THE APPLICATION OF FMEA TO STUDY THE CRITICAL BARRIERS TO DEPLOYING CARBON CAPTURE AND STORAGE IN A THAI PETROLEUM REFINERY

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การประยุกต์ใช้ FMEA เพื่อศึกษาอุปสรรคในการปรับใช้เทคโนโลยีการดักจับและการกักเก็บคาร์บอนของโรงกลั่นปิโตรเลียมในประเทศไทย

น.ส.อมรรัตน์ เศรษฐี

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Thesis Title	THE APPLICATION OF FMEA TO STUDY THE CRITICAL BARRIERS TO DEPLOYING CARBON CAPTURE AND STORAGE IN A THAI PETROLEUM REFINERY
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เทคโนโลยีการดักจับและการกักเก็บคาร์บอน (CCS) เป็นเทคโนโลยีการลดก๊าซเรือนกระจกที่อยู่ในช่วงต้นของการพัฒนา ซึ่งยังคงไม่รวมอยู่ในแผนการลดการเปลี่ยนแปลงสภาพภูมิอากาศในประเทศไทย ซึ่งในปัจจุบันยังไม่มีทรัพยากรและการส่งเสริมทางการตลาดมากเพียงพอเพื่อส่งเสริมการพัฒนาและการปรับใช้ เนื่องจากมีความต้องการในการใช้พลังงานเพิ่มขึ้นอย่างต่อเนื่อง ทำให้เทคโนโลยีการดักจับและการกักเก็บคาร์บอน (CCS) มีบทบาทสำคัญที่ช่วยในการลดการปล่อยก๊าซเรือนกระจกในอีกไม่กี่ปีข้างหน้า ทั้งนี้เพื่อให้การประยุกต์ใช้เทคโนโลยีดังกล่าวประสบผลสำเร็จและมีประสิทธิภาพมากขึ้น จำเป็นต้องศึกษาข้อจำกัดและประเมินความเสี่ยงที่จะเป็นอุปสรรคต่อการปรับใช้และวางแผนการดำเนินการประยุกต์ใช้เทคโนโลยีดังกล่าว

การศึกษาครั้งนี้ผู้วิจัยมีวัตถุประสงค์เพื่อระบุข้อจำกัดและอุปสรรคในการพัฒนาและการปรับใช้เทคโนโลยี CCS ในโรงกลั่นปิโตรเลียมของไทย เพื่อใช้เป็นกลยุทธ์ในการลดการปล่อยก๊าซเรือนกระจก โดยใช้กรอบการทำงานของเทคโนโลยี - องค์กร - สิ่งแวดล้อม (TOE) และประเมินจากความเสี่ยงที่เกิดขึ้นภายในโรงกลั่นปิโตเลี่ยม จากการประยุกต์ใช้ FMEA โดยมีจุดมุ่งหมายในการค้นหาหมายเลขวิกฤติ (Criticality Number) ของแต่ละอุปสรรค โดยอ้างอิงจากความรู้และประสบการณ์ของผู้เชี่ยวชาญในโรงกลั่นปิโตรเลียมของไทย มีการศึกษาอุปสรรคทั้งหมด 29 จุด โดยแบ่งออกเป็น 9 เทคโนโลยี 9 องค์กร 11 สิ่งแวดล้อม และได้แสดงบนอิชิกาวะไดอะแกรม รวมถึงการวิเคราะห์พาเรโต้ ซึ่งผลลัพธ์ที่ได้คือ ลำดับความสำคัญของอุปสรรคต่อการนำเทคโนโลยีดังกล่าวมาประยุกต์ใช้ที่โรงกลั่นปิโตเลี่ยม และได้มีการจัดทำแผนการและกลยุทธ์ในการจัดการความเสี่ยงที่เหมาะสมกับผลลัทธ์ที่ได้มา โดยประเมินจากเกณฑ์ดังนี้ ความสำคัญของอุปสรรคและความเห็นจากผู้เชี่ยวชาญในโรงกลั่นปิโตรเลียมของไทย

