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Evaluation of potential sedimentary basins in Malaysia for carbon dioxide storage

Radzuan Junin[a,b], Dayang Zulaika Abang Hasbollah[b]*

[a]*UTM-MPRC Institute of Oil & Gas, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia*

[b]*Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia*

[*]*Corresponding author's mail: r-razuan@utm.my*

Abstract

This paper presents workflow of evaluating the potential storage sites suitability and storage capacity assessment for CO_2 sequestration in sedimentary basins of Malaysia. This study is the first of its kind that made an identification of potential storage sites and assessment of CO_2 storage capacity within the deep saline aquifers in the country. The CO_2 storage capacity in saline formation assessment was conducted based on the method for quick assessment of CO_2 storage capacity in closed and semi closed saline formations modified to suit the geology setting of Malaysia. Then the data was compiled using GIS-based evaluation tools to provide the potential storage sites for CO_2 sequestration. This study concentrated on the assessment of major sedimentary basins in Malaysia both onshore and offshore where potential geological formations which CO_2 could be stored exist below 800 meters and where suitable sealing formations are present. Based on regional study and amount of data available, there are 14 sedimentary basins all around Malaysia that has been identified as potential CO_2 storage. Meanwhile, from the screening and ranking exercises, it is obvious that Malay Basin, Central Luconia Province, West Baram Delta and Balingian Province are respectively ranked as the top four in the ranking system for CO_2 storage. 27% of sedimentary basins in Malaysia were evaluated as high potential area for CO_2 storage. This study should 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 capture and sequestration (CCS) projects in Malaysia.

Keywords: CCS; CO_2 sequestration; storage capacity; sedimentary basin; deep saline aquifer; GIS

1. Introduction

The increase in atmospheric carbon dioxide (CO_2) over the last two and a half centuries has been attributed mainly due to emissions from fossil fuel combustion and industrial processes [1]. Because the use and supply of global energy is projected to grow, especially as developing countries pursue industrialization, fossil fuels are expected to maintain their dominance in the global energy mix until 2030 and beyond. According to International Energy Agency [2], the global CO_2 emissions have increased by 1.9% per year from 20.9 billion tons of CO_2 in 1990 to 32.3 billion tons of CO_2 in 2013. The real challenge in mitigating the climate change effects is the reduction of CO_2 emissions to the atmosphere [3]. Potential mitigation 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 (CCS) [4]. CO_2 geological sequestration is one approach that could play an important role in these efforts [5]. CO_2 sequestration is a process that involves all four steps of CO_2 capture, separation, transportation, and finally storage. Geological CO_2 storage, ocean storage, below seabed storage, and CO_2 mineral sequestration are the practical techniques of CO_2 sequestration [6]. To date only storage in geological media in deep saline aquifers and oil and gas reservoirs have been successfully demonstrated at pilot and commercial scales [7].

While the developed countries are conventionally the main emitters of CO_2 emissions, however in recent decades, developing countries' (such as Malaysia) emissions are now seen to surpass developed country's emissions due to rapid economic development growth [8]. Data from IEA (2014) [9] shows that compared to other Southeast Asia nations, Malaysia has relatively high CO_2 emission rates based on per capita and per GDP measures at 6.46 (tonnes CO_2 per capita) and 0.47 respectively. The Ministry of Energy, Green Technology and Water Malaysia is planned to commit in reducing significant volumes of CO_2 emitted by Malaysian point sources using CCS technologies. CCS is believed will help Malaysia in achieving its commitment to cut carbon intensity by 40% in 2020 based on 2005 levels [10]. Besides, Malaysia is one of the few countries in the world to be actually a natural gas producer and net exporter which may turn to become a net importer if the production is not developed significantly to cover future needs. So far Petronas identified 15 offshore gas fields to have a high content of CO_2**.** All together these fields contain 13.2 trillion cubic feet (tcf) of natural gas for 27.32 tcf of CO_2 [11]**.** Therefore the development of these fields**,** require to capture this CO_2 and to store in deep saline equifers or re-inject it in oil fields to boost the production of maturing crude oil fields in Malaysia.

