values of the year 2009.
(8) The average selling price of methanol is $250 per ton in Middle East [43].
(9) The tax for CO_2 emission is considered to be $12 per ton [44].(this is based on the tax credit for 2009)
(10) Global warming potential of flare gas mixture is presented in the Table 5.
(11) Greenhouse gas (GHG) emission taxes accounted for the total product cost will have a negative value if flare gas is not recovered.
(12) Purge gas emissions are considered for estimating environmental taxes.

Table 5. Global Warming potential (GWP) of flare gas [45]

Chemical Formula	GWP
CO_2	1
CH_4	21
N_2O	310

4. Results and Discussion

4.1 Costs and Emissions

Capital cost is broadly classified into indirect Cost, working Capital Cost, and direct Cost. Figures 3 and 4 represent the capital costs of Marun and Siri in US$. Siri is a larger methanol producing plant when compared with Marun so capital cost of Siri is eventually higher. Direct Cost is broke down into (1) Equipment cost, (2) service facilities, (3) piping cost, (4) purchased equipment installation, (5) instrumentation and control, (6) building cost, (7) electrical system, and (8) yard improvement.

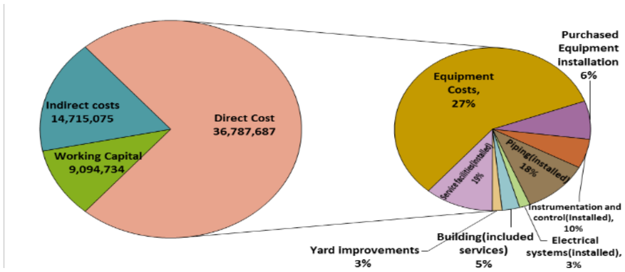


Figure 3. Marun's capital cost (US$)

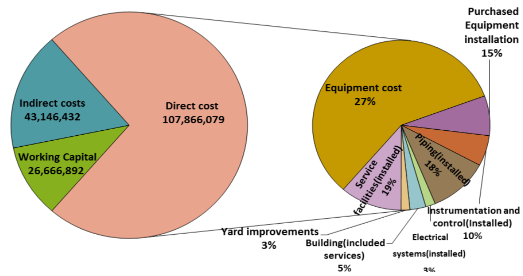
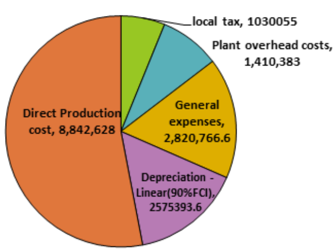
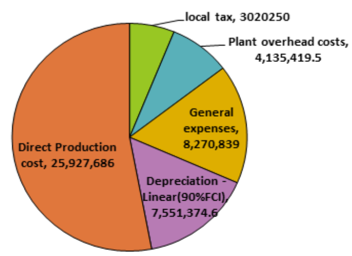


Figure 4. Siri's capital cost (US$)

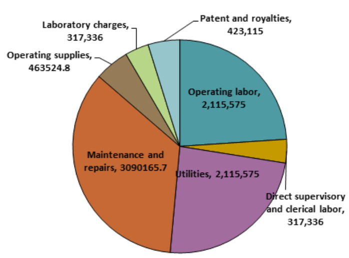
Production cost of Siri is high when compared to Marun (Figure 5). Production cost is a tool to identify the various expenses involved within the company. Investment of Siri is very high due to the demand for the product. Figure 5(a) and 5(b) give the production cost of Marun and Siri. The investment and plant capacity of Siri is high due to which Siri has a high production cost when compared to Marun. Figure 5(c) and 5(d) gives more details on the direct production cost of Marun and Siri. The direct production cost of Siri is thrice that of Marun. Figure 6 gives the Annual GHG emissions. The productivity of Siri is high when compared with Marun due to which Siri emits higher greenhouse gases.