สาขาวิชา	การจัดการทางวิศวกรรม	ลายมือชื่อนิสิต	....
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KEYWORD: Failure modes and effects analysis (FMEA), carbon capture and storage, CCS Technology, GHG mitigation, TOE Framework, barriers to deployment, Petroleum Refineries, Thai Petroleum Refinery

Amornrat Sethi : THE APPLICATION OF FMEA TO STUDY THE CRITICAL BARRIERS TO DEPLOYING CARBON CAPTURE AND STORAGE IN A THAI PETROLEUM REFINERY . Advisor: PARAMES CHUTIMA

The carbon capture and storage (CCS) technology is still in early phase development and not considered a competitive greenhouse gases (GHG) mitigation technology in Thailand to be included in the climate change mitigation plans, causing the lack of resources and market and other challenges to promote its development and deployment. CCS will play a crucial role as a GHG emission mitigation strategy in the coming years globally as the energy demand grows continuously. In order to successfu lly deploy the technology in different industries in Thailand, especially the energy sector, it is essential to identify all of the potential causes of hurdles that prevent its deployment, and plan actions to mitigate the risks associated with them.

The purpose of this study is to identify the critical barriers that are preventing the development and deployment of the CCS technology in a Thai petroleum refinery as a GHG emission mitigation strategy. The objective of this study is to identify and organize th e barriers to deploying CCS technology in a Thai petroleum refinery using Technological-Organizational-Environmental (TOE) Framework and assess the risks of the barriers using Failure Mode and Effect Analysis (FMEA) by finding the criticality number of each barrier from the knowledge and experience of the experts of the case company refinery. A total of 29 barriers were identified; 9 Technological, 9 Organizational and 11 Environmental barriers, and they are depicted on Ishikawa Diagram. Pareto Analysis and 80/20 rule was applied. The Pareto Analysis showed that there are 22 critical barriers; 7 Technological, 7 Organizational and 8 Environmental barriers. A roadmap suggesting short, medium and long-term action plans to overcome the recognized critical barriers to promote the deployment of the CCS technology at a Thai petroleum refinery is also developed. The strategies and policies on the roadmap are planned based on two criteria, the criticality of the barriers and the expertise of the experts from the case company.

Field of Study: Engineering Management		Student's Signature ....
Academic Year: 2019		Advisor's Signature ....

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Amornrat Sethi

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Chapter 1 Introduction

1.1 Background of the Study

The Earth's surface temperature has been rising due to the greenhouse effect. The issue of global warming and ozone depletion has been a global concern in the past decades. The combustion of fossil fuels increases the concentrations of greenhouse gases (GHG) in the atmosphere including carbon dioxide, methane, nitrous oxide and sulfur oxide which traps the infrared energy, increasing the temperature of the global surface. Thailand is ranked 22nd on the global list of greenhouse emitters and may face serious problems from global warming if the level of emission is not reduced (Sabpaitoon, 2018). Thailand's CO_2 emissions per GDP was 25.29 tons CO_2/Million Baht in 2017 (EPPO, 2018). The majority of Thailand's national emission is contributed by the combustion of fossil fuels in the energy sector. Thailand is the second largest economy among the ASEAN countries and also the second-largest emitter of CO_2 (Shrestha et al., 2008). According to the UNFCCC (2015), the energy sector produces the highest GHG emission, 73.13% of total Thailand GHG emission with CO_2 being the largest GHG produced.

The oil industry is one of the most powerful industries in the global economy and fossil fuel continues to be a primary source of energy in the world economy despite the continuous development of alternative energy sources (Gabr et al., 2016). Crude oil is an essential resource for many products including petrol, jet fuel, diesel, lubricants and plastics. The global refinery capacity has been increasing over the years as the demand for energy has accelerated. In 2019, the global demand for oil is 100.8 million barrels a day (Statista, 2019). The higher energy demand has caused the emissions of GHG to increase globally. These gases have adverse effects on human health as well as the environment. The raise in the environmental concerns have caused petroleum refineries across the world to explore different ways to minimize its GHG emissions, including fuel switching, CO_2 capture, process improvement and renovation of equipment design to increase energy efficiency.