Since Malaysia is well known as petroleum bearing country and possessing a very unique geological formation, the suitability of Malaysian basin has to be assessed in order to investigate the potential of CO_2 geological storage deployment. To the best of our knowledge, there have been no comprehensive studies of the CO_2 sequestration to the potential candidate geologic storage formations in Malaysia. The suitability of sedimentary basins in Malaysia is yet to be assessed whether it is suitable to be CO_2 geological storage in term of its tectonism and geology, the geothermal gradient, the storage capacity, the existence of sealing formation and economic value. Hence this research embarks to evaluate suitability of potential geological storage sites available in Malaysia and to assess of CO_2 storage capacity within the deep saline aquifers in the Malaysia Basins.

2. Basin Scale Evaluation Framework

The preliminary evaluation to identify potential geologic CO_2 storage sites involves four main tasks which consist of (i) Development of site suitability evaluation methodology (ii) Development of screening criteria (iii) Extensive data gathering on key indicators that influence the performance of geological storage media, and (iv) Basin screening and ranking based on the criteria selected using Excel-based tool.

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 CCS project. 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 and Adams, 2003 [12], multi-criteria analysis by Ramirez et al., 2009 [13] and others.

Hasbollah and Junin, 2015 [14] simplified the framework developed by Ramirez et al., 2009 [13], integrated with selected screening criteria from Wei et al., 2013 [15] while the scores and weights were aggregated based on Bachu's approach [12]. 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 [12], 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.

Fig. 1 shows the schematic diagram of methodology and workflow to evaluate potential sedimentary basins for CO_2 sequestration in Malaysia. The screening is based on the criteria which possibly influencing the performance of basin as a geological storage for CO_2. The selection of criteria and key indicators for basin screening was developed from literature survey and opinion from a panel of experts. The scores and weight for each indicator were also adapted from literature review and were aggregated in screening tools.

3. Methodology

This section follows the methodology and flow of information across the different steps shown in Fig. 1. It provides details on injection strategy, indicators for site suitability criteria, mathematical method, and sedimentary basin scale characterization in Malaysia both onshore and offshore where potential geological formations in which CO_2 could be stored exist below 800m and where suitable sealing formations are present.

Based on regional study and amount of data available, there are 14 sedimentary basins all around Malaysia that has been identified as potential CO_2 storage. Most of them are well explored and possess a good sealing formation. A set of 12 criteria has been modified to suit the geological characteristics of Malaysia for assessment and ranking of sedimentary basins in terms of their suitability for CO_2 storage.

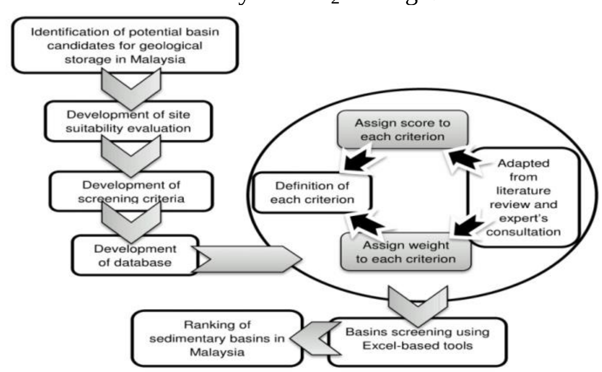

Fig. 1 Schematic map of the methodology used in preliminary evaluation of sedimentary basins in Malaysia [14]

3.1 Selection of criteria

The selection of criteria and indicators is basically fulfilling three main conditions to develop a safe and effective storage site; (i) Storage optimization, (ii) Risk minimization, and (iii) Feasibility. It also will consider possible natural (faults, tectonic setting, etc) and manmade (wells, etc) geological defects that might jeopardize the storage security. Feasibility study determines the ease to deploy CO_2 sequestration considering the accessibility of the storage sites, public perceptions, economic considerations, and land use issues for onshore sequestration. Therefore, the development of screening criteria should satisfy these conditions to arrive at a quantitative evaluation in terms of basin suitability for CO_2 sequestration. The criteria have been reselected to suit the geological characteristic of Malaysia for example the type of tectonics setting. There are 13 criteria used in this study as listed in Table 1 in Appendix 1. The weights and scores of each criterion were determined based on their relative importance with respect to the Malaysian basins as CO_2 storage.

