Carbon Dioxide Storage Potential in Malaysian Sandstone Aquifer: An Overview

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Abstract. Carbon dioxide (CO_2) emission rate from energy industries in Malaysia has increased exponentially in these few years. Based on this alarming increment of CO_2 emission rate from previous data, carbon dioxide sequestration in deep saline aquifer has been identified as one of the way to reduce and overcome the increment of CO_2 emission rate in Malaysian atmosphere. Malaysian geology consists of enormous amount of deep saline aquifer which most of the aquifer material is sandstone. Malay Basin has been identified as the most potential basin for CO_2 sequestration in Malaysia by previous researchers. There are four sites in Malay Basin which has potential to be CO_2 sequestration site such as Jerneh, Dulang, Tangga and Semangkok because they contain the formation of fine-grained sandstone, mudstone and coal properties. This paper aims to discuss CO_2 storage potential in Malaysian sandstone aquifer particularly Malay Basin in terms of potential injection location, properties of Malaysian sandstone aquifer, available technologies of injection, injection parameter as well as issues and challenges of carbon sequestration implementation in Malaysia.

1. Introduction

Power plant and industrial point are the main sources of CO_2 for carbon capture, storage and utilization (CCSU). According to [1], CCUS technologies has two important functions which to store the CO_2 in deep saline aquifers and to create a new important product from the CO_2 process. Moreover, the CCUS technologies are also using two resources from fuel combustion and industrial processes where all the CO_2 will transfer by using pipeline services or with water transportation which is by ship. Eighty-one percent of energy comes from the used of fossil fuels with 61% of total anthropogenic contributed to the greenhouse gas (GHG) emissions [2]. The second contribution is from industrial processes with 5% of global GHG emissions (as illustrated in Figure 3).

According to the projection of energy use worldwide, global CO_2 emissions are expected to increase by 55% between 2004 to 2030 (see Figure 1, World Data, 2019) CO_2 emission is projected to increase by one-third between 2012 and 2040 from 32.3 bil metric tons to 43.2 bil metric tons. Since Malaysia is one of the main oil-producing countries in the world, [3] the CO_2 that was generated from petroleum production or fossil fuel combustion has been identified as one of the main contributors to the emissions of CO_2 in Malaysia other than natural gas refining and cement manufacturing. Up to June 2019, 7.83 tonnes per capita of CO_2 has been emitted to Malaysia atmosphere and this scenario is anticipated to continue well in the future if there are no mitigation taken to manage CO_2 emission in Malaysia. Figure 2 also shows the increasing trend of emission rate has reduced slightly from 2016.

