Life Cycle Analysis of Carbon Dioxide Emission Utilization in Enhanced Oil Recovery (EOR) Activity

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Abstract

The focus of this research is to analyze potential environmental impact in the utilization of carbon dioxide (CO_2) as miscible gas injection on Enhanced Oil Recovery (EOR) activity. The reinjection of CO_2 would reduce the amount of CO_2 release in the air and is considered relatively as a new innovative approach. Responsible innovation (RI) is a research framework that considers aspects of sustainability both in terms of social, economic, and environmental toward an innovation made with five dimensions; reflexivity, deliberation, anticipation, responsiveness, and participation. However, RI does not have a specific quantitative approach to support the analysis. Therefore, this research proposes the use of simplified Life Cycle Assessment (LCA) as the quantitative analysis tool to support the RI analysis, using the case study of Subang Gas-Well, West Java, Indonesia. The case study has four main process units of CO_2-Enhanced Oil Recovery, from the Well in Subang, CO_2 Recovery, CO_2 Transmission and the EOR Oil Well in Jatibarang. Based on the calculation, among the various impact categories, the biggest potential environmental impact is the contribution to acidification impact, followed by photo-oxidant formation, climate change and depletion of abiotic resources.

Keywords:*Carbon dioxide gas emission utilization, enhanced oil recovery, life cycle assessment, responsible innovation*

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1. INTRODUCTION

The increased concentration of carbon dioxide (CO_2) level in the atmosphere has spurred worldwide concern of potential global climate change among international organizations, governments, and environmental scientists[1]. From the 18th century to the present, this concentration has increased from 280 to 360 part per million by volume (ppmv)[1].A total of 50% of this increase is mainly caused by human activities. The source of these greenhouse gas emissions mostly comes from fuels burning to produce energy.

Not only the use of fossil fuels, the sources of CO_2 emission in Indonesia also came from multiple industries such as power plants, oil and gas processing plants, steel and ammonia plants and cement factories. On a gas sweetening plant, Subang Field, which is located West Java operated by Pertamina, the gas production is 200 MMSCFD with 23% CO_2 content[2]. The CO_2 content of the processed gas is reduced to 5%, CO_2 release is 36 MMSCFD or 1895 ton/day or 624.812 ton/year[2].

The Indonesian government has committed to a reduction of the country's carbon emission up to 26% by 2020 from businesses as usual scenario[3]. Therefore, the reduction of CO_2 emissions in Indonesia can be realized through various policy options that include energy efficiency and the development of materials, planting forests, increasing the use of renewable energy and nuclear energy, as well as lowering the carbon intensity of fossil fuels. The last option requires a change in the planning of the intensity of carbon fuels with CO_2 capture and storage more commonly known as Carbon Capture and Storage (CCS)[4]. Carbon Capture and Storage is a very effective technology for capturing and storing CO_2 emissions generated from a variety of sectors. International Energy Agencystated that without the application of CCS technology, the cost to reduce emissions from 2005 to 2050 increased by 70% from the previous budget[5].

As an effort to anticipate the increase of greenhouse gas (GHG) emissions, Indonesia has to consider the use of CCS technology. Setiawan and Cuppen already mentioned about the implementation of CCS in Indonesia, focusing on the perspectives of key actors[6]. There is no further explanation on how the CCS could be implemented in Indonesia or how the technology could utilize the GHG emissions so that the emission would be reduced. Indonesia should not just save the GHG emissions but also utilize it to support industries, since CO_2 can be used in various sectors, such as inert atmosphere and dry ice in the food industry, raw materials for making soft drinks in the beverage industry, gas seal in the process of making wine and as a miscible gas for injection old wells oil through Enhanced Oil Recovery (EOR)[7].

As a developing country, Indonesia has the considerably high economic growth rate and it is estimated that in the range of 2006 – 2030, the average growth rate would be about 6% per year[8]. In line with this growth, the estimated energy requirement will increase to more than 4 times from 815 million BOE (barrels of oil equivalent) in 2005 to 3629 million BOE in 2030[8]. Most of the existing oil wells in Indonesia have been classified as old wells while the phase of current production is mostly located in the primary recovery phase. Oil production has decreased gradually with an average reduction rate of 12% per year[9].

