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Analysis of CO_2 transmission pipelines for CO_2 enhanced oil recovery networks: gas field X to oil field Y

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Abstract. The aim of this study is to analyze the CO_2 transmission pipeline from gas field X to oil field Y by comparing alternative routes, CO_2 phases, design parameters, equipment used and economic aspects, with the objective of identifying the most efficient transmission system. The 100 MSCFD of CO_2 that is normally removed from gas field X will be used and transmitted to oil field Y for enhanced oil recovery (EOR). CO_2 can be transported in three phases – gas, fluid or dense vapour. Because of the corrosive properties of CO_2 when in contact with water, materials with high corrosion resistance, such stainless steel or reinforced carbon, should be used. Stainless steel is commonly used for the transport of corrosive fluids such as CO_2 but is expensive, while the least expensive material commonly used is reinforced fibre; however, this material has low strength at high pressure. On the other hand, while carbon steel is known for its high strength and durability it has poor resistance to corrosion. Therefore, the selection of materials for pipeline construction and the design parameters applied will be studied here to determine the best option for CO_2 transmission. For comparison, two alternative routes, one with existing rights of way (the ROW route) and one all-new route, will be compared with each other. Then, CO_2 phase transmission will be compared for liquid, gas and dense vapour phases, together with the design parameters applied and required equipment. Pipe diameter will be calculated along with pipe wall thickness and other requirements of parameter design for transmission of CO_2. Economic analysis will then be performed for each scenario to ascertain the minimum cost while still meeting necessary technical requirements. Capital expenditure (CAPEX), operating expenditure (OPEX) and other variables will be investigated and analyzed using sensitivity testing to determine the influence of each component variation on each CO_2 transmission pipeline. From the analysis applied to each scenario the optimal pipeline transmission scenarios in terms of design and cost to meet the CO_2 enhanced oil-recovery-network needs for gas field X to oil field Y will be obtained.

1 Introduction

To increase oil production in oil field Y it is necessary to apply an enhanced oil recovery (EOR) process. In 2017, original oil in place (OOIP) in the oil field was approximately 302.9 thousand stock tank barrels (MSTB) able to be recovered. Among the many EOR methods available, CO_2-EOR has been chosen as the research option for this field because of the potential for using CO_2 released from gas field X which is located in close proximity to oil field Y. Gas field X is one of the largest natural gas production sites in Indonesia, reaching output of more than 315 thousand standard cubic feet per day (MSCFD). Because of its corrosive properties, the presence of CO_2 in gas stream production is avoided because of its corrosive effect on mechanical equipment and potential decrease in the heating value of the production gas. Therefore, CO_2 is removed from gas field X and can be used for EOR in oil field Y.

CO_2-EOR itself has two main advantages: additional hydrocarbon recovery that encourages energy independence and CO_2 storage to reduce CO_2 emissions into the atmosphere. The role of CO_2 is to increase oil miscibility, enabling oil to be more easily lifted to the surface. To achieve mixing between CO_2 and oil, the reservoir pressure must exceed minimum miscibility pressure (MP). MP values can be obtained from laboratory experiments or correlations [14].

The injection of CO_2 has been shown to increase oil gain significantly, in the range of 5–10% of OOIP [11] The EOR-CO_2 method requires a high level of CO_2 purity, of more than 95% mole, and a water content of less than 1% mol [9] Therefore, CO_2 transmitted from gas field X to oil field Y needs processing to meet these requirements. Following the processing of the CO_2, an appropriate transmission scheme is needed so that optimal additional oil production can be achieved at an acceptable cost.

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More than 100 MSCFD of CO_2 are being produced and this gas needs to be transmitted from gas field X to the oil field Y. CO_2 is a chemical compound that is acidic when it reacts with water, and equipment and materials chosen for use in transmission therefore need serious consideration. Depending on working temperature and pressure, CO_2 occurs in three phases – gas, liquid or solid. In gas and liquid phases, CO_2 can be transmitted using pipelines or in vehicle-mounted tanks, while in the solid phase CO_2 can only be transported by the latter method. The most frequently transmitted CO_2 phases are gas and liquid. With the distance in this case between gas field X and oil field Y being only approximately 40 km or 25 mile, the use of pipelines is considered to be more efficient.

In terms of the corrosive properties of CO_2 when in contact with water, highly resistant materials need to be used for both equipment and pipelines. Stainless steel is commonly used for the transport of corrosive fluids such as CO_2 but it is expensive. Reinforced fibre, which is the least expensive material commonly used, has the drawback of low strength under high pressure. Carbon steel is known for its high strength and durability but has poor resistance against corrosion and so needs additional cladding with resistant materials.