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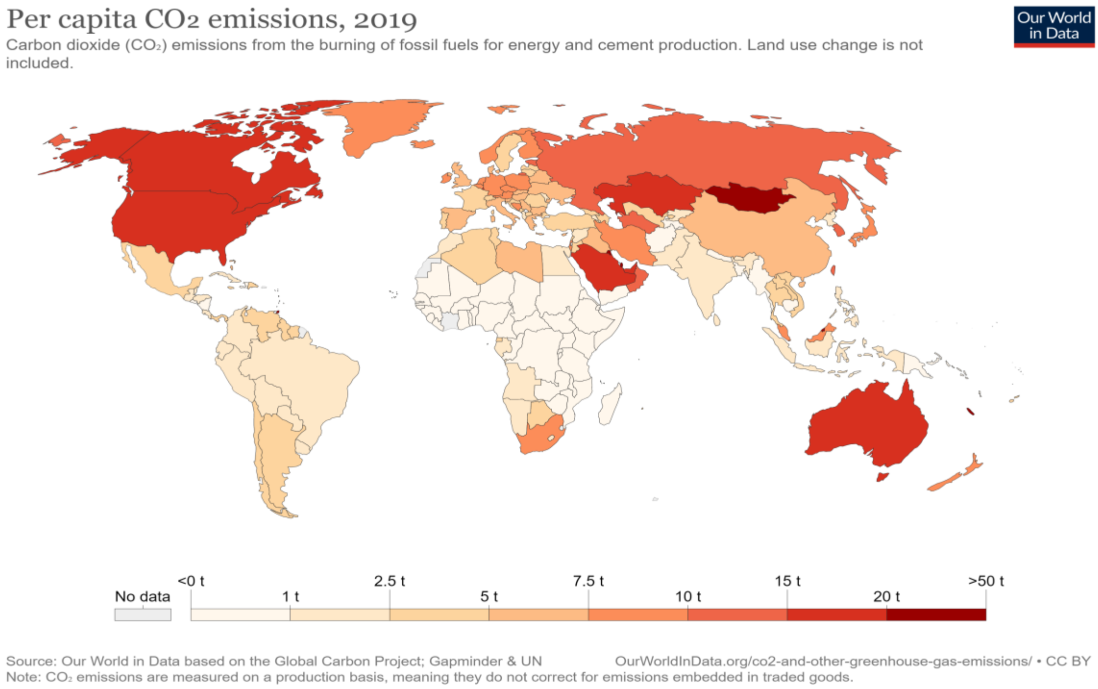
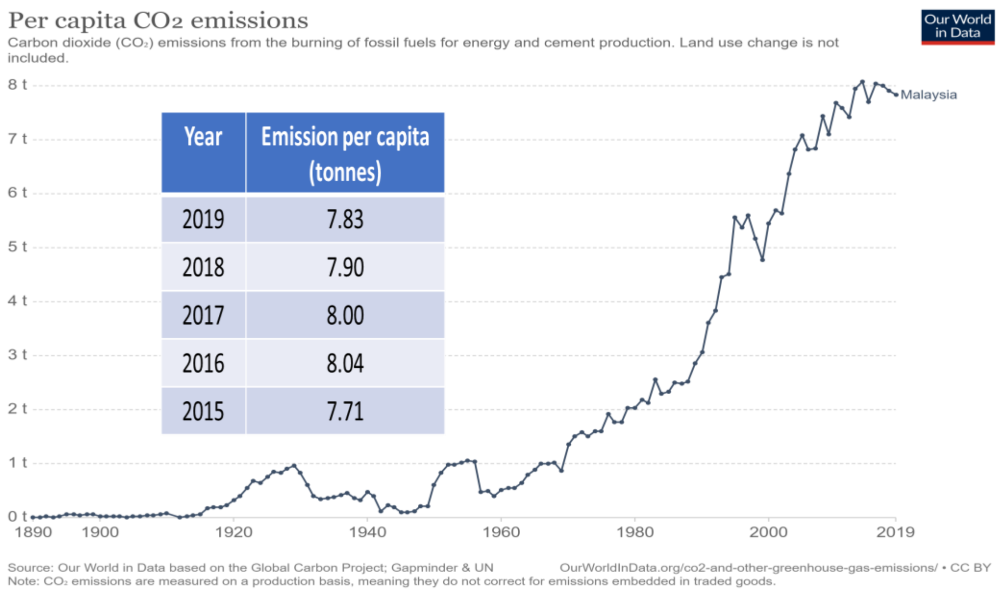


Figure 1. Global CO_2 Emission per Capita in 2019 (World Data).

According to [4], Malaysia, Thailand and Indonesia categories as a moderate emission around 10^2 Mt/year and storage prospectively which refer to the current CO_2 emissions.



Year	Emission per capita (tonnes)
2019	7.83
2018	7.90
2017	8.00
2016	8.04
2015	7.71

Figure 2. Trend of CO_2 Emission in Malaysia (World Data).

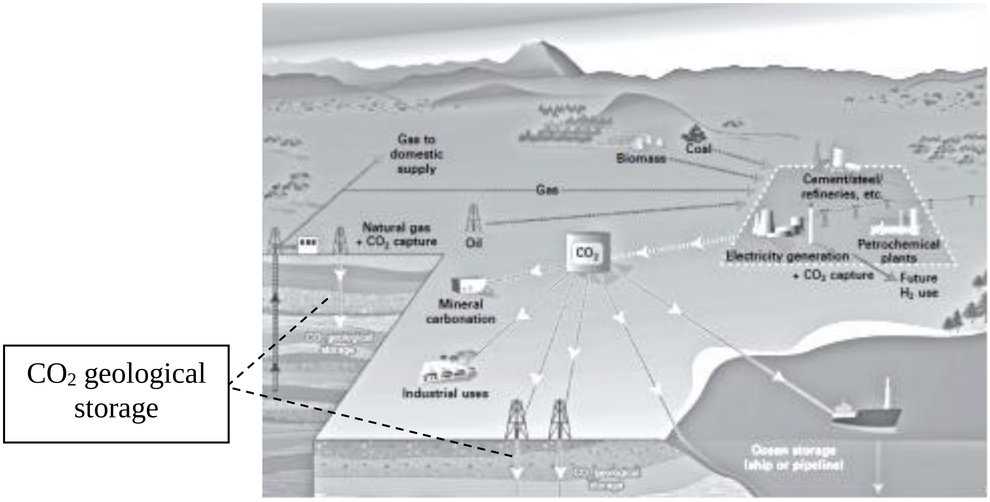


Figure 3. Schematic Diagram of CO_2 Storage System [5].

