ERIA Research Project Report FY2021 No. 25

Study on the Potential for Promoting Carbon Dioxide Capture, Utilisation, and Storage (CCUS) in ASEAN Countries

Vol. II

Edited by

Shigeru Kimura

Kikuko Shinchi

Ulysses Coulmas

Ayami Saimura

Study on the Potential for Promoting Carbon Dioxide Capture, Utilisation, and Storage (CCUS) in ASEAN Countries Vol. II

Sentral Senayan II 6th Floor

Jalan Asia Afrika no.8, Gelora Bung Karno

Senayan, Jakarta Pusat 10270

Indonesia

ERIA Research Project FY2021 No. 25

Published in March 2022

Preface

At the 4th East Asia Energy Forum (EAEF4) held on 13 September 2021, ‘participant VIPs, experts, and audiences discussed ‘A Low-Carbon Energy Transition in the ASEAN Region’. In the forum’s panel session 2, experts discussed how available technologies, including carbon capture, utilisation, and storage (CCUS), and hydrogen and fuel ammonia, will contribute to reducing CO2 emissions around 2040–2050. The CCUS was again recognised as an important technology in achieving energy transition in the region. The Asia CCUS Network (ACN), established officially in June 2021, started its activities in 2021–2022, which included knowledge sharing, research study, and capacity-building training. This report covers the following activities: (i) capacity building training to provide basic lectures on capturing, transporting, and carbon recycling and storing of carbon dioxide (CO2); (ii) research study on the analysis of carbon capture and storage (CCS) cost applying a model case as well as a legal framework; (iii) workshop as a knowledge-sharing conference to introduce major results of the research study.

CCUS comprises carbon capture, carbon utilisation, carbon transport, carbon storage, and capacity-building training provided audiences a clear understanding of each CCUS technical element. The cost analysis of CCS applying a model case suggests overall CCS cost (about US$60/t-CO2), which is in the range of published research papers, and capturing CO2 marks the highest cost compared to transport and storage. This result is similar to the Tomokomai CCS project operated by Japan CCS Co., Ltd.

I hope this report will provide ACN members, especially ASEAN policymakers, a correct understanding of CCUS technology and contribute to lowering CCUS deployment cost in the ASEAN and East Asia region in the future.

Prof. Hidetoshi Nishimura

President, Economic Research Institute of ASEAN and East Asia

Acknowledgement

This project received tremendous support from Japan's Ministry of Economy, Trade and Industry (METI). Many findings on the model case study (MCS) and the current state of the regulatory framework included in the report are based on a METI-commissioned research project since 2019. The invaluable advice from METI throughout the planning and implementation stages of the project enabled a fruitful discussion on the topic of proposing collective action for CCUS. The project members also extend their appreciation to the members of the Asia CCUS Network Advisory Group, organised by the Economic Research Institute for ASEAN and East Asia (ERIA), and all speakers at the technical workshop and the MCS workshop who willingly participated in discussions and provided valuable inputs to our study.

Kikuko Shinchi (Ms.)

Senior Researcher

Climate Change Solutions Group

Sustainability Division

Mitsubishi Research Institute Inc.

List of Project Members

Shigeru KIMURA, Special Adviser to the President on Energy Affairs, Economic Research Institute for ASEAN and East Asia

Kikuko SHINCHI, Project Manager, Senior Researcher, Mitsubishi Research Institute (MRI)

Kuniyuki NISHIMURA, Senior Researcher, MRI

Ulysses COULMAS, Researcher

Ayami SAIMURA, Researcher

Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

ACN	Asia CCUS Network
ADB	Asian Development Bank
ASEAN	Association of Southeast Asian Nations
CAPEX	capital expenditure
CCS	carbon capture and storage
CCUS	carbon capture, utilisation, and storage
CO_2	carbon dioxide
EOR	enhanced oil recovery
ETS	emission trading scheme
EU	European Union
GCCSI	Global Carbon Capture and Storage Institute
MCS	model case study
METI	Ministry of Economy, Trade and Industry
MRI	Mitsubishi Research Institute
MRV	measurement, reporting, and verification
Mt	megatonne
$MtCO_2/y$	megatonne carbon dioxide per year
NETL	National Energy Technology Laboratory
OPEX	operating expenditure
PCI	Plant Cost Index
RITE	Research Institute for Innovative Technologies for the Earth
UK	United Kingdom
US	United States

Executive Summary

The study involves knowledge-sharing and capacity-building activities conducted as part of Asia CCUS Network (ACN) Activities from July 2021 to January 2022, and research and analysis on the cost structure of a model CCUS case study in Asia.

Firstly, as described in chapter 1, the capacity-building activity was planned to instil knowledge on technologies needed in each segment of the CCUS, namely capture, transportation, utilisation, and storage. Three technical workshops were arranged where lecturers and leading academic and business experts introduced the mechanism of respective technologies and conditions required for such technologies to be feasible for the introduction. These sessions identified key technology-related issues that should be considered in planning a CCUS project. For example, regarding carbon capture technology, while proven capture technologies in chemical absorption are available, their cost competitiveness depends on the availability of land and low-cost energy due to space and energy requirements. There is growing attention to the shared use of pipelines for transport, which leads to cost reduction possibilities and a hub-and-cluster model where multiple CO2 sources and sinks are connected through a common transport mode. As for CO2 storage, technical know-how of storing in depleted oil reservoirs and saline aquifers has been gained, and tools are being developed and tested. It was also pointed out that monitoring and verification of stored CO2 is the key to cost reduction in the long run. It enables risk communication and opens the door to gaining public support. Various efforts on carbon utilisation are ongoing to use captured CO2 efficiently, including industrial application. CO2 conversion to fuels and chemicals is deemed one of the promising areas. As for their impact on climate change mitigation, fuels, such as methanol, were stressed to be the target product as displacement of fossil fuel utilisation can maximise CO2 avoidance.

Secondly, the cost of CCUS was studied through the conceptualisation of the model case study (MCS), as described in chapter 2. Through a literature survey, the study clarified cost structure and major cost components throughout the value chain of a model CCS project. The results of the study revealed that the unit cost of CCS projects in an ASEAN country is approximately US$63/t-CO2, with greater than 70% of the cost belonging to carbon capture. This is in line with assessments made in preceding studies and demands further attention when considering future actions for improving commercial viability. The study also demonstrates that some costs remain highly variable depending on local or project-specific circumstances or largely unknown, as in the case of shipping, requiring further study and consideration through a more in-depth feasibility study.

Thirdly, the study introduces an overview of the regulatory and legal framework in CCUS-leading countries and their current status in the Association of Southeast Asian Nations (ASEAN) counties, as described in chapter 3. The existing literature shows that risks outside of technology and costs are largely related to the clarification of responsibilities of concerned parties, such as ownership, licensing, operation, monitoring, and liability, amongst others. Also, countries with advanced CCUS projects have robust regulatory frameworks that address these issues and provide clarity. The study on the regulatory framework introduced in countries with advanced CCUS projects revealed three basic approaches in developing a regulatory framework: (i) enhancing existing oil and gas regulations with the addition of CCS-specific provisions, (ii) introducing a stand-alone regulation specific to CCS, and (iii) introducing a project-specific CCS regulation. For a suitable approach towards developing a regulatory framework in the ASEAN region, the study proposes developing regional guidelines or basic principles, which each member state can follow when considering its legal options to speed up the development process and address cross-border issues. The study also demonstrates that in countries with advanced CCUS projects, policies to promote CCUS have been introduced alongside regulatory frameworks. The policy-based incentives, such as public funding for capital and operation costs and tax credits, are key factors in reducing initial investment costs while providing creditworthiness to projects to mobilise further finance and commitment from private companies. The study also proposes adopting a regional approach to formulate such policies and incentives in the ASEAN and Asian regions.

In chapter 4, the study explores a regional approach that clarifies issues to promote CCUS further. The tentative regional framework envisages that Asian countries and international and regional partners agree on basic principles for establishing a regulatory framework in each member state and plans for creating regional incentive schemes, such as regional funds and a regional carbon market. Such action will accelerate regulatory framework development while also setting the scene for developing projects that encompass national borders to combat climate change as a region.

The MCS outcomes and the consideration for developing a regional approach were presented at the knowledge-sharing workshop (chapter 5). At the workshop, a panel of experts expressed positive reactions to the idea of a regional approach. They commented that a regional approach provides trust and foundation for essential work needed to scale up CCUS – such as engagement in feasibility and demonstration studies, regional financing framework, including a regional fund and carbon market scheme – and guidelines or basic principles on developing a regulatory framework. Based on the experts' inputs, it is recommended that concerned parties join the effort of the 'Asia CCUS Collective Action Initiative (tentative)'. Through knowledge sharing, capacity building, feasibility study and demonstration, and formulation of a dedicated organisation (chapter 6), further engagement in collaborative activities – classified under the pillars of 'technology', 'business model', 'regulatory framework', 'policy', and 'finance' – would provide a great push to developing a large-scale CCUS project that would positively impact energy transition and climate change mitigation of the region.

Chapter 1

Technical Workshops

1. Overview

This workshop aimed to serve as an opportunity to instil knowledge about the latest technologies and the current trend of CCUS through actual case studies by top-notch lecturers.

The goals of the CCUS technical workshops were to (i) promote knowledge sharing on the latest CCUS technology through lecture sessions, (ii) accelerate further consideration of the application of mainstream CCUS technologies in the ASEAN region, and (iii) exchange ideas on and issues about CCUS technology.

Three workshops were organised on 5–7 October 2021. Two lecturers were invited to speak on their expertise for every daily session. A total of six lecturers with various backgrounds (professors, researchers, and from private companies) were invited.

Day 1 of the workshop focused on the technical aspects of carbon capture technology. Lecturers from the Global Carbon Capture and Storage Institute (GCCSI) and the Mitsubishi Heavy Industries Engineering shared their knowledge on capture technologies.

Day 2 covered the technical aspect of transport and storage technology. Lecturers from the Mitsubishi Research Institute (MRI) and the Research Institute for Innovative Technologies for the Earth (RITE) provided an overview of transportation and storage, respectively.

Day 3 focused on the utilisation of CO2. Lecturers from Pertamina RTC, Indonesia and the National University of Singapore shared CO2 utilisation from the perspective of the oil and gas sector and academia.

Participants averaged around 100 per day and were from various backgrounds in ASEAN member countries.

2. Workshop on Capture Technology (Day 1)

2.1. Agenda

Lecturers from the GCCSI and the Mitsubishi Heavy Industries Engineering were invited to discuss capture technologies.

The GCCSI lecturer presented the overview of carbon capture technologies and expressed his opinions regarding their advantages and disadvantages. In addition, he compared the pros and cons of membrane-based adsorption and solvent/solid-based adsorption used as capture technologies that are mainly used today.

On the other hand, Mitsubishi Heavy Industries Engineering also gave insight into chemical absorption technologies using several case studies. Real cases, such as Petra Nova projects, were introduced, and applications in gas turbine combined cycle power plant, LNG liquefaction plant, cement manufacturing, and steel/iron making were also mentioned.

Table 1.1: Workshop on Capture Technology

	Topic	Lecturer/Presenter
1	Overview of Asia CCUS Network	Han Phoumin, Senior Energy Economist, ERIA
2	Introduction to capacity building and overview of CCUS business development in Asia	Kikuko Shinchi, Senior Researcher of Mitsubishi Research Institute
3	Technical aspects of carbon capture technology	
3-1	Overview of carbon capture technologies, their advantages, and disadvantages	David T. Kearns, Principal Consultant CCS Technology, Global CCS Institute
3-2	Case study on chemical absorption technologies	Takashi Kamijo, Chief Engineering Manager/Project Director Decarbonization Business Department, Mitsubishi Heavy Industries Engineering
4	Q&A and discussion	(Details in 1.2.2)

2.1. Main topics of discussion

Capturing cost and technological readiness of available capturing technologies were mainly discussed.