As suggested by Seiersten and Kongshaug [16], low-alloy carbon steel pipes can be used to transport CO_2 with water content of below 100 percent per million (ppm). Therefore, before entering such pipelines, CO_2 needs to be conditioned to meet this requirement through the use of additional equipment such as dehydration units. Problems in terms of working pressures and temperatures can be tackled by the inclusion of additional compressors and/or cooling systems (chillers). In conclusion, the selection of construction materials and design parameters will be studied to determine the best option.

Another important factor for CO_2 transmission is pipe selection, including rating and schedule. Pipes are the medium for the flow of process fluids from one unit to another. Generally, the characteristics of pipes are determined based on the material of construction. The diameter of the pipe is based on the 'nominal' diameter between the outer diameter and the inner diameter. Pipe materials in relation to their usefulness are as follows:

- Carbon Steel
  Carbon steel pipe or steel pipe is widely used in the oil and gas industry. This pipe has high strength and is thoughness, weldable and durable. Its disadvantage is not being resistant to corrosion attacks by H_2SO_4, carbonate (K_2CO_3) and seawater. Therefore, for pipes installed underwater and underground, a special coating or lining of some resistant material is required.
- Stainless Steel
  Stainless steel pipe has resistance to oxidation and corrosive substances, and this type of liquified natural gas facility is used in CO_2 removal units, to distribute carbonates and for flare stacks. Stainless steel pipe has a high thermal strength (1.5 times that of carbon steel) [12].
- Cast Iron
  Cast iron pipes are corrosion resistant and have a high degree of hardness but are also highly friability and so are not suitable for facilities in which contraction and high vibration are experienced.
- Galvanize
  Galvanized pipe is a made from a type of carbon steel but with the outer and inner surfaces coated with zinc to provide resistance to rust. This type of pipe is used for drains and conduits.
- Fiber Reinforced Plastic (FRP)
  Reinforced plastic fiber such as PVC is reinforced so it can handle pressure and temperature better than regular plastic pipe. Reinforced fibre pipe is not subject to corrosion.

The transmission pipeline to be designed for this study is to operate from the CO_2 tapping point of the dehydration unit at gas field X to the CO_2 storage tank facility located at oil field Y. For each route, the phases used in the pipeline network will be compared for inlet and outlet pressure, temperature and mechanical equipment requirements.

The pipeline networks are located in the East Java area of Indonesia and cover total distance of approximately 40 km. In the pipeline routes to be analysed, the ROW requirements of the new route will be compared to those of the existing route. Evaluation of the technical aspects of CO_2 phase transmission and the economic value of CO_2 transmission for each pipeline transmission scheme will then be investigated to enable identification of the optimal method of transmission for CO_2 from gas field X to oil field Y for use in the CO_2-EOR process.

The main objective of this study is to compare different phase conditions of CO_2 transmission by considering the design parameters and equipment requirements for each condition. Additionally, carbon steel material that is generally not used for corrosive fluids is compared to corrosion-resistant materials, so as to allow consideration of cheaper design balanced with optimal efficiency by considering technical aspects of each design parameter.

Limitations in the piping design systems used are as follows: (1) the inlet pressure of the transmission pipeline network is 600 psia and the inlet temperature is 120 °F ; (2) pipe material used for this design is carbon steel with alternative lining or no lining; (3) the design is undertaken does not consider the more detailed pipeline accessories; and (4) soil surface topography is not reviewed (alignment sheet and crossing are not taken into account).

2 Methodology

Input data collection for the pipeline transmission systems is required to design according to CO_2-EOR requirements. CO_2-EOR requires CO_2 purity of more than 95% of the volume and water content of less than 50 ppm with injection pressure and temperature respectively 3000 psi and 160 ^{o}F [7,9]. Pipeline transmission will be between the dehydration unit in gas field X and the storage tank in oil field Y. Detailed assumptions for the dehydration unit outlet are presented in Table 1:

Table 1. Dehydration unit characteristics

Design data		
Flow rate	100	MSCFD
Pressure	600	PSI
Temperature	120	^oF
Composition		
Water (H_20)	10	Lb/MSCF
Carbon dioxide (CO_2)	99.8	% mol
C1 and other (% mol)	0.2	% mol

CO_2 for the injection is in liquid phase for the EOR requirement. Storage tank inlet pressure is at least 340 psia with a temperature range of -122 ^oF to +122 ^oF [20] Therefore, before entering the storage tank, CO_2 is cooled by a chiller and after the storage tank, a pump unit is used to boost pressure to the CO_2 injection requirement. Pressure and temperature outlet from the dehydration unit (inlet data for system transmission) are 600 psi and 120 ^oF respectively with flowrate of CO_2 of 100 MSCFD.