2. Potential Sedimentary Basins of Malaysia for CO_2 Sequestration

The previous study shows the high potential CO_2 storages which were located in three area of basin such as Malay Basin offshore in Terengganu, Central Luconia Province in Sarawak basin offshore and West Baram Delta also in Sarawak basin offshore was classified as the storage site among twenty-seven percent of geological storage in Malaysia [6]. These potential basins for CO_2 sequestration are not equally suitable in terms of its suitability. There are various factors that influence the evaluation of sedimentary basins mostly due to lack of crucial data for poorly explored basins. It is critical to determine if the sedimentary basins of Malaysia can provide a safe storage for CO_2 before commencing the sequestration as potential leakage and catastrophe escape may cause remnant of disputes in terms of environmental issues and might have some problems with public perceptions.

Table 1 and Figure 4 showed a ranking list of sedimentary basins in Malaysia which has been assessed in terms of their suitability for CO_2 storage capacity based on certain criteria and their location respectively. From the list, it is shown that Malay Basin scored the most and ranked as the most potential basin for carbon sequestration in Malaysia.

Table 1. Ranking for Sedimentary Basins in Malaysia [7].

Rank	***Basin***	***Score***	***Rank***	***Basin***	***Score***
1	Malay Basin	0.8113	*8*	Penyu Basin	0.5554
2	Central Luconia Province	0.7356	*9*	Tatau Province	0.4938
3	West Baram Delta	0.7041	*10*	West Luconia Province	0.4553
4	Balingian Province	0.6938	*11*	Tinjar Province	0.4200
5	Sabah Basin	0.6864	*12*	Northeast Sabah Basin	0.3543
6	East Baram Delta	0.6260	*13*	Southeast Sabah Basin	0.3370
7	Straits of Melaka	0.6200	*14*	North Luconia Province	0.2659

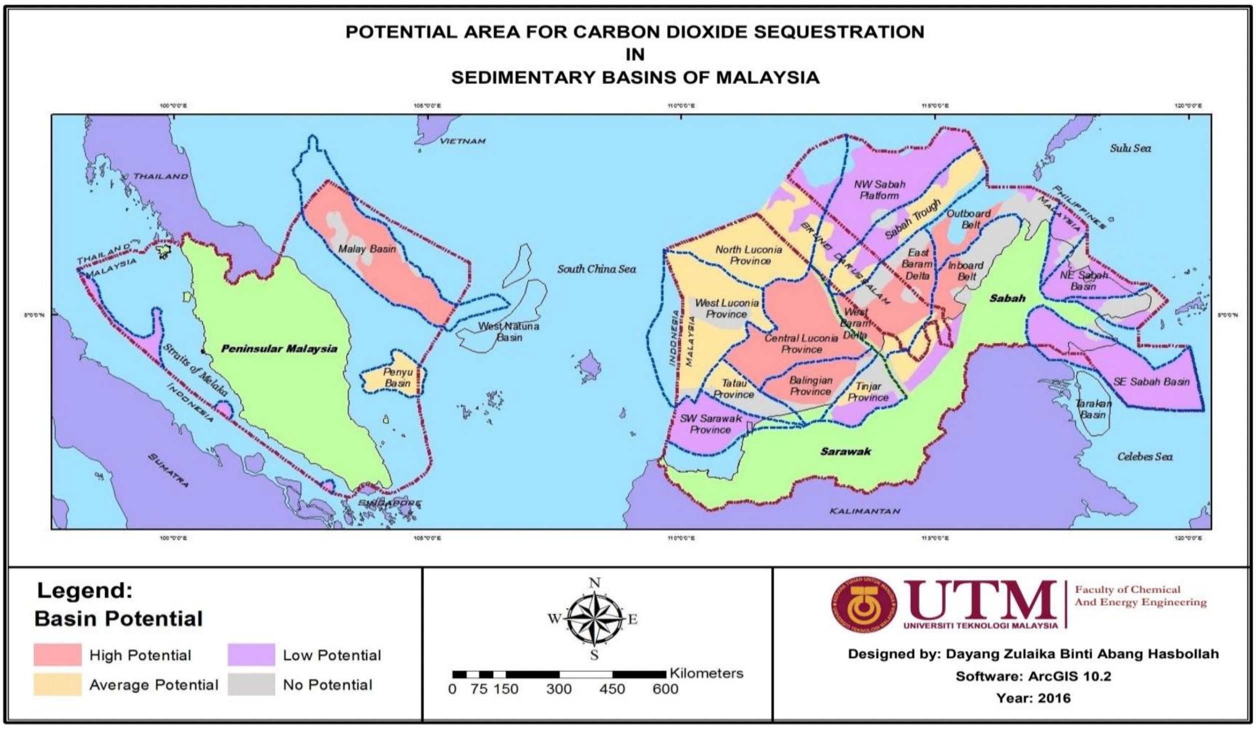


Figure 4. Location Map of Study Area in The Malay Basin, Offshore Peninsular Malaysia.

