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A Review on the Basin-Scale Evaluation Framework of Potential Sedimentary Basins for Carbon Dioxide Sequestration

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***Abstract:* -** Carbon dioxide (CO_2) emission in the atmosphere has become one of the most discussed topic recently. With the increasing amounts of carbon dioxide in the atmosphere over the decades, a proper mitigation alternative should be taken to resolve this problem and at present, injection into underground geological formation is the most promising and developed method although these formations naturally need to be characterized and screened to ensure long-term sequestration. A proper framework should be established to plan the workflow in evaluating the potential storage sites suitability for CO_2 sequestration in sedimentary basins before commencing large-scale deployment of CO_2 sequestration and also to aid the selection of promising CO_2 storage sites with characteristics suitable for long term storage. This is to prevent work redundancy, to keep the idea organized and to keep track of the project progress. Indirectly, with a proper planning, it will increase the work efficiency and save project costs. This review paper discusses and compares the basin scale evaluation frameworks used by Australia, Norway, Netherlands, China and Malaysia for the evaluation of potential sites to sequester CO_2. Some of the countries have been successfully implemented the geological CO_2 storage project and some of them are still in preliminary evaluation phase.

Keywords: *-carbon dioxide capture and storage, carbon dioxide sequestration, geological storage, sedimentary basin, evaluation framework, greenhouse effects*

I. INTRODUCTION

Worldwide interest in carbon emission reduction in atmosphere has increased at an exponential rate in recent years. Increasing concentrations of carbon dioxide (CO_2) and other greenhouse gases, could lead to significant climate warming and weather changes with serious consequences for everyone on earth [1]. According to projections of energy use worldwide, global CO_2 emissions are expected to increase by 55% between 2004 and 2030 or 1.7% per year [2].

The real challenge in mitigating the climate change effects is the reduction of CO_2 emissions to the atmosphere [3]. CO_2 geological sequestration is one approach that could play an important role in these efforts [4]. Potential approaches include increasing plant efficiency, employing fuel balancing or fuel switching, making enhanced use of renewable energy and employing CO_2 carbon capture and sequestration [5]. At present, injection into underground geological formation is the most promising and developed method although these formations naturally need to be characterized and screened to ensure long-term sequestration [6].

However, a proper framework should be established to plan the workflow for preliminarily evaluating the potential storage sites suitability for CO_2 sequestration in sedimentary basins before commencing the of carbon capture and storage project. Before large-scale deployment of CO_2 sequestration can commence, a framework is needed to aid the selection of promising CO_2 storage sites with characteristics suitable for long term storage [7]. This is to prevent work redundancy, to keep the idea organized and to keep track of the progress. Indirectly, with a proper planning, it will increase the work efficiency and save project costs.

Many methodologies and frameworks are being used previously for site suitability evaluation and site selection in many countries for example site selection guideline by Bachu [8], multi-criteria analysis by Ramirez et al. [9] and others.

II. GEOLOGICAL CARBON DIOXIDE STORAGE

Bachu (2004) [10] has defined geological sequestration and storage as the removal of CO_2 directly from anthropogenic sources (capture) and its disposal in geological media, either permanently (sequestration) or for significant time periods (storage). The geological storage and/or sequestration of CO_2 currently represent the best short- to medium-term option for significantly enhancing CO_2 sinks, thus reducing net carbon emissions into the atmosphere.

In contrast, Bouzalakos and Valer defined geological storage as a combination of engineering processes to ensure safe and long term isolation of CO_2 from the atmosphere and they agree that deep saline aquifers are likely to be the most promising of other geological options, but there is still uncertainty regarding their capacity and geological / geochemical properties [11]. Geological storage CO_2 captured from large stationary industrial sources comprises injecting it into porous rocks deep in the Earth's crust so as to isolate this gas from the atmosphere. It is the only technology that has the potential, on human timescales, to permanently avoid CO_2 accumulations in the atmosphere from fossil fuel at significant scale [12]. As for Dahowski, geological carbon storage happens when the CO_2 is compressed and transported to a suitable injection site where it is injected in deep into underground formations that provide secure, long term storage of the CO_2 [13].