Some oil companies strive to increase their oil production through secondary recovery stages and tertiary recovery[10]. EOR is a technology that is used to restore and optimize the exploration of depleted oil reserves at the stage of tertiary recovery[11]. In terms of environmental issue, the re-use of CO_2 emissions is one of the solutions to deal with the CO_2 emissions.

CO_2 is injected into the reservoir and will be precipitated or stored in the reservoir. The amount of CO_2 that come out in the process of oil exploration is very small compared to the amount of CO_2 injected. However, the amount of CO_2 which can be precipitated or stored in the reservoir is highly dependent on the reservoir characteristics such as pressure, temperature, size, etc[7]. In addition to increasing the volume of oil exploration by using CO_2 as a solvent in EOR injection, this method also can provide incentives to reduce the environmental impacts of the oil operations.

EOR has been identified as a method of sequestering CO_2 recovered from gas well exploration (CO_2-EOR). In CO_2-EOR, CO_2 is injected to an oil reservoir to reduce oil viscosity, reduce interfacial tension and cause oil swelling which improves oil recovery[12]. Injecting CO_2 into an oil reservoir to improve oil recovery has been applied for more than three decades and can be considered as an established technology. United States is the world leader in applying this technology by using 32 million tons of CO_2 per year and producing as much as 206,000 BOPD of oil recovery. By injecting CO_2 into oil reservoirs, oil will be mobilized through miscible or immiscible displacement, which can improve oil recovery. A miscible flood is more advantageous than immiscible flood because it results in higher oil recovery factors[2]. By using EOR, approximately 30-60% of the original oil reserves of the reservoir can be extracted[13].

Therefore, this research will discuss how potential environmental impacts are generated from the utilization of CO_2 emissions for oil and gas industry through EOR activities (CO_2-EOR) using Life Cycle Analysis (LCA) model. It is then combined with Responsible Innovation framework to generate indicators of the environmental impacts.

2. METHODS

Utilization of CO_2 emissions as a miscible gas for injection EOR can be seen as a form of innovation. Despite the potential positive effects to the society, an innovation may also bring potential negative effects or unexpected outcomes and fail in achieving its goal. This issue has become a public concern and henceforth responsibility becomes an important theme in the innovation practice. As a result, Responsible Innovation (RI) emerged as the concept and method that aims to address this issue. The basic idea is that responsibility should be presented from the early stage and throughout the innovation process with the goal to achieve sustainability in terms of economy, social, and environment

RI is a research framework that considers aspects of sustainability both in terms of social, economic, and environmental upon the innovation made[14]. RI is considered as a process-based approach for pursuing innovation which pays attention to all stages of innovation process and therefore it offers careful observation of the potential impacts since the early stage through the inclusion of stakeholders and innovation actors[14]. The RI concept proposed by Singh and Kroesen reflects three major components of RI: sustainability as the goal, values that should be embedded in the innovation, and the five dimensions (anticipation, reflexivity, deliberation, responsiveness, participation) as the guiding mechanism to achieving the goal and insuring that certain values can be embedded[14].

The first dimension, anticipation, is the act of looking forward and foreseeing the possible impacts of innovation[14]. Anticipation is about seeking the opportunity, challenge, risk and dealing with it beforehand[15]. The second dimension is reflexivity which indicates a circular or iterative process of creating and shaping innovations[14]. The third dimension is deliberation which explores the process and its holistic aspects and to find a way to move forward[14]. The fourth dimension, responsiveness, denotes as being able to readily respond or address such circumstances due to different needs, requirements, views, issues, and values[14]. The fifth dimension is participation which addresses interests of stakeholders over the issues[14]. The five dimensions as a guiding mechanism is not performed in a linear but in an iterative way. Fig. 1 depicts the five dimensions of RI based on Singh and Kroesen[14].