Malay Basin has the highest score because it fulfils most of the criteria of suitable basin for carbon sequestration. Detailed basin-scale assessment of Malay Basin was discussed profoundly by [8]. However, in terms of potential injection sites, the structure of Jerneh, Tangga, Dulang and Semangkok field are highly recommended to be explored for CO_2 sequestration area in the Malay Basin (Figure 5). The discussion on the suitability of geological structure for carbon sequestration in these four potential sites is focusing on the basin stratigraphy, permeability, porosity and capacity of storage system.

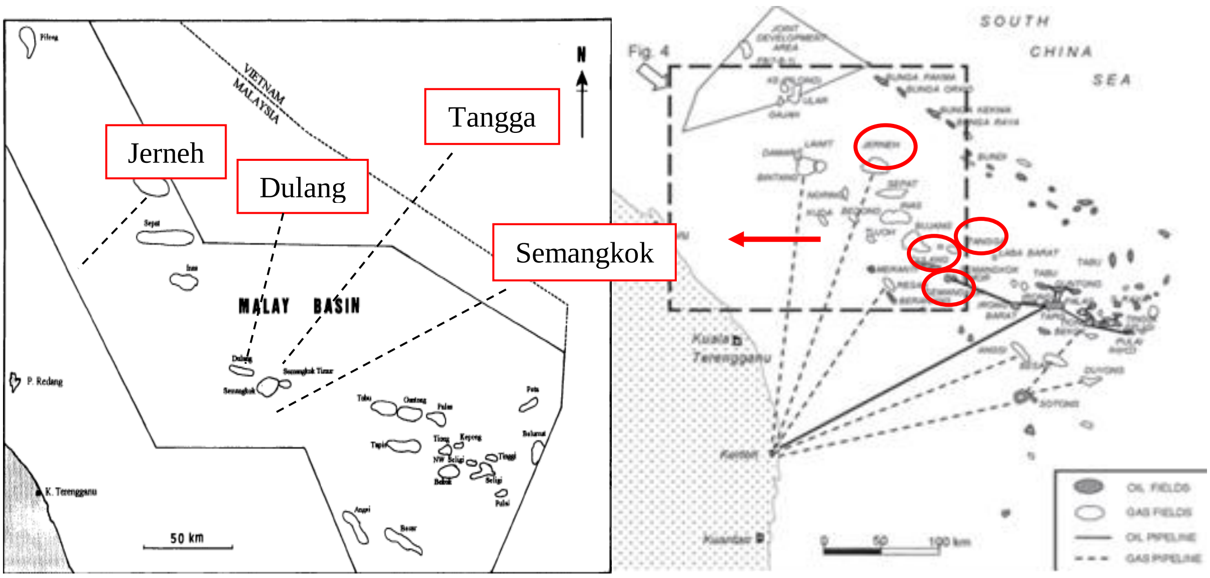


Figure 5. Location of Potential Field in the Malay Basin.

2.1 Basin Stratigraphy of Potential Injection Sites

Malay Basin comprises of numerous grabens and compressional anticlines that some of it has not been penetrated because of the great depths. Figure 6 showed the basin structure of Malay Basin which has been classified using alphabet A to M. Groups D down to K are found to be sandstone reservoirs where most of the hydrocarbons of this basin are found. The depositional environments of the sandstones vary with the stratigraphy. In older groups like K, L and M reservoirs are mainly consists of fluvial channels in a nonmarine – lacustrine setting. Meanwhile in younger groups such as J to I, the sandstones are predominantly fluvial – deltaic to estuarine channel complexes.

Sandstone reservoirs are well known to be a good medium for long-term CO_2 storage. Cleaner and coarser grained sandstones tend to have the best reservoir properties. Meanwhile, Groups D and E have been interpreted as tidal, deltaic to lower coastal plain deposits. The sandstones were interpreted as deltaic and include distributary mouthbar, shoreface and channel sediments formed during a Middle-Late Miocene regression. The classification of sedimentary rocks especially in group M show the types soil with fine particles until coarse particles, followed by shapes of subangular and subrounded form and comes from immature sandstone properties [9]. Thus, it is developed in major of feldspar formation (feldspathic arenite) and some micro-structure for examples silica, carbonate cements, authigenic kaolinite and subordinate illite can be defined by using SEM images.

Group E (Jerneh field) has the formation of fine-grained sandstone, mudstone and coal, while having a mineral for example litharenite and feldspathic litharenite cover the group E properties. According to [9] again, based on previous core data sandstones also are developed through modification of three types of rocks which are from metamorphic, igneous and combination of sedimentary rocks. Moreover, it is controlled by the syn-rift tectonics and developed by factors of certain climatic conditions and uncertainty of fluctuations in lake level. On the other hand, according to [10], there is a high potential sandstone formation in the Mesohellenic through with mineralogical shown calcite with 47% is the highest mineral recorded. Table 2 below show a property of mineral from previous study recorded by [10] which is determined using XRD analysis.