- **What are the challenges of using amine as capturing solvent?**

Amine is often used to capture CO2. The biggest challenge is solvent degradation, a thermal degradation that occurs from repeated heating and cooling. Understanding the mechanism and counteracting the degradation is the first step.

- **What efforts can reduce the capture cost?**

The cost of capturing is currently highest amongst all stages in the CCS value chain, and ways to reduce it remain a big issue. The way forward is to drive new technology development and aim for economies of scale. In other words, bringing the capital cost down is key; beyond that is obtaining low-cost electricity from Iceland, such as geothermal electricity.

- **What actions should be considered if no CO_2 user is available nearby?**

If no CO2 users are near the source, or if the CO2 off-taker is far from the source, liquefication of the CO2 for shipping can be an option.

3. Workshop on Transportation and Storage Technology (Day 2)

3.1. Agenda

Lecturers from the MRI and RITE were invited to share the overview of transportation and storage, respectively.

The MRI overviewed transportation technology. The four main methods to transport captured CO2 are pipelines, trains, ships, and trucks. Pipelines and shipping are mainly discussed here. Repurposing existing pipelines and connecting pipelines from several sources based on a hub-and-cluster network are options to reduce the initial investment. However, challenges may appear, such as difficulty managing CO2 streams in multi-source networks with varying flow levels, flow rates, or CO2 quality. Shipping is one of the ways of transporting CO2 when no pipelines exist in certain areas or the distance is too far to reach. However, the main challenge would be when shipping induces more associated CO2 transport emissions than pipelines due to additional energy use for liquefaction and fuel use in ships. The MRI also shared ways and solutions to overcome the challenges of pipelines and shipping.

The RITE chief researcher provided an overview of storage technologies, providing deep insight into what is happening in the reservoir during CO2 injection. During his session, he introduced the correspondent technology to observe CO2 accumulation in reservoirs and CO2 saturation profiles. He also mentioned CO2 monitoring for permanence and safety based on Canada's Quest project and issues revolving around it.

Table 1.2: Workshop on Transportation and Storage Technology

	Topic	Lecturer/Presenter
1	Overview of Asia CCUS Network	Han Phoumin, Senior Energy Economist, ERIA
2	Introduction to capacity building and overview of CCUS business development in Asia	Kikuko Shinchi, Senior Researcher, Mitsubishi Research Institute (MRI)
3	Technical aspects of carbon transport technology	
3-1	Overview of transportation technologies	Ulysses Coulmas, Researcher, MRI
3-2	Overview of storage technologies	Ziqiu Xue, Chief Researcher, CO2 Storage Technology Group, Research Institute for Innovative Technologies for the Earth (RITE)
4	Q&A and discussion	(Details in 1.3.2)

3.2. Main topics of discussion

- **What are the example projects that utilise existing oil and gas infrastructure (mainly pipelines)?**

  The use of existing oil and gas assets contributes to reducing initial investment costs and increasing the efficiency of the CCS value chains. Examples of industrial-scale projects that have used existing oil and gas infrastructure are Northern Light, and one from the United Kingdom (UK)'s east coast cluster. On the other hand, projects like Porthos (Port of Rotterdam CO2 Transport Hub and Offshore Storage) are using new pipelines. Despite the difference of effort seen here, the main idea is still the same: connecting the CO2 source from several clusters.

- **What should be done to accelerate cross-border CO2 transport within the ASEAN region?**

  ASEAN has been working on cross-border gas pipelines for a long time with limited progress. First, issues must be determined and studied to figure out proper actions and solutions to accelerate CO2 cross-border transportation. Some regions do not have pipelines because of earthquake-related issues, landscape, and soil quality. As for ASEAN countries, the geographical path plays an important role. European countries are connected by land, while ASEAN countries are mostly connected by maritime routes, which are more complicated. Also, cross-border in ASEAN countries is not as strong as in Europe. Europe has more schemes and regulations for a better base to cooperate with multinational companies.

- **How do you see the possibility of CO_2 leaking to the surface?**

  The concept for CO_2 storage is similar to the oil and gas industry. The reservoir structure is made so that oil and gas can be safe in reservoirs overlaid by caprock.

- **How long is CO_2 monitoring needed to prove the safety of post-injection period?**

  The US Environmental Protection Agency requires monitoring post-disclosure for 50 years. Reducing the time length may be considered under several conditions.

4. Workshop on CO_2 Utilisation (Day 3)

4.1. Agenda

Lecturers from Pertamina, Indonesia and the National University of Singapore (NUS) were invited to share CO_2 utilisation from the perspective of the oil and gas sector and academia. Pertamina gave insight into the general knowledge of CO_2 utilisation and Pertamina's ongoing CO_2 utilisation-related research studies. From chemical products such as methanol, polymer to biocapture using algae was covered in the session. The Pertamina lecturer also shared collaboration and partnership opportunities at the end of her session. NUS shared a deeper insight on chemical conversion based on laboratory data and the potential of CCU.

Table 1.3: Workshop on Utilisation Technology

	Topic	Lecturer/Presenter
1	Overview of Asia CCUS Network	Han Phoumin, Senior Energy Economist, ERIA
2	Introduction to capacity building and overview of CCUS business development in Asia	Kikuko Shinchi, Senior Researcher, MRI
3	Utilisation of CO_2	
3-1	Research activities CCU technologies in Indonesia	Dewi Mersitarini, Advisor CCUS, Pertamina RTC, Indonesia
3-2	CO_2 Utilisation Research Activities and Potential Industrial Application	Ning Yan, Dean's Chair Associate Professor, Head of Green Catalysis Lab, National University of Singapore
4	Q&A and discussion	(Details in 1.4.2)

4.2. Main topics of discussion

- **Can CCU contribute to net CO_2 reduction?**

Even if CO2-derived methanol is blended into gasoline used as fuel, the consumption of the fuel will also release CO2, which will eventually re-enter the atmosphere. The important part here is what has been replaced during the process. When methanol is made by CO2, compared to fossil fuel as feedstock, the avoided CO2 from the exploration and production of fossil fuel and the CO2 captured for methanol production are the total CO2 abated that should be considered. The way we look at CCS is slightly different from how we should look at CCU. The comparison must be made on what has been replaced to see the value of CO2 abatement using CCU.

- **Are there any options other than using palladium as a catalyst in producing CO2-derived methanol?**

Copper is another good option, but the effect might not be as good as palladium. In terms of sufficiency for supply, copper might be a better option. From the overall production point of view, the catalyst contributes to less than 10% of the cost; therefore, the cost of the catalyst would not be a major problem. However, from the large gigatonne-level scale production point of view, there is not enough palladium currently; in this case, copper is preferred.

Chapter 2

A Model Case Study: CCUS Cost Estimation

1. Background and Introduction

This model case study (MCS) for a CCS project at a CO2-intensive industrial facility in the ASEAN region, such as a coal-fired power plant, was conducted to help visualise the whole value chain of a full-scale CCS project – from capturing to storing the CO2 at its final destination. Based on public source information, the case study provides a preliminary financial analysis for the main technical segments of a full-scale CCS project.

The study aims to better understand CCS in general by analysing the basic cost structure of a hypothetical project and offer input for future policy and regulatory changes that can support and accelerate CCS implementation in the ASEAN region and other member countries of ACN on a larger scale.

2. Survey of Previous Studies

Over the decades, CCS has gained recognition as a key technology to achieve climate targets. Much time and effort worldwide have been dedicated to evaluating CCS strengths and challenges. As part of those efforts, many studies have already been conducted to analyse the cost structure of CCS projects in general or for specific components of the CCS value chain in particular. The analytical work on breaking down the cost structure on a common formula, with a detailed evaluation of each component, has been limited so far. This is partly because the deployment of commercial CCS facilities is still limited. Another reason is that project-specific factors have a big impact on all components of the CCS value chain. How much is the additional energy cost needed to operate the CCS facility? On what kind of terrain will the pipeline be built? How deep must the well be? These are just a few factors that can easily double the cost of each affected component. Economies of scale are another important factor for the cost optimisation of CCS.

A major work on this matter is GCCSI's report, published in the first quarter of 2021. It examines the technology readiness of each component of the CCS value chain and reviews the factors that influence the cost of carbon capture, compression, transport, and storage. The study offers various cost scenarios for different emitting sources in type and scale. For coal power plants with a capture capacity of 0.18 to 1.8 MtCO2 per year, the study estimates a capture cost range of about US$50–US$65 per tonne CO2, with a clear tendency of lower costs for larger plants.

Another important work on CCS costs is RITE's 'Report on Carbon Dioxide (CO2) Fixation and Effective Utilisation Technology: Results of the CO2 Underground Storage Technology Research and Development Project'. It dates back to 2005, but it is probably the most detailed analysis of the costs of a full-scale CCS project. The report offers a comprehensive breakdown of the capturing site for different emitting sources, such as a newly constructed coal power plant, a retrofitted coal power plant, or a steelworks plant. The estimated capturing costs for those plants range from about US$30 to US$60/t-CO_2. The publication year might give an outdated impression, but the detailed and comprehensive content makes this report a unique work in CCS cost analysis. The report is still a reference in newer studies as Japan CCS Co., Ltd. (JCCS)' demonstration project in Tomakomai.

'The Cost of CO_2 Capture and Storage' (Rubin et al., 2015) well overviews the cost changes affecting the full CCS value chain over 10 years starting in 2005. It updates the costs reported in the 2005 Intergovernmental Panel on Climate Change's *Special Report on Carbon Dioxide Capture and Storage* by comparing the costs to recent studies focusing on electric power plants. The study offers an excellent overview of cost ranges for a wide variety of scenarios, depending on combustion and capturing technology, as well as differences between newly built plants and retrofits.

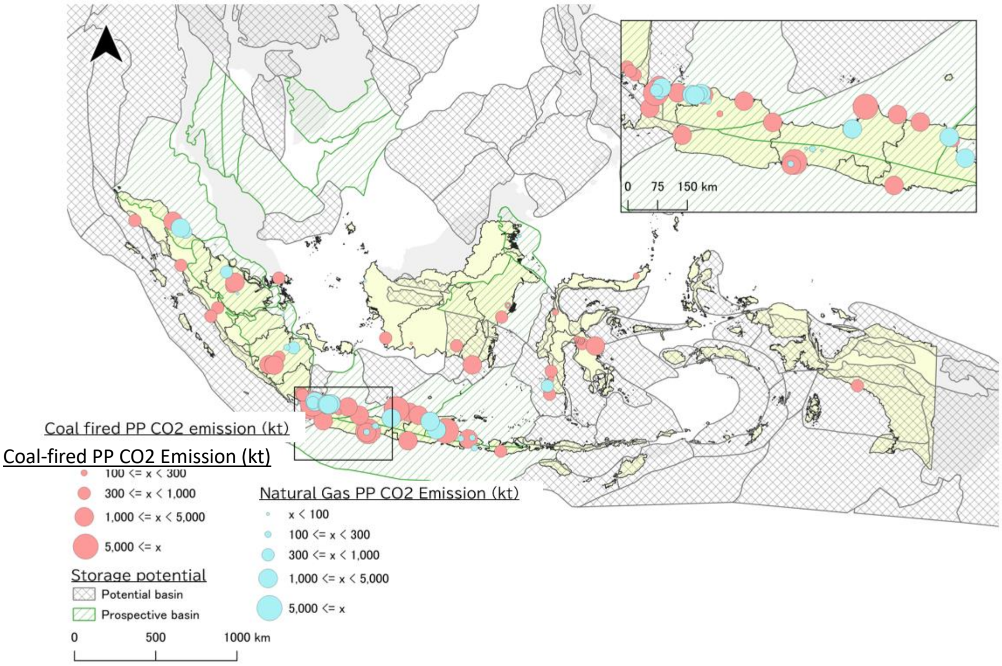
3. Region Selection

The study team considered several ASEAN member countries for the model project. Indonesia was chosen due to its position as a major oil, gas, and coal producer. In addition, Indonesia is by far the biggest ASEAN member population-wise; about 40% of the ASEAN population lives in Indonesia.