However, RI does not have any specific quantitative approach to support the analysis. Therefore, this research proposes the use of simple Life Cycle Assessment (LCA) as the quantitative analysis tool to support the RI analysis. A measuring tool must be in place to ensure that the very systems employed to mitigate global warming do not generate other types of environmental burdens[16]. Measuring the environmental benefits of the entire system can be a complex task. LCA is the systematic approach of looking at a product's complete life cycle, from raw materials to final disposal of the product. It offers a "cradle to grave" look at a product or process, considering environmental aspects and potential impacts[17]. LCA is a tool to analyze the effects on the environment of each stage in a product life cycle, from resource extraction, material production, component production, to final product production, and management functionality after the product is consumed, either with re-used, recycled or discarded (valid from cradle to grave)[18]. The entire system of units processed included in the product life cycle is called a product system.

This research deploys LCA modeling combined with RI approach. A practical framework which allows us to demonstrate the application of LCA modeling in the RI approach is proposed. Fig. 2 provides a schematic illustration of the proposed practical framework used for our case studies. By combining both framework, we can get a combination between quantitative and qualitative approach in an integrated way. First, we conduct LCA as quantitative approach to calculate the problem, then RI as qualitative approach to analyze the problem. In this regard, we will focus on 5 dimensions which reflect the concerns of this study. The first dimension, reflexivity, is related to understanding the life cycle of innovation. The second, deliberation, is related to calculating the possible impact due to the innovation. The third, anticipation, is related to analyzing and dealing with the upcoming trends of impacts of innovation. The fourth, responsiveness, is related to responding action to the impact of innovation. And the fifth, participation, is related to addressing all stakeholders' interest over the issues.

For the first step, we conduct LCA approach. LCA methodology is consisted of three phases namely goal and scope definition, inventory analysis, and impact assessment.

2.1. Goal and scope definition

The scope of the EOR employed in this research is cradle-to-gate. This means that the EOR is started by exploring natural gas in gas field which produces an amount of carbon dioxide emissions huge enough to be utilized in EOR.

2.2. Inventory Analysis

In inventory analysis phase, the production system is defined. This is done by translating each incoming and outgoing flow of the system into environmental interventions. The translation process is then mapped into an input-output table; see Table 1 and Fig. 3 for the diagram of simplified LCA calculation. In this research, the data needed for the input-output tables were collected from the literatures and from a preliminary study. Data were collected from literatures which investigate natural gas exploration in gas fields[16,19,20], CO_2 Recovery fields[16], CO_2 transmission fields[16] and CO_2-EOR oil fields[16,21].

Fig. 1. Five Dimensions of Responsible Innovation

Table 1. Input and Output Table of CO_2-EOR Oil Wells Field

Input		Output	
CO_2 (ton/d)	4,186	Oil Recovery	1.08E+03
Energy Recompression and Injection (kWh)	37,674	CO_2 Exploration	4.21E+01
		CH_4	2.16E-01
Energy for Oil Recovery (kWh/ton of oil)	94	Hydrocarbons	9.74E-05
Energy for Oil Pumping (kWh/ton of oil)	138	N_2O	6.06E-04
		PM 10	3.25E-05
		SO_2	2.84E-01
		NO_x	1.07E-01

Table 1. Input and Output Table of CO_2-EOR Oil Wells Field (cont'd)

Input	Output	
	Metals	3.77E-04
	CO_2 Effects	
	CO_2 Sequestered	3.98E+03
	CO_2 leaking	2.09E+02

This research uses a study case from Subang field. Table 2 shows the data of gas composition in gas wells in Subang field. This composition is derived from literatures[2,19]. The concentration of carbon dioxide makes 23% of the gas composition in Subang field. The gas production projection data in Subang gas wells were gathered from Pertamina EP and are tabulated in Table 3. Both data were used to simulate the process of gas exploration using UniSim.