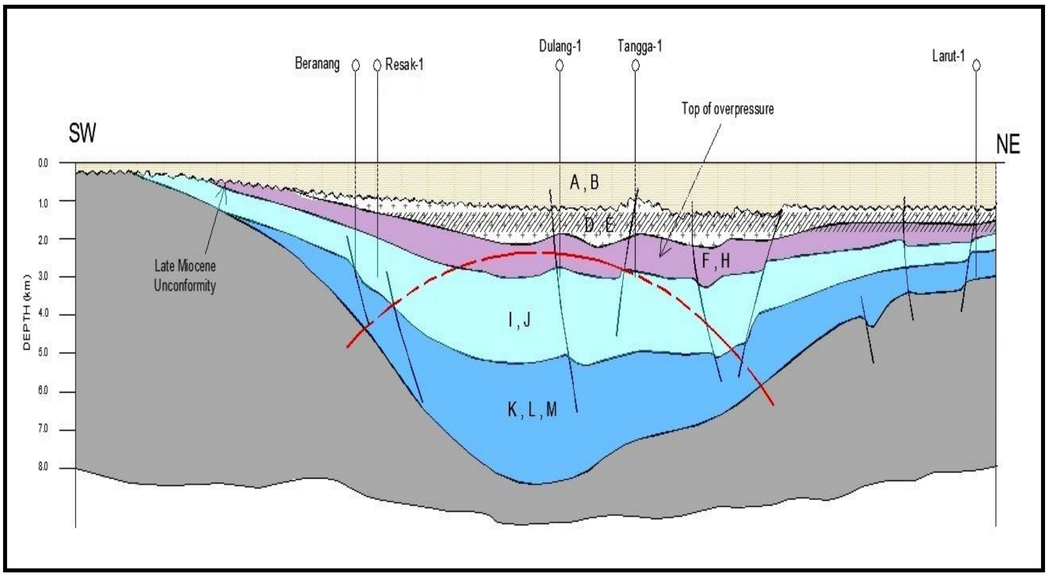


Figure 6. Basin Stratigraphy of Malay Basin.

Table 2. Mineral Properties of Group E in Malay Basin.

Mineral	Percentage
Calcite	47%
Quartz	16%
Feldspar	14% (12% plagioclace, 2% K-feldspar)
Clay minerals	8%
Mica	7%
Clorite	5%
Dolomite	3%

3. Injection Technology Development for Carbon Sequestration

The development of industry related to CO_2 sequestration has been updated by Global CCS Institute. According to [11], there are two types of facilities of CO_2 storage capacity. The large scale includes a facility related to the industrial sources and power generation consists a capacity of 400 and 800 ktpa. Besides, industrial and power generation sources which is not similar with large scale threshold are some of pilot and demonstration facilities criteria. Some examples of commercial CCS facilities for natural gas processing such as Terrell, Sleipner, Shute Creek, Core Energy, Snohvit, Century Plant, Lost Cabin, Petrobras Santos, Uthmaniyah, Cnpc Jilin, Gorgon, Qatar LNG CCS, Santos Cooper Basin and Abu Dhabi CCS 2.

According to Figure 7, the development of pipeline has shown a decreased especially in total capacity in year 2011 to 2017 due to global financial crisis change the scenario when they turn to focus in short term uses by two sectors of private and public. However, there are increasing in year 2018 onwards derived to achieve reduction on emissions especially related to greenhouse gas (GHG) in development countries/ cities. However, to overcome the financial issue because of high cost CCSU projects, Clean Energy Ministerial (CEM) at Abu Dhabi in April, 2011 conclude the cooperation within stakeholders to fund and develop CCSU operations by relationship with World Bank, Asian Development Bank (ADB) and World Resources Institute [2],[12]. CEM in London in 2012 also raised a fund worth US$100 million for development of CCSU in developing countries. Malaysia as a signatory of Kyoto Protocol and member of non-annexure I obligate to control carbon emissions by introduced National Policy on Climate Change in 2010. According to [13], here are some recommended from CCSU exploration and implementation:

- CCSU has the potential to reduce emissions in power, oil, gas and other industrial sectors
- The cost of electricity produced by fossil fuel plants with CCSU is equal to other low-emission power generating sources, example solar and wind
- CCSU encourage Malaysia to achieve low emission of 2005 by 2020 (approximately 40% reduction in 2020)