After selecting the country, the study team analysed the distribution of gas and coal-fired power plants within Indonesia. Figure 2.1 shows that most power plants are located in Java. Additionally, GCCSI data gave a big picture of the potential basins in this area. The data showed a wide-ranging potential for subsurface CO_2 storage around Java.

The high density of CO_2-intensive sources and the good accessibility to storage potential were key requirements in selecting the region. These requirements were both met in Java.

Figure 2.1: The Java Region of Indonesia as a Suitable Terrain for the CCS Model Case Study



Source: Created by the Author, storage information provided by GCCSI.

The definite location was further narrowed down by analysing existing reservoir examination reports. The reservoir characterisation and simulation by Tsuji et al. (2013) showed that the Blora Regency of the Central Java Province (see red box in Figure 2.2) offers suitable conditions to safely store the captured CO2 with a sandstone formation of over 1,000 m depth.

Figure 2.2: Map of Java Island, Indonesia, with Coal-fired Power Plants in Operation

Note 1: The Author added the red box described as the 'Selected Area' to visualise the targeted location for the model case.

Note 2: The numbers in the brown circles describe the number of operating units at that location.

Source: Global Energy Monitor, Global Coal Plant Tracker, https://globalenergymonitor.org/projects/global-coal-plant-tracker/tracker/ (accessed 29 October 2021).

4. Specifications and Characteristics of the Model Project

After the regional conditions were determined, the technical specifications and characteristics of the model project were defined. As many ASEAN members still rely on coal-fired power plants as a relatively cheap energy supplier, there is a real demand for retrofitting existing power plants with carbon capture technology. The study team decided to take a medium-scale ultra-supercritical coal-fired power plant as an example for the MCS, as they are likely to be the last ones to be shut down.

It will be a 500-megawatt (MW) plant, with an expected lifespan of 25 years after the retrofit. A capacity factor of 80% and a thermal efficiency of 40% were applied. Chemical absorption–based capture technology using monoethanolamine with a capture rate of 90% was chosen, being one of the best-proven capture technologies over the past decades.

The captured CO2 will be transported to the injection well at a deployed gas field through a 50 km onshore pipeline. The lithology at the selected area is a sandstone formation of about 2,000 meters.

Table 2.1: Specifications and Characteristics of the Model Project

Capacity	500 MW
Type of Power Plant	USC coal
Capacity Factor	80%
Thermal Efficiency	40%
Default Emission Factor for Lignite	101,000 kgCO2/TJ
Fuel Consumption	31,536 TJ
Type of Capture Technology	Chemical absorption (Amine)
Capture Efficiency	90%
Estimated CO2 Emission	3.19 MtCO2/y
Captured CO2	2.87 MtCO2/y
Pipeline Length	50 km
Pipeline Design	12 in
Well Depth	2,000 m
Project Lifespan	25 years

TJ = tera joule, USC = ultra supercritical.

Source: Created by the Author. Default Emission Factor for Lignite taken from IPCC (2006).

5. Capture Costs

The cost analysis was split into the three obvious components of the CCS value chain: capturing, transporting, and sequestering CO2.

RITE's 'Report on Carbon Dioxide Fixation and Effective Utilisation Technology: Results of the Carbon Dioxide Underground Storage Technology Research and Development project' was used as a reference to analyse the capture costs. It is an older study dating back to 2005. However, due to the detailed and comprehensive breakdown of all components of a CCS project, its results are still used as a reference in several feasibility studies and demonstration projects, such as the Tomakomai Demonstration Project. RITE's study offers multiple scenarios, including a basic cost breakdown of a capturing site at a retrofitted coal-fired power plant, with a generation capacity of 540 MW and a capture capacity of 1 MtCO2/year. All costs are calculated with an annual expense ratio of 9% and repair costs of 3%. The evaluation does not include CAPEX Labour.

Table 2.2: Capture Costs: a Basic Case Study

	Category	Component	Unit	Cost
CAPEX	Equipment	Supporting boiler	US$ million	91.94
		Higher desulphurisation	US$ million	10.2
		Other related equipment	US$ million	48.75
	Total		**US$ million**	**150.89**
OPEX	Operation of supporting boiler	Fuel	US$ million /y	8.35
		Other variable costs	US$ million /y	1.62
	Absorbent	Amine	US$ million /y	2.53
	Desulphurisation	NaOH (sodium hydroxide)	US$ million /y	0.63
	Labour		US$ million /y	18.1
	Total		**US$ million /y**	**31.23**

CAPEX = capital expenditure.

Note: US dollars (2005), Calculated from ¥ to $ with yearly average TTS rate (111.21) of MUFG.

Source: Created by the Author based on RITE (2005).

The three major carbon capture technologies – pre-combustion CO_2 capture, post-combustion CO_2 capture, and oxyfuel CO_2 capture – are primary adaptions of conventional combustion systems.

Pre-combustion	• Separation of CO_2 by converting fuel into a gaseous mixture of hydrogen and CO_2 before main energy conversion, produced by gasification of solid fuels or reforming of gases • Applied in natural gas processing; only applicable for power generation in case of newly built projects
Post-combustion	• Separation of CO_2 using a liquid solvent carried out downstream of a largely unchanged conventional combustion process, comparable to the wet desulphurisation of flue gases • Often applied in the food and beverage industry; applicable for retrofitting power plants
Oxyfuel	• Combustion of carbonaceous fuels with (nearly) pure oxygen, resulting in flue gas of CO_2 and water vapour from which storable CO_2 is recovered by simple drying

As this model project targets to retrofit a coal-fired power plant, the post-combustion capture method will be applied. RITE's numbers were adjusted and scaled up to a capture capacity of 2.87 $MtCO_2$ per year to calculate the capture cost of the model plant. The supporting boiler is the most cost-intensive component within the CAPEX breakdown. Additional components for such a system may include an absorber, desorber, condenser, and other heat exchange equipment.

Fuel and labour have the biggest impact on operating costs. Obviously, the amine absorbent is also an important factor.

Table 2.3: Capture Costs Breakdown

Cost Factor	Category	Component	Unit	Cost
CAPEX	Equipment	Supporting boiler	US$ million	263.87
		Higher desulphurisation	US$ million	29.27
		Other related equipment	US$ million	139.91
	Total		US$ million	433.05
OPEX	Operation of supporting boiler	Fuel	US$ million /y	23.96
		Other variable costs	US$ million /y	4.65
	Absorbent	Amine	US$ million /y	7.26
	Desulphurisation	NaOH (Sodium hydroxide)	US$ million /y	1.81
	Labour		US$ million /y	51.95
	Total		US$ million /y	89.63
Unit cost			US$/t	37.27

Note: US dollars (2005), calculated from ¥ to $ with yearly average TTS rate (111.21) of MUFG.
Source: Created by the Author based on RITE (2005).

6. Transportation Costs

Multiple studies that examined the cost of CO2 transportation were compared and analysed.

Even though CO2 pipelines are designed for higher pressure than common gas pipelines, these are a relatively mature technology, with multiple thousand miles already in operation (Smith et al., 2021). Pipeline costs are highly variable, depending on the type of terrain, infrastructure crossings, and other factors (Table 2.4). The following table appeared in the National Energy Technology Laboratory (NETL) report as an example of typical rule-of-thumb costs for various terrains, as quoted by a representative of Kinder Morgan at the Spring Coal Fleet Meeting in 2009. The cost range is from US$50,000/mile up to US$700,000/mile.

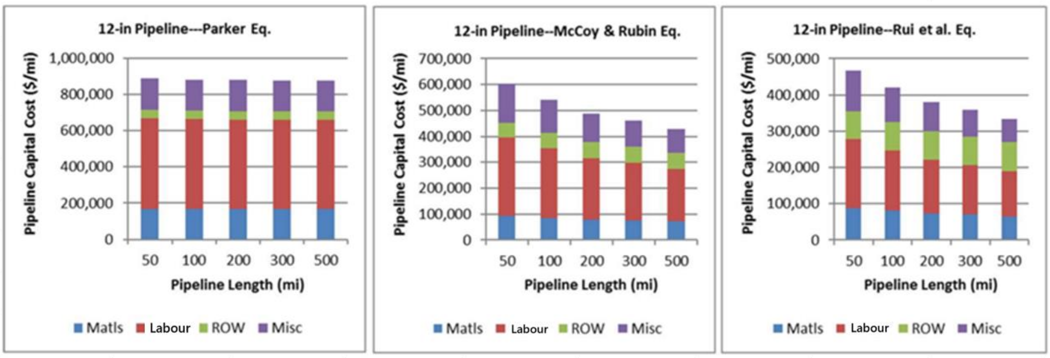
Table 2.4: Transportation Costs (US$)

Terrain	CAPEX
Flat, dry	50,000
Mountainous	85,000
Marsh, wetland	100,000
River	300,000
High population	100,000
Offshore (150–200 ft depth)	700,000

Source: NETL (2017).

In 2018, the NETL designed an Excel-based mathematical model to calculate the cost breakdown for a CO2 pipeline. The model offers the possibility of getting multiple cost estimation patterns (Figure 2.3) by filling in the necessary variables, such as pipeline length, diameter, capture capacity, etc.

Figure 2.3: Breakdown of Natural Gas Pipeline Capital Costs Using Different Equations



Note: Author changed 'Labor' to 'Labour' for consistency.
Source: NETL (2018a).

Using NETL's model, the potential costs of a 50 km long, 12-inch pipeline were calculated (Table 2.5). The Blora Regency, targeted as the storage destination of this project, is characterised by hilly, densely vegetated forests and agricultural lowlands ranging from 25 to 500 meters above sea level. The geographical conditions are important cost-driving factors, as stated earlier. Considering the difficult terrain, Parker's calculation model, which was the most expensive result out of the three options, was chosen for this project.

Next to the apparent costs like labour, materials, and pumps, it is important to consider the right-of-way costs and damages. Included components are highly corrosion-resistant pipelines, pigging facilities, line break valves (usually installed at an interval of 10 km each), monitoring, and control facilities.

Table 2.5: Pipeline Capital Costs (US$)

	CAPEX (Parker)	CAPEX (McCoy)	CAPEX (Rui)
Materials	5,233,256	2,991,604	2,897,806
Labour	15,605,339	10,277,736	6,501,388
Right-of-way and damages	1,511,438	1,723,411	2,313,738
Miscellaneous	5,390,104	5,117,930	3,885,668
CO2 surge tanks	1,244,744	1,244,744	1,244,744
Pipeline control system	111,907	111,907	111,907
Pumps	1,468,064	1,468,064	1,468,064
Total	**30,564,853**	**22,935,396**	**18,423,315**

Source: NETL (2018b).