It can be implied that, geological storage of CO_2 is a technologically feasible mitigation measure to reduce the emissions of anthropogenic co2 into the atmosphere by sequestrating it into geological media that possesses right geological condition for CO_2storage to provide safe long term storage. Geological storage of CO_2 is considered to be the most practical option at present for preventing atmospheric emissions from large industrial sources. The potential for storage of CO_2 is huge and many CO_2 storage projects are planned or underway. Therefore, sequestration of CO_2 in oil and gas reservoirs and deep saline aquifers is potentially a viable option to mitigate global warming.

2.1 Evaluation framework for basin-scale assessment in Australia

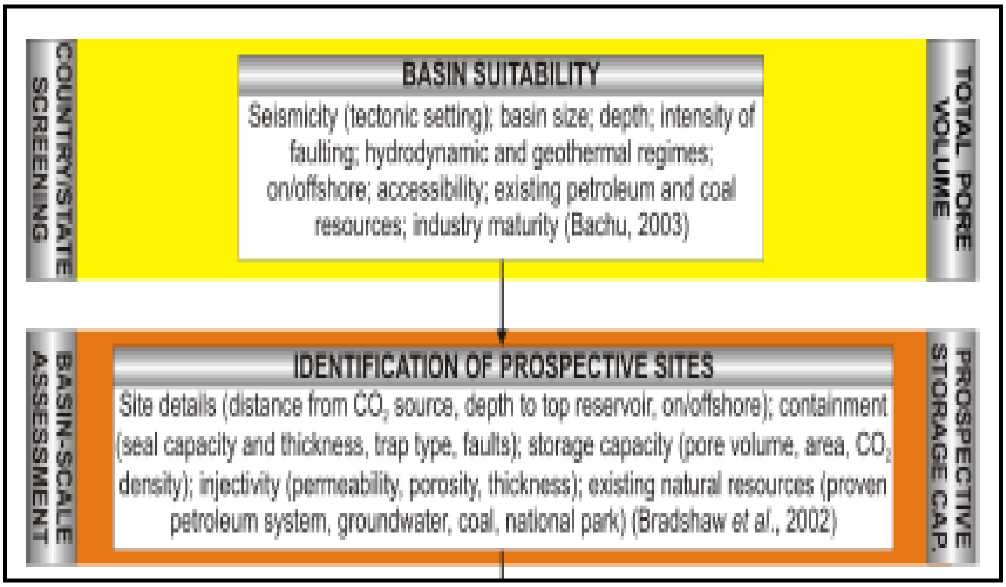

Figure 1: Site characterisation workflow for geological storage of CO_2 in Australia

CO2CRC has published a comprehensive guideline and framework for every level of site evaluation. The level of site evaluation is very important for assessing site suitability. The evaluations range from an initial regional screening to very detailed site-specific characterization. It is important to note that with increasing level of detail in the data and evaluation methods reduces the uncertainties in the final conclusions and also increases the amount of efforts required to compile and analyze the data. However, this paper is reviewing and discussing the framework from initial stage until basin-scale assessment only.

The framework started with the country-scale screening which represents the coarsest scale of assessment with the least site-specific detail [14]. It focuses on large geographical area and evaluates overall suitability of sedimentary basins for CO_2 storage. The methodology for this level of evaluation is consists of identifying sedimentary basins, reviewing characteristics of sedimentary basins and qualitatively or quantitatively rank sedimentary basins in order of suitability. The reviewing of characteristics stage, screening criteria modified from Bachu [8] has been selected to access the suitability of sedimentary basins for geological storage. By compiling data on the criteria selected, different basins are compared and contrasted and ranked for their suitability to be potential CO_2 storage. The ranking is done either by using quantitatively or semi quantitatively as per Gibson-Poole et al. [14] or quantitatively as per Bachu [8] where scores and weights were given to each criterion. This methodology can be done to any geological sites either saline aquifer, depleted oil and gas fields or coal seams but as long as the analysis are done separately.

Meanwhile in basin-scale assessment, the results from country-scale is analysed in detail to locate possible injection and storage sites. Potential sites then also are scored and ranked in order to identify the highest prospect sites to store CO_2 geologically. Those sites that have the highest prospect of becoming a successful CO_2 storage sites, will warrant a further detailed site characterisation in the next level of evaluation. There are three basic steps to identify possible CO_2 injection site and storage sites that include reviewing basin stratigraphy of entire sedimentary basin fill to identify suitable rock combinations that may provide reservoir-seal pairs, determining the reservoir-seal pair and assessing CO_2 migration pathways and possible trap. Once the prospective site have been identified, relative merits of one potential site over another are compared and contrasted by using ranking utilizing scheme, GEODISC program where data are compiled for each potential storage site to assess five key factors fundamental that include storage capacity, injectivity potential, site logistics, containment and existing natural resources. Once potential storage sites have been identified and ranked during basin-scale evaluation, a prospective site has to be further evaluated through site characterization.