1.1.1 Carbon Capture and Storage (CCS) Technology

As fossil fuel will remain as the primary source of energy, this end-of-pipe technology will allow the reduction of carbon emissions by preventing it from being released into the atmosphere as it is designed to remove CO_2 from emission sources. The logic behind the CCS technology is straight forward; The CO_2 is captured from the source and transported to a storage unit, preventing it from entering the atmosphere which would contribute to global warming. According to the International Energy Agency (IEA, 2012), along with the increased use of renewable energy and improvement in energy efficiency, CCS is also an important technology. The technology is explained in Section 2.

1.1.2 Petroleum Refineries in Thailand

Petroleum industry is a large contributor towards Thailand's economy (CIA, 2017) and one of the highest energy consuming industries. There is an enormous opportunity for the refineries to reduce the amount of GHG they emit into the atmosphere. Thailand has the second largest refining capacity in the ASEAN region with 1.235 million barrels per day and the industry is expected to continue growing with the increase in the domestic demand for petroleum products, which makes up 80% of the refined oil produced by Thai refineries consumption (Leingchan, 2018).

Thailand has developed a national GHG emissions inventory by following the Revised 1996 IPCC Guidelines for National GHG Inventories to report the sources and removals of GHG emissions, both direct and indirect. The importance of emission sources and sinks are ranked using the key category analysis to determine the sources and sinks that contribute to 95% of the total emissions of Thailand. From the 2013 key category analysis report, petroleum refining is one of the top 15 emission sources, demonstrating that there is an opportunity to reduce emissions from the refineries.

There are seven major players in the petroleum refining industry in Thailand, PTT Global Chemical (PTTGC), ThailOil (TOP), IRPC Public Limited (IRPC), ESSO, Star Petroleum Refining Public Company (SPRC), Bangchak Petroleum (BCP) and RPCG.

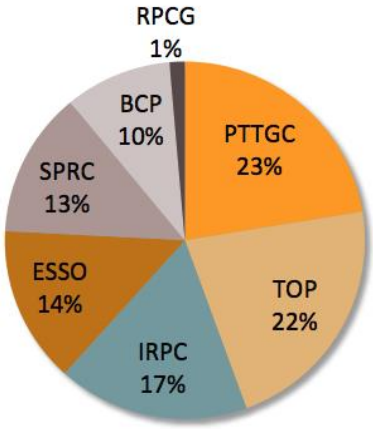

Figure 1: Refinery Capacity of Each Player in the Industry

Source: Leingchan (2018).

1.1.3 The Sources of GHG Emissions in Refineries

The process of converting crude oil into light, useful petroleum products, such as liquefied petroleum gases, gasoline, jet fuels and lubricants, is energy intensive. The oil refining industry is one of the highest energy consuming industries, consuming fossil fuels for combustion. The major cause of emissions in the refinery industry is the energy use (Worrell and Galitsky, 2005). Oil refineries consist of different processing units and arrangements dependent on the refined products desired, with almost every refinery having a crude oil distillation unit (CDU) as the first process. Fossil fuels are composed of carbon, hydrogen, sulfur and nitrogen, and the combustion of fossil fuels that provides energy for the processes produces GHG emissions. Majority of the processes in a refinery requires facilities including power generators, boilers, heaters, and utilities like steam, water, air and electricity, and according to IEA (1999), these are the main sources of CO_2 emissions in a refinery. The carbon content in the fuel used to operate the refinery defines the CO_2 emission. CO_2 is the largest GHG emission from the refinery with refinery fuel use as the source of highest emission.