Operating costs (OPEX) are relatively project-specific. Existing documents do not uniquely define the exact operating expenditure for operations and maintenance of the assets. The total OPEX also includes elements related to overhead and allocation of costs from other functions and their equipment. Annual operating costs, such as fuel for the compressor stations, repair and pigging costs, information technology, and telecommunications, should be considered.

Usually, a share of the capital costs of 3.5% is applied for a common onshore gas pipeline, as stated in Ulvestad and Overland (2012). The OPEX for the model project's CO2 transportation was also calculated using NETL's model (Table 2.6). The energy costs for the pumps are the biggest cost-driving factor, responsible for almost 70% of the transportation OPEX.

Table 2.6: Pipeline Operating Costs (US$)

	OPEX
Pipeline operations and maintenance	262,784
Pipeline related equipment and pumps	112,989
Electricity costs for pumps	748,898
Total	**1,124,671**

Source: NETL (2018b).

In total, the unit cost for the transportation component is US$0.82/t-CO2.

Table 2.7: Pipeline Unit Cost

	Cost Components	Unit	Cost
CAPEX	Materials	US$ million	5.23
	Labour	US$ million	15.61
	Right-of-way and damages	US$ million	1.51
	Miscellaneous	US$ million	5.39
	CO2 surge tanks	US$ million	1.24
	Pipeline control system	US$ million	0.11
	Pumps	US$ million	1.47
	Total	US$ million	30.56
OPEX	Pipeline O&M	US$ million /y	0.26
	Pipeline-related equipment and pumps	US$ million /y	0.11
	Electricity costs for pumps	US$ million /y	0.75
	Total	US$ million /y	1.12
Unit Cost		US$/t	0.82

Source: Created by the Author based on the results of NETL's calculation model.

Besides pipelines, shipping is a major transportation option for longer distances. The CO2 chain for ship transport of CO2 includes liquefaction at the capture site, intermediate storage before transport, loading, transport, and unloading. Costs of a marine transport system comprise many elements. Besides ships, investments are required for loading and unloading facilities, intermediate storage, and liquefaction units. Further costs are for operation (such as labour, ship fuel and electricity, harbour fees) and maintenance.

For marine transport, CO2 is liquefied before being loaded onto ships to reduce its volume. It is cooled down from 0℃ to -20℃ and compromised from about 2 kg/m3 to about 1,100 kg/m3, which is 1/550 in volume. This means a CO2 ship must carry more mass than an equivalent LNG or LPG ship, where the cargo density is about 500 kg/m3.

The downside of CO2 shipping is that marine transport induces more associated CO2 transport emissions than pipelines due to additional energy use for liquefaction and fuel use in ships.

Table 2.8 shows the results of the Zero Emissions Platform study, which estimated the costs for a 'point-to-point' transport case by ship, with 2.5 Mtpa CO2 to storage sites on a distance of 180, 500, 750, and 1,500 km.

Table 2.8: Transport Cost by Shipping

	180 km	500 km	750 km	1,500 km
Number of ships	1	1	1	1
Ship size in m3	22,000	29,300	36,600	25,700
CAPEX (US$ million)	193.36	218.82	243.06	297.95
Annual costs (US$ million /y)	46.95	51.39	55.22	68.99

Note: Costs calculated using the average exchange rate of 2011 from euros to US dollars (US$1.3924)
Source: ZEP (2011).

The estimations mainly consider coaster ships, targeting mid-range transportation for a limited area close to the coast. The CAPEX for such a ship for the widest available range was estimated at US$297.95 million, with an annual expenditure of US$68.99 million. The given range of 1,500 km would cover only a limited area of Indonesia, as shown with a red circle in Figure 2.4. In creating a vast network range covering the whole ASEAN community, many member states of which are separated by sea, it is inevitable to have a fleet of CO2-transport ships that can cover at least a distance of 3,000–5,000 km. At this stage, further improvements will be essential to lower the cost for large-scale, long-range shipping to a feasible level.

Figure 2.4: Geographical Range of 1,500 km in Indonesia

Note: The Author added the red circle and distance of the radius to visualise the range of the ships.
Source: HERE WeGo Maps.

7. Storage Costs

In the storage cost model, multiple stages must be considered. Much subsurface research must be done in the site screening and selection phases, which usually take several years to complete. The duration for permitting depends strongly on the country where the project takes place.

The technologies and equipment used for geological storage are widely used in the oil and gas industries. However, there is a significant range and variability of costs due to site-specific factors, especially if the injection site is onshore or offshore and depending on the reservoir depth.

As for the capture component, RITE's study was a good reference in calculating the storage costs. The study offers multiple cost scenarios for different site specifications (Table 2.9). All costs are calculated with an annual expense ratio of 9% and repair costs of 3%.

Table 2.9: Storage Costs

Type (Water Depth)	Distance from Coast (km)	Depth of Sink (m)	Drilling Costs 100 kt/y Well (US$ million)	Drilling Costs 500 kt/y Well (US$ million)	Offshore Pipeline (US$ million)	Onshore Engineering (US$ million)
Onshore	0	1,000	62.9	12.6	0	0
Onshore	0	2,000	122.3	24.3	0	0
Offshore (30 m)	20	1,000	161.9	40.5	24.3	4.5
Offshore (30 m)	20	2,000	261.7	60.2	24.3	4.5
Offshore (30 m)	20	3,000	344.4	76.4	24.3	4.5
Offshore (150 m)	70	1,000	162.8	40.5	89.9	4.5
Offshore (150 m)	70	2,000	262.6	60.2	89.9	4.5
Offshore (150 m)	70	3,000	345.3	76.4	89.9	4.5

Note: US dollars (2005), calculated from ¥ to $ with yearly average TTS rate (111.21) of MUFG.
Source: RITE (2005).

Besides the sink depth, well size and distance from the coast are very important factors immensely impacting the total storage costs. This model project's case will be an onshore storing site with a well depth of 2,000 m.

Six 500 kt/year wells will be drilled to store the estimated yearly emissions of 2.87 MtCO2/year. Tables 2.10 and 2.11 show the CAPEX for onshore drilling, pre-exploration of the storage site, compressor stations, and OPEX for continuous monitoring. Operating costs for the compressors are not included.

Table 2.10: Drilling Costs and Total CAPEX for Wells

Type	Depth of Sink (m)	Drilling Costs 500 kt/Well (US$ million)	Number of Wells	Total CAPEX for Wells (US$ million)
Onshore	2,000	24.3	6	145.8

Source: Created by the Author. Based on RITE (2005).

RITE calculated additional fixed costs for each well (Table 2.11).

Table 2.11: Additional Fixed Costs for Each Well

Cost Factor	Unit	Costs (US$ million)
Pre-exploration of site, including 3D modelling	US$ million	7.76
Compressor station	US$ million	12
Monitoring	US$ million /y	4.42

Source: RITE (2005).

Combined with the high variability of costs depending on the actual subsurface situation and the fact that the operating costs for the compressor station are not included, it can be assumed that the actual unit cost can rise to double the US$12.92/t-CO2 (Table 2.12).

Table 2.12: Unit Cost of Storage Components

	Cost Factor	Unit	Costs (US$ million)
CAPEX	Wells	US$ million	145.8
	Pre-exploration of site, including 3D modelling	US$ million	46.56
	Compressor station	US$ million	72
	Total	US$ million	264.36
OPEX	Monitoring	US$ million	26.52
Unit Cost		US$/t	12.92

Source: Created by the Author.

8. Applying Plant Cost Index (PCI) Development

As various sources date from different years, a PCI published by Japan's METI was applied to adjust the costs to the year 2020. The baseline at this index is set at 100 for the year 2000. Table 2.13 shows the adjusted unit cost for each component. The total unit cost for this model project is US$62.8/t-CO2.

Table 2.13: Plant Cost Index (PCI)

Year	PCI			
2005	130.0			
2011	137.6			
2020	160.2			
	Capture	**Transport**	**Storage**	**Total**
Unit Cost before adjustments (US$/t-CO2)	37.27	0.82	12.92	51.01
Unit Cost after adjustments (US$/t-CO2)	45.92	0.95	15.93	62.80

Source: JMCTI (2020).

9. Summary of Cost Estimation

Breakdown-wise, the capture costs are the most expensive, over 70%. The additional energy consumption especially has a huge impact on the total costs over the project's lifespan. The associated CO2 emissions, due to additional energy usage, are also an important point to be improved to increase the carbon reduction potential of CCS.

Transportation costs are minimal, which is no surprise, considering the short distance and all parts are onshore. However, as mentioned earlier, storage costs can rise significantly, so the cost balance between capture and storage might differ.

Table 2.14 shows the capture cost is the most expensive component, with over 70% of the overall costs. Transportation costs are minimal due to the short distance, and all parts are onshore. Depending on the storage location, storage costs can rise significantly, so the cost balance between capture and storage might differ in other cases.

Table 2.14: Cost Breakdown Ratio by Component

	Capture	Transportation	Storage
US$/t-CO2	45.92	0.95	15.93
%	73.12	1.52	25.36

Source: Created by the author.

Chapter 3
Regulatory and Policy Study

1. Background and Introduction

The main barrier inhibiting investment in CCS projects is the uncertainty of the scope of responsibility and risks that CCS operators need to undertake. Ensuring a legal and regulatory framework covering the entire life cycle from the planning to post-closure and clarifying processes and responsibilities is an important step to remove those barriers and advance CCS deployment in ASEAN countries. This section examines approaches to formulate the CCS legal framework in ASEAN countries by investigating (i) the general outline of CCS legal frameworks, (ii) the status of CCS legal frameworks in ASEAN countries, (iii) a global case study in CCS regulatory frameworks of CCS-leading countries, and (iv) possible solutions that ASEAN countries can adopt. This section also covers the policy incentives introduced for CCS/CCU in various countries.

2. General Outline of CCS Regulatory Framework

A legal and regulatory framework for CCS addressing the entire life cycle of CCS projects and clearly defining the steps and responsibilities of each participating party is a crucial part of improving the chances of large-scale CCS deployment. In considering the framework, the following items are generally recommended to be examined to establish a high-level outline of the CCS legal and regulatory framework. Each item is elaborated in the following section.

Table 3.1: Summary of the General Outline of CCS Legal and Regulatory Frameworks

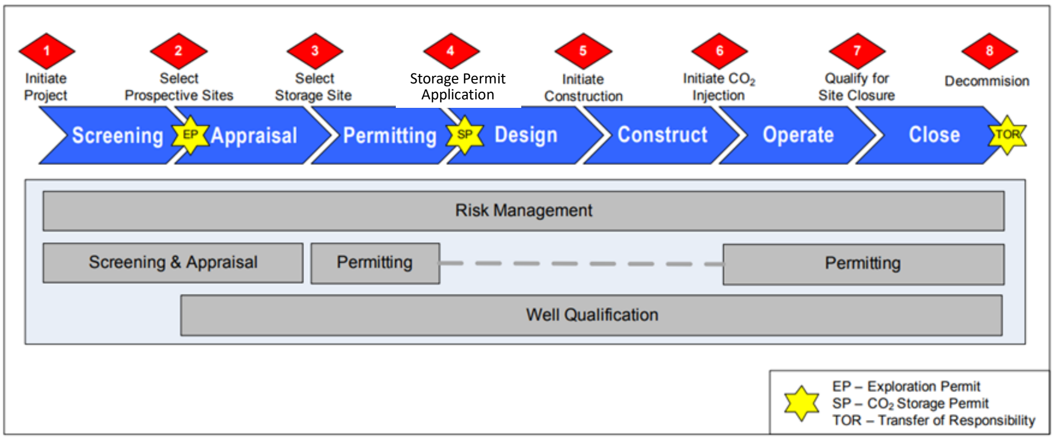
Theme	Contents
Coverage	A CCS legal and regulatory framework covering a whole CCS project life cycle and aligning with the project life cycle is desirable to clarify roles and responsibilities for each participating party in each step of a CCS project.
Issues	Barrier issues specific to CCS projects should be addressed in legal and regulatory frameworks. Some barriers will be addressed in coordination with existing rules where appropriate.
Scope	The legal and regulatory frameworks for CO2-EOR and CO2-CCS operations offer different models as the objectives of each operation differ.
Approach	Developing a CCS legal and regulatory framework varies from country to country. These include utilising the existing regulations that govern the oil and gas sector, developing stand-alone CCS-specific regulations, or developing project-specific CCS regulations.