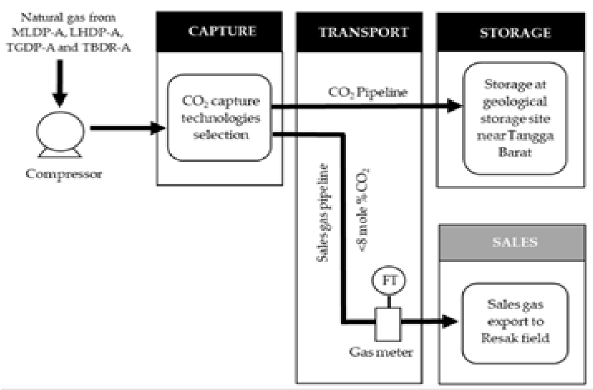


Figure 7. Concept of Tangga Barat gas field operated by Petronas Carigali Sdn Bhd (PCSB)

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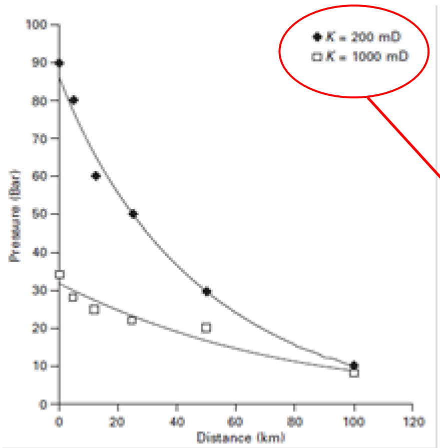
4. Parameter for CO_2 Injectivity Control

According to [14], if there any changes in injectivity system will affected the loss of reservoir/ caprock or may happen an overburden integrity. The effect from CO_2 injectivity to the saline aquifer are may fracturing the sandstone formations, it will definitely increase a local permeability and also enhance the injectivity. On the other hand, there are some factors affected the injectivity system to be study which is formation permeability, injectivity loss, wellbore design and injection well pressure. From the previous study [15], there was a problem at the beginning stage where it goes peak rate in the pressure from CO_2 injectivity. Then, the other way to resolve this issue is by adding of Monoethyleneglycol (MEG) which is good in high pressure and low temperature to reduce the hydration especially in the low temperature at the injection well [3].

4.1 Formation Permeability

Permeability of a rock/ sandstone formation in the Malay Basin show that how the rock will permit the passage of fluids. The formation of permeability affected on porosity and those relationship summarize that when it is become higher porosity simultaneously increase to the higher permeability (shown in Figure 8). Moreover, the connectivity between pore spaces is contribute by size and shape of grains, the grain size distribution and operation of capillary forces in the sandstone properties. According to [16],[17],[18], the main controlling parameter for CO_2 injection is from formation permeability. The higher permeability is suitable near to wellbore due to enhance an injectivity while to maximize the rate of residual trapping, dissolution and mineral trapping by having a lower permeability far from wellbore radius [3].



Permeability Value (mD)	*Classification*
<10	Fair
10 - 100	High
100 - 1000	Very High
>1000	Exceptional

Figure 8. Pore Variations vs Formation Permeability on CO_2 Injectivity Data from Generic Reservoir Simulations in Saline Aquifer [4].

4.2 Injectivity Loss

There are factors contribute to the loss of injectivity by process in the CO_2 reaction are comes from precipitation of halite reaction, the particles movement, incorporate and sweep along in its flow (fine particles) also reactions of chemical. According to [19], the evaporation effect happens when dry supercritical CO_2 has been injected and incorporate (similar time) at the accumulated of brine location. The effect will be continued to the reaction of dry formation waters to ensure the halite precipitation are happened. This is similar to [20], which is mentioned how the supercritical of CO2 also dissolves amount of water inside the storage of natural gas affected the injection rates. In addition, the particles will be spread and move (change in location) inside the pore throats with narrow condition due to the particle's movement [21].

Unfortunately, the mobilized will decrease a local permeability, other than that will completely plugging the rock formation. The loss injectivity by geochemical reaction products and effects happen when CO_2 injected react (dissolution) with certain reservoir matrix minerals. The effects from that, there were increase porosity and permeability in the initial stage after CO_2 saturated brine. Nevertheless, it will sediment downstream after there are not settle in a reaction product and potentially to have a plug pore throat. However, it is important to understand the minor effect of loss injectivity which comes from impurities in the injection stream. The impurities of gases inside the CO_2 injection will be affected the storage of CO_2 and give the consequences to the geochemical reactions especially for the purpose of plugging inside pore throats reservoir. The consequences of loss injectivity due to the impurities of gases depend on impurities category inside the injection rate and the condition of reservoir minerology (reactive nature).

However, the Malay Basin is showing the highest potential of CO_2 storage while having a good formation of caprock, will reduce any leaking (loss) of CO_2 injection. According to [8], Malaysia's sandstone has a criterion in terms of tectonic setting which found to be a foreland, limited faulting and does not have any seismic activity. In addition, with the properties of warm basin related to geothermal regime, average porosity of 17% and shale of caprock formation, the CO_2 injection will better in store for a long period (years) without shows any loss of injectivity.

