RISKS ANALYSIS OF CARBON DIOXIDE STORAGE IN GEOLOGICAL FORMATIONS

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ABSTRACT

Concerning to global climate change, Indonesia has committed to reduce CO_2 emissions. The CO_2 injection and storage in underground geologic formations is one practical method for reducing large volumes of CO_2 emissions into the atmosphere. However, the risks associated with the geological storage of CO_2 are a key factor affecting the implementation of Carbon Capture and Storage (CCS). A better understanding and quantification of these risks is required to ensure risks associated with CO_2 storage in underground formations meets acceptable safety standards. In this paper, the risks are quantified and justified by using Subjective Risk Assessment method. The results show that the risks are low through medium for three types of geological formations i.e. depleted oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.

Keywords: *CO_2 storage, geological reservoirs, risks analysis*

I. INTRODUCTION

Concern about global climate change due to anthropogenic greenhouse gas (GHG) emissions has grown significantly over the last decade. Fossil fuels combustion is accounted for the increasing of greenhouse gas (which are dominated by CO_2) concentration in the atmosphere. To overcome this problem, many countries in the world including Indonesia has committed to reduce CO_2 emissions. However, as a developing country Indonesia still relies largely on fossil fuels to provide energy demand. Moreover, coal is projected to grow at the fastest rate of 4.7 percent per year, followed by oil and natural gas at 2.8 percent, hydro at 2.6 percent and renewables at 1.3 percent[1] as described on Figure 1 below.

As a result of an increasing energy demand, total CO_2 emissions from the energy sector are projected to increase from 292 million tonnes of CO_2 in 2002 to 746 million tonnes of CO_2 in 2030[1]. The source of CO_2 emissions are evenly distributed among the industry, transport and electricity sectors, with each taking about one-third of total CO_2 emissions.

Carbon Capture and Storage (CCS) is seen as most promising option for CO_2 abatement because large amounts of carbon dioxide emitted from power generations or industries are potentially to be captured and sequestered underground. Thus if CCS were deployed straight away it could contribute significantly to achieving emission reduction targets.

However, a key factor affecting the implementation of CCS are the risks associated with underground CO_2

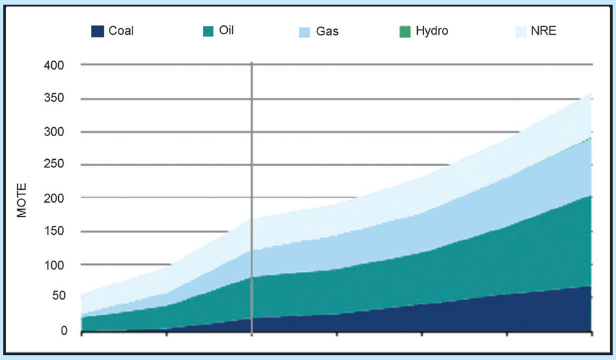

Figure 1
Primary energy demand

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storage. Risk assessment is a first step in a strategy to set up management and control measures to minimise the risks. For this reason, the objective of this study is to identify and quantify potential risks associated with long-term storage of CO_2 in geological formations, where risk denotes a combination of the probability of an event happening and the consequences of the event.

II. GEOLOGICAL FORMATION TYPES

After CO_2 capture process, CO_2 needs to be stored therefore it will not be emitted into the atmosphere. In general, geological reservoirs must fulfil these requirements for site selection: (1) adequate capacity and injectivity (2) adequate porosity and permeability (3) satisfactory sealing caprocks to keep CO_2 in the storage and avoid CO_2 escapes (4) sufficiently stable geologic environment. According to these requirements, there are three types geological formations which are being considered suitable for CO_2 storage. Those are depleted oil and gas reservoirs, unmineable coal seams and deep saline aquifers.

A. Depleted Oil and Gas Reservoirs

Depleted reservoirs consist of rocks with sufficient high porosities to held oil and/or gas in their pore spaces in significant quantities. The caprock, the part of the formation that formed a seal to trap oil and gas, prevented the original hydrocarbon resource from escaping. The fact that depleted oil and gas fields demonstrating their ability to keep gases and liquids for millions of years leads to the assumption that the gas injected can certainly be retained in these structures over long timescales without loss.