CCS = carbon capture and storage, EOR = enhanced oil recovery.
Source: Created by the Author (2021).

2.1. Coverage: Life cycle diagram for a CCS project

Figure 3.1 shows the life cycle diagram of a CO2 geological storage project. The decision gates for a CCS project include (i) initiating the project; (ii) selecting prospective sites; (iii) selecting storage sites; (iv) storage permit application; (v) initiating construction; (vi) initiating CO2 injection; (vii) qualifying for site closure; (viii) decommissioning; and (ix) a responsible agency granting permits to a CCS operator for exploration, CO2 storage, transfer of responsibility, or their equivalent during the life cycle of a CCS project. In clarifying each participating party's roles and responsibilities in a CCS project, it is necessary to consider the legal and regulatory framework that covers the whole project life cycle.

Figure 3.1: Life Cycle Diagram of a CO2 Geological Storage Project



Note: Well qualification - the process of providing the evidence that a given well will function within specific limits with an acceptable level of confidence.
Source: DNV (2013).

2.2. Issues: CCS-specific barrier issues

Table 3.2 summarises barrier issues specific to the CCS planning phase thru the post-closure phase. In developing and deploying CCS, legal and regulatory frameworks should address these barrier issues and clarify operators' processes, responsibilities, and roles in implementing CCS. Some barriers, such as pipeline access and environmental requirements, should be addressed in coordination with existing rules where appropriate. On the other hand, other issues, such as long-term liability, stewardship, and public acceptance, are anticipated to be handled with specific provisions for CCS.

Table 3.2: Barrier Issues for CCS Projects

Item	Barrier Issue
Pore space and storage site access	• CCS projects must have access to geological pore space for CO2 storage and/or access to storage sites. • In some jurisdictions, pore space and/or storage sites are privately owned or owned by the national, provincial, or state government.
Pipeline access	• CCS projects must have access to pipelines and pipeline routes to transport CO_2 from source to storage facility. • Some jurisdictions have existing rules for CO2 pipelines or other pipeline rules that may be used or modified.
Rules for geological storage	• Some jurisdictions have no rules for geological storage facilities. • Establish rules for permanent storage that address site selection; suitability of storage formations; environmental requirements; purity of stream requirements; ownership of injected CO2; MRV requirements; storage operator financial responsibility and financial security; site closure, certification, and abandonment; and harmonisation with hazardous waste rules
Long-term liability and stewardship	• CO_2 must be stored indefinitely. However, indefinite responsibility and liability for storage facility operators are neither practical nor conducive to CCS deployment. • Assumption of liability and long-term stewardship by government bodies, trusts, or other entities with perpetual existence after completion of the post-injection monitoring period
Public acceptance	• Public acceptance is essential to CCS deployment because of concerns about CCS effectiveness and risk associated with transport and underground storage of large quantities of material.

MRV = measurement, reporting, and verification.
Source: Created by MRI based on Russial (2011).

2.3. Scope: CO2-EOR and CO2-CCS operations

The legal and regulatory frameworks for CO2-EOR and CO2-CCS operations offer different models (Table 3.3). For CO2-EOR, hydrocarbon recovery is the primary objective, and CO2 storage is incidental so that the regulatory model could be built on the existing law governing oil and gas and related activities. In contrast, CO2 reduction is the primary objective for CO2 storage, so a more detailed definition is required to ensure that CO2 is injected for permanent storage.

Table 3.3: Legal and Regulatory Frameworks for CO_2-EOR and CO_2-CCS

Topic	CO_2–based EOR	CCS–based CO_2 Injections and Storage
Overview	In the CO_2-EOR model, geologic storage of the injected CO_2 is a necessary incident of hydrocarbon recovery operations but is not itself an objective.	In CO_2–CCS operations, the objective is to ensure reductions of anthropogenic CO_2 emitted into the atmosphere.
Legal and regulatory framework	The regulatory model is built on a foundation of the commercial law governing oil and gas and related activities.	The principal components are based, to a significant degree, on pre-existing waste disposal regulations, especially for the CCS Directive of the European Union.
Feature	There has traditionally been no need to develop standards for measuring, verifying, or monitoring the CO_2 injections or reporting such data on a standardised basis to verify permanence.	The standards being considered for adoption may be considerably more prescriptive and extensive than those applied to otherwise comparable CO_2 injections in EOR operations.

EOR = enhanced oil recovery.
Source: Created by MRI based on GCCSI (2013).

2.4. Approach: examples for developing legal and regulatory frameworks

Approaches to developing CCS-specific legal and regulatory frameworks vary from region to region and country to country. The United States (US) has enhanced the existing legal framework by adding CCS-specific provisions. On the other hand, the European Union (EU) has opted to develop a stand-alone CCS-specific legal framework. Some regional governments in Australia have opted for a stand-alone CCS legal framework. In contrast, other regional governments have introduced CCS regulations for a specific project, such as The Barrow Island Act in Australia.

Table 3.4: Different Approaches for CCS-specific Legislation

Approach	Description	Examples
1. Enhance existing legal frameworks with CCS-specific provisions	• A method that builds on existing laws and regulations governing oil and gas and related activities and adds CCS-specific laws and regulations • The resulting legal framework includes requirements for permitting exploration and storage activities, monitoring and reporting obligations, liability and financial security provisions, as well as a process to enable the eventual closure and long-term stewardship of storage sites.	• United States
2. Stand-alone CCS-specific legal frameworks	• Legal frameworks that include coherent processes for selecting underground storage sites, permitting exploration and storage activities, monitoring and reporting, liability and financial security provisions, and closure and long-term stewardship of storage sites	• European Union • Australia
3. CCS project–specific legislation	• CCS project-specific legislation regulates the operations of a single project. An example may be found in The Barrow Island Act regulating Western Australia's Gorgon CO2 injection project.	• The Barrow Island Act in Australia

Source: Created by MRI based on GCCSI (2021a).

3. Status of CCS Legal and Regulatory Framework in ASEAN

As illustrated in Table 3.5, the Asian Development Bank (ADB) and others investigated the legal and regulatory frameworks for CCS in Indonesia, the Philippines, Thailand, and Viet Nam. These studies mentioned that CCS legal and regulatory frameworks are not yet in place in these four countries, except for some provisions for CO2-EOR. On the other hand, Indonesia developed a draft of a CCS-specific legal framework (draft CCUS presidential decree) with ADB's support in 2019. The contents of the regulations are based on existing Indonesian regulations for the upstream oil and gas sector, with additional content specific to CCS. Given the similarities between regulations governing oil and gas and legal and regulatory frameworks for CCS, the studies indicate that utilising existing oil and gas laws is a possible step to be taken to develop legal and regulatory frameworks for CCS in these four countries.

Table 3.5: Status of Regulatory Framework in Some ASEAN Countries

<table>
<tr><th colspan="2">Issue</th><th>Indonesia</th><th>Philippines</th><th>Thailand</th><th>Viet Nam</th></tr>
<tr><td rowspan="2">Surface and subsurface rights for CO2 transport and storage</td><td>Status</td><td colspan="4">No laws exist for CCS ownership, grant, or lease of surface or subsurface pore space. Only the government has the power to grant mineral rights (including oil and gas), which are typically provided through production-sharing contracts.</td></tr>
<tr><td>Required for CCS</td><td colspan="4">CCS will require long-term access through ownership, grant, lease, or contract to surface and subsurface rights, including access to pore space for storage.</td></tr>
<tr><td rowspan="2">CO2 transport</td><td>Status</td><td colspan="4">No existing regulator for CO2 pipeline.</td></tr>
<tr><td>Required for CCS</td><td colspan="4">Clear regulatory and legal framework defining who can build, own, and operate pipelines (or other means) used to transport CO2 for CCS.</td></tr>
<tr><td rowspan="2">Legal liability of CCS operations and for stored CO2</td><td>Status</td><td colspan="4">No current framework for legal liability exists for CCS.</td></tr>
<tr><td>Required for CCS</td><td colspan="4">Short-term and long-term liabilities can arise. Short-term liability relates to operations (environment, health, safety). Long-term liability relates to environmental and health risks from leakage, contamination, or migration. CCS liability can be addressed by adapting existing liability rules for minerals.</td></tr>
<tr><td>Environmental protection</td><td>Current status</td><td colspan="4">No environmental protection rules exist for the CO2 capture process, transport, injection, or storage.</td></tr>
<tr><td rowspan="2">Health and safety</td><td>Status</td><td colspan="4">Standards for general occupational health and safety, as well as health and safety specific to oil and gas, are available. No CCS-specific standards currently exist.</td></tr>
<tr><td>Required for CCS</td><td colspan="4">A clear definition of health and safety for workers and for CCS operations will be required; some will be adapted from existing rules.</td></tr>
<tr><td rowspan="2">Enhanced oil recovery (EOR)</td><td>Status</td><td colspan="4">Limited regulations for CO2-EOR are available in some countries.</td></tr>
<tr><td>Required for CCS</td><td colspan="4">A clear approach to how CO2-EOR will be integrated into the production-sharing arrangement and built into oil-gas field development programmes will be required.</td></tr>
</table>

Source: Created by MRI based on ADB (2013).

4. Global Case Study in Legal and Regulatory Framework for CCS

Table 3.6 shows the regulatory framework in CCS-leading countries, including the EU, Australia, the US, and Norway. Out of leading countries in CCS, the EU has introduced a comprehensive regulation while the US has developed CCS regulations based on existing environmental legal frameworks. Australia has developed stand-alone CCS legislation for federal, state, and project levels. In many EU and European Economic Area countries, the CCS Directive was later incorporated into the existing legal frameworks of each country. For example, some existing regulations were used in Norway or amended, while some were newly created to implement the EU CCS Directive.

ASEAN can also adopt a similar pattern, where basic principles are set for the region while each country develops its regulations either by amending existing ones or creating new ones.

