EVALUATION AND CLASSIFICATION OF POTENTIAL SEDIMENTARY BASINS IN MALAYSIA FOR CARBON DIOXIDE STORAGE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Petroleum Engineering)

Faculty of Chemical and Energy Engineering
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DECEMBER 2017

For Dad…

There are so many things I want to share, so many secrets I want to bare…
Wish you were here to be proud of my accomplishments and to see the person I've become.

May your soul rest in peace pak..

Al-fatihah

IN LOVING MEMORY

ABANG HASBOLLAH BIN ABANG KIPRAWI
(1942-2008)

For my family…

Who always believes in me

ACKNOWLEDGEMENT

First and foremost, all praises are to Him the Almighty without whose guidance, I may not be able to complete this thesis. Secondly, I would like to express my heartfelt gratitude to my supervisor, Prof. Dr. Radzuan B. Junin for his guidance, encouragement and constant supervision as well as providing necessary information regarding my research. Without him, the completion of this thesis would be impossible.

I am also highly indebted to Assoc. Prof. Mohamad Nor B. Said because willing to spend his time to introduce and explain ArcGIS to me. I also would like to express my appreciation to GIS staff in G&P Sdn. Bhd for their kind guidance and assistance in my process of learning how to use ArcGIS.

Not to forget, special thanks are accorded to my family and friends for always giving me supports, ideas and attention in any situation I had faced. Honestly, these 4 years I have encountered so many challenges and obstacles but their continuous love and support somehow make my journey easier and meaningful.

Finally, I wish to express my acknowledgement to Universiti Teknologi Malaysia and Ministry of Higher Education Malaysia for their generous funding of my research by awarding GUP (Vot No: 06H82) and FRGS (Vot No: 4F562) grants.

ABSTRACT

The purpose of this study is to evaluate and classify potential sedimentary basins in Malaysia for carbon dioxide (CO_2) storage that includes screening and ranking of potential sedimentary basins based on selected criteria by using parametric normalization, mapping of potential sedimentary basins by using ArcGIS, and finally estimation of theoretical storage capacity and anticipation of potential injection zone based on the basin stratigraphy of the highest potential area for CO_2 sequestration. The screening and ranking of potential sedimentary basins was conducted quantitatively by assigning score and weight to each of the screening criteria and analyzed using Excel-based evaluation tools to rank the potential storage sites for CO_2 sequestration in Malaysia. The mapping was conducted by using ArcGIS and revealed that 27% of the study area was classified as high potential area, 23% was average potential area, 30% was low potential area, and 20% was classified as no potential area. Based on the screening and ranking results supported by mapping output, detailed assessments on the top two potential basins (i.e. Malay Basin and Central Luconia Province) were conducted qualitatively which comprised the estimation of theoretical storage capacity using methods proposed by CSLF and US-DOE-NETL. From the calculation, the estimated theoretical storage capacity for Malay Basin was approximately 114 Gt (CSLF) and 75 Gt (US-DOE-NETL) while for Central Luconia Province was approximately 84 Gt (CSLF) and 56 Gt (US-DOE-NETL). The potential injection sites for both basins were identified at the depth ranging from 1000 to 1500 m considering they are warm basins. This study can provide a basis for further work to reduce the uncertainty in these estimates and also provide support to policy makers on future planning of carbon storage projects in Malaysia.