2.2 Evaluation framework for basin-scale assessment in Norway

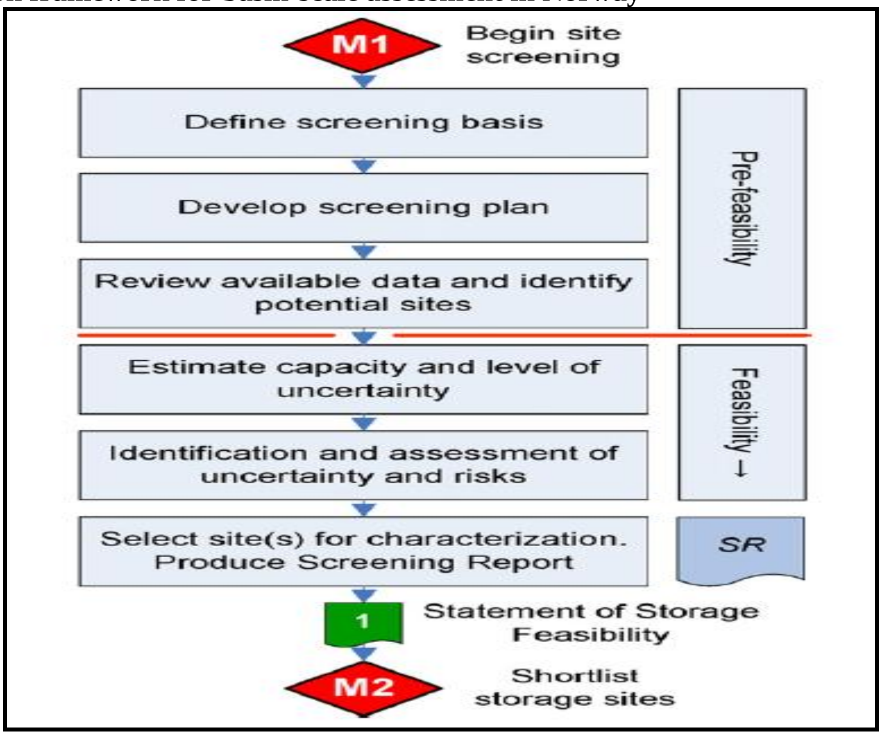

Figure 2: Workflow for site screening stage in Norway

The CO2QUALSTORE guideline has been developed by Det Norske Veritas (DNV) in collaboration with industrial partners. This guideline is globally applicable and adopts a risk based approach to the selection, characterization and qualification of sites and projects for geological storage of CO_2. The objective of CO2QUALSTORE guideline is to provide a systematic approach to selection and qualification of sites and projects CO_2 geological storage. In the guideline, it clearly explains the framework for site screening stage. This stage is to identify sites that may be suitable for

CO_2 geological storage with an adequate level of certainty to enable the decision to invest in further site assessment [16].

Fig. 2 shows a workflow for the screening stage of CO_2 geological storage project. The workflow is basically divided into three phase which include pre-feasibility phase, feasibility phase and screening report. The pre-feasibility phase is performed prior to the starting of an integrated carbon capture and storage project. Meanwhile, the feasibility phase is focusing on the capture and transport options and it is important for potential site developer to initiate the full carbon capture and storage project before moving to the next phase of evaluation.

In pre-feasibility phase, there are steps that have to be followed before considering moving to the next phase. That includes defining the criteria that a geologic site should fulfill in order to qualify for further site characterization, describing the activities for gathering sufficient information to allow a decision for investment in further site assessment and reviewing data and identifying potential sites. Meanwhile, in feasibility phase the estimation of storage capacity is conducted and detailed site assessment is carried out to decrease the uncertainties. The identification and assessment of risks and uncertainties based on the available data are recorded in a database for future references and guiding further characterization. Finally, the screening report is produced if the storage sites have fulfilled the criteria in screening basis. The screening report should review the activities and findings of the site screening stage and document the basis to help in budgeting.