Table 3.6: Regulatory Framework in CCS-leading Countries

Regulatory Type	Region/ Country	Main Regulation	Major Projects
Comprehensive/ stand-alone CCS regulation	European Union	CCS Directive	CarbFix, Acorn, etc.
	Australia	Federal Level: ・ Offshore Petroleum and Greenhouse Gas Storage Act State Level: ・ e.g. Victoria's Greenhouse Gas Geological Sequestration Act 2008 Project Level : ・ e.g. Barrow Island Act 2003 applied to Gorgon Project (for onshore and offshore within 3 nautical miles)	Gorgon Project
Using existing environmental regulation	United States	'UIC Program' based on Safe Drinking Water Act	Various
Comprehensive regulation is incorporated into existing regulations	Norway	**[Existing]** ・ 1963 Act on Research, Exploration and Exploitation of Other Natural Resources than Petroleum on the Ocean Floor ・ 1996 Act Relating to Petroleum Activities ・ 1981 Act Concerning Protection Against Pollution and Concerning Waste **[Amended or developed based on CCS Directive]** ・1997 Regulations to Act Relating to Petroleum Activities	Longship/ Northern Lights

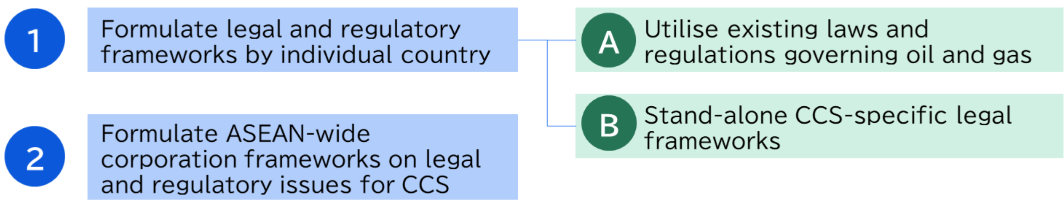
		・2014 Regulations Relating to Exploitation of Subsea Reservoirs on the Continental Shelf for Storage of CO2 and Relating to Transportation of CO2 on the Continental Shelf ・2017 Regulations Relating to Material and Documentation in Connection with Exploration for and Exploitation of Subsea Reservoirs on the Continental Shelf for Storage of CO2	

Source: Created by MRI based on METI (2020).

5. Desired Regulatory Framework for ASEAN

As mentioned in the previous section, there are several approaches to develop legal and regulatory frameworks for CCS, including enhancing existing legal frameworks with CCS-specific provisions, stand-alone CCS-specific legal frameworks, and CCS project–specific legislation (Figure 3.2). Whichever approach is adopted, CCS-specific issues – pore space and storage site access, pipeline access, rules for geological storage, long-term liability/stewardship, public acceptance, etc. – must be addressed to clarify the processes, responsibilities, and roles of each participating party. Based on the CCS regulatory frameworks of CCS-leading countries, the following three optional approaches can be adopted in the ASEAN region, where legal and regulatory frameworks for CCS will be newly developed as CCS projects gain importance in the context of emission reductions.

Figure 3.2: Possible Approaches for Developing a Regulatory Framework in ASEAN



ASEAN = Association of Southeast Asian Nations; CCS = carbon capture and storage.
Source: Created by MRI (2021).

Out of three options, option 1A – formulating legal and regulatory frameworks by individual country or utilising existing laws and regulations governing oil and gas – may be the first step in developing a CCS-specific legal and regulatory framework since it can be considered in a single country and can use existing regulations as a fundamental basis. Option 1B – formulating legal and regulatory frameworks by individual country/stand-alone CCS-specific legal frameworks – would be another option for a single country to develop and use as a comprehensive legal framework. On the other hand, option 2 –

formulating ASEAN-wide corporation frameworks on legal and regulatory issues for CCS – may be a desirable approach for the ASEAN region in the long run for the following reasons:

- Large-scale emission reductions, including hard-to-abate sectors, will be required to achieve net-zero emissions in the future, and robust legal and regulatory issues for CCS will play a significant role in the ASEAN region.
- Multiple issues are specific to CCS, and it will take time to examine the legal and regulatory issues for CCS in individual countries.
- Emission sources and possible storage sites may be located far away from each other, so cooperation amongst multiple countries may be necessary to develop regional hub-and-cluster projects in the ASEAN region in the future.

The delay in the development of CCS laws and regulations that clarify the scope of risks and responsibilities will cause a delay in securing financing, ending up hindering the scalability of CCS projects. An ASEAN-wide cooperation framework on legal and regulatory issues for CCS, which serves as a common guideline for CCUS in the ASEAN region that breaks through the limitations of individual legal systems, will potentially advance CCUS development in the region.

6. Policy Incentives for CCUS

This section covers the policy incentives for CCS, CCUS, and CCU projects. The scale of CCUS projects is relatively large compared to other emission reduction measures. It requires long-term risk management; therefore, CCUS faces specific challenges, especially in the initial scaling-up phase. In developing CCUS projects as profitable business cases, policy incentives can accelerate the smooth transition from the R&D phase to the demonstration phase and the demonstration phase to the commercial phase. Policy measures for CCUS include direct capital grants, tax credits, carbon pricing mechanisms, operational subsidies, etc. Continuous support for innovation is also needed to drive down costs and develop and commercialise new technologies. Table 3.7 shows representative policy instruments adopted in various counties to promote CCUS.

Table 3.7: Main Policy Instruments for CCUS Development and Deployment

Category	Types	Examples
Grant support	• Capital funding provided directly to targeted projects or through competitive programmes to overcome high upfront costs	• UK CCUS Infrastructure Fund • EU Innovation Fund
Operational subsidies	• Tax credits based on CO2 captured/stored/used • Contracts-for-difference (CfD) mechanisms covering the cost differentials between production costs and a market price • Feed-in tariff mechanisms with long-term contracts with low-carbon electricity producers • Cost-plus open book mechanisms in which governments reimburse some costs as they are incurred, reducing risk for the contractor	• US 45Q and 48A tax credits • Netherlands' SDE++ scheme • UK power sector • CfD arrangements
Carbon pricing	• Carbon taxes, which impose a financial penalty on emissions • Emission trading schemes (ETSs) involving a cap on emissions from large stationary sources and trading of emissions certificates	• Norway carbon tax on offshore oil and gas • European ETS • China ETS • Canada federal Output-based Pricing System
Demand-side Measures	• Public procurement of low-CO2 building materials, transport fuels, and power, including those produced with CCUS • Border adjustments, adding a carbon tariff on imported goods to prevent competition from those with higher CO2 and a lower price	• Canada's and The Netherlands's rules favouring low-CO2 material inputs for construction projects, etc.
CCUS-specific market mechanisms	• Tradable certificates or obligations, such as fuel standards favouring low-carbon fuels for transport or stationary applications • Carbon storage units based on a verified	• Carbon sequestration units of Saudi Arabia • C-capsule, tradable

	record of CO2 securely stored, which could be purchased by emitters from those storing carbon (proposed).	carbon removal certificate (private initiative)
Regulatory standards and obligations	• Mandates on manufacturers to meet emissions criteria or oblige firms to purchase a minimum share of products with low life-cycle CO2 emissions • Regulated asset base, a model for investment recovery through a regulated product price passed on to consumers • Emissions standards establishing limits on unabated CO2 emissions	• EU Renewable Energy Directive II • Australia–Gorgon LNG project CCS requirement • UK energy and infrastructure markets employ a regulated asset base model, etc.
Risk mitigation measures	• Loan guarantees covering project developers' debt should they default on loans • Pain-gain risk-sharing mechanisms whereby partners share some projects risks • CO2 liability ownership, in which governments take a share of liability for stored CO2, particularly after project closure	• Australian legislation allowing the transfer of CO2 liability to the state
Innovation and research and developmen t (R&D)	• Funding for R&D, either directly in state-run research institutions or indirectly through grants and other types of subsidy for private activities • Competitive approaches to support R&D for low-carbon technology	• Canada/US Carbon XPRIZE • EU Horizon 2020 • US Department of Energy CCUS R&D programmes

Source: Created by MRI based on IEA (2020).

The UK CCUS Infrastructure Fund and US 45Q tax credits are summarised as examples of policy instruments for CCUS development and deployment.

Example #1: Grant Support: UK CCUS Infrastructure Fund

The UK government has committed to deploying CCUS in two industrial clusters by the mid-2020s and four industrial clusters by 2030. The CCS Infrastructure Fund (CIF) supports capital expenditure on transport and storage networks and industrial carbon capture projects (Table 3.8).

Table 3.8: Summary of UK CCUS Infrastructure Fund

Item	Description
General information	The CIF is expected to primarily contribute to the capital costs of establishing transport and storage (T&S) infrastructure and early industrial capture projects. The CIF will support in delivering the following: • Establishing a new CCUS sector • Enabling low-cost decarbonisation in multiple sectors • Developing a market for carbon capture
Phase	The CIF will be allocated to projects via the two-phase cluster sequencing process. • Phase 1: the government will provisionally sequence those that are most suited to deployment in the mid-2020s onto Track 1 • Phase 2: the government will receive applications from individual projects across capture applications to connect to the Track 1 clusters
Budget	The allocation of £1 billion was confirmed in November 2020.
Allocation	The CIF is expected to be allocated to clusters through the proposed cluster sequencing process, along with: • Business models for T&S, power, industrial carbon capture (ICC), low-carbon hydrogen, and potentially bioenergy with carbon capture and storage, which include: ➢ a revenue mechanism to bring through private sector investment into ICC and hydrogen projects; ➢ an economic licence that grants the licensee a regulated revenue stream facilitated by the right to charge a regulated fee (the 'T&S fee') from completion of construction; and • capital expenditure for CCUS-enabled 'blue' hydrogen projects from the £240 million net-zero hydrogen fund. Funding for electrolytic 'green' hydrogen projects will be allocated separately.

Source: Created by MRI based on BEIS (2021).

Example #2: Operational subsidies: US 45Q Tax Credit

The carbon oxide sequestration credit – 45Q – named after the relevant section in the US Tax Code, applies to carbon dioxide (CO_2) and other carbon oxides (e.g. carbon monoxide). It provides a certain amount of monetary credit for carbon oxide permanently stored via usage, tertiary oil injection, or in geologic formations, as described in Table 3.9.

Table 3.9: Summary of US 45Q Tax Credit

Item	Description
Credit amount (per metric tonne of CO_2)	• Geologically sequestered CO_2: US$31.77 in 2020. Increasing to US$50 by 2026, then inflation-adjusted • Geologically sequestered CO_2 with EOR: US$20.22 in 2020. Increasing to US$35 by 2026, then inflation-adjusted • Other qualified use of CO_2: US$20.22 in 2020. Increasing to US$35 by 2026, then inflation-adjusted
Claim period	• 12-year period once the facility is placed in service.
Claim period	• Begin construction before 1 January 2026
Annual capture requirements	• Power plants: capture at least 500,000 t. • Facilities that emit no more than 500,000 t/year: capture at least 25,000 t • Direct Air Capture (DAC) and other capture facilities: capture at least 100,000 metric tonnes
Eligibility to claim credit	• The person who owns the capture equipment and physically or contractually ensures the disposal, utilisation, or use as a tertiary injectant of the CO_2.

Note: Different elements are applied for the equipment placed in service before 9 February 2018.
Source: Created by Author based on Congressional Research Service (2021).