2.3. Impact Assessment

The category selected to be used in this research is baseline impact categories which is consisted of 11 measured impacts. This selection is made to take into account the diversity of industry characteristics of each production process.

The characterization method selected in this research is the basic method which is used for all categories in the baseline impact categories [18] except for the acidification, for which a different baseline category was employed.

Table 2. Gas Composition in Subang Field's Gas Wells

Component	Mole Fraction
Methane	0.614
Ethane	0.0624
Propane	0.03
i-Butane	0.003
n-Butane	0.002
i-Pentane	0.002
n-Pentane	0.0015
Nitrogen	0.025
CO_2	0.23
H_2S	0.03
H_2O	0.0001

After selecting a characterization method, the classification phase was conducted to identify and measure the input and output that contribute to the environmental impact. From this phase, it has been found that there are only 9 out of 11 measured impacts that can be observed, i.e., depletion of abiotic resources, climate change, human toxicity, eco-toxicity (freshwater aquatic eco-toxicity, marine aquatic eco-toxicity, and terrestrial eco-toxicity), photo-oxidant formation, acidification, and eutrophication. The remaining measured impacts—i.e., land use impact and stratospheric ozone layer depletion—could not be observed due to unavailability of input and output data.

Result of the impact assessment phase is shown in the time period of 15 years. The data were then grouped into 4 major processes, namely gas exploration in gas field, CO_2 recovery field, CO_2 transmission field and CO_2-EOR oil field. These data were later processed in CO_2-EOR performance calculation. According to Khoo& Tan[16]and Sugihardjo[21], there are three rule-of-thumb in calculating CO_2-EOR performance:

- An increase in the amount of oil that can be obtained from CO_2-EOR is approximately 8-16% of Original Oil in Place (OOIP).
- The amount of CO_2 that can be used in EOR is approximately 5-10 Mcf/bbl
- The ratio of the amount of CO_2 stored in the reservoir gas wells (sequestered) to total CO_2 injected was 0.95 and the remaining 0.05 will leak into the air as CO_2 gas emissions

Table 3. Subang Gas Production Projection

Years	Gas Production Projection (MMSCFD)
1	346.99
2	281.38
3	216.45
4	175.80
5	135.33
6	96.11
7	51.52
8	33.69
9	9.51
10	7.27
11	5.31
12	3.87
13	2.83
14	2.06
15	1.51

3. RESULTS AND DISCUSSION

From the Fig. 2, it can be seen that this research is divided into two major steps, i.e., (1) Defining goals and value of innovation and (2) Analysis of RI Dimension using LCA

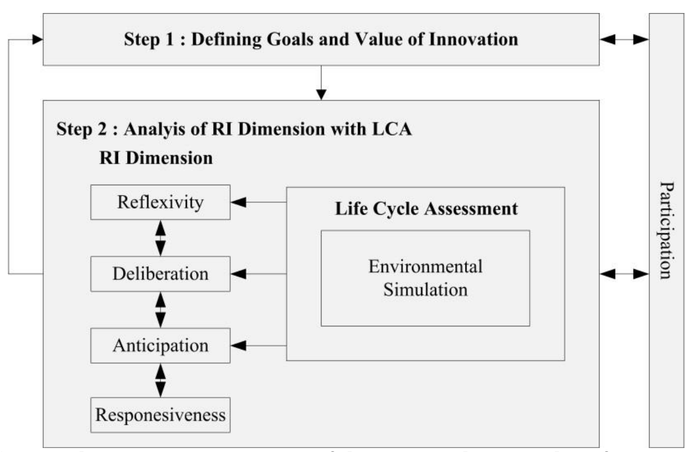

Fig. 2. Schematic representation of the proposed practical RI framework

3.1. Defining goals and value of innovation

The Indonesian government has committed to reducing the country's current carbon emission up to 26% by 2020 using business as usual scenario. In Indonesia, reducing emissions can be performed through many ways, one of which is through carbon capture.