ABSTRAK

Tujuan kajian ini adalah untuk menilai kesesuaian dan mengklasifikasikan lembangan sedimen yang berpotensi di Malaysia untuk storan karbon dioksida (CO_2) yang merangkumi proses saringan dan penentuan kedudukan lembangan sedimen yang berpotensi berdasarkan kriteria yang dipilih menggunakan kaedah taburan normalisasi parametrik, pemetaan lembangan sedimen yang berpotensi menggunakan perisian ArcGIS, dan akhir sekali penganggaran muatan teori storan serta pengenalpastian zon suntikan yang berpotensi berdasarkan stratigrafi lembangan yang paling berpotensi untuk sekuestrasi CO_2. Proses saringan dan penentuan kedudukan lembangan sedimen yang berpotensi dilaksanakan secara kuantitatif dengan memberi skor dan pemberat kepada setiap kriteria saringan dan dianalisis menggunakan perisian Excel bagi mengatur kedudukan tapak storan yang berpotensi untuk sekuestrasi CO_2 di Malaysia. Proses pemetaan yang dilaksanakan menggunakan ArcGIS menunjukkan bahawa 27% daripada kawasan kajian telah diklasifikasikan sebagai kawasan yang berpotensi tinggi, 23% ialah kawasan yang berpotensi sederhana, 30% ialah kawasan yang berpotensi rendah, dan baki 20% sebagai kawasan yang tiada potensi. Berdasarkan keputusan saringan dan penentuan kedudukan yang disokong hasil pemetaan, penilaian secara terperinci terhadap dua buah lembangan yang berpotensi (iaitu *Malay Basin* dan *Central Luconia Province*) telah dilaksanakan secara kualitatif yang mencakupi penganggaran muatan teori storan menerusi penggunaan kaedah yang dicadangkan oleh CSLF dan US-DOE-NETL. Muatan teori storan bagi *Malay Basin* dianggarkan bernilai 114 Gt (CSLF) dan 75 Gt (US-DOE-NETL) manakala bagi *Central Luconia Province* pula ialah 84 Gt (CSLF) dan 56 Gt (US-DOE-NETL). Zon penyuntikan yang berpotensi untuk kedua-dua lembangan telah dikenalpasti, iaitu dari kedalaman 1000 m hingga ke 1500 m dengan menganggap lembangan adalah suhu panas. Kajian ini menyediakan asas untuk kajian lanjut bagi mengurangkan ketidakpastian dalam penganggaran terbabit dan juga sebagai rujukan bagi penggubal dasar dalam merancang masa depan projek storan karbon di Malaysia.

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LIST OF ABBREVIATIONS

CAD	-	Computer Aided Design
CH_4	-	Methane
CO_2	-	Carbon Dioxide
CO2CRC	-	Carbon Dioxide Cooperative Research Centre
CSLF	-	Carbon Sequestration Leadership Forum
DBMS	-	Database Management System
EEA	-	European Energy Agency
EIA	-	Energy Information Administration
EOR	-	Enhanced Oil Recovery
ESRI	-	Environmental Systems Research Institute
GHG	-	Greenhouse gas
GIS	-	Geographical Information System
Gt	-	Giga tons
H_2S	-	Hydrogen sulphide
IEO	-	International Energy Outlook
INDC	-	Intended Nationally Determined Contributions
IPCC	-	Intergovernmental Panel on Climate Change
JMG	-	Jabatan Mineral dan Geosains
km	-	Kilo meter
kW	-	Kilo Watt
LNG	-	Liquefied Natural Gas
Ma	-	Magnitude
MCO_{2t}	-	Geometric volume of the structural trap down to the spill point
GCO_2	-	Geologic storage of CO_2 in saline aquifer
Bt	-	Billion tons

N_2O	-	Nitrus oxide
NE	-	Northeast
ppmv	-	Parts per million by volume
STP	-	Standard Temperature and Pressure
tcf	-	Trillion per cubic feet
TW	-	Tera Watt
UNFCCC	-	United Nations Framework Convention on Climate Change
USDOE	-	United States Department of Energy
USGS	-	United States of Geological Survey
INC	-	Initial National Communication
NC2	-	Secondary National Communication
NETL	-	National Energy Technology Laboratory
OECD	-	Organization for Economic Cooperation and Development
DNV	-	Det Norske Veritas
GETSCO	-	Geological Storage of CO_2 from Combustion of Fossil Fuel
RCSP	-	Regional Carbon Sequestration Partnership
PCS	-	Project Coordinate System
WHF	-	Western Hinge Fault