For this study, inlet pressure of the piping transmission system will be calculated from 1050 psig to 1500 psig, with sampling systems in place to identify the optimal flow and least pressure drop for the transferred CO_2. An additional compressor system is required to achieve inlet pressure of the pipeline of at least 1050 psig. CO_2 can be transmitted using a pipeline at a pressure of not less than 73 bars or about 1050 psig [4,5,15,16].

The piping system route used will be compared for two alternatives:

- Alternative 1, using existing rights of way and with a length of approximately 44 km or 28 mile.
- Alternative 2, using new rights of way and with a length of approximately 24 km or 15 mile.

Route selection will determine the assumed minimum inside diameter of the pipe used for this study. In terms of length of pipeline, at first glance alternative 2 looks better than alternative 1. However, other aspects need to be investigated to determine the best route for CO_2 transmission.

Materials for piping systems and transfer equipment such as compressors and pumps are designed to handle the particular fluid in flow, in this case CO_2. Pipes made of low-alloy carbon steel can be used to transport CO_2 if its water content is below 100 ppm [7,14,16]. For the pumps used, cold temperatures are required at the inlet to maintain the liquid phase in the pipeline [6,8]. Alternative materials such as stainless steel can be used because of their resistance to the corrosion caused by the reaction of CO_2 with water. The other option is carbon steel pipe lined inside with stainless steel or duplex.

Construction material for the compressor, pump and chiller should be stainless steel or duplex.

The simulations and calculations in this study are performed using a spread sheet, after creating an algorithm for calculating the pipe diameter manually and determining pipe stability.

For this study, the Panhandle equation is used to generate the optimal diameter for the design. This equation is commonly used for pipelines of over the 20 miles in length. The Reynold's number will be required to achieve an equation that is close to the optimum result. The Reynold's number used for CO_2 in the pipeline for this equation is approximately 5 million [21].

Economic calculations include costs, investment and economic feasibility analysis, and analysis sensitivity will use levelized and cashflow methods.

3 Results and discussion

In this study, there are three main evaluations, namely selection of the route, calculation of pipe diameter based on various pressures in each scheme and economic analysis for each scheme.

3.1 Selection of the route

Taking into account safety factors and required land clearance, alternative 1 has a lower investment cost than alternative 2 because, unlike alternative 2, the land required for alternative 1 is already cleared. However, when analysis of the alternatives takes into account the length of the pipe from the dehydration unit tap-out point in gas field X to the point of storage in oil field Y, alternative 2 is shorter than alternative 1.

The length of pipe transmission will determine the required minimum pipe diameter. The comparison of the alternatives is presented in Table 3.

Table 3. Comparison of alternative routes

Parameters	**Alt 1**	**Alt 2**	**Notes**
Distance	28 mile	15 mile	Alternative 1 has higher investment costs than alternative 2
Existing ROW	Available	Not	Alternative 2 uses all new ROW
Existing land clearance	3 mile	15 mile	Land clearance along new ROW route needed
Civic areas crossed	Low	High	Alternative 2 crosses several civil areas
Safety	High	Low	Using existing route means better safety

Taking into consideration the factors presented in Table 3, alternative 1 for pipeline transmission design for CO_2-EOR from gas field X to oil field Y is the safer option. However, this comparison does not take account of the pipe diameter required for each route. Determination of the minimum pipe diameter for each route can be performed using the gas flow equations for the pipe, i.e. the Panhandle equation, which for long pipelines and CO2 transmission has a Reynold's number of 5–10 million [15,21]. The Panhandle equation is indicated by equation (1) :

$$Q = 435{,}87 \, x \left({}^{T_b}/_{P_b}\right)^{1{,}0778} x \, D^{2{,}6182} x \, E \left[\frac{P_1^{\,2} - P_2^{\,2} - \dfrac{0{,}0375 x G x (h_2 - h_1) x P_{avg}^{\,2}}{T_{avg} x P_{avg}}}{G^{0.8539} x L x T_{avg} x Z_{avg}} \right]^{0{,}5394} \tag{1}$$

where
Q = 100 MSCFD   T = 546 R
P1 = 600 psig   P2 = 625.4 psig
Pb = 14.7 psig   Tb = 573 R
Pavg = 640.2 psig E = 1
Δh = 120 ft for Alt 1 & 230 ft for Alt 2
L = 28 mile for Alt 1 &
15 mile for Alt 2

This equation can be used to estimate the final pressure at the end-point of the design. From the assumed data, at the tapping point of the dehydration unit is a pipeline operating pressure of 600 psi [1,6,7].