Currently, there are many technologies that can be used to perform carbon capture, one of which is CO_2-EOR. It is a technology that is used to restore and optimize the exploration of depleted oil reserves at the stage of tertiary recovery by using CO_2. After CO_2 is injected into the reservoir, it will be precipitated or stored in the reservoir. There, the injected CO_2 will reduce oil viscosity, reduce interfacial tension, and cause swelling roommates. In the end, this will improve oil recovery[12].

The goal of this activity is to analyze potential environmental impacts in the utilization of CO_2 as miscible gas injection on EOR activity and to identify new opportunities to reduce environmental impacts throughout the life cycle of its activities to achieve environmental sustainability.

3.2. Analysis on RI Dimension using LCA

A model of LCA was developed using spreadsheet to calculate each input and output data in detail. This involves the calculation of the whole CO_2-EOR production which is consisted of one gas wells unit, one CO_2 recovery unit, one CO_2 transmission unit and one CO_2-EOR wells unit. In relation to RI, the LCA shows that the gas wells in Subang generate the largest potential of environmental impacts in all aspects of RI, i.e., reflexivity, deliberation, anticipation, responsiveness, and participation.

3.2.1. Reflexivity

The innovation of the utilization of CO_2 at EOR oil wells is questioned due to its level of potential environmental impacts such as its high level of CO_2 emissions which contributes to climate change. In Indonesia, gas exploration produces one of the largest amounts of CO_2 emissions. This is also the case in Subang gas wells where the gas composition has been found having a concentration of CO_2 of 23%. After 15 years of simulation, it has been found that 1.65E + 07 kg of CO_2 emissions is produced per day. On the EOR unit, the calculation was carried out manually by using the rules of thumb. From the calculation, it has been found that during 15 years of oil recovery by using CO_2-EOR, as many as 6.28E + 04 BOPD (barrels of oil per day) is produced (see Table 4).

Based on the data obtained from Pertamina, OOIP produced in Jatibarang area is 651.1 MMSTB. This means, in 15 years, the maximum amount of oil that can be obtained from the CO_2-EOR is 62.82 MMSTB (9.65% of OOIP). This number is in accordance with one of the rules of thumb which states that the number should be in the range of 8-16%. Based on the rules of thumb of CO_2-EOR, it can be calculated that the total CO_2 amount that can be saved is 1.57E + 04 ton/day for 15 years (95% of the total injected). Table 6 illustrates the amount of CO_2 emissions that can be stored in the reservoir.

From the 15 years of simulation, it has been found that CO_2-EOR can generate a positive result, and in accordance with the rule of thumb, the CO_2 emissions can be stored in petroleum reservoirs in a very long time (approximately for 500 years).

3.2.2. Deliberation

The identified environmental impacts per unit have to be normalized. Normalization enables easier comparison of impacts between different units. The results after the normalization are shown in Table 7. Table 5 and Fig. 5 show that the Gas wells unit produces the highest contribution to the environmental impacts compared to other process units of all the activities of utilization of carbon dioxide emissions in CO_2-EOR (up to 67.49% of the overall environmental impact).

From Table 7 and Fig. 4, it can be seen that there are four impacts that have significantly contributed to the overall process of utilization of CO_2 emissions in EOR activities. These are (from highest to lowest contribution) Acidification, Photo-oxidant formation, Climate change and Depletion of abiotic resources. Results of the 15 years of simulation show that the first four years (from the 1st year until the 4th) have the greatest contribution towards the four potential impacts.