Until now Indonesia does not have CO_2 storage project in depleted oil and gas fields eventhough there are thousands of depleted wells which might be considered for CO_2 geological storage[2] as shown on Figure 3.

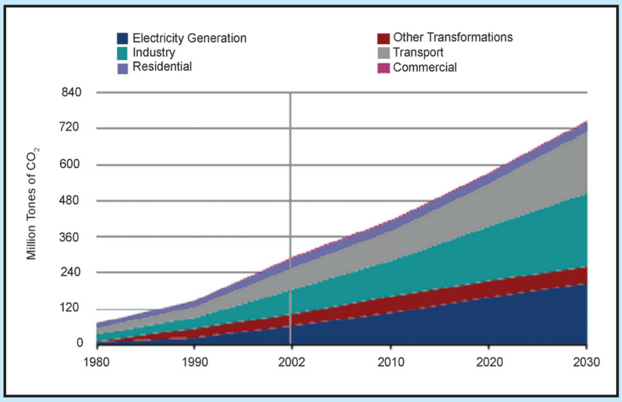

Figure 2
CO_2 emissions by sector

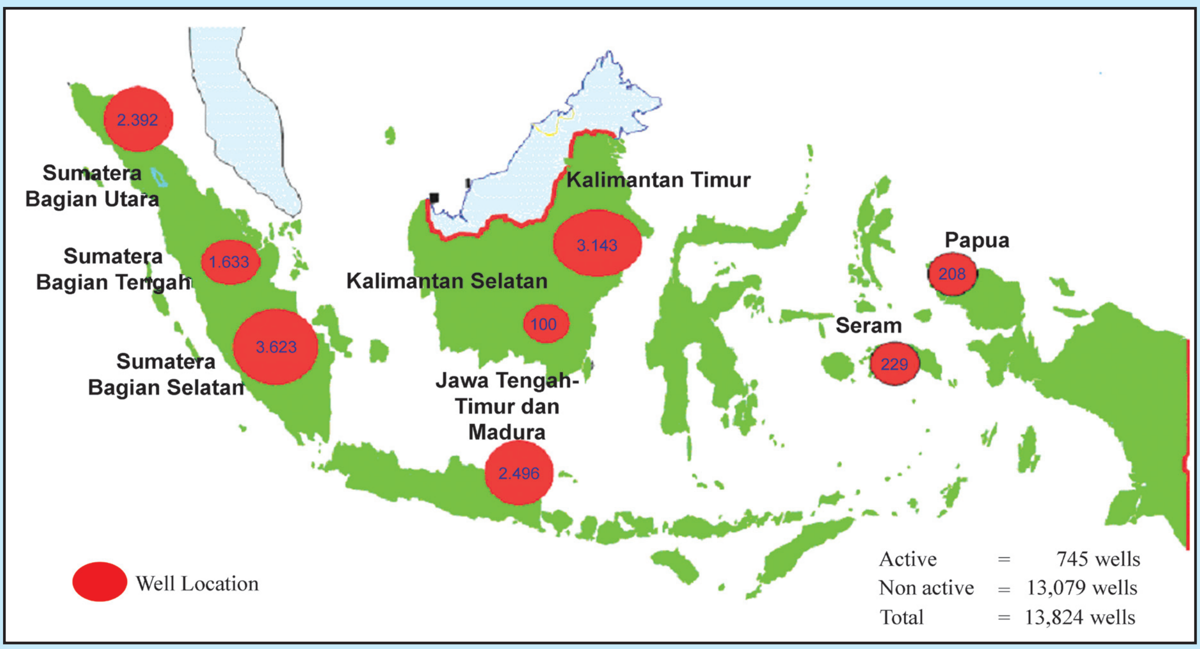

Figure 3
Location of depleted oil wells in Indonesia

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Advantages[3]

Depleted oil and gas reservoirs are considered prime candidates for CO_2 storage for several reasons:

- Oil and gas originally trapped did not escape for millions of years, demonstrating the structural integrity of the reservoir,
- Extensive studies for oil and gas typically have characterized the geology of the reservoir,
- Computer models have often been developed to understand how hydrocarbons move in the Reservoir, and the models could be applied to predicting how CO_2 could move,
- Infrastructure and wells from oil and gas extraction may be in place and might be used for handling CO_2 storage.