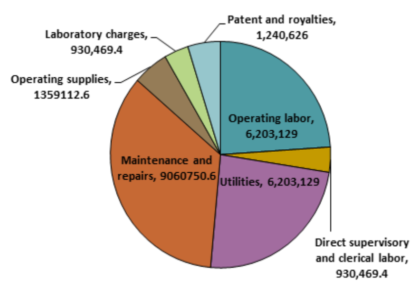
(a) Production cost of Marun



(b) Production cost of Siri



(c). Direct production cost of Marun



(d). Direct production cost of Siri

Figure 5. Estimated cost for Marun and Siri (US$)

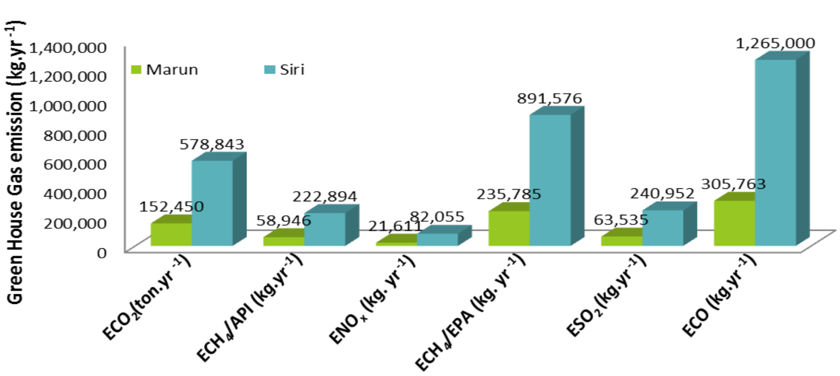
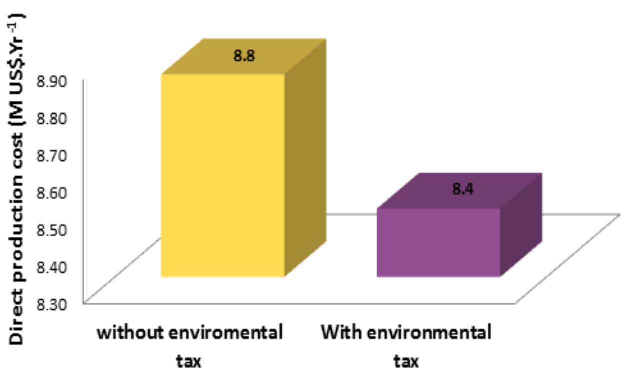


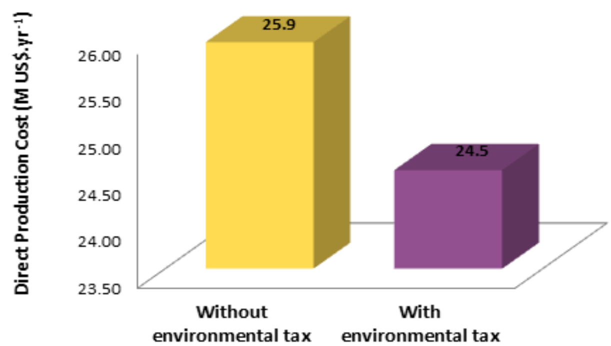
Figure 6. Annual greenhouse gas emissions

4.2 Scenario Generation

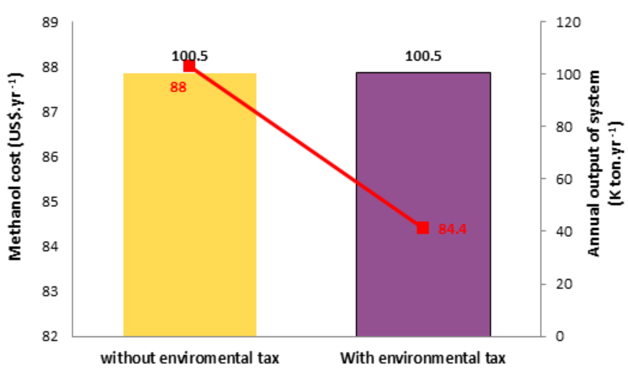
Taxes involved for the production of greenhouse gas varies in different countries. Two scenarios are examined including (1) by considering the environmental tax and (2) Without consideration of environmental tax. In the contemporary condition, the flare gas is burned in the oil fields of Marun and Siri, therefore, its price is assumed to be \$0 per cubic meter. Figure 7 displays the comparative study based on two scenarios for Marun and Siri. Figures 7(a) and 7(b) depicts the direct production cost of these two plants. In both cases, direct production cost decreases when environmental taxes are considered. Figures 7(c) and 7(d) represent the annual methanol production and the breakeven cost of methanol for Marun and Siri plants by consideration of environmental tax and without consideration of it. Annual methanol production of Siri is higher than Marun, while the breakeven cost of it is lower. Moreover, environmental taxes decrease the methanol breakeven cost in both plants. Figures 7(e) and 7(f) show the variation in net present value of Marun and Siri for two different discount ratios of 5% and 18%, respectively. The lower the discount rate, the higher will be the NPV. Siri is highly stable in comparison with Marun. Furthermore, the consideration of environmental taxes makes the NPV increased in both cases. Figure 7(g) gives the payback periods for Marun and Siri. The lower period for return of investment indicates that the company is solvent. Siri has lower payback period when compared with Marun in both cases, hence Siri is highly solvent. The payback period will be decreased while taking in to account the environmental taxes. The payback period of Siri and Marun is around 4 and 6 years, respectively.