4.3 Wellbore Design

Wellbore design are important to ensure it is suitable and in good condition while storing to make sure CO_2 injectivity in saline aquifers, preserve an environment surrounding also maintain the integrity of wellbore usually from operation time until it is completed an injectivity time [22]. Normally for CO_2 wellbore design are follow to the oil and gas industry especially in drilling and construction practices. For examples in Weyburn field in Canada especially for enhanced oil recovery (EOR) and Salah Project in Algeria where is inside the 20 m thickness with low permeability has been injected with CO_2 sequestration [23]. The wellbore design is separately into three types which in vertical alignment, horizontal and inclined well alignment. It is certified that the horizontal wells much more benefit compared to the vertical wells as mention below:

- It will reduce a quantity of horizontal wells as it is using a horizontal injector to spread the CO_2 into deep saline aquifers. Refer to Figure 9.
- It will impact to the connection through permeable sections of saline aquifers as long to enhance injectivity of CO_2.
- It will decrease the pressure needed for any given volume of fluid and as a benefit to reduce the load capacity on the CO_2 compressors then subsequent energy requirements.
- The horizontal wellbore design also would reduce potential flowing adverse effect by having a high permeability zone entering and create the injection profiles layout.

According to [24], there was collaboration between Japan Oil, Gas and Metal National Corporation (JOGMEC), JX Nippon Oil and Gas Exploration and PETRONAS to use core technologies from EOR instruments including design of wellbore, pipeline and others. From there, CCUS will develop with EOR technologies to ensure an initiative for long term purpose especially an economic value through recovery, storage of CO_2 and an environmentally friendly in resource development. Therefore, from this project of high CO_2 gas fields in Helang and Layang in Sarawak will enhance the perspective of CO_2 sequestration especially in the Malay Basin.

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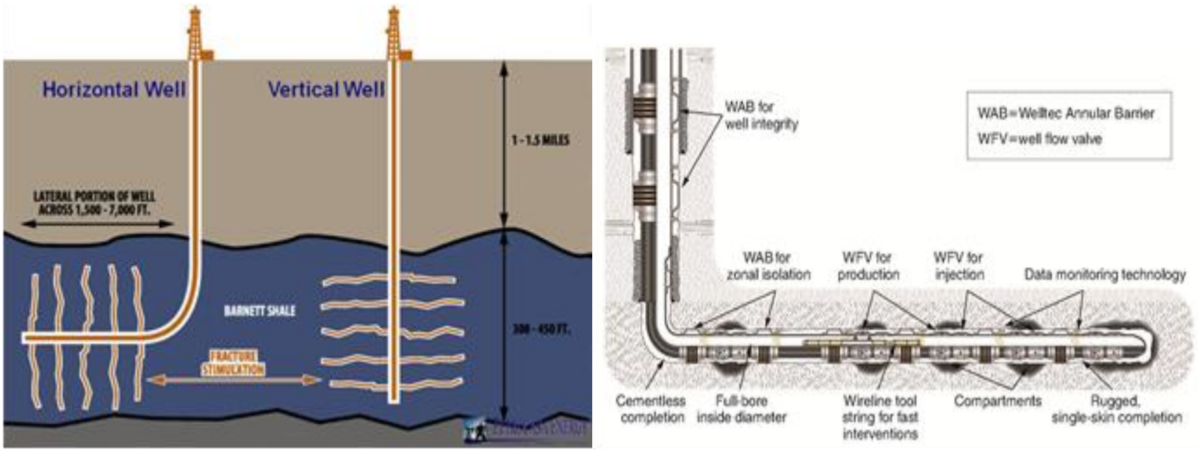

Figure 9. Illustration of Two Wellbore Design *(left*), Horizontal Injector to Distribute CO_2 into Saline Aquifer (*right*).

4.4 Factors Affecting Well Integrity

4.4.1 Seismic Events

The certain quantity of stress in reservoir itself would affect the well integrity and will cause failure with commence of micro-earthquake or induced earthquakes. For examples, there are parameters which contributed to the induced earthquake such as hydraulic fracturing, gas storage, production (reservoir compaction), low-porosity reservoirs, high injection pressures, fluids consumer, stress regimes and natural fractures and faults. According to [25], the similar of gas which is for production and injection, there are seismicity happen when a main fault has been active in the gas field located at depth 2.5 km +- 0.5 km with magnitude of 1 to 3.5 richer scale. According to [26], the latest earthquake happens in 2004, Acheh in Indonesia with 8.9M earthquake which is triggered Tsunami and Ranau, Sabah recorded 5.9M earthquake in 2015. From the previous study, it is shows that the seismic activities are considered dormant event though there are increasing in seismic activities, high frequency and intensity in and around Malaysia. Then, there was shown the fault lines from seismic activities and did not disturbing the area of the Malay Basin.