This condition will certainly be under a pressure which does not reach the minimum required for a CO_2 pipeline of 1050 psi, and therefore the addition of a compressor for the pressure to be increased to at least 1050 psi is required.

For the gas phase of CO_2, pressure in the pipeline design can range from 600 psig to 1200 psig. In this equation, 1050 psig and 1200 psig will be used. The dense vapour phase is transitional from gas to liquid. In this phase, the CO_2 content will mostly become a vapour from 1250 psig up to less than 1500 psig. For this study, the used pressure for dense vapour is 1250 psig and 1350 psig. And for the liquid phase of CO_2, working pressure in the pipeline should be at least 1500 psig.

In using the Panhandle equation mentioned above, the minimum diameter required for each alternative is 12 inches for alternative route 1 and 10 inches for alternative route 2. The actual pricing for these two pipe sizes does not differ greatly, therefore pipe material price for each scheme will differ according to pipe length, which is approximately twice as long for alternative 1 than alternative 2.

Therefore, alternative 2 can be consider cheaper than alternative 1 in terms of pipe material, at approximately US$ 7,250,000 for alternative 2 and US$ 10,380,000 for alternative 1.

As for the land clearance required, alternative 1 needs approximately 3 mile of clearance while alternative 2 needs approximately 24 km of clearance. In terms of total cost for land clearance, alternative 2 is much more expensive than alternative 1. Alternative 1 land clearance and safety costs are approximately US$ 1,150,000, while for alternative 2 they are approximately US$ 5,350,000. Based on these figures it is clear that alternative 1 is cheaper than alternative 2.

In addition, if comparing all other investment costs, alternative 1 is also much cheaper because both less land clearance is required, and it is located at safe distance from civic areas. Consequently, the route which is selected is alternative 1, which uses existing rights of way, and is 44 km or 28 mile in length with nominal pipe size (NPS) of 12 inches.

3.2 Determining the phase of CO_2 transmission

Having chosen alternative 1, the next step is to determine the optimal transmission phase, using variables of working pressure and pipe diameter for alternative route 1. These pressures range from 1050 psi which the is gas phase of CO_2, up to 1500 psi for the liquid phase.

Construction material for each phase will be determined by corrosive resistance at designated pressure as per API and ASTM standards. For this study, carbon steel will be used as the pipe material. This selection is made because the CO2 that enters the pipeline is already dehydrated to less than 100 ppm, as suggested in the study by Seiersten and Kongshaug [16] . The assumed water content from the outlet dehydration unit is approximately10 ppm and therefore the material used for the pipeline will be low-alloy carbon steel API 5L for the dense vapour phase [2]. For the liquid phase, the material used will be carbon-steel-lined stainless steel and stainless steel. For each phase, the flowrate and diameter of pipe required will be calculated by using the Panhandle equation (equation 1). Details of the output pressure of the pipelines for each alternative with constant flowarate (Q) = 100 MMSCFD can be seen in Tables 4 and 5.

Table 4. Diameter calculations use constant Flowrate (Q)

Q (MSCFD)	ID (in)	P2 (psi)	Us (ft/s)	Phase
100	12.38	1050	27.67	Gas
100	12.46	1200	26.94	Gas
100	13.52	1250	25.36	Dense vapour
100	13.73	1350	25.19	Dense vapour
100	15.48	1500	24.68	Liquid

Where, Q are Fluid Flowrate, ID are Inside Diameter of the pipe, P2 are Outlet Pressure, and Us are Fluid Velocity on the pipeline.

From the information presented in Tables 4 and 5 it can be seen that that there are three different pipe sizes for the various phase transmissions of CO_2. For the gas phase pipe, the nominal size is 12 in, for the dense vapour phase, 14 in, and for the liquid phase, 16 in.

In terms of safety, it is preferable to use the larger size with thicker walls. Because handling corrosive

Equipment	Three-stage compressor	Booster compressor	Air cooler (chiller)
Capacity	100 MSCFD	100 MSCFD	5 MSCFD
Suction pressure	600 psig	1350 psig	
Disc pressure	1250 psig or 1500 psig	1500 psig	
Temp.	120 ^{o}F	87 ^{o}F	85 ^{o}F
Power	0.1 mw	50 kw	150 kw
Construction material	Stainless steel or duplex	Stainless steel or duplex	Stainless steel or duplex

material such as CO_2 can erode wall thickness, it is safer to use NPS 16 in for every working phase of CO_2.