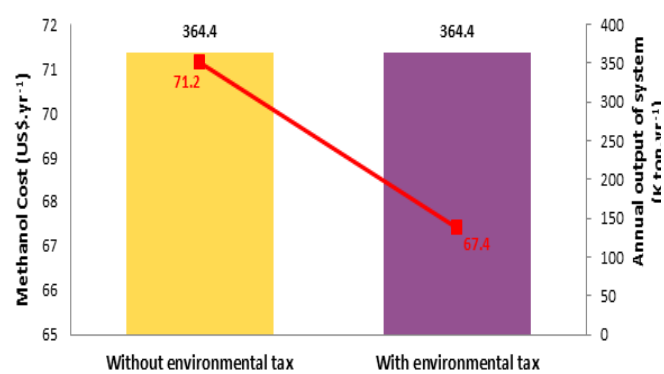
(a) Direct prodcution cost of Marun



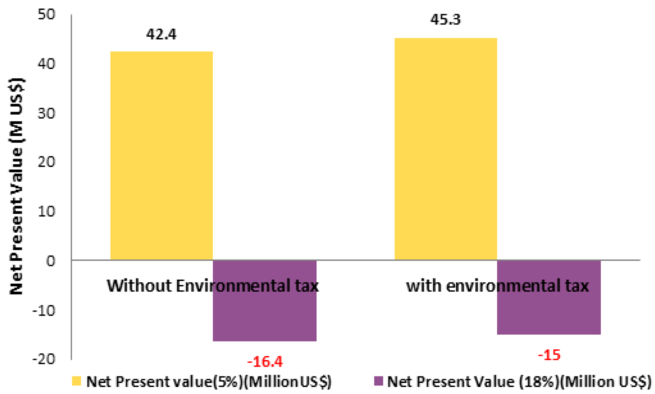
(b) Direct production cost of Siri



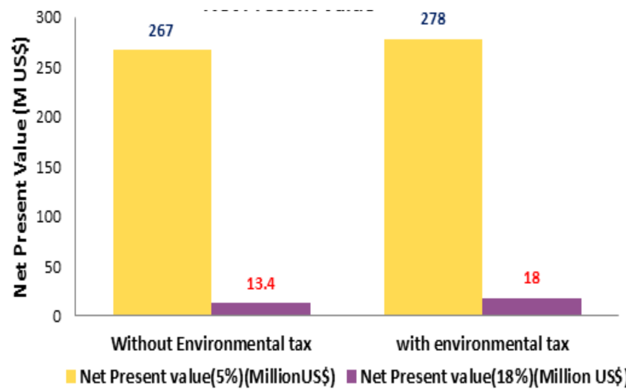
(c) Annual output of system and methanol cost for Marun



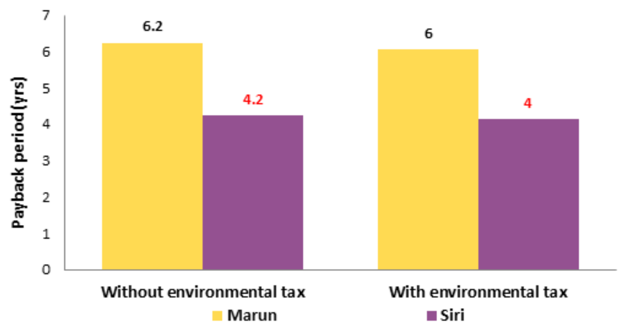
(d) Annual output of system and methanol cost for Siri



(e) Net present value for two discount ratios of 5% and 18% of Marun



(f) Net present value for two discount ratios of 5% and 18% of Siri



(g).Payback period for Marun and Siri

Figure 7. Comparative study based on two scenarios for Marun and Siri

4.3 Sensitivity Analysis

In this section, the sensitivity analysis is conducted over economic parameters such as product price along with input gas cost and technical parameters namely the flow rate of the methane percentage of input gas.