LIST OF SYMBOLS

A	-	Area
A_t	-	Total geographical area of the basin
E_{saline}	-	CO_2 storage efficiency of saline formation
h	-	Thickness
h_g	-	Gross thickness of saline formation
m^3	-	Meter cubic
S_{wirr}	-	Irreducible water saturation
ρ	-	Density of CO_2 within the reservoir
ϕ	-	Porosity
ϕ_{tot}	-	Total porosity in volume defined by the net thickness
Ca^{2+}	-	Calsium cation
Fe^{2+}	-	Ferrous cation
Mg^{2+}	-	Magnesium cation

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CHAPTER 1

INTRODUCTION

1.1 Background of study

The alarming increase in concentration of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere has recently become one of the most-discussed issues in relation with the world's concern on climate change. Based on the data compiled by U.S Energy Information Administration (EIA), global energy-related CO_2 emission is projected to increase by one-third between 2012 and 2040 from 32.3 billion metric tons in 2012 to 35.6 billion metric tons in 2020 and to 43.2 billion metric tons in 2040 (IEO, 2016). The increase is most likely contributed by countries outside of the Organization for Economic Cooperation and Development (non-OECD) such as China and India.

Malaysia is a developing country and currently undergoing a transformation to become a high income economy with sustainable development in mind. The high use of fossil fuels is foreseen to increase rapidly in the future in line with the transition and transformation. The Malaysian economy, as well as the economies of neighbouring countries, is highly dependent on industry and agriculture, which partly contributes to the increase of CO_2 emission in atmosphere. With the development pace experienced by Malaysia and other Southeast Asian countries in recent decades, it was predicted that without any mitigation measures being taken up resulting in fast increase of CO_2 emissions will bring challenge of reducing unwanted greenhouse gas emissions in Malaysia.

Malaysia is also well known as one of the main oil-producing countries in the world. Malaysia produced about 697,000 barrels of oil per day in 2014, most of which was extracted from offshore fields (Carpenter, 2015). Malaysia also holds proven oil reserves of 4 billion barrels as of January 2014 and according to EIA database, up to January 2016, the production of crude oil has decreased to 688,000 barrels of oil per day (EIA, 2016).

Malaysia is also well known as one of the top natural gas producer and exporter country. Up to now, Petronas has identified 15 offshore gas fields that have high content of CO_2 that contain 13.2 trillion cubic feet (tcf) of natural gas for 27.32 tcf of CO_2 (Jalil *et al*., 2012). The development of these fields for example K5 carbonate reservoir located in Sarawak which contains approximately 70% of CO_2 require the finest way to manage this natural CO_2 to prevent unnecessary emission into the atmosphere. Jalil *et al.*, (2012) suggested there is a possibility to inject and sequester natural CO_2 into depleted gas field nearby (M4 field). Due to the immense exploration of oil and gas in this country, CO_2 emission as a result of petroleum production has been identified as one of the contributors to the emission of CO_2 in Malaysia.

Up to 2016, 263.8 million tonnes of CO_2 has been emitted to Malaysian atmosphere (BP, 2017). The increase of CO_2 emission rate in Malaysian atmosphere is anticipated to continue well in the future if there are no mitigation taken to manage CO_2 emission in Malaysia. For this distressing reason, Malaysia has taken a few iniatiatives to deal with this problem and one of it is by making a pledge to cut down carbon intensity by 45% by 2030 (Goh, 2015).

Under this pressure, local researchers and academicians have come out with various suggestions on how to manage with CO_2 emission in Malaysia. For instance, Amran *et al*. (2013) suggested to take carbon trading into consideration and some of them also suggested terrestrial ecosystem and ocean disposal. As for this research, it suggests another possible way to deal with CO_2 emission in Malaysia which is by way of geological carbon storage in deep saline aquifer. The term ‘carbon storage’ is used to describe the containment of CO_2 in the ocean, terrestrial environments and

geologic formations like deep saline aquifer after CO_2 is removed from the atmosphere or diverted from emission sources (USGS, 2008). Meanwhile, the removal process of CO_2 directly from anthropogenic or natural sources and its disposal in geological media, either permanently (sequestration) or for significant time periods (storage) is called 'carbon sequestration'.