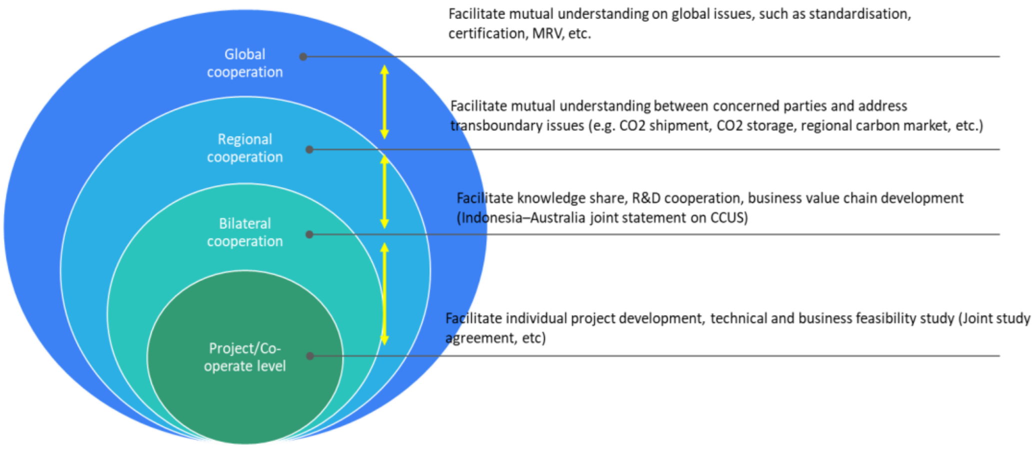
Chapter 4

Regional Cooperation Concept

1. The Concept

As explained in chapter 2, CCUS requires large-scale investment. As such, wide-ranging technical and transboundary policy issues can be addressed through a multilayered cooperation framework encompassing national borders. A large-scale CCUS project can greatly benefit from business or project-level cooperation, country-to-country cooperation that can lead to regional, and eventually to global cooperation (Figure 4.1). Further details of this multilayered cooperation concept is described in the subsequent subsections.

Figure 4.1: Further Actions for a Regional Cooperation Concept



Source: Created by author (2021).

2. Project and/or Corporate Level Cooperation

Table 4.1 describes issues that can be addressed, potential players, and actual examples of project and/or corporate-level cooperation. Such cooperation can contribute to individual project development. Examples include the implementation of technical and business feasibility studies through joint agreements.

Table 4.1: Project and/or Corporate-level Cooperation

Issues that can be addressed	• Storage potential survey • Site survey • Technical feasibility • Economic feasibility • Business model development • Estimation of GHG emissions reduction
Players	• National oil companies • International oil majors • Off-takers • Technology suppliers • Research institutes
Examples	• Memorandum of understanding (MOU) between Pertamina and ExxonMobile on CCUS potential study • MOU between Petronas and ExxonMobile on CCUS potential study • Joint Study Agreement between Japan Petroleum Exploration Col, ltd., LEMIGAS, and Pertamina for Sukowati CCUS project (Indonesia) • Joint Study Agreement between JGC Corp, Japan NUS, J-Power, Institut Teknologi Bandung, and Pertamina for Gundhi CCUS project (Indonesia)

GHG = greenhouse gas.
Source: Created by MRI.

3. Bilateral Cooperation

Table 4.2 describes issues that can be addressed, potential players, and actual examples of bilateral cooperation. Bilateral cooperation can facilitate knowledge sharing, research and development cooperation, and the creation of a business value chain. Examples include the Joint Statement on CCUS between Indonesia and Australia and the Joint Crediting Mechanism between Japan and key Southeast Asian countries – Cambodia, Indonesia, the Lao PDR, Myanmar, the Philippines, Thailand, and Viet Nam – that aim to put an economic value on CO2 reduction through the introduction of advanced low-carbon technologies.

Table 4.2: Bilateral Cooperation

Issues that can be addressed	• Government commitment through shared objectives • Comprehensive cooperation (R&D to global business value chain development) • Financial support • Paris Agreement, Article 6 on Collaboration (e.g. Joint Crediting Mechanism)
Players	• Governments • National research institutions
Examples	• Australia–Indonesia Joint Statement on Cooperation on the Green Economy and Energy Transition • Include reference to supporting CCS/CCU projects through green finance, carbon offset project collaboration, etc.) • Japan–Saudi Vision 2030 • Include CO2-free ammonia production with CCUS • Japan–Indonesia bilateral agreement on Joint Crediting Mechanism

Source: Created by author (2021).

4. Regional Cooperation

Table 4.3 describes issues that can be addressed, potential players, and actual examples of regional cooperation. Regional cooperation can facilitate mutual understanding between concerned parties and address transboundary issues, such as CO2 shipment and CO2 storage that cross borders and the regional carbon market. Such cooperation can lead to raising larger funds and creating larger businessed that benefit various players of value chain encompassing multiple countries, such as high CO2-emitting industries, countries with depleted oil and gas fields, shipping companies, and construction companies, amongst others.

Table 4.3: Regional Cooperation

Issues that can be addressed	• Regional policy development • Knowledge share, capacity development • Financial support • Transboundary issues
Players	• Governments • Regional organisations (ERIA, ASEAN Centre for Energy, ADB, Coordinating Committee for Geoscience Programmes in East and Southeast Asia, etc.)
Examples	• ASEAN Petroleum Service Agreement (introduced as a joint effort to tackle energy shortage) • Asia CCUS Network (capacity development, storage mapping, enabling environment discussion) • EU CCS Directive (regulation for permitting and enabling CCS) • ERA-NET (EU regional funding and networking support for research activities) *ACT Acorn received funding from the UK Government Department for Business, Energy and Industrial Strategy, the Research Council of Norway, and The Netherlands Enterprise Agency and is co-funded by the European Commission under the ERA-NET instrument of the Horizon 2020 programme.

Source: Created by author (2021).

5. Global Cooperation

Table 4.4 describes issues that can be addressed, potential players, and actual examples of global cooperation. Global cooperation can facilitate mutual understanding on global or international issues, such as standardisation; certification; and methods for measurement, reporting, and verification (MRV) of CO2 emissions reduction. The work towards gaining international recognition will lead to increased confidence in CCUS business in the Asian region, facilitating further project development and investment.

Table 4.4: Global Cooperation

Issues that can be addressed	• Regional policy development • Knowledge share, capacity development • Financial support • Transboundary issues
Players	• Governments • Regional organisation (ERIA, ASEAN Centre for Energy, ADB, Coordinating Committee for Geoscience Programmes in East and Southeast Asia, etc.)
Examples	• Communiqué G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth 2019 (taking note of work on 'Carbon Recycling' and 'Emissions to Value') • Clean Energy Ministerial (high-level policy network) • Oil and Gas Climate Initiative (industry-led platform) • Global CCS Institute (international think-tank)

Source: Created by the author (2021).

Chapter 5
Workshop on the Model Case Study

1. Overview

Based on the outcome of the model case study (MCS), including cost analysis, regulatory and policy frameworks, and regional institutional and policy proposals were presented to stakeholders of the ACN members on 18 January 2022. In addition to the report on the MCS outcome, four panellists from various backgrounds (government, industry, academic, and financial industries) were invited to exchange ideas on possible scenarios for project development in ASEAN.

2. Agenda

Table 5.1: Agenda of Model Case Study (MCS) Workshop

	Topic	Presenter
1	Welcome address and introduction to Asia CCUS Network and its 2021 activities	Shigeru Kimura, Special Advisor on Energy Affairs, Economic Research Institute for ASEAN and East Asia (ERIA)
2	Outcomes of MCS, cost analysis, and policy proposal	Ulysses Coulmas, Researcher, Mitsubishi Research Institute (MRI) Ayami Saimura, Researcher, MRI
3	Panel Discussion Topics will include the following: 1) CAPEX/OPEX reduction potential 2) Policy/legal requirement 3) Regional cooperation approach 4) Further project development needs towards commercialisation 5) Findings from model case exercise Moderated by Kikuko Shinchi, Senior Researcher, MRI	1) Yoshihiro Sawada, Corporate Adviser, General Manager of International Affairs Department, Japan CCS Co., Ltd. 2) Mohammad Rachmat Sule, Lecturer, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung 3) Jinmiao Xu, Energy Specialist, Energy Sector Group, Sustainable Development and Climate Change Department, Asian Development Bank 4) Yukimi Shimura, Director, Planning & Development

		Department, Sustainable Business Division, MUFG Bank, Ltd. 5) Ulysses Coulmas, Researcher, MRI
4	Closing remarks	Han Phoumin, Senior Energy Economist, ERIA

3. Main Topics of Discussions

As discussed in the MCS in previous chapters, a collective effort is needed to push CCUS forward. But, first, the barriers that could be overcome and the effort that could be made by all parties involved had to be understood and made known to the public. A few topics and issues raised are as below.

- **Cost reduction through scaling up and learning by doing**

According to the JCCS' study of the Tomakomai demonstration project in Japan, based on the assumption of 25 years' operation, the unit price of 200,000 t/year of capacity model is calculated, excluding pilot and demonstration facility. Then, the 200,000 t/year is scaled up to 5 times, which is 1,000,000 t/year, and the model is further calculated.

The result, the unit cost of 200,000 t/year of capacity model, is 123 US$/t-CO2 while the unit cost of 1,000,000 t/year of capacity model costs US$67/t-CO2. This implies that with scaling up of capacity to five times more, the unit cost is reduced to half. This has proven that scaling up is important in cost reduction.

For reference, a study of unit costs for a full-chain project in Norway estimated that the cost of storing 1.5 million t/year would be more than US$100/t-CO2, and the cost of storing 300 million t/year would be less than US$30/t-CO2. In other words, scaling up is important.

The CO2 capture cost accounts for 76% of the total cost in Tomakomai's case, indicating that reducing the capture cost is important in lowering the CCS cost. The MRI study results also show that the capture cost is approximately 70%, in the same range as the JCCS cost study. Technological innovation is needed to reduce the recovery cost. Also, in this study, the operating cost is huge compared to the capital cost because fuel and electricity prices are commercial prices. If the energy produced in the facility could be used, the operating costs would be much lower.

The importance of scaling up and reducing CO2 capture costs to reduce the cost of CCS is indispensable. Still, another thing to emphasise is the importance of cost reduction through experience or learning-by-doing. Without experience, there is a possibility of over-equipping and inappropriate planning and design.

- **Policy and legal framework**

From the private sector's perspective, it may be preferable to have a common guideline, and that would be helpful for project development if we were to consider regional hub and cluster. It is also essential that stakeholders, such as banks and corporations, be included in the regional framework. Also, demonstration projects in Asia should be increased to provide lessons to be learnt. Incentive schemes to enable the bankability of projects should include carbon credits. Green finance schemes should also be developed and promoted further in the region.

Indonesia, together with ADB, had developed a legal framework in 2019. A new draft is currently being prepared by the Ministry of Energy and Mineral Resources of Indonesia. New aspects expected to be included are a measurement of CO_2 and ways to monetise CO_2.

Although several well-established CCUS-related legal frameworks in developed countries can be used as a reference, none of them can be replicated as in Asia and ASEAN specifically. Starting projects in the oil and gas sector, where legal jurisdiction is slightly clearer, helps regulatory framework development.

- **The obstacles in developing a bankable scheme**

There are still many unknowns in terms of the responsibilities of stakeholders in CCUS. For example, some regulatory issues can be covered in the existing framework even in Asia, but the responsibility is still not clear in many aspects. However, there is no precedence for financial institutions to judge in case of unexpected events, making financing CCUS projects a hard decision to make.

Government commitment is also important. Government subsidies play an important part in developing CCUS. The long-term commitment by the government may be the key to ensuring confidence for the private sector when making its decisions.

- **The need for more capacity building and sharing of experience**

Capacity building should be increased. The decade-long collaboration between Indonesia and Japan and technical feasibility studies can advance project development. The priority on joint work should be on storage capacity determination. Sharing experience and learning would lead to increased confidence of investors and other stakeholders of CCUS in the region.