3.2 Screening criteria

Table 1 (see Appendix 1) is a modified version of the basin scale criteria for CO_2 storage developed by Bachu, 2003 [16] and lists the criteria that can be used for the assessment and ranking of sedimentary basins in terms of their suitability for CO_2 sequestration or storage. For each criterion, the classes are arranged from least favourable to most favourable from left to right across the table.

3.3 Development of the screening tool

The method to assess the suitability of sedimentary basins in Malaysia for their CO_2 storage potential was adapted from the basin screening criteria of Bachu, 2003 [16]. Each of the criteria presented in Table 1 (Appendix 1) is given a value based on criterion-specific defined classes, where the lowest and highest values characterize the least and the most suitable classes, respectively. These scores reflect the relative importance of the categories within a given indicator. Each indicator is divided into categories. The scores and weights were adapted from previous studies and literature reviews modified to suit Malaysia geological condition. The input generated in the tool is then used to calculate an average score per site. The basic calculation is a simple linear aggregation using the scores and weights between categories and indicators using the approach of Bachu, 2003 [16]. The resulting scores per site from the assessment are representative for the relative scoring without indicating an absolute site performance. For each criterion, i ($i=1,2,3,..13$), an exponential parameterization of a function (F_i) is used to define the range of numerical values for each class of that criterion. The numerical values of F_i are assigned to describe a value placed on the specific class, j ($j=1,2,3…n$) for that criterion. The lowest and highest values of this function characterize the worst and best class in terms of suitability for that criterion.

For any sedimentary basin, k that is evaluated in terms of its general suitability for CO_2 sequestration or storage, the corresponding class j for each criterion i is identified (Table 1), resulting in a corresponding score $F_{i,j}$. Because the function F_i has different ranges of values for each criterion, making comparisons and manipulations difficult, the individual scores $F_{i,j}$ are normalized according to Eq. 1:

$$P_i^k = \frac{F_{i,j} - F_{i,1}}{F_{i,n} - F_{i,1}} \quad (1)$$

where $P_i = 0$ for the least favorable class and $P_i = 1$ for the most favorable class for all the criteria. These can subsequently be used in the basin ranking process to produce a general ranking score (R) (method is adapted from Bachu, 2003 [16] that latter be used in the final ranking (Eq. 2) of sedimentary basins of Malaysia.

$$R^k = \sum_{1}^{15} w_i P_i^k \quad (2)$$

where w_i are weighting functions that satisfy the condition (Eq. 3),

$$\sum_{1}^{15} w_i = 1 \quad (3)$$

3.4 Ranking of Sedimentary Basins

By compiling data on the criteria above, different basins can be compared, contrasted and ranked for their suitability for CO_2 storage quantitatively if scores are given for each criterion [16]. This allows the sedimentary basins in Malaysia to be ranked in order of their suitability for geological storage of CO_2. The range of numerical values (function, F_i) for the classes in a given criterion has an exponential form because subjectively these classes differ in importance. 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.

Once a sedimentary basin has been identified as potentially suitable for CO_2 storage, a basin scale assessment can be conducted to locate possible injection sites. Potential sites then can be scored and ranked in order to identify those that have the highest prospect of successful CO_2 storage and warrant further detailed site characterization. It is necessary to recognize that the list of criterion selected in the screening criteria can be expanded further if more criteria are developed and more data are available for assessment. For each basin, data were 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.

Site suitability evaluation was performed by using ArcGIS 10.2 based on spatial data available. The characteristics have been compiled in the form of GIS database which includes geological structures, seismic intensity, basin maturity, depth, well data and geological map of Malaysia. The evaluation criteria were developed based on a combination of literature review, collective input and available data. The overlay of these spatial data produced a map of potential area for CO_2 sequestration in sedimentary basins of Malaysia.