4.3.1 Economic parameters (methanol price and flare gas cost)

The profitability index deeply depends on feedstock cost and product price. For a robust assessment, variability in the product price should be considered. Future product price should be taken into account rather than the present product price when a real commercial plant is constructed. Figures 8 and 9 give the payback period and internal rate of return of Marun for different methanol price and flare gas cost. Figurs10 and 11 describe the payback period and internal rate of return of Siri for different methanol price and flare gas cost. Increase in selling price of methanol from 220 to $300 per ton reduces the payback period from 11 to 5 years. In other words, when the product price increases 36%, doubly reduces the payback period. The graph shows that the payback period becomes lower by decreasing the flare gas cost and increasing the methanol selling price. The internal rate of return (IRR) will increase by decreasing the input gas cost. For instance in Figure 11, the internal rate of return decrease from 16% to 12.5% at constant methanol price of $250 per ton which increases the input gas cost from 0.5 to 1.5 cent per cubic meter. It means that the profitability of the project decreases by 22% when the input gas cost increases by 66%. The profitability of a project will grow with an increase in methanol price. When the methanol price increases from $250 to $300 per ton, the internal rate of return increases from 14% to 21.5% at the constant input gas cost of 1 cent per cubic meter; in other words, the profitability of the project increases by 54% for a 20% increase in methanol selling price.

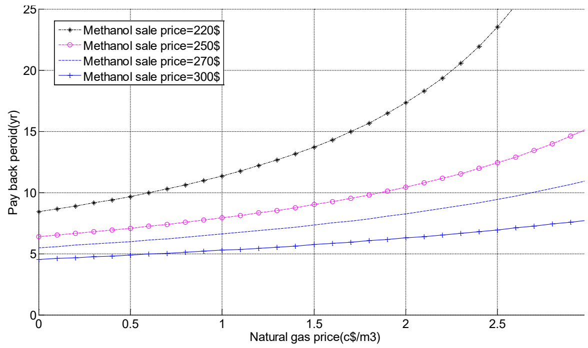


Figure 8. Payback period of Marun verses flare gas cost in different selling price of methanol

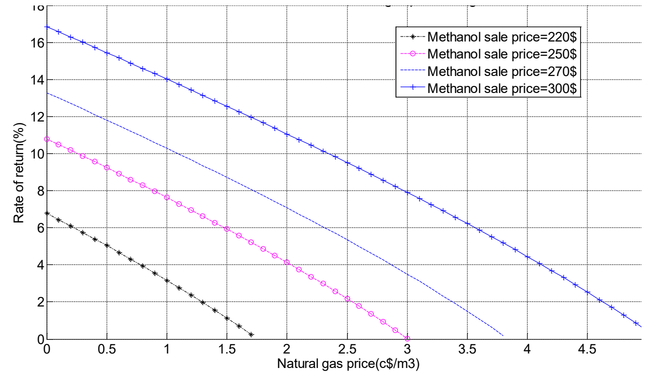


Figure 9. Internal rate of return for Marun versus flare gas cost in different selling price of methanol

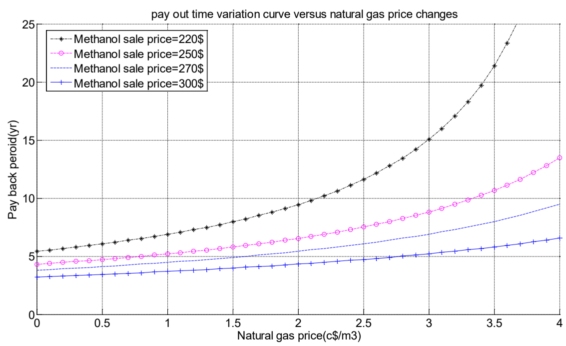


Figure 10. Payback period of Siri verses flare gas cost in different selling price of methanol