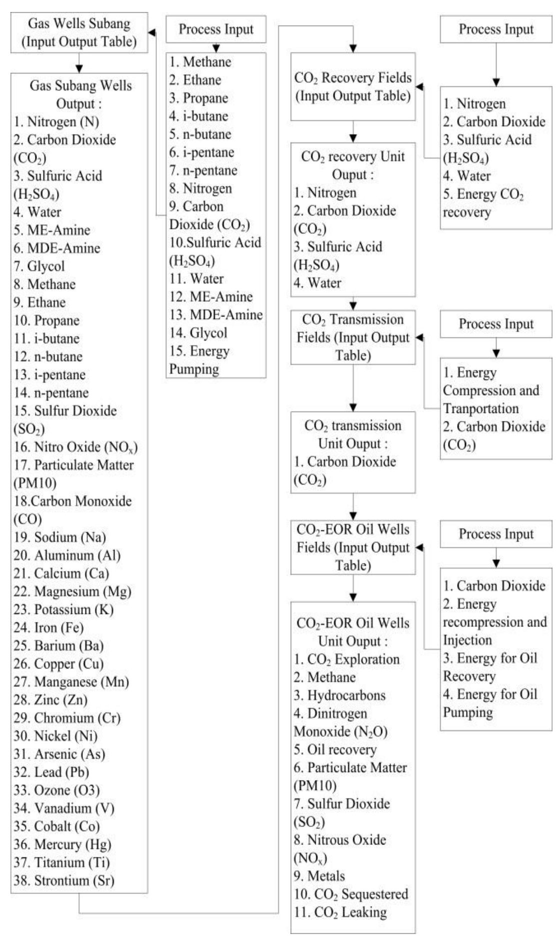

Fig. 3. Diagram of Simplified LCA Calculation

3.2.3. Anticipation

Table 9 shows that each impact has its own major cause. By identifying the cause, the potential impacts can be anticipated. Special attention is thus needed to be paid in order to anticipate the impacts.

3.2.4. Responsiveness

Based on the analyses of the three dimensions above, four recommendations can be formulated, which need special handling, treatment and attention in order to minimize environmental impacts to make innovations sustainable. The recommendations are as follows:

1. Out of the nine impacts identified, there are 4 potential impacts, which are Acidification, Photo-oxidant formation, Climate change and Depletion of abiotic resources.
2. The first four years have contributed the most to the four potential impacts.
3. Subang gas wells unit produces the highest environmental impacts compared to other process units.
4. The reduction in the environmental impacts causes tradeoffs against other effects, i.e., the impact of acidification. Therefore, more attention shall be paid for the handling and treatment of the causes of the acidification impacts so as to fully minimize the environmental impacts.

3.2.5. Participation

Stakeholders can be generally defined as the actors involved in the innovation process which utilizes CO_2 emissions in EOR activities Therefore, the stakeholders involved in this study, are Pertamina EP as the operator of the work, SK Migas as the creator of regulation of work and Public society as consumers and appraisers their work. Table 8 shows the stakeholders and their relation to environmental impacts. This table maps the actors involved and their roles in the activities of the utilization of CO_2 emissions on the activities of EOR. Based on the duty and responsibility of the actors involved, if the current arrangement of duties and responsibilities is properly followed, it will lead to a successful operation of the utilization of CO_2 emissions in EOR activities. Thus, it will create values and bring positive impacts to the innovation, especially in terms of environmental impacts. These values can encourage the actors to be more responsible in performing their duties and responsibilities

Table 4. Total Oil Recovery with Enhanced Oil Recovery for 15 Years

Years	Oil Recovery (BOPD)
1	15,914.16
2	12,904.89
3	9,927.38
4	8,062.71
5	6,206.70
6	4,407.76
7	2,362.91
8	1,545.00
9	436.32
10	333.33
11	243.33
12	177.63
13	129.67
14	94.66
15	69.10
Total	**6.28E+04**

(Source: Model calculation)

Table 5. Contribution Percentage per Unit to Environmental Impacts

Unit	Impact Total (yr)	%
Gas Wells	4.62E-05	67.49%
CO_2 Recovery	2.11E-05	30.79%
CO_2 Transmission	2.37E-08	0.03%
Oil EOR Wells	1.15E-06	1.68%
Total	6.85E-05	100.00%

Table 6. The amount of CO_2 stored in Reservoirs for 15 years

Years	CO_2 Stored (Ton/Day)
1	3,976.75
2	3,224.77
3	2,480.73
4	2,014.77
5	1,550.98
6	1,101.44
7	590.46
8	386.08
9	109.03
10	83.29
11	60.80
12	44.39
13	32.40
14	23.65
15	17.27
Total	**1.57E+04**