3.5 Storage Capacity Assessment

In this study, theoretical storage capacity of Malay Basin and Central Luconia Province are determined by using the volumetric method for CO_2 capacity calculations in the deep saline formations. The method proposed by the U.S Department of Energy (US-DOE) is intended for external users to produce prospective CO_2 resource assessments of potential CO_2 storage reservoir at regional and national scale [17]. For saline aquifers, the boundary conditions are considered to be open. The volumetric formula (Eq. 4) to calculate the CO_2 storage resource mass estimate, G_{CO2} for geologic storage in saline formations is:

$$G_{CO2} = A_t \, x \, h_g \, x \, \phi_{tot} \, x \, \rho \, x \, E_{saline} \qquad (4)$$

Where A_t is the total geographical area of the basin being assessed for CO_2 storage, h_g is the gross thickness of the saline formation for which CO_2 storage is assessed within the basin, ϕ_{tot} is the total porosity in volume defined by the net thickness, ρ is the density of CO_2 at the formation temperature and assumed to be 620 kg/m^3 across the basin. In this study, the calculation of theoretical storage capacity is made by assuming E_{saline} to be 2.0% for clastic and 1.5% for limestone formations based on 50th percentiles [17].

4. Results and discussions

4.1 Ranking of Sedimentary Basins

Table 2 shows the ranking of 14 identified sedimentary basins in Malaysia that have potential for CO_2 storage. From the screening and ranking exercises, it is obvious that Malay Basin, Central Luconia Province, West Baram Delta and Balingian Province are among the best candidates for CO_2 storage.

Table 2 List of Ranking for Sedimentary Basins in Malaysia

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

These basins hold the same attributes such as possessing an excellent sealing formation, actively explored by energy industries therefore plenty of data available for evaluation of CO_2 storage and also a major oil-producing provinces in the nation.

4.2 Suitability and Site Potential Evaluation

The results of site suitability evaluation are mapped in Fig. 2 and shown in percentage in Table 3. This map is produced by using overlay method which is one of the key functions in ArcGIS. In this evaluation, the suitability of sedimentary basins was classified into 4 different groups to show the potential level of the area for CO_2 sequestration that include highest potential, average potential, low potential and no potential area. From the figure, it is obvious that Malay Basin, Central Luconia Province, West Baram Delta and part of East Baram Delta belong to the high potential area.

As shown in Table 3, 27% of sedimentary basins in Malaysia were evaluated as high potential area for CO_2 storage. Mostly these sites are located in productive and mature basins which are actively explored for oil and gas. Actively explored basins provide abundant data that are useful for this evaluation of site potential for CO_2 storage. Besides that, these sites are generally characterized as being free or limitedly faulted by major faults and having no to low seismic intensity. These characteristics are believed to be able to provide a safe and effective storage for CO_2 for a long time for it might prevent CO_2 leakage and upward migrations of CO_2 that will be affecting public perceptions as well as their health. The risk of CO_2 containment breach is almost zero.

In addition, the well density within the area determine the effective of the storage sites for the distance between storage sites and CO_2 sources will affect the project costs and the infrastructure is already in place such as access roads, pipelines and wells and injection sites are easy to access and inexpensive to develop.

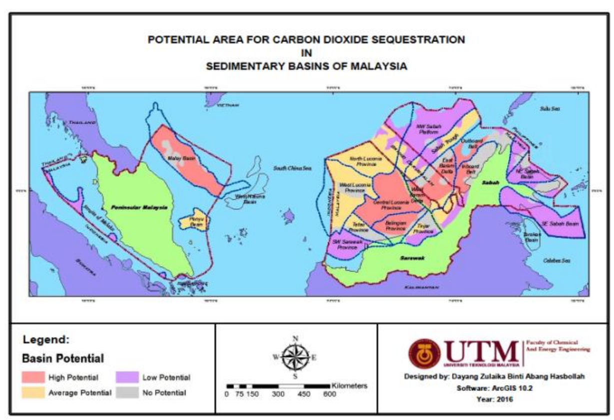

Fig. 2 Potential areas for CO_2 sequestration in sedimentary basins of Malaysia

Table 3 Percentage of potential area in sedimentary basins

Basin Potential	Area Percentage (%)
High Potential Area	27
Average Potential Area	23
Low Potential Area	30
No Potential Area	20

4.3 Detailed Assessments on the Most Potential Sedimentary Basins

In this study, the two high potential areas i.e Malay Basin and Central Luconia Province are chosen for detailed assessment for CO_2 storage capacity.