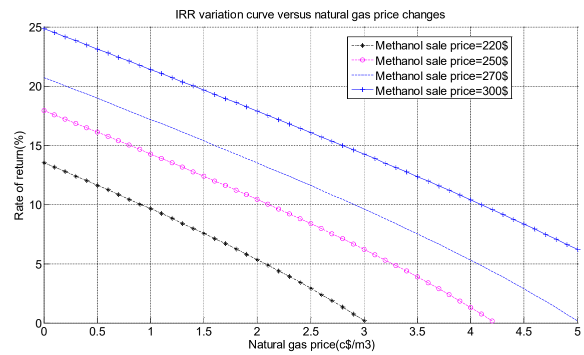


Figure 11. Internal rate of return for Siri verses flare gas cost in different selling price of methanol

It can be deduced that the methanol price affection on profitability of the project is more than the input gas cost. It can be inferred from the comparison of the plots related to Marun and Siri input feed, the higher methane percentage and flow rate of input gas, the more the internal rate of return and the less the payback period.

4.3.2 Technical parameters (Methane percentage in the input gas and Flow rate of input gas)

The operational flow rate of feedstock varies in different oil and gas fields. In order to generalize the results for different flare gas, sensitivity analysis is performed over technical data such as methane percentage and the flow rate of input gas. The optimum percentage of methane is determined from the study. The percentage of methane varies from 50% to 81% for a constant input gas flow rate of 35 MMSCFD. A decrease in methane percentage in the feedstock will subsequently increase the CO_2, NO_2, and CO content in the input gas which affects the quality of the input feed stock.

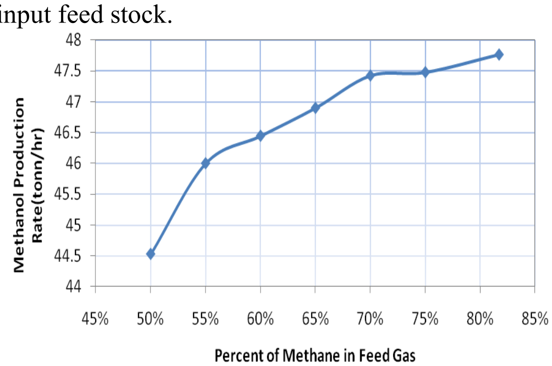


Figure 12. Methanol production versus percentage of methane in feed gas-flow rate 35MMSCFD

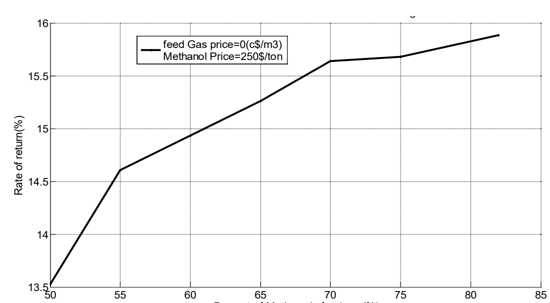


Figure 13. Internal rate of return versus percentage of methane in feed gas-flow rate of 35MMSCFD

Figures 12 and 13 give the variation in methanol production and the internal rate of return, respectively, for various methane percentages in the input gas. An increase in methane percentage scantly increases the methanol production and internal rate of return. To illustrate, the internal rate of return is found to be 15.5%, for 68% of methane in the input gas. Reducing the gas quality at a constant flow rate will decrease the internal rate of return and profitability of the project.

Equipment sizing and costing is determined for various input gas flow rates. The capital cost is obtained subsequently. Figure 14 and 15 depict the methanol production rate and internal rate of return, respectively, at constant feed gas content and various input gas rates. As can be seen, the internal rate of return will increase by increasing the input flow rate. To illustrate, the internal rate of return is found to be 15% for a flow rate 25 MMSCFD.

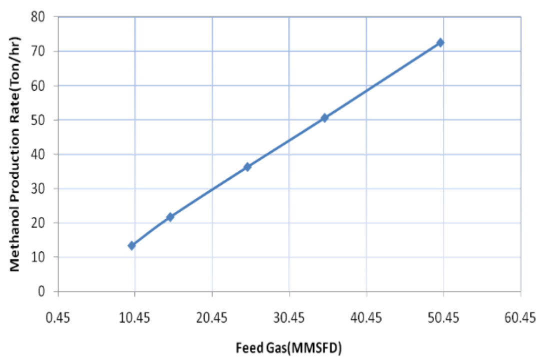


Figure14. Methanol production for various feed gas flow rate.