The geological storage of CO_2 currently represents the best short- to medium-term option for significantly enhancing CO_2 sinks, thus reducing net carbon emissions into the atmosphere (Bachu *et al.*, 2004). Bachu (2000) also suggested that CO_2 geological storage has a significant potential for hydrocarbon rich region ergo in this case would be Malaysia. Taking into account the expected increase of energy demand for sustainable development in this country, the potential for CO_2 geological storage in deep saline aquifer should be investigated as a potential way of reducing CO_2 emission in Malaysia.

To the best of our knowledge, there have been no comprehensive studies of the CO_2 geologic storage in deep saline aquifer of Malaysia. Since Malaysia is well known as petroleum bearing country, CO_2 are constantly generated during the process of oil production including finding, extracting and processing hydrocarbon resources. Fortunately, Malaysia possesses very unique geological formations such as enormous unoccupied sedimentary basins that are more extensive than oil and gas fields and coal seams that lie underneath of our country. The DOE defines saline aquifer as layers of porous rock that are saturated with brine (US-DOE-NETL, 2012). To make use of these unoccupied sedimentary basins, the suitability of Malaysian basin has to be assessed in order to investigate the potential of CO_2 geological storage deployment in Malaysia. Identifying the most attractive site for CO_2 geologic storage based on consistently applied criteria is necessary for early stage deployment of CO_2 storage project.

There are 14 identified sedimentary basins in Malaysia. Malay Basin alone covers an area of about 80000 km^2 and filled with 14 km or more sediments (Madon, 2007). This shows that sedimentary basins in Malaysia potentially can be an enormous geological storage for CO_2. However, not all sedimentary basins are

suitable for CO_2 storage. The suitability of sedimentary basins of Malaysia has to be assessed strictly based on the merits of certain criteria that will be discussed later without regard to the proximity of CO_2. The evaluation criteria are selected based on the compilation of literature review and expert advice. This is a crucial step in this research as the evaluation criteria will determine the accuracy and reliability of the evaluation results.

Having the concept in mind, the sedimentary basins in Malaysia has to be screened and ranked in preliminary evaluation to narrow the potential sites candidates. Based on previous study, the screening and ranking can be done by using normalized parametric equation. This normalization procedure transformed the characteristics of each basin into quantitative data that vary between 0 and 1. The score for each basin can be normalized using the approach of Bachu (2003b). Subsequently, the basin ranking can simply be done by using the normalized score for each basin multiply with weights that express the relative importance of each criterion to produce a general ranking score, R. After the basin screening and ranking, the potential sites for CO_2 geological storage are identified and mapped by using ArcGIS software. Geographical Information Systems (GIS) are used to perform a number of fundamental spatial analysis operations such as topological map overlay. When the potential sites had been identified, the storage capacity of the aquifers is estimated. There are various ways to do estimation. The most common one is the CSLF approach suggested by Bachu *et al.* (2007). The next one is method by Goodman *et al.* (US-DOE-NETL, 2010; 2012). In this research, theoretical estimation is being done due to limited data available.

A large number of studies have shown that CO_2 geological storage technology will play an important role in reducing CO_2 emissions in this century. The EIA (2006) studies indicated that, in the global power industries and industrial fields, the reduced emissions of CO_2 by CO_2 geological storage in deep saline aquifer will take 10% in total global energy-related emission reduction till 2030 and by the year of 2050 the contribution of CO_2 geological storage to the emission reduction will reach 19% in total global energy-related emission reduction. Some of the successful commercial projects of CO_2 storage in deep saline aquifer are located in Alberta,

Canada and Sleipner, Norway. With such a huge potential of reducing emissions, CO_2 geological storage in deep saline aquifer is believed to be one of the most important emission reduction technologies.