(Source: Model calculation)

Table 7. Impact Assessment (15years)

Impact	Total (yr)	% Grand Total
Depletion of Abiotic resources	**5.77E-06**	**8.42%**
Climate Change	**8.79E-06**	**12.83%**
Human Toxicity	2.23E-08	0.03%
Freshwater Aquatic Eco-toxicity	2.89E-09	0.0042%
Marine Aquatic Eco-toxicity	2.37E-08	0.03%
Terrestrial Eco-toxicity	5.54E-08	0.08%
Photo-oxidant Formation	**2.01E-05**	**29.32%**
Acidification	**3.23E-05**	**47.11%**
Eutrophication	1.48E-06	2.16%
Total	**6.85E-05**	**100.00%**

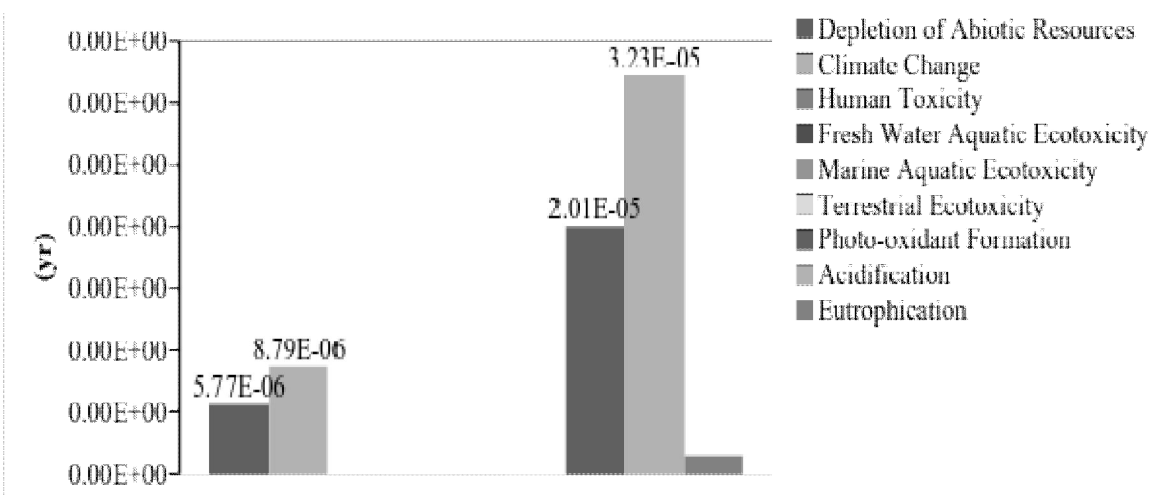

Fig. 4. Impact Assessment Graph per Category

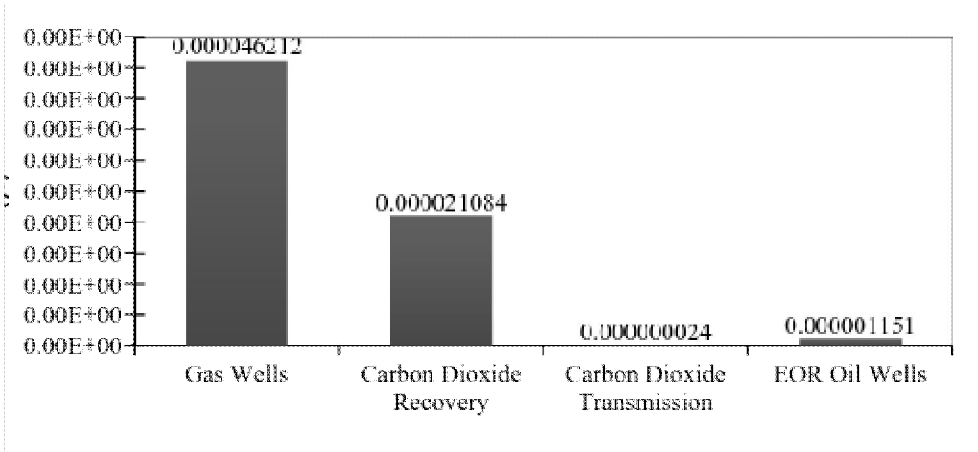

Fig. 5. Impact Assessment Graph per unit

Table 8. Stakeholder and Environmental Impact Analysis

Actor	Motivation	Responsibilities	Impact Environment	Benefit
PT. Pertamina EP	Gain a business profit in the oil and gas sector and act as a company which provides exploration activities of oil and gas	Meeting the needs of the national energy demand for fuel such as oil and gas (i.e. by implementing CO_2-EOR program, providing budget for the running costs of the project, performing maintenance activities on the project)	(+) The use of CO_2 emissions as an EOR miscible gas injection can provide the need for energy consumption in a sustainable and environment-friendly manner. (i.e. reduced emission of carbon dioxide gas)	The increasing number of exploration of oil produced and also environmental benefit the environment such as CO_2 emission reduction
SKK Migas	The establishment of national energy security in the national oil and gas sector.	Creating rules and regulations for activities in the oil and gas sector in Indonesia. (i.e. regulation or standardization of CCS and CO_2-EOR program implementation in Indonesia)		High competitiveness and environmental friendly conduct in the oil and gas sector
Public Society	Fulfill daily needs to support the actions of work and activities of each individual and organization	Provide fair payment to the needs of the energy required (i.e. gasoline, liquefied petroleum gas and raw materials such as gas pipelines) and provide an assessment of the performance that has been done (feedback of satisfaction)	(-) Fault on the utilization of CO_2 emissions in EOR activity can lead to resistance to the use of new environment-friendly technologies and lead to the return of the use of the previous conventional and not environment-friendly technology.	Able to run each activity supported by sufficient energy supply and has an environment-friendly, healthy, and supportive state.