2.3 Evaluation framework for basin-scale assessment in The Netherlands

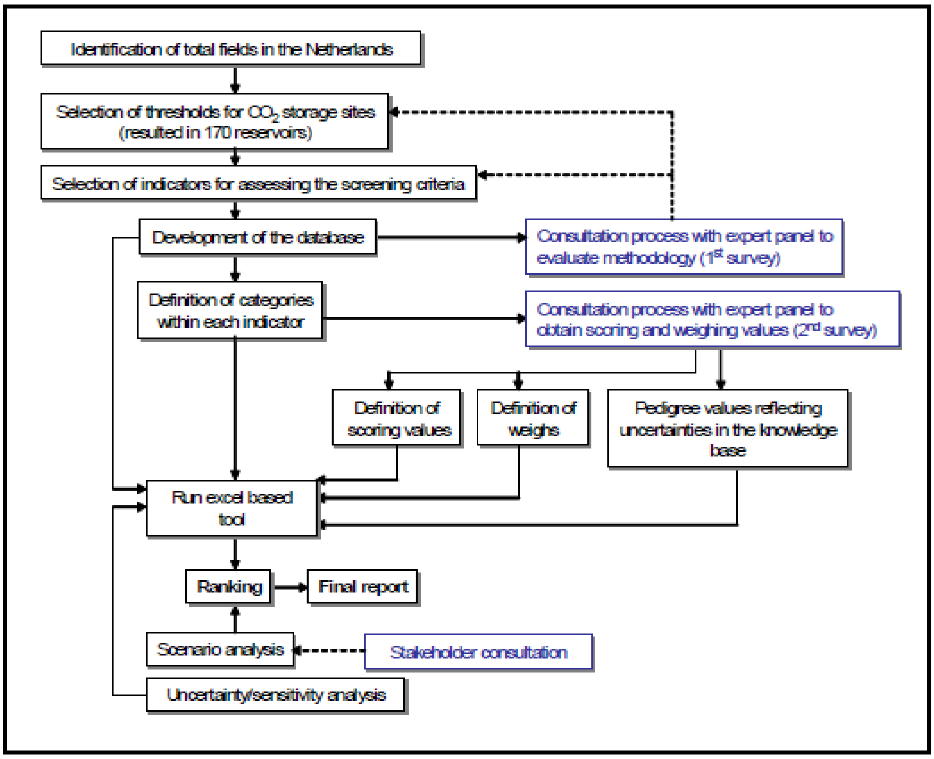

Figure 3: A schematic diagram of frameworks for potential site evaluation in the Netherlands

Ramirez et al. [9] has developed a methodology to screen and rank Dutch reservoirs for long term scale CO_2 storage. The screening however, is focused on off- and on-shore individual aquifers, gas and oil fields. The evaluation works has focused on two main areas which are the assessment of total capacities per country which has resulted in inventories on storage capacities in developed countries which later will be used by modelers to set physical boundaries for national deployment of carbon capture and storage. The second area to be covered is the risk assessment and uncertainty analysis of CO_2 storage which has resulted in the on-going development of methodological frameworks for risk assessment. The frameworks are mainly based on semi qualitative assessment and quantitative mathematical modeling that comprises major involvement of many experts, detailed studies and extensive modeling work. The framework is aimed to integrate theoretical knowledge, expert knowledge and publicly available data for a consistent systematic and transparent site characterization.

Fig. 3 shows a schematic diagram of the methodology used to develop framework for site characterization. The most important step in this methodology is the consultation round with an expert panel. The first round with experts was to seek their opinion on the criteria and indicators that has been selected. Meanwhile the second consultation with a panel of eight international experts was focusing on gathering the information needed to aggregate weight and score of the criteria for risk management. Those experts were asked to provide scores and define weight among the indicators in the screening tool for screening and ranking purposes. The framework is started with the identification of total fields in the Netherlands and followed by the first screening based on thresholds for CO_2 storage sites. Next will be followed by the selection of screening criteria, the experts consultations, aggregation of weights and scores for screening criteria and finally the scores and weights will be used in final screening and ranking of the potential CO_2 storage sites by using Excel based tool.