Disadvantages[4]

- Field might not facilitate supercritical injection,
- Very low pressures in field can pose stability problems,
- Operational HSE exposure may be higher due to layout of old facilities.

B. Unmineable Coal Seams

Another potential site for CO_2 storage is unmineable coal seams. Some coal resources are unmineable because economically infeasible due to: beds are not thick enough, too deep, too unsafe to mine; too high in sulphur or mineral matter, or be too low in heat value.

Based on the data from Directorate General of Mineral Coal and Geothermal, Indonesia has abundant coal seam reserves and around 49 percent coal quality is low rank coals or low in heat value. It means some coal field potential to be applied for CO_2 storage. Figure 4 shows the coal basins distribution in Indonesia[5].

To make the sequestration process more economically attractive, this technique would allow not only storage of CO_2, but also methane recovery (ECBMR – Enhanced Coal Bed Methane Recovery). This is possible because coal surface has a preferred affinity for adsorption of CO_2 than for methane with a ratio of 2:1.

However, not all types of coal beds are suitable for CBM extraction. Sites for CO_2 storage in coal beds and CBM recovery should[6]:

- Possess adequate permeability of at least 1–5 mD (this relates to injectivity),
- Posses minimal faulted and/or folded,
- Be homogeneous and confined,

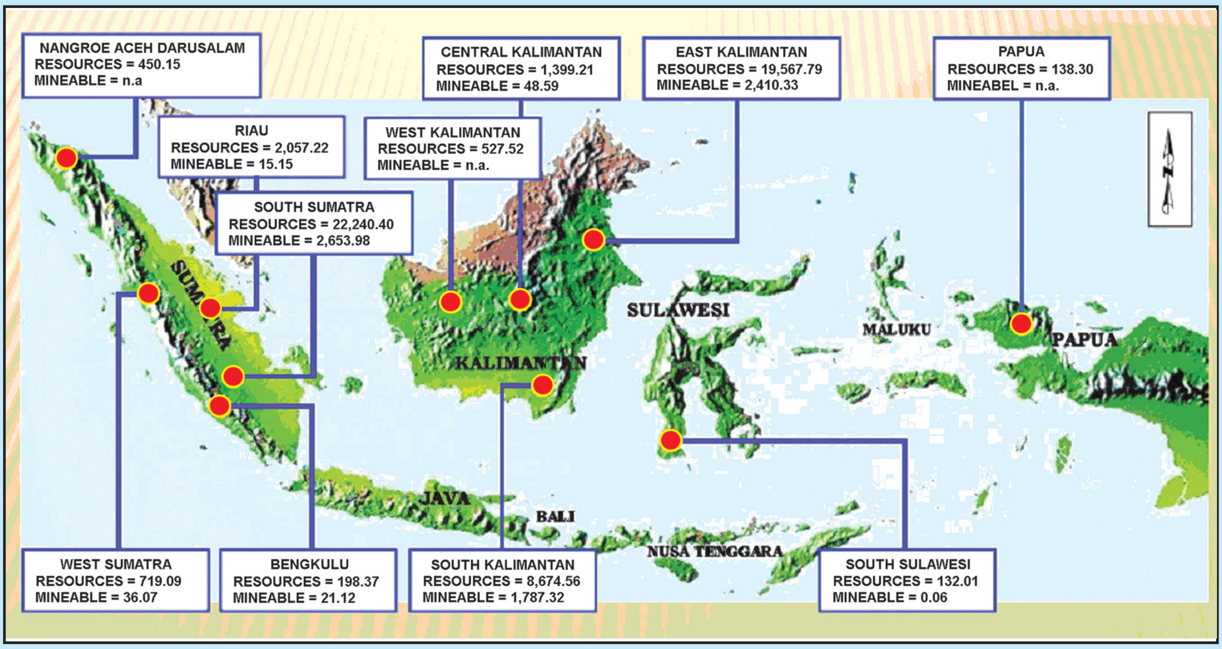

Figure 4
Coal basins in Indonesia

- Have low water saturation,
- Have concentrated coal deposits (fewer, thick seams).