Table 9. Identification of Significant Impact

Impact	Significant Impact	Cause
Acidification (47.11%)	65.10% of impact is caused by CO_2 recovery unit	Purifying carbon dioxide gas by removing all substances H2S into the air
Photo-Oxidant Formation (29.32%)	99.98% of impact is caused by natural gas unit	Releasing of carbon monoxide (CO), sulfur dioxide emissions (SO_2) and hydrocarbons including methane, ethane, propane, i-butane, n-butane, i-pentane and n-pentane
Climate Change (12.83%)	99.64% of impact is caused by natural gas unit	Producing high methane substance
Depletion of Abiotic Resources (8.42%)	80.23% of impact is caused by natural gas unit	The use of fossil fuel and natural gas substance for energy which has the greatest contribution

4. CONCLUSIONS

This research proposes the use LCA as the quantitative analysis tool to support the RI analysis.By using LCA in the framework, RI is considered as a process-based approach for pursuing innovation which pays attention to all stages of innovation process and therefore it offers careful observation of the potential impacts since the early stage through the inclusion of stakeholders and innovation actors.

Based on the LCA calculation model development in this research of the utilization CO_2 emissions in EOR activities which consist one unit gas wells, one unit CO_2 recovery, one unit CO_2 transmission and one unit CO_2-EOR oil wells, it can be concluded based on aspects of RI: anticipation, reflexivity, responsiveness, deliberation and participation that Subang gas wells is the process unit that accounted for the largest environmental impact (63.74%) followed by CO2 recovery unit (30.79%), CO_2-EOR Oil Wells unit (1.68%) and CO_2 unit transmission unit (0.03%).

Based on calculations for the 15-year-period, the maximum amount of oil that can be obtained from EOR is 6.28E + 04 BOPD (barrels of oil per day) or 62.82 MMSTB (9.65% of OOIP) and as much as 1.57E +04 ton / day of CO_2 emissions can stored in the reservoir.

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