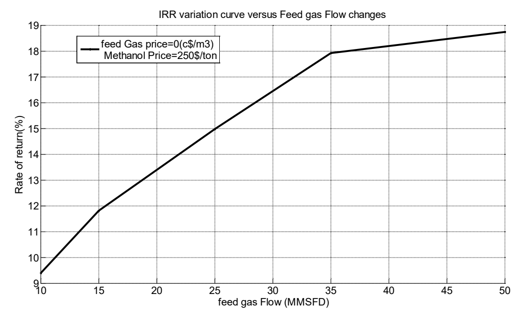


Figure15. Internal rate of return for varies feed gas flow rate

5. Conclusion

Considering the environmental litigations and economic resources which are wasted through flare gas, this paper addresses the technical and economic feasibility of recovering flare gas to produce methanol. Methanol is a popular feedstock which is used as a liquid fuel and producing various value added products with a drastically increase in its worldly demand. Flare gas has a very high potential of producing Syngas which is the feedstock for methanol synthesis process. A conceptual design of methanol production from flare gas is simulated in ASPEN HYSYS. A steam reformer is used to convert the flare gas to Syngas. The actual case study of the simulation is performed with the help of data obtained from two oil fields of Marun and Siri. The plant economics are determined with the help of various parameters such as payback period, net present value, and internal rate of return. A comparison was made between the two plants to determine the profitability index. Two scenarios are considered for cost calculation by considering environmental taxes, and without environmental taxes. Finally, Sensitivity analysis is performed over technical and economic parameters. In summary, the following results are inferred:

- Payback periods imply that both plants are solvent.
- Considering the environmental taxes, the payback period will decrease. However, this reduction is not high due to greenhouse gas emissions of methanol plant.
- Higher methanol selling price and lower input gas cost will increase the profitability of the project and internal rate of return.
- The effect of methanol price over profitability of the project is more than the effect of input gas cost.
- The profitability of the project and internal rate of return increase with input gas flow rate.
- An increase in methane percentage of the input gas increases the profitability of the project and the internal rate of return at a constant feedstock flow rate.
- A decrease in methane percentage implies an increase in CO, CO_2, and NO_2 content in feedstock. Therefore, the feasibility study of deploying biomass as an input gas will be performed for future works for the current simulation.

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Nomenclature:
List of Symbols

r_{MeOH}	Rate of methanol production
r_{WGS}	Rate of water gas shift reaction
$\boldsymbol{k^*}$,k_3^*	Equilibrium constants
k_j	Rate constant
A_j, B_j	Arrhenius constants
F_i	Molar flow of i^{th} component
l	Reactor length
T	Temperature inside the reactor
ρ	Density of catalyst
a	Cross-sectional area of reactor
ΔH_i	Heat of reaction
C_{p_i}	Molar heat capacity of i^{th}component
p_i	Partial pressure of i^{th} component
p	Total pressure
F_t	Total molar flow rate
Y_{CH_3OH}	Yield of methanol
$(F_{CH_3OH})_{outlet}$	Outlet flow rate of methanol
$(F_{CO_2})_{inlet}$	Inlet flow rate of CO_2.
MMSCFD	Million standard cubic feet per day
S	Annual net saving

t	Time interval
n	Number of years
CF	cash flow
CC	Capital cost
Y	Payback period
ROR	rate of return
IRR	Internal rate of return

Biography

Azadeh Maroufmashat obtained her B.Sc. degree in mechanical Engineering in 2007 and her M.Sc. and PhD in Energy system engineering in 2010, and 2015, respectively, all from Sharif University of Technology, Tehran, Iran. During her PhD, she was a visiting scholar at the University of Waterloo. She has over 10 years of research and industry experience in energy systems modeling and optimization. Presently, she is a research associate at GERAD, HEC, Montreal and prior to this she was a postdoctoral fellow in the Department of Chemical Engineering at the University of Waterloo. Her areas of interests are the integration of energy systems, Energy Hub Modeling, Optimization, Power to Gas, as well as Hydrogen Economy.

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