Advantages

CO_2 in coal seams should be relatively stable as long as the seam is otherwise undisturbed. The methane in coal seams has been kept in place for perhaps millions of years, and there is no reason that CO_2 cannot be sequestered for at least thousands of years.

Disadvantages

Technical challenges for CO_2 storage in coal seams include the ability to inject the CO_2 due to the typically low permeability characteristics of the coal cleat system (especially with increasing depth and coal maturity) and the economic viability due to the large number of wells that may need to be drilled. More addition, unmineable coal seams have the smallest potential capacity for storing CO_2 globally compared to oil and gas fields or deep saline formations.

C. Deep Saline Aquifers

This option potentially has the largest storage capacities compare to the other formations. Saline formations are deep sedimentary rocks filled with brines containing high concentration of dissolved salts, which makes them unsuitable for potable water or agricultural use[7]. A portion of the injected CO_2 will dissolve in the saline water and slowly react with the formation to produce mineral carbonates, trapping the CO_2. Although saline aquifers do not have proven 'tightness', the Sleipner Project in the North Sea is the best available example of a CO_2 storage project in a saline formation.

Advantages[4]

- Operational Health, Safety and Environmental risk lower, with no simultaneous operations (no production),
- Containment risk low,
- Few puncture points (old wells) in the caprock
- Tectonically less stressed than for depleted fields (fewer faults – aquifers not typically in anticline structure),
- Chemical reactivity may lead to increase or decrease in capacity or injectivity,

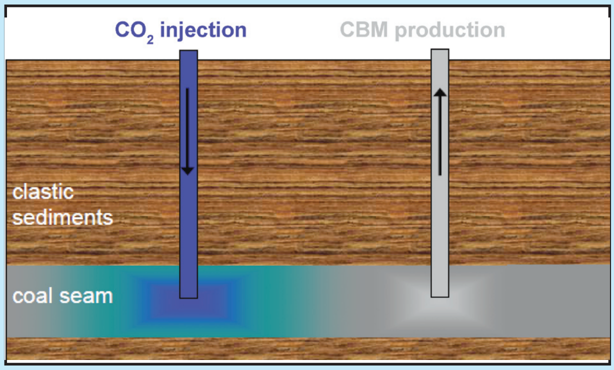

Figure 5
ECBM process

- Vast aquifer size makes it easier to locate areas at the right depth to sustain supercritical state of CO_2,
- No additional costs to assess integrity of old wellls.

Disadvantages[4]

- Data density lower – may require a higher number of appraisal wells compared with depleted field option,
- Lateral migration of CO_2 plume more uncertain due to few structural closures in aquifer settings
- 3D seismic less likely to be available, therefore higher appraisal costs,
- Lower injection rates to start with, due to comparatively higher pressures,
- More prone to digenesis. Aquifers typically do not have a proven ability to contain large amounts of gases and have not been studied so extensively as hydrocarbon structures,
- The estimates of potential storage volume are lower – to what extent the aquifer pore volume can be filled with CO_2.

III. METHODOLOGY

Currently, there is no standardized method or set of methods for evaluating risks of CO_2 long-term storage in geological reservoirs because it is a new field. By using the definition of risk which is a combination of the probability and the severity of the consequence[8], the following methodology was used to define the magnitude of risk:

- Identify hazards or events that may occur. Hazard is a potential to threaten human life, health or the environment.
- Estimate probability of this event occurring.
- Estimate potential consequences from the release.
- Determine risk level.

Figure 6 Shows the detail flowchart of risk analysis.

For this study, a semi-quantitative analysis based on historical data was used to develop a risk matrix that determines the risk to the surrounding community. Indices of probability (i.e., frequent, possible, rare, etc.) and consequences (catastrophic, critical, moderate, etc.) were combined to develop a risk matrix (Tables 1 through 3). As presented in the risk level, Table 4, risk levels of 10 and above are considered a high risk category, levels of 4 and above present medium risk levels, levels of 1 through 3 present a risk that is low with controls or mitigation.