Potential Injection Site in Malay Basin

As shown in Fig. 3, Groups D and E are thought to be the most suitable sediments for CO_2 sequestration. This is because of these groups are located within the 1000 m to 1500 m depth which is favorable considering Malay Basin is a warm sedimentary basin. Hence, injection within this depth can provide safe long term storage for CO_2 as injection within this depth CO_2 will be in dense phase and it will maximize the storage volume.

Besides, Groups D and E consist of sandstones that form an important group of reservoirs in the central part of the Malay Basin. The main concern of this study is to evaluate the suitability of saline aquifers within the basin as geological CO_2 storage and saline aquifers with high potential for CO_2 storage are assumed to be present in Groups D and E sediments at depth of 1000 m to 1500 m.

Groups D and E fulfill the depth requirement for safe storage unit, with average porosity of 17% and a permeability of 40mD which are good properties for CO_2 storage aquifer according to Kartikasurja, 2008 [19]. In addition, the presence of Late Miocene unconformity provides an excellent lateral sealing formation and these strata are excluded from overpressure zone. Not to mention the existing infrastructure and facilities available within the area that will minimize project costs and increase project efficiency.

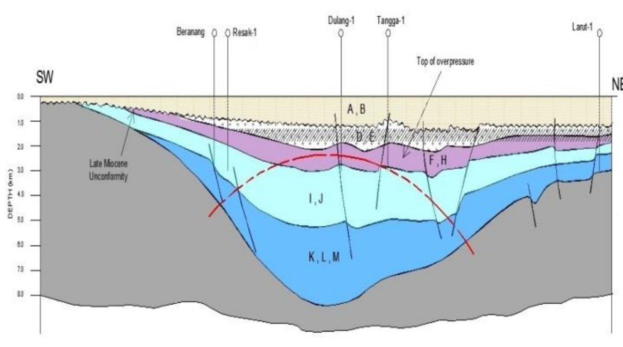

Fig. 3 Potential injection sites for CO_2 in Malay Basin

Possible Injection Site in Central Luconia Province

Fig. 4 shows that Cycles V and VI sediments are the perfect candidate for potential injection site for CO_2 in Central Luconia Province. This is because the cycles are located within the required depth to provide safe storage for CO_2 which 1000 m to 1500 m considering Central Luconia is a warm basin. The injection that commence at this depth will make sure the CO_2 to be stored in dense phase that will maximize the storage volume.

Besides, Cycles V and VI Miocene sediments are mostly consist of carbonates buildups and sandstones. These cycles are also possessing attractive reservoir properties with average porosity of 20%. With thickness of Cycle V around 680 m and Cycle VI around 90 m with length approximately 150 km, promise an abundant storage volume for CO_2. Besides, these Miocene sediments are overlaid Cycle VII which is rich with shale content that will be acting as a lateral sealing for this area. This will minimize leakage and upward migration of stored CO_2.

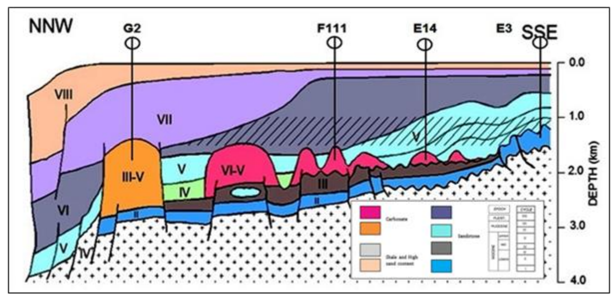

Fig. 4 Potential injection site in Central Luconia Province

4.4 Estimation of storage capacity

The results of the evaluation of theoretical storage capacity are summarized in Table 4. From the calculation using US-DOE method [19], the estimated storage capacity of CO_2 for Malay Basin is approximately 84 Gt, while for Central Luconia Province the storage capacity obtained is approximately 56 Gt. The efficiency and reliability of these two methods is profoundly discussed and compared in Goodman et al., 2013 [18].