After determining the NPS as 16 in, the flowrate at the end point of the pipe is calculated by calculating flowrate and pipeline velocity for each phase. Table 5 shows the flowrate at the end point (the CO_2 storage tank).

Table 5. Flowrate (Q) and Fluid Velocity (Us) at the tap-out point – calculation with constant diameter

ID (in)	Q (MSCFD)	P2 (psi)	Us (ft/s)	Phase
16	100	1050	31.67	Gas
16	98.74	1200	31.25	Gas
16	97.38	1250	30.54	Dense vapour
16	97.21	1350	30.13	Dense vapour
16	95.89	1500	29.14	Liquid

Terms in ASME B.31.3 and ASME B31.8 [4,5,19] state that the velocity in the pipeline flow should be below 30.84 m/s. Therefore, the phases that can be chosen are either the dense vapour or the liquid phase. From the results of the variations to pipe diameter and flowrate it can be concluded that the diameter of pipe to meet requirements is 16 in.

Based on the information in Table 5, there is more loss from the liquid phase than the dense vapour phase. It can therefore be concluded that the dense vapour phase is preferable to the liquid phase. After determining the diameter of pipe and output flow for each CO_2 phase, the next step required is calculation of pipe wall thickness, determined as the pipe schedule. According to ASME standards[3-5], in working pressure of up to 1600 psig, pipe schedule should be API 5L Schedule 80, and this is therefore the chosen pipe wall thickness.

On the other hand, CO_2 in the liquid phase can be stored directly in the storage tank without requiring additional equipment. Both phase alternatives need a chiller to preserve the liquid phase in the storage tank. Based these factors, it can be said that mechanical equipment and material construction of equipment for each phase (dense vapour and liquid) should be different.

Design parameters for the additional mechanical equipment are shown in Table 6.

Table 6. Design for additional mechanical equipment

As detailed, the CO_2 is transmitted to a storage tank. Here, the CO_2 will be in the liquid phase so it can be used easily in the CO_2 injection pump in oil field Y. Therefore, for the dense vapour phase, CO_2 needs to be converted to the liquid phase before entering the storage tank by using an additional compressor stage to increase pressure from 1350 psig to 1500 psig.

The difference between each is considered for the additional compressor used and the additional lining of the pipeline. Each has advantages and disadvantages in comparison with the other. However, to be able to compare accurately, economic analysis is used. For the compressor and chiller in the dense vapour phase, stainless steel or duplex material are used, according to the corrosive properties of CO_2 and API standards.

In the dense vapour phase, carbon steel is used as the material of construction of the pipelines. Similar to the dense vapour phase, additional equipment used in the liquid phase is made with stainless steel and duplex with exception. For liquid phase pipelines, additional non-corrosive materials are used for internal pipe lining because of design parameters and the fluid properties of CO_2.

3.3 Economic Analysis

To be able to determine the optimum design of the CO2 transmission system, each scheme is compared. Optimization relates to three main components, namely objective function, model and optimization techniques. The objective function in this study is to minimize the cost of the CO2 transmission system, namely capital expenditure (CAPEX) and operational expenditure (OPEX), both in terms of pipeline condition and required equipment for the transmission system. The objective function is to minimize CAPEX and OPEX, and the objective function can be formulated as in equation 2 :

$$J\,min = [CAPEX + OPEX]_{pipeline} + [CAPEX + OPEX]_{equipment} \quad (2)$$

Where, *Jmin* is the total investment cost for the CO2 transmission system. Total invesment cost for this project are summary of the CAPEX and OPEX cost for pipeline construction and equipment installation.

Investment cost for each phase (dense vapour and liquid) is calculated and assumed for mechanical equipment such as compressors and chillers by using reference data for similar capacities. Operational data will also be assumed using reference field data.

This CO_2-EOR transmission system will be calculated for a 20 year term with CAPEX and OPEX which differ for each transmission scheme phase, along with possible revenue for each.

By calculating investment cost and then comparing with system revenue, complete economic analysis of CO_2 transmission will indicate which is the best scheme.

The assumed CO_2-EOR can be assessed for additional production of oil from oil field Y from 1100 barrel oil per day (BOPD) to 18,000 BOPD, and the revenue for each year can be calculated. Gross revenue for dense vapour and liquid phases can be determine by using output flow for each phase with assumed oil recovery at CO_2 injection per MSCFD multiplied by oil price. Therefore, gross revenue would be US$24.5 million for the dense vapour phase and US$24.3 million for the liquid phase. Based on this, cashflow calculation can be performed to determine an economic indicator for each compared phase of CO_2 transmission.