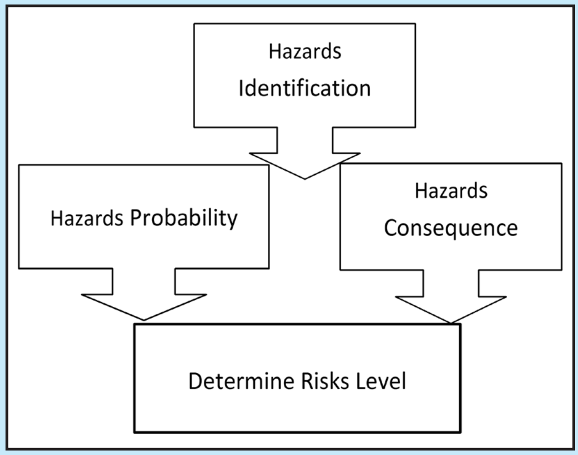

Figure 6
Risk analysis flowchart

Table 1
Probability index[9]

Range	Probability	Description
5	Very Frequent	Likely to occur (e.g., probability > 0.1)
4	Frequent	Probably will occur (e.g., 0.1 > probability > 0.01)
3	Possible	May occur (e.g., 0.01 > probability > 0.001)
2	Rare	Unlikely to occur (e.g., 0.001 > probability > 0.000001)
1	Extremely Rare	Improbable (e.g., 0.000001 > probability)

Table 2
Consequence index[9]

Range	Consequences	Description
4	Catastrophic	May cause death, permanently disabling injury, large destruction to systems, facilities, and environment
3	Critical	May cause severe injury or illness, major property damage to systems, facilities, and environment
2	Moderate	May cause minor injury or occupational illness; minor property damage to systems, facilities, and environment
1	Negligible	Would not adversely affect personal safety or health; damage to systems, facilities, and environment

Table 3
Risk matrix

		Extremely Rare	Rare	Possible	Frequent	Very Frequent
		1	2	3	4	5
Negligible	1	1	2	3	4	5
Critical	2	2	4	6	8	10
Moderate	3	3	6	9	12	15
Catastrophic	4	4	8	12	16	20

IV. RESULTS AND DISCUSSION

In this part the potential risks are identified and quantified for each geological formation. To quantify the risk, Tables 1 through 4 will be used and the justification will be carried out by using Subjective Risk Assessment method. This method is usually used when the personnel who justify the risk has incomplete knowledge, therefore opinion, intuition, and other non-quantifiable resources are used[10].

Table 4
Risk level

Range	Risk
10 – 20	High
4 – 9	Medium
1 – 3	Low

A. Depleted oil and gas reservoirs

1. CO_2 leakage

Eventhough depleted oil and gas fields obviously to be safe sinks for CO_2 sequestration, there is a risk that CO_2 escapes from the reservoir through or along wells or by means of caprock failure. Leakage along or through wells, faults and fractures are generally considered to be the most important leakage pathways. CO_2 leakage through the caprock is less controllable and more dependent upon geological characteristics than CO_2 migration through or along wells. This makes it more difficult to quantify the probability it may occur and the possible health, safety and environmental consequences[11].

2. Groundwater contamination

No known contamination of groundwater has occurred from injection of CO2. However, unintended leakage of CO2, either from wells or along faults and fractures, could impact groundwater quality. Increases in dissolved CO_2 concentration that might occur if CO_2 migrates from a storage reservoir to the surface would alter groundwater chemistry, potentially affecting shallow groundwater used for potable water and industrial and agricultural needs. Dissolved CO2 forms carbonic acid, altering the pH of the solution and potentially causing indirect effects, including mobilization of metals, sulphate, or chloride, and possibly giving the water an odd odor, color, or taste. In the worst case, by-products of CO_2 migration into groundwater resources might reach dangerous levels, excluding the use of groundwater for drinking or irrigation[11].

3. Soil acidification

Similar to the other harms discussed, the risk of soil acidification is very dependent on the specific scenario at the geological storage site. However, it is similarly dependent on an enabling leak in order for any soil acidification to take place. Thus the likelihood of occurrence is similarly low, and the impact is also low since the greatest impact will be the loss of vegetation to a localized area[11].