Table 4 CO_2 storage capacity estimation based on 50th percentile [19].

Sedimentary Basin	CO_2 Storage Capacity (Gt)
Malay Basin	84
Central Luconia Province	56

5. Conclusions

The main aim of this study was to identify and evaluate the potential for CO_2 storage in the deep saline aquifer formations in the sedimentary basins in Malaysia, and hence produce a preliminary CO_2 storage atlas. Among the 14 identified sedimentary basins, Malay basin, Central Luconia, West Baram Delta and Balingian Province are respectively ranked as the top four in the ranking system. Data compiling using

GIS-based evaluation tools has resulted 27% of sedimentary basins in Malaysia were evaluated as high potential area for CO_2 storage. Mostly these sites are located in productive and mature basins which are actively explored for oil and gas. Malay Basin and Central Luconia Province are ranked as the most potential basins for offshore CO_2 storage hence they deserve extra attentions in the assessment of storage capacity. The estimated results suggest that the Malay Basin and Central Luconia Province can store about 84 Gt and 56 Gt of CO_2, respectively. This study should provide preliminary insights in the next prospective site assessment before the deployment of the large scale project can take place and can be used in making decisions for large scale implementation for CCS deployment in Malaysia.

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Appendix 1:

Table 1: Evaluation criteria for preliminary evaluation of CO_2 geological storage in Malaysia (modified from Bachu, 2003)[16]

	Criterion, *i*	Classes, *j*										
		1	Score	*2*	Score	*3*	Score	*4*	Score	*5*	Score	*w*
1	Tectonic setting	For arc	1	Back arc	3	Platform	7	Deltaic	15	Rift valley	15	0.09
2	Faulting intensity	Extensive	1	-		Moderate	5			Limited	9	0.1
3	Reservoir seal pair	Poor	1	-		Medium	3			Excellent	7	0.1
4	Depth	Very shallow (<300m)	1	Shallow (300-800m)	3			Deep (>3500m)	5	Intermediate (800-3500m)	15	0.08
5	Size	Very small (<1000km^2)	1	Small (1000-5000km^2)	3	Medium (5000-25000km^2)	5	Large (25000-50000km^2)	9	Very large (>50000km^2)	15	0.06
6	Geothermal	Warm basin (>40°C/km)	1	-		Moderate (30-40°C/km)	3			Cold basin (30°C/km)	7	0.09
7	Hydrogeology	Shallow, short flow systems	1	-		Intermediate flow system	3			Long range flow system	7	0.08
8	Maturity	Unexplored	1	Exploration	2	Developing	4	Mature	8	Super-mature	10	0.08
9	Hydrocarbon potential	None	1	Small	3	Medium	7	Large	13	Giant	21	0.06
10	Onshore/Off-shore	Deep offshore	1	-		Shallow offshore	4			Onshore	10	0.1
11	Accessibility	Inaccessible	1	Difficult	3			Acceptable	6	Easy	10	0.03
12	Infrastructure	None	1	Minor	3			Moderate	7	Extensive	10	0.05
13	Climate	Arctic	1	Sub-arctic	2	Desert	4	Tropical	7	Temperate	11	0.08

Commonwealth Energy and Sustainable Development Network (CESD-Net)

CESD-Net is a major global initiative in energy and sustainable development. The objective of network is to promote energy and sustainable development in commonwealth countries.
Focussing on Multidisciplinary Research, Promoting Future Low Carbon Innovations, Transferring Knowledge and Stimulating Networking among Stakeholders to Ensure the UK Achieves World Leading Status in Energy and Sustainable Development. https://www.weentech.co.uk/cesd-net/

The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:
Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.
Dr. Kumar is visiting faculty at Prince of Songkla University, Thailand. He have 16 years of research and teaching experience in the field of solar energy, drying and energy efficiency.

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