1.2 Problem Statement

In recent years throughout the world including Malaysia, there has been alarming concern about the rate of CO_2 emission in the atmosphere. Global energy-related CO_2 emission is projected to increase by one-third between 2012 and 2040 from 32.3 billion metric tons in 2012 to 35.6 billion metric tons in 2020 and to 43.2 billion metric tons in 2040 (IEO, 2016). Statistics shows that the emissions rate of anthropogenic CO_2 in Malaysia is anticipated to increase in the future as the high use of fossil fuels in Malaysia foreseen to continue well too. Up to 2016, 263.8 million tonnes of CO_2 has been emitted to Malaysian atmosphere (BP, 2017). There is an urgency to resolve the increasing of CO_2 emission rate in the atmosphere of Malaysia for the CO_2 emissions rate in Malaysia for the past few years which does not seem to lessening anytime soon.

As a major role of greenhouse gases (GHG), anthropogenic CO_2 that is generated from human beings activities such as the burning of fossil fuels contribute globally to the most to anthropogenic effects on climate change which can have serious consequences for human beings and environment. The burning of fossil fuels such as coal, natural gas and oil, solid waste release CO_2 and other GHG therefore can raise global temperature. Carbon dioxide persists in the atmosphere for 50 to 200 years, so emissions released now will continue to warm the climate in the future if there is no mitigation being taken. The increasing of CO_2 in the atmosphere might as well will result in the shrinking of water supplies as climate change is expected to increase rainfall in some area, thereby causing an increase in the sediment and pollutants washed into drinking water supplies. Besides, global warming which has been caused by the increase of CO_2 concentration in the atmosphere has the potential to result in increasing incidents of severe weather such

as wildfires, droughts and tropical storm. All of these can happen in Malaysia if there are no mitigation taken to manage CO_2 emission in Malaysia.

Carbon dioxide storage in deep saline aquifer has been identified by previous studies as one of the best potential options for large volume geological storage of CO_2 (Bachu, 2000; Bradshaw *et al*., 2002). Furthermore, according to Gibson-Poole *et al.* (2008), CO_2 can be effectively stored in deep saline formations because of its high density and high solubility in formation water at the relatively high formation pressures encountered. Hence this research embarks to evaluate the suitability of potential sedimentary basins in Malaysia for CO_2 storage by classifying the potential basins, identifying potential injection zone and estimating basin storage capacity for CO_2 storage.

1.3 Objectives of the Study

The main purpose of this research is to evaluate and classify the potential sites for CO_2 storage in sedimentary basins of Malaysia. Since the rate of CO_2 emission in Malaysia is increasing rapidly, such evaluation is essential to be conducted as an initiative to prevent excessive CO_2 intensity in the atmosphere from happening and to prepare in case this scenario happens in Malaysia in the future. The feasibility of this project to be carried out in Malaysia has to be considered so the budget for the project can be allocated and will give some time for public to accept the idea. The main objectives can further be divided as the followings:

i. To screen and rank sedimentary basins of Malaysia in terms of their suitability for CO_2 storage based on selected criteria that suits the geology setting of Malaysia.

ii. To produce a visual interpretation of potential sedimentary basins in Malaysia to estimate the area (in percentage) of the potential sites for CO_2 storage.

iii. To categorize the potential sites for CO_2 storage in sedimentary basins of Malaysia.

iv. To anticipate the potential injection zone and to estimate theoretical storage capacity in the most potential basins for CO_2 storage in Malaysia based on basin properties.

1.4 Scope of Research

This research concentrated on the assessment of 14 major sedimentary basins in Malaysia both onshore and offshore where potential geological formations in which CO_2 could be stored exist below 800 m and where suitable sealing formations are present. The study area was chosen because there is no comprehensive study on CO_2 storage in deep saline aquifer of Malaysia up until now. The study area was also chosen because there were available data regarding these area provided by oil and gas company and Mineral and Geosciences Department Malaysia.

Data for screening and ranking such as depth of the basin, tectonic setting, geothermal conditions, basin stratigraphy, and basin properties were collected from PETRONAS and other relevant literature reviews mostly in hardcopy form. For each basin, data was collected and interpreted and assessed according to its geological characteristics and available data. The data available for each basin were highly variable in coverage, type, quality and source. Meanwhile data for potential sites mapping were collected mostly from Mineral and Geoscience Department Malaysia as well as PETRONAS such as fault map, seismic map and basin maturity map. Those maps were converted into digital data by digitizing the hardcopy map and converted into spatial data by using ArcGIS 10.2 software.