Chapter 6

Conclusions and Recommendations

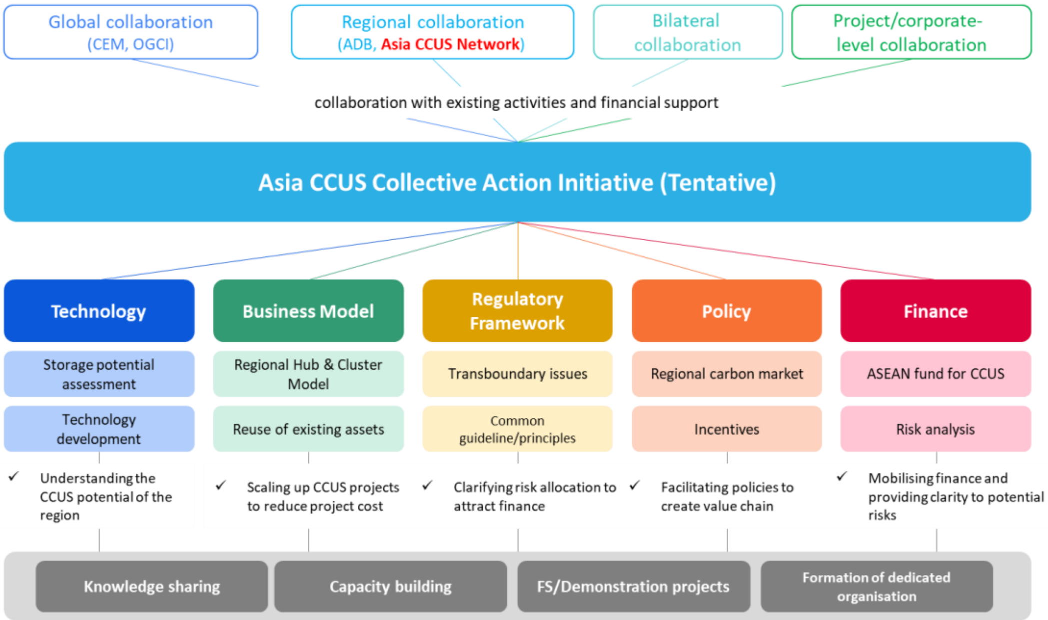
The CCUS value chain cost assessment conducted in the MCS (chapter 2), regulatory and policy study (chapter 3), and the discussion at the MCS workshop (chapter 5) have revealed that cost reduction effort and development of regulatory and policy framework complement each other. As discussed at the workshop, cost reduction is most likely achieved through technological development and business scale-up, facilitated by investment through policy support. Moreover, large-scale financing will only be possible with clarified responsibilities of each concerned party accompanied by clear risk allocation.

Although many cooperative activities are already taking place (chapter 4), laying the foundations for CCUS promotion in the Asian region, they remain somewhat fragmented. To achieve this virtuous cycle of facilitation of CCUS deployment and the development of an enabling environment, the following are suggestions for comprehensive and cohesive further regional engagement, based on the comments obtained from the MCS workshop participants.

- Continuous implementation of joint feasible studies and demonstration projects that lead to workable business model creation
  Technological development and building know-how through 'learning by doing' are keys to cost reduction.
- Increased capacity building to raise awareness on regulatory issues and policies share lessons learnt from advanced cases studies from Asia and outside of Asia for engaging with those countries that have yet to start a deep discussion on regulatory and policy issues to promote CCUS
- Collection of more storage capacity data to create business opportunities
  Data collection is a lengthy and costly process that can greatly benefit from regional collaboration.
- Regional finance mobilisation through positioning CCUS within regional green finance framework, and developing a regional carbon market a regional CCUS fund

Considering the suggestions above, a collective action initiative of CCUS in the Asian region, tentatively called 'Asia CCUS Collective Actions Initiative' through which participating countries can agree on basic principles and areas for joint efforts to promote CCUS, is recommended. Areas of cooperation can be broadly categorised into technology, business model, regulatory framework, policy, and finance (Figure 6.1). In technology, a collaborative approach in storage potential assessment and technology development can lead to a better understanding of CCUS potential in the region to possibly identify increased business opportunities. In the business model, networking different business entities to create a business model fit for regional hub and cluster model and efficient use of infrastructure, including reuse of existing assets, would lay the foundation for scaling up CCUS projects to increase cost performance. In regulatory framework, setting common guidelines or principles, referring to international case studies and local situations, will provide participating countries the necessary know-how and materials to discuss CCUS-specific regulatory issues, such as liability and CO_2 monitoring in each country in a regional cohesive manner. In policy, a regional carbon market and incentives can be designed to create a CO_2 value chain. Last but not least, in finance, creating a regional fund through collaboration with international and regional partners would demonstrate the region's commitment for decarbonisation through CCUS, acting as an anchor to mobilise private finance.

Figure 6.1: Concept of 'Asia CCUS Collective Action Initiative (TBC)'



Source: Created by author (2021).

The keys to enabling the work in the areas described above to produce results are knowledge sharing, capacity building, feasibility study and demonstration projects, and the formation of an organisation to spearhead the effort. Hopefully, the ACN will start the initiative in this area as a regional and collective CCUS framework.

References

ADB (2013), 'Prospects for Carbon Capture and Storage in Southeast Asia', https://www.adb.org/sites/default/files/publication/31122/carbon-capture-storage-southeast-asia.pdf (accessed 16 November 2021).

ADB (2019), 'Pilot Carbon Capture and Storage Activity in the Natural Gas Processing Sector: Gundih Block Feasibility Design and Costing Consultant's Report', https://www.adb.org/sites/default/files/project-documents/49204/49204-002-tacr-en.pdf (accessed 16 November 2021).

BEIS (2021), 'The Carbon Capture and Storage Infrastructure Fund An Update on the Design of the CCS Infrastructure Fund', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/984001/ccs-infrastructure-fund-cif-design.pdf (accessed 24 January 2022).

Congressional Research Service (2021), 'Carbon Storage Requirements in the 45Q Tax Credit', https://crsreports.congress.gov/product/pdf/IF/IF11639#:~:text=In%20tax%20year%202020%2C%20Section,in%20other%20qualified%20industrial%20processes (accessed 24 January 2022).

DNV (2013), 'Geological Storage of Carbon Dioxide', https://rules.dnv.com/docs/pdf/dnvpm/codes/docs/2013-07/RP-J203.pdf (accessed 16 November 2021).

GCCSI (2013), 'Bridging the Gap: an Analysis and Comparison of Legal and Regulatory Frameworks for CO2-EOR and CO2-CCS', https://www.researchgate.net/publication/277188485_Bridging_the_gap_an_analysis_and_comparison_of_legal_and_regulatory_frameworks_for_CO2-EOR_and_CO2-CCS (accessed 16 November 2021).

GCCSI (2021a), 'CCS in the Circular Carbon Economy: Policy and Regulatory Recommendations', https://www.globalccsinstitute.com/wp-content/uploads/2021/08/Fee-for-Service-Circular-Carbon-Economy-Policy-Regulatory-Recommendations-1.pdf (accessed 16 November 2021).

GCCSI (2021b), 'Technology Readiness and Costs of CCS', https://www.globalccsinstitute.com/wp-content/uploads/2021/04/CCS-Tech-and-Costs.pdf (accessed 24 January 2022).

Global Energy Monitor, Global Coal Plant Tracker, https://globalenergymonitor.org/projects/global-coal-plant-tracker/tracker/ (accessed 29 October 2021).

HERE WeGo Maps, https://wego.here.com/?map=1.55771,152.46378,4,normal (accessed 30 November 2021).

IEA (2020), 'Energy Technology Perspectives 2020', https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf (accessed 16 November

2021).
IPCC (2005), 'The IPCC Special Report on Carbon Dioxide Capture and Storage', https://www.researchgate.net/publication/239877190_IPCC_Special_Report_on_Carbon_dioxide_Capture_and_Storage (accessed 22 November 2021).
IPCC (2006) 'IPCC Guidelines for National Greenhouse Gas Inventories', https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf (accessed 30 October 2021).
JMCTI (2020), 'Summary of Plant Cost Index', https://www.jmcti.org/planthomepage/report/2020PCI_LF_summary.pdf (accessed 22 November 2021).
METI (2020), 'FY2019 Study on the Infrastructure Development Project for Acquisition of JCM Credits (International Cooperation in CCUS) Report', https://www.meti.go.jp/meti_lib/report/2019FY/000272.pdf (accessed 16 November 2021).
NETL (2017), 'Quality Guidelines for Energy System Studies: Carbon Dioxide Transport and Storage Costs in NETL Studies', https://netl.doe.gov/projects/files/QGESSCarbonDioxideTransportandStorageCostsinNETLStudies_110617.pdf (accessed 16 November 2021).
NETL (2018a), 'FE/NETL CO2 Transport Cost Model (2018): Description and User's Manual', https://netl.doe.gov/projects/files/FENETLCO2TransportCostModel2018DescriptionandUsersManual_050718.pdf (accessed 16 November 2021).
NETL (2018b) 'FE/NETL CO2 Transport Cost Model', https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fnetl.doe.gov%2Fprojects%2Ffiles%2FFENETLCO2TransportCostModel2018_050118.xlsm&wdOrigin=BROWSELINK (accessed 16 November 2021).
RITE (2005), 'Report on Carbon Dioxide Fixation and Effective Utilisation Technology: Results of the Carbon Dioxide Underground Storage Technology Research and Development Project'. http://www.rite.or.jp/results/result_reports/pdf/2005-chichu-6.pdf (accessed 19 November 2021) (in Japanese).
Rubin, E.,S. J.E. Davison, and H.J. Herzog (2015), 'The Cost of CO2 Capture and Storage', https://www.sciencedirect.com/science/article/pii/S1750583615001814 (accessed 31 January 2022).
Russial, T.J. (2011), 'Carbon Capture and Storage – Legal and Regulatory Framework', US Carbon Sequestration Council, https://usea.org/sites/default/files/ccc17012011_Carbon%20capture%20and%20storage%20-%20legal%20and%20regulatory%20framework_ccc179.pdf (accessed 16 November 2021).
Smith, E., J. Morris, H. Kheshgi, G. Teletzke, H. Herzog, and S. Paltsev (2021), 'The Cost of CO2 Transport and Storage in Global Integrated Assessment Modelling', *International Journal of Greenhouse Gas Control*, Volume 109, 2021, 103367, ISSN 1750-5836,

https://doi.org/10.1016/j.ijggc.2021.103367 (accessed 16 November 2021).
Tsuji, T., M.Y.N. Khakim, K. Kitamura, Y. Yamada, T. Matsuoka, K. Onishi, A. Asikin, T. Ariadji, W. Kadir, and Gundih CCS Project Team (2013), 'CCS Project in Gundih Gas Field, Indonesia (Part 2): Reservoir Characterization and Simulation', https://www.researchgate.net/publication/262379254_CCS_Project_in_Gundih_gas_field_Indonesia_Part_2_-_Reservoir_characterization_and_simulation (accessed on 24 January 2022).
Ulvestad, M. and I. Overland (2012), 'Natural Gas and CO_2 Price Variation: Impact on the Relative Cost-efficiency of LNG and Pipelines', *The International Journal of Environmental Studies*, 69(3), pp. 407–26. https://doi.org/10.1080/00207233.2012.677581 (accessed 16 November 2021).
ZEP (2011), 'The Costs of CO2 Transport: Post-demonstration CCS in the EU', https://www.globalccsinstitute.com/archive/hub/publications/119811/costs-co2-transport-post-demonstration-ccs-eu.pdf (accessed 22 November 2021).