Commonly used economic indicators to determine project value are net present value (NPV), internal rate of return (IRR) and payback period (PBP). For economic analysis, total investment along with gross revenue for each year will be simulated by using cashflow analysis for a 20-year period. Using a production-sharing contract (PSC) of government 70 % and contractor 30 % of investment mechanism, analysis will be performed for 9 % and 12 % rates of interest [18,19].

The total investment cost of the two options is shown in Table 7 for the estimated cost for each scheme.

Table 7. Estimated costs for CO_2-EOR transmission systems

Description	Costs – vapour dense phase (US$)	Costs – liquid phase (US$)
Investment costs		
1.Material for pipe construction	12,640,000	12,640,000
2. Additional lining	1,624,000	5,232,000
3. Compressor	16,850,000	15,312,000
4. Air cooler	2,580,000	-
5. Installation and construction	25,050,000	30,120,000
6. Testing and other	1,915,000	1,205,000
Operational cost per month		
1.Main power	88,200	52,000
2.Rent facility	781,000	781,000
3.Maintenance	64,000	20,000
4.Utility costs	12,000	5,000
Mobilization and demobilization costs	128,100	119,500

As shown in Table 7, the investment cost for the dense vapour phase scheme will be approximately US$ 62,082,300 which is less than the liquid phase, which is US$ 63,506,500. However annual costs for the liquid phase scheme are less than for the dense vapour phase scheme.

The next step in the economic analysis is PBP analysis for the two schemes. Pay-out time or PBP is the period required for the return of the capital invested. In general, PBP is measured from when the field starts producing, not since the investment was originally made. Figure 1 compares the PBP for the dense vapour phase and liquid phase schemes.

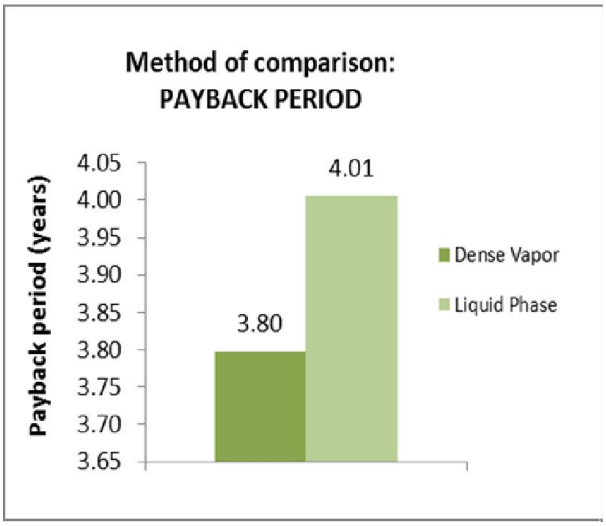

Figure 1. Comparison of PBP of the CO_2 phase schemes

As shown in Figure 1, PBP for the dense vapour phase scheme is 3.8 years and for the liquid phase scheme is 4.01 years. Projects that have a short PBP are seen as being feasible; however, PBP can also be used as an indicator of project risk. The longer the PBP, the greater the risks faced by the project and its investors. For situations with high levels of uncertainty, such as in countries with unstable governments, investors will prefer projects with short PBPs. Based on this data, dense vapour phase CO_2 transmission pipelines are a better option than liquid phase pipelines.

Projects are attractive or economical if rate of return value is above interest rate (9 % and 10 %) and there is an additional risk factor of 2 % to 5 % [1,18,19]. Therefore, the minimum IRR that should be achieved is 12 %. Comparison of NPV for each scheme to ascertain which is higher will indicate the optimal and most economical transmission system.

IRR and NPV can be calculated in relation to contract duration, in this case, 20 years, and rate of interest; in this study two sample rates of interest are used. For the first option, a rate of 9 % is used based on the certificate interest rate of Bank Indonesia (SBI) for US$. The other option is a rate of 12 %, based on field data and references for this project. Figure 2 shows the method of comparison for the CO_2 transmission phases for 9 % and 12 % rates of interest.

IRR is a rate of interest that results in NPV equal to zero. If the IRR calculation is greater than the discount factor set by the company, then the project proposal is accepted; if it is the same as the discount factor the company would break-even; if below zero, then the proposed project is not feasible. If the investment value for the company is equal to or greater than the prevailing bank interest rate then such an investment would be seen as very feasible for investors in the company. Figure 2 compares internal rate of return (IRR) for discount rates of 9 % and 12 % for the CO_2 transmission phase schemes.