4. **Induced seismicity**

Geologic carbon sequestration requires injecting large quantities of fluid – supercritical CO_2 – under high pressure. The resulting stresses can fracture the surrounding rock. Highly porous rock is less likely to fracture than is low-porosity rock, since porous rock will allow more fluid migration and thus relieve some pressure. Other factors affecting the probability of fracturing are the injection rate and the strength of the rock most seismic events triggered by deep well injection are too small to be noticed. The problem of seismicity might be more serious when CO_2 is injected into a reservoir in tectonically active regions, which can be found in e.g. Japan and California[11].

All of identified hazards above are quantified by using Tables 1 through 3 to get the risk level.

B. Unmineable coal seams

1. **CO_2 leakage**

CO_2 is more easily adsorbed to coal than methane. It is argued that if coal seams have held methane for millions of years, it will probably retain CO_2 for another thousand of years as well, provided that CO_2 sequestered at formation pressure. When operating at overpressure, the risk of CO_2 leakage is higher.

There are still several aspects to be studied on the interaction between CO_2 and coal seam. Especially the chemical and physical reactions that could occur during CO_2 injection into coal seams and their impact on the integrity of the coal seams require further research. One of these reaction is swelling of the coal matrix when injecting CO_2, which may cause a reduction in the permeability. Swelling might also induce stresses on the overlying and underlying rock strata in non ideal coal seams which could cause faulting and possible migration pathways out of the coal seam[11].

2. **Loss of water quantity**

Based on available data from multiple basins, less than 1% of domestic water wells surrounding producing CBM wells are at risk of experiencing declines in water yield. Except for those wells completed within or immediately adjacent to the producing CBM horizon, perceived declines in water yield is likely to be due to fouling of the near well-bore environment. Less than 1% of affected wells are likely to experience real declines in aquifer levels[9]. The percentage of wells that may be susceptible to damage from CBM operations must be estimated based on available water well completion records.

3. **Water contamination**

More than 50% of domestic water wells surrounding producing CBM wells are likely to experience water quality problems during the life cycle of a CBM development project. For example among the nearly 100 domestic water

Table 5
Risk of depeleted oil and gas reservoir

Hazard	Probability	Consequence	Risk	Level
CO_2 Leakage	2	4	8	Medium
Groundwater Contamination	1	2	2	Low
Soil Acidification	1	1	1	Low
Induced Seismicity	1	3	3	Low

Table 6
Risk of unmineable coal seams

Hazard	Probability	Consequence	Risk	Level
CO_2 Leakage	1	3	3	Low
Loss of water quantity	1	2	2	Low
Water contamination	2	2	4	Medium
Methane seeps	1	3	3	Low

wells sampled during 2001 by the COGCC in the Raton Basin, 45% were found to contain elevated concentrations of at least one or more common dissolved constituents (e.g. sulfate, nitrate, total iron and manganese, total dissolved solids) that exceed primary drinking water standards[9]. In the Colorado portion of the San Juan Basin, the majority of water wells drilled into bedrock aquifers exceed primary drinking water standards for Fluoride. These are largely in areas unimpacted by CBM development.

4. Methane seeps

Events that trigger seeps change their spatial and temporal expression, and are also periodic. Impending earthquakes, changes in barometric pressure, long term changes in local precipitation rates, and variable rates of pressure buildup and release (natural valving) in the pore systems that accommodate methane all affect the timing and location of seeps. The origin of methane in such seeps is also varied and includes thermogenic, biogenic, and abiogenic sources. Seeping methane physically displaces normal oxygen levels in soil, thereby killing vegetation, or thwarting its growth. Along the Fruitland outcrop belt, for example, evidence of historic crown deaths among old Ponderosa pines is only visible along the outcrop. Active gas seeps can also noticeably alter the vegetative landscape by creating linear patches of dead vegetation, usually parallel to outcrop bedding and major fractures. Springs influenced by seeps commonly leave large patches of insoluble iron and manganese oxide deposits on the surface[9].

More addition, one of the characteristics of CH_4 is more mobile than supercritical CO_2. Since the global warming potential (GWP) of methane is circa 23 times that of CO_2, CH_4 leakage is an important factor to be assessed in order to verify the effectiveness as greenhouse gas mitigation option.

All of identified hazards above are quantified by using Tables 1 through 3 to get the risk level.