5. Issues and Challenges in Malaysia

The implementation of CO_2 in Malaysia is facing issues and challenges for example regulatory framework, costing/ expenses (capital cost, generation cost, funding, impact on tariff), capacity building, technology issues, commercial framework across value chain, availability of sequestration sites and transportation of CO_2 to sequestration site [27]. The research and development in CO_2 storage has gained less interest in researcher, non-governmental organization (NGO) and companies in Malaysia due to the limited access of data for deep exploration in the CO_2 storage implementation and also quick tough in site accessibility for their data collection.

For example, in year 2020 a joint venture between Japan Oil, Gas and Metals National Corporation (JOGMEC) with JX Nippon Oil & Gas Exploration and Petronas to explore the potential gas field in Helang and Layang fields of offshore Sarawak shown a cooperation of experienced companies with expertise to access the location by their own technologies. The government also facing a challenge to raised funds to encourage the R&D of the CO_2 storage among the stakeholders. Nevertheless, the government need to strengthening their governance system especially the level of awareness on CO_2 storage benefit to the all stakeholders, NGO, University and community. The only way to overcome this challenge is by having a specific framework on CO_2 storage implementation in Malaysia.

The study from Petronas found that there are few challenges regarding to the CO_2 development in Malaysia with every stage recorded the barrier of implemented projects. For example, there are five

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(5) stage indicated on how does Malaysia need to face the challenge or issue in future such as in field appraisal, development option, CO_2 separation, CO_2 transport and last but not least the CO_2 disposal and usage as presented in Table 3[28].

Table 3. Stage in CO_2 Challenges Implementation in Malaysia [28].

Field Appraisal	High CO2 content which is 85%
Development Option	a. Economic outlook for field development alone due to the return an investment and totally need some holistic approach b. Optimal development solution needs to balance between time to meet gas demand and most economic development option
CO_2 Separation	a. Technology not fully ready to deal with very high CO_2 content coupled with very high flow rate b. Large footprint and exotic materials lead to astronomical capital expenses
CO_2 Transport	a. High pipeline cost due to tolerance for CO_2 b. Users or disposal locations scattered and far from production area
CO_2 Disposal and Usage	a. Kyoto protocol becoming legally binding b. Massive CO_2 by products from field production c. Meeting EOR requirement

5.1 CO_2 Storage and Scenario

Joint venture among two participants from government which is Ministry of Energy, Green Technology and Water (KeTTHA) and Global CCS Institute has create a program such as Malaysian CCS Capacity Development. The aim is to guide stakeholders to prepare on the CO_2 sequestration activity in future. According to [2], it was summarised from participants in various types of expertise regarding the CCS implementation issues. The whole issues are as follows:

- Regulatory framework in Malaysia is not defined any CO_2 matters.
- The process of capture, transport and storage are not very clear in term of implementation by agency.
- CCS need some legislation to be applied for all of chain and sectors.
- There are no standards use as proper guideline especially how does CO_2 capture start until completed the injection for example the way to describe pipeline specification, proper site determining, how to select, monitor, measurement and verification.
- The safety part especially in every CCS chain need to be solve under Occupational health and safety department.
- For ensure all participants be responsible to their liability, need to create ownership system and can apply in other chain.
- The land acquisition and environment impact assessment (EIA) will be important criteria to access in the CO_2 sequestration and need coordination from public and awareness of technology.
- Relationship between cross boundaries country are serious aspects to be focus in term of regulation and management of CO_2 sequestration.

From all the major issues listed, there are some planning or further analysis to progress in next step without containing CCS policy mandate since there is no clear agency, legislation, policy and regulatory has been developed. The further planning that should be considered are describing and determining CO_2 whether it is under waste, pollutant, resource or GHG using existing regulatory framework. This is important to enhance the outcomes for the milestone in any CCS implementation. Besides, the stakeholders and agencies could play their role in the CCS chain and it is easier to handle for the capture, transport and storage activity. Besides, it would be additional value especially to the transboundary relationships while having a relevant expertise from geological field, experience with pipelines and engineering field. Other than that, a comparison in CCS legislation and regulation of framework (capture, transport and storage), without consider any factor of cost, suitability and implementation procedure should be done.

6. Conclusion

From the previous assessment, it was identified that the Malay Basin has the highest potential for CO_2 sequestration site since it fulfils the criteria from [29], which mentioned the characteristic of deep saline aquifers with formations greater than 800 m thick, caprock from shale properties layer as sealing function, good in porosity and permeability in high scale volumes and flow rates of pressure. In addition, it has been suggested that the EOR development and technologies could be adopted for CO_2 injection. Government of Malaysia and stakeholders should collaborate to develop the potential area such as the Malay Basin, establishing a master plan for offshore injection sites including pipeline systems and management of CO_2 sources.

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