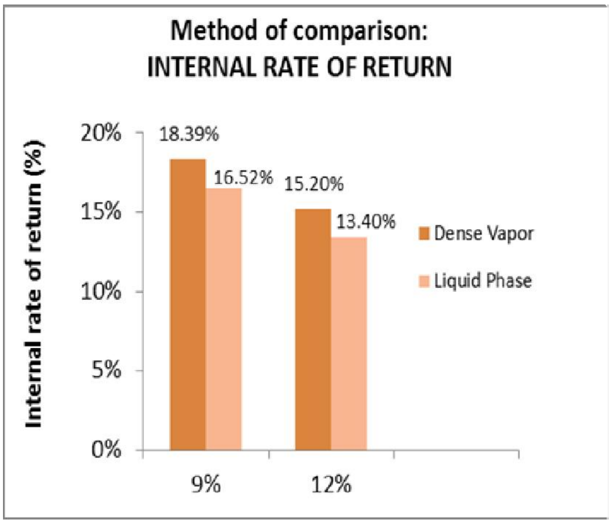

Figure 2. Comparison IRR of the CO_2 phase schemes

As shown in Figure 2, the IRR for the dense vapour phase scheme is 18.4 % for a 9 % rate of interest and 15.2 % for a 12 % rate of interest. IRR for the liquid phase scheme is 17.3 % for a 9 % rate of interest and 13.4 % for a 12 % rate of interest. Based on previous explanations, IRR needs to be at least 12 % for a project to be feasible. It can therefore be seen that both of these schemes are feasible. IRR for the dense vapour phase scheme is better than for the liquid phase scheme, and this means that CO_2 transmission in dense vapour phase is more feasible and a better option than the alternative liquid phase scheme.

The other indicator for economic aspects of a project is NPV. NPV is one method of investment analysis that is widely used in measuring the feasibility of a proposed project. If the NPV calculation is greater than zero, then the proposed project is feasible to run; otherwise, if it is less than zero the project is not feasible. If the NPV calculation is equal to zero, it means the project would break even. Figure 3 are shows the NPV comparison for the two CO_2 transmission phase schemes for rates of interest of 9 and 12 %.

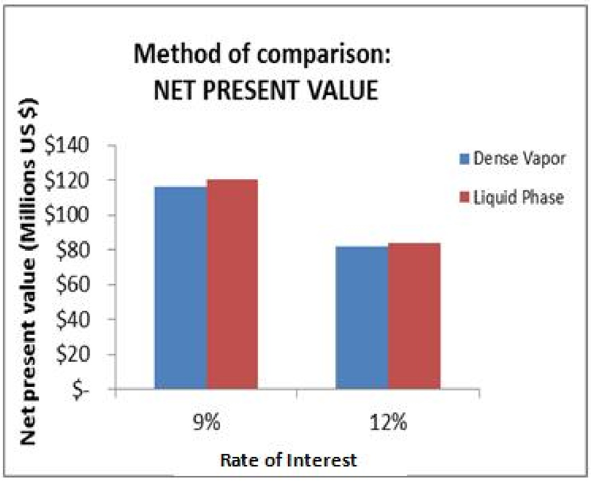

Figure 3. Comparison NPV of CO_2 phase schemes

As shown in Figure 3, the NPV for the dense vapour phase scheme is US$ 116.6 million for a rate of interest of 9 % and US$ 81.7 million for a rate of interest of 12 %. For the liquid phase scheme, the NPV value for rate of interest of 9 % is US$ 120.4 million and for 12 % is US$83.7 million. This means that NPV for the liquid phase scheme is better than for the dense vapour phase scheme.

Based on the economic indicators for dense vapour phase and liquid phase CO_2 transmission pipelines obtained from PBP, IRR and NPV, the schemes for CO_2 transmission pipeline are compared. Economic analysis shows that the optimal CO_2 transmission pipeline uses the dense vapour phase. This option has better PBP and IRR, both of which can attract more investors for such projects.

4 Conclusion

This study proves that both CO_2 transmission in dense vapour phase and liquid phase are feasible, but CO_2 transmission in gas phase is not possible because velocity flow is under the minimum requirement (30.84 m/s) of ASME standards. Alternative route 1 using existing rights of way is more efficient than alternative 2 despite being longer, because this route has lower land clearance and safety costs. From calculations for minimum diameter required for CO_2 pipelines reviewed as minimum inside diameter of pipe of 12 in for gas phase, 14 in for dense vapour phase and 16 in for liquid phase, 16 in is used for this design. The material construction for the CO_2 pipeline chosen is low-alloy carbon steel API 5L Schedule 80. An additional booster compressor (1250 psig to 1500 psig) and air cooler (chiller) are also required.