C. Deep saline aquifers

1. CO_2 leakage

Exploration and production wells which have been drilled through some deep saline aquifers might created potential leakage pathways. For risk assessment input, leakage from a "typical" deep saline aquifer has been modelled to estimate leakage rates from wellhead and cap rock failure. The result is the leakage through a failed cap rock causes the highest risk to all environmental media. The calculated flux from a continuous fracture aperture of 2000 microns corresponds to a leakage rate of 0.1% the total volume stored per year. Leakage rates through permeable zone in the cap rock are estimated at 0.05% of the total volume stored per year[11]. Although the spatial frequency of cap rock failures is estimated low, the consequences of such event are larger.

2. Water contamination

In many cases, dissolution of CO_2 into water is desirable, and some sequestration projects deliberately inject CO_2 into deep saline reservoirs. The CO_2 saturated brine is expected to become denser than the surrounding unsaturated brine and will therefore sink, reducing the risk of upward migration. Although often desirable, dissolution of CO_2 into water can also be problematic. The water will be acidified, which may allow it to degrade geologic formations which may toxic compounds that leach out. Water saturated with CO_2 is also not useful as drinking water. Over time, water contaminated with toxins or with CO_2 could migrate and contaminate groundwater aquifers or other resources[7].

3. Terrestrial impact

Stored CO_2 and any accompanying substances, may affect the flora and fauna with which it comes into contact. Impacts might be expected on microbes in the deep subsurface and on plants and animals in shallower soils and at the surface. However, the probability of leakage is low and there is no evidence of any terrestrial impact from current CO_2 storage projects[7]. Nevertheless, it is important to understand the hazards should exposures occur.

4. Induced seismicity

Underground injection of CO_2 or other fluids into porous rock at pressures substantially higher than formation pressures can induce fracturing and movement along faults. Induced fracturing and fault activation may pose two kinds of risks. First, brittle failure and associated microseismicity induced by over pressuring can create or enhance fracture permeability, thus providing pathways for unwanted CO_2 migration. Second, fault activation can, in principle, induce earthquakes large enough to cause damage. Deep-well injection of waste fluids may induce earthquakes with moderate local magnitudes. Seismicity induced by fluid injection is usually assumed to result from increased pore-fluid pressure in the hypocentral region of the seismic event. CO_2 storage in an aquifer will induce a temporary pressure increase in the reservoir, because the space to store CO_2 only becomes available as a result of compression of the fluids and rock in the reservoir, or displacement of formation water into adjacent formations or to the surface[7].

5. Brine displacement

The injection of CO_2 in aquifers might cause displacement of saline groundwater (brine). Brines displaced from deep formations by injected CO_2 can potentially migrate or leak through fractures or defective wells to shallow aquifers and contaminate shallower drinking water formations by increasing their salinity. In the worst case, infiltration of saline water into groundwater or into the shallow subsurface could impact wildlife habitat, restrict or eliminate agricultural use of land and pollute surface waters[11].

Table 7
Risk of deep saline aquifers

Hazard	Probability	Consequence	Risk	Level
CO_2 Leakage	1	3	3	Low
Water contamination	1	2	2	Low
Terrestrial impact	1	1	1	Low
Induced seismicity	2	3	6	Medium
Brine displacement	1	3	3	Low

All of identified hazards above are quantified by using table 1 through 3 to get the risk level

V. CONCLUSIONS

Geological storage of CO_2 may provide a solution to the problem of reducing anthropogenic emissions of greenhouse gases to the atmosphere. The type of geological formation in which CO_2 is sequestered is an important factor for leakage. Depleted oil and gas fields are generally considered to be safe reservoirs for CO_2 sequestration. Coal seams generally have held coal bed methane for million of years and, moreover, CO_2 is adsorbed more easily than methane, so the risk is expected to be low. Deep saline aquifers need to be studied in more detail considering the seal integrity has not been proven.

Overall, risk analysis which is conducted for three types of geological formations gives a result that the risk is low through medium. It is an indication that CO_2 can be safely injected and stored at well characterized and properly managed sites.

VI. RECOMMENDATIONS

Although there is no high risk of stored CO_2 has been observed in any of the current projects in the world but it still needs careful storage site selection followed by characterization of the selected site in terms of geology, hydrogeology, geochemistry and geomechanics (structural geology and deformation in response to stress changes) if CCS project will be applied in Indonesia.

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