Table 1: Major CO_2 Emission Sources at a Typical Refinery

Source	Description	% of total refinery emissions
Furnaces and boilers	Heat required for the separation of liquid feed and to provide heat of reaction to refinery processes, such as reforming and cracking	30-60
Utilities	CO_2 from the production of electricity and steam at a refinery	20-50
Fluid catalytic cracker	Process used to upgrade a low hydrogen feed to more valuable products	20-35
Hydrogen production	Hydrogen is required for numerous processes and most refineries produce it on-site via steam methane reforming or with a gasifier	5-20

Source: Straeleen et al. (2010, cited in Chan et al., 2016)

1.1.4 GHG Emissions Mitigation Efforts

According to literature, 8% of the worldwide anthropogenic CO_2 emission is from activities in the petroleum industry (Aycaguer et al., 2001). There are many efforts being put to try to reduce the GHG emission to the atmosphere including improving energy efficiency, developing renewable energy sources, using low carbon content fuels and capture and storage units. Thailand is undertaking the concept "sufficient economy" to reduce the country's emission level. According to Thailand's Nationally Appropriate Mitigation Actions (NAMAs), using renewable energy as an alternative energy source and improving energy efficiency are strategies for mitigating GHG from the energy and transportation sectors (TGO, 2014).The Energy Policy developed two master plans by Ministry of Energy Thailand, the Energy Efficiency Development Plan and the Renewable and Alternative Energy Development Plan to transition into a low-carbon future (Chaiyapa et al., 2017, cited in Matsumoto et al., 2017). The oil and gas companies in Thailand have incorporated climate change mitigation into their business strategy including measuring and reporting GHG data, increasing energy efficiency, reducing flared gas, investing in renewable or alternative energy and developing green products.

Energy Efficiency

According to literature (Gabr et al., 2016; Morrow et al., 2015), improvement of energy efficiency is one of the most cost-effective approaches to reduce GHG emissions. There has been a continuous innovation on the processes of energy recovery and integration technology in the past few decades as the cost of energy is gradually increasing and the inefficiency of energy recovery would increase the operating cost of the refinery. Petroleum refineries have many processes that consume a lot of energy, for instance, the hydrotreating process in catalyst reforming, which is a source of GHG emission. The process needs to be well designed to maximize efficiency to reduce cost and emission. According to the research, the revamp of the hydrotreater unit can be done by two ways, energy management of the heat integration to provide maximum energy recovery heat exchanger network and switching of fuel. The redesigning of the hydrotreater unit by applying pinch technology reduced GHG emissions by 19% and produced a net saving of $1,189,981 per year. The result has shown that switching fuel oil to natural gas further reduces GHG emission to 40% CO_2 reduction and produces an annual saving of $3,265,021 per year.

There are many energy practices and technologies commercially available and successfully implemented within refineries globally that demonstrates energy efficiency improvement and emission reductions. The opportunities for energy improvement include areas of utilities (30%), fire heaters (20%), process optimization (15%), heat exchangers (15%), motor and motor applications (10%) and other areas (10%) (Worrell and Galitsky, 2005). EPA (2010) reported 37 efficiency improvements/CO_2 emission reduction measures that can be implemented in petroleum refineries including improvement of insulation and maintenance and control of processes in the refineries.

The report did not include the total impact on the total emission from the refinery but discussed how employing different measures can improve the efficiency of different process units. Refineries in Thailand have been initiating several projects to improve energy efficiency of their operations which would reduce emissions. The projects implemented in one of the largest refineries in Thailand includes: improving efficiencies of stationary combustion units, implementation of biofilter to reduce VOC, hydrocarbon loss prevention projects, improvement of insulation and heat transfer efficiency, regular maintenance of equipment to reduce fuel consumption etc.

There are many energy efficiency improvement opportunities suggested in the literature. Energy Guide, a research conducted by Energy Star discussed energy management tools and strategies that refineries can implement to reduce