Ultimately, the chosen design is a dense vapour phase CO_2 transmission pipeline with working pressure of 1250 psig. The cost of developing this pipeline transmission for CO_2-EOR from gas field X to oil field Y is US$ 62,082,300 for an investment scenario of a government 70 %/contractor 30% production-sharing contract. Given these conditions, the IRR is 18.4 %, NPV is US$ 116.6 million, rate of interest is 9 % and PBR is 3.8 years.

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References

1. A.H. Saputra, Ardiansyah, Makara, Teknologi, **13**, 1, 37-41 (2009)
2. American Petroleum Institute (API) 5L, *Specification for line pipe* (2008)
3. American Petroleum Institute (API) Standard 617, *Axial and centrifugal compressors and expander-compressors* (2010)
4. American Society of Mechanical Engineering (ASME) B31.3 *Process piping guide* (2010)
5. American Society of Mechanical Engineering (ASME) B31.8, *Gas transmission and distribution piping system* (2014)
6. Bilio, M., Brown, S., Fairwheather, M., Mahgerefteh, H., *CO_2 pipeline material and safety considerations,* IChemE Symposium Series: HAZARDS XXI Process Safety and Environmental Protection, **155**, 423–429 (2009)
7. B.Rai, *CO2 Dehydration after CO2 Capture*, (University College of Southeast Norway, Norway, 2016)
8. Foster Wheeler Italiana, *Rotating equipment for carbon dioxide capture and storage*, IEAGHG (2010). Retrieved from https://ieaghg.org/docs/General_Docs/Reports/2011-07.pdf
9. J.P.Meyer, *Summary of carbon dioxide enhanced oil recovery (CO_2 EOR) injection well technology* (Contek Solutions, Texas, 2005)
10. K. van 't Veld, O.R. Phillips, The Energy Journal, 31-55 (2009)
11. Kusrini, Eny., Lukita, Maya., Gozan, Misri., Susanto, Bambang H., Widodo, T.W., Nasution, D.A., Wu, Sheila., Rahma, Arif., Siregar, Yusraini D. I., *Biogas from Palm Oil Mill Effluent: Characterization and Removal of CO2 using Modified Clinoptilolite Zeolites in a Fixed-Bed Column*, International Journal of Technology,**7**,4,(2016)
12. L.W. Lake, *fundamental of enhanced oil recovery, 2nd Ed.* (Society of Petroleum Engineering, 2014)
13. McAllister, E. W., *Pipeline rules of thumb handbook, 2nd. Ed*. (Gulf Publishing Company, Texas, 1992)
14. M. Khalil, Buyanto, R. Totok, *Optimasi CO_2 Captured dan Distribusi untuk Enhanced Oil Recovery,* (ITS, Surabaya, 2013)
15. M.K.Verma, *Fundamentals of carbon dioxide-enhanced oil recovery (CO_2-EOR)—A supporting document of the assessment methodology for hydrocarbon recovery using CO_2-EOR associated with carbon sequestration* (USGS, Virginia, 2015)
16. M. Nyarko, International Journal of Energy Engineering, **4**, 6, 202-205 (2015)
17. M. Seiersten, K. O. Kongshaug: "*Materials Selection for Capture, Compression, Transport and Injection of CO_2* . CO_2 Capture Project, Capture and Separation of Carbon Dioxide from Combustion Sources, **2**, 16, 937 (2005)
18. M.S.A. Perera, R.P Gamage,T.D Rathnaweera, A.S. Ranathunga, A. Koay, X. Choi., Energies, **9**, 481 (2016)
19. S. Siregar, Arsegianto, E. Soewono, Surjadi, I.S. Widiasri, N.Ariani., *Optimasi Desain Pipa Transmisi Gas: Kasus Jaringan Sumatera Selatan-Jawa Barat,* (Departemen Teknik Perminyakan ITB, Bandung, 2003)
20. M.S. Peters, K.D. Timmerhaus, *Plant Design and Economics for Chemical Engineers, 4th ed.* (McGraw-Hill, Singapore, 1991)
21. S. Roussanlay, A-A. Grimstad, Energy Procedia **63**, 7836-7843 (2014)
22. S. Amir, H. Nicoleta, E. Christoph, *Towards CFD Modelling of Carbon Dioxide Turbulent Pipe Line Transportation,* Energy Procedia, **40**, 408-417 (2013)