2.4 Evaluation framework for basin-scale assessment in China

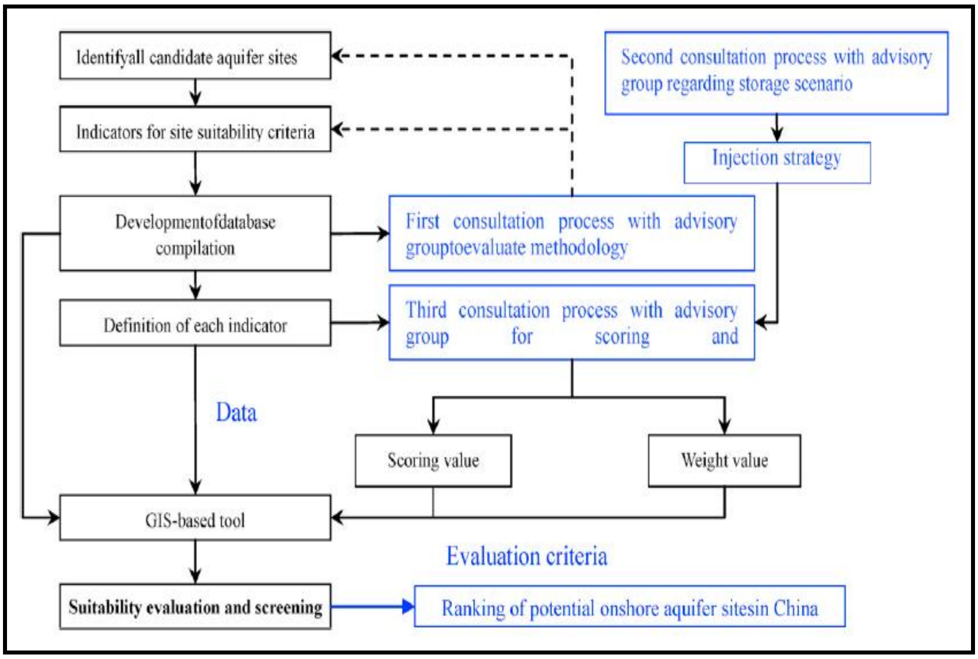

Figure 4: Schematic map of the methodology used in the evaluation of potential sites in China

In 2013, Wei et al. has developed a sub-basin scale evaluation framework. Sub-basin scale evaluation represents the maximum evaluation level. This level has automatically reduces uncertainty and also increases the amount of effort to compile and analyze the data. This framework was developed especially to assess the suitability of potential onshore deep saline aquifers for CO_2 storage in China is intended to provide first-order ranking of site suitability at the sub-basin level [15]. The methodology was modified from multi criteria analysis developed by Ramirez [9]. However the framework has been modified to fulfill four objectives including storage optimization in terms of storage capacity and injectivity, risk minimization, environmental restriction regarding surface and subsurface use and economic considerations. In contrast with original framework developed by Ramirez et al.[9], this new modified framework was designed to provide insights into both the suitability of potential aquifer storage sites as well as the priority for early deployment of carbon capture and storage with existing CO_2 sources.

There are three main steps in the evaluation framework for identification of potential geologic CO_2 storage in China which consists of the development of site suitability evaluation methodology

based on existing screening processes and data, the extensive data compilation on the key indicators and the application of evaluation methodology and data compilation by using GIS-based tools.
Fig. 4 shows the schematic map of the methodology used in the sub basin scale evaluation process. This framework also requires consultation from a panel of experts. A panel of twenty experts from various fields has been chosen to be part of the evaluation processes. In this evaluation, it demands three rounds of consultation with experts, firstly to obtain input for framing refining the appropriate method and criteria to be applied, secondly to review the future injection strategy which helped define the basis for the evaluation framework and thirdly to gather information needed to assign weights and scores on key characteristics. The weights and scores that have been developed by experts then will be used in the GIS analysis for data layering. This evaluation process is also based on a combination of various criteria that respond to quantitative and qualitative expressions of a number of indicators as the methodological framework developed by Ramirez et al. [9].

The evaluation framework is started by figuring out the injection strategy for the chosen sub-basin. This is based on the recommendation from the advisory group that believe by figuring out the injection strategy, it can help to increase the storage capacity and optimizes underground pore space usage, lower the risk of deformation of the geological formation, reduce the risk of unanticipated CO_2 migration, minimize leakage through imperfect caprock, fracture and faults under high injection pressure and potentially reduces the number of necessary injection wells at the same time will save costs. Based on the injection strategy, the criteria were developed based on literature reviews. The major evaluation parameters were established and weights and scores were aggregated based on recommendation by experts. The weights and scores latter will be used in GIS analysis to evaluate the suitability of the sub basin and to rank the potential onshore aquifer sites for CO_2 storage in China.