The whole process of the research includes extensive data gathering from a variety of public and private sources for basin screening and ranking to narrow down the potential sites by modifying screening criteria proposed by Bachu (2003b). The

screening criteria were modified to suit geology setting of Malaysia. Next, the potential sites were mapped by using ArcGIS 10.2 software and area of potential sites was estimated according to potential class. The coordinate system that used in the mapping was world coordinate system WGS 1984. Afterward, detailed basin assessment for the most potential basins was conducted to locate potential injection zone and theoretical storage capacity of the potential sites were estimated by using CSLF and US-DOE-NETL methods.

However, this research was not including and discussing CO_2 trapping mechanism in sedimentary basin, the chemical reaction of CO_2 and brine, the brine management and the flow formation of CO_2 in the aquifer. It was also not discussing in detail on how CO_2 is generated and captured.

1.5 Significance of Research

The main contribution of this research is to evaluate the potential sites for long-term CO_2 storage in sedimentary basins of Malaysia as an initiative to reduce the intensity of CO_2 in the atmosphere of Malaysia and to the best of our knowledge, there have been no comprehensive studies of the CO_2 geologic storage in deep saline aquifer of Malaysia. This research also aims to modify evaluation criteria by Bachu (2003b) to suit the geological setting of Malaysia for basin screening and ranking. The methodology that this research implores is possibility of combining screening and ranking with GIS mapping to locate potential injection zone and to combine basin-scale detailed assessment and storage capacity estimation.

In terms of economic perspective, this research is considered as a good investment as the market of geological CO_2 storage in Malaysia is huge. The findings of this research are valuable for oil and gas industries as it suggests an alternative to manage CO_2 as a result of petroleum production. Mapping of potential sites for CO_2 storage in Malaysia mapped by using ArcGIS is very accommodating to locate the injection zone. Consequently, early budgeting can be done and the

project efficiency will increase. The outcome of this research will be useful as a cornerstone for future researchers to study on CO_2 geological storage in Malaysia. Politically speaking, the outcome of this research serves as a good point of reference for policy makers and legislators to emulate legislations relating to CO_2 emission in Malaysia.

In addition, this research provides preliminary insights into basin-scale site suitability evaluation and screening for early deployment of geological carbon storage technology in Malaysia. This research is conducted to consider CO_2 geological storage as an alternative way to reduce CO_2 emission by making use of the unoccupied basins in Malaysia.

1.6 Structure of thesis

The thesis is structured as follows:

Chapter 1 introduces the background of the research and the specific problem being addressed, the objectives of the research, delineates the scope and the significance of the study.

Chapter 2 gives more explanation about the fundamental of CO_2 storage in deep saline formation as well as the definition of CO_2 geological sequestration and storage. This chapter also includes the discussion about previous research and projects on CO_2 geological storage in other countries.

Chapter 3 discusses thoroughly the phases of methodology that have been applied in this study. These include the workflow for preliminary screening and ranking of sedimentary basins in Malaysia, mapping of potential sites for CO_2 storage and detailed basin-scale evaluation as well as storage capacity estimation.

Chapter 4 discusses the results of the preliminary screening and ranking of major sedimentary basins in Malaysia based on certain criteria and suitable for CO_2 storage.

Chapter 5 presents the mapping of potential sites in sedimentary basins of Malaysia for CO_2 storage. This chapter also includes the area of potential sites in percentage according to its potential class.

Chapter 6 discusses on basin-scale detailed assessment for the most potential basins that provides the location of potential injection zone as well as theoretical storage capacity estimation.

Chapter 7 presents the conclusions drawn from the research, which summarizes the findings in terms of the research question and the result obtained. It also highlights several issues and recommendation to be discussed further in future research.

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