2.5 Evaluation framework for basin-scale assessment in Malaysia

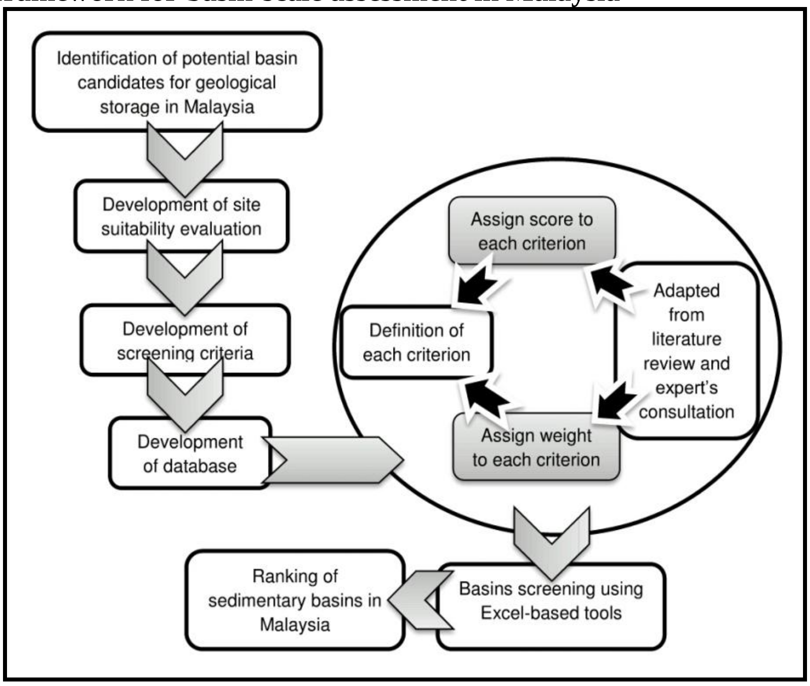

Figure 5: Schematic map of the methodology used in preliminary evaluation of sedimentary basins in Malaysia

However in 2015, Hasbollah and Junin [7] simplified the framework developed by Ramirez [9], integrated with selected screening criteria from Wei [15] while the scores and weights were aggregated based on Bachu's approach [8]. Both qualitative and quantitative basin-scale assessment has been made to preliminarily evaluate the potential storage sites suitability for CO_2 sequestration in sedimentary basins of Malaysia. The weights and scores were assigned to each criterion suits the geology setting of Malaysia that have been selected based on experts recommendations. Then the data is compiled in the Excel evaluation tools to rank the most potential storage sites for CO_2 sequestration in order of their suitability. The results from basin-scale assessment are used in the next more detailed level of evaluation.

The framework is started with the identification of all potential basins for CO_2 geological storage in Malaysia. The relevant data of sedimentary basins were obtained from various sources including oil and gas companies and local authorities. The screening criteria then will be developed from the available data. By using Bachu's approach [8], the weights and scores were aggregated on those criteria and finally will be analyzed in Excel-based tool to rank the suitability of potential basins. The results from this assessment will be used in the next stage of evaluation and warrant a further detailed assessment.

III. CONCLUSION

Geological CO_2 storage is an alternative of reducing greenhouse emissions into the atmosphere. The identification of basins and site evaluations are the crucial early step before any CO_2 geological storage project deployment. A framework is needed to aid the identification and selection of promising CO_2 storage sites with characteristics suitable for long term storage. This is to prevent work redundancy at the same time increasing project efficiency and save costs. It is mostly important for deep saline aquifer as knowledge and information on the type of formation is limited.

The frameworks for site suitability used by fellow researchers discussed in this paper were developed from previous literature review. The modifications have been made to suit their local geology setting and new ideas have been inserted as well. Most of the frameworks were using quantitative and qualitative analysis when assigning the weights and scores to the screening criteria. Those weights and scores were used for ranking purposes when the scores and weights were analyzed by using screening tools such as GIS and Excel. The potential sites for CO_2 sequestration are ranked based on their suitability and the results are used in the next level of assessment which will be more detailed.

This paper discussed and making comparison on basin-scale framework between several countries in the world. Some of the countries have been successfully implemented the geological CO_2 storage project and some of them are still in preliminary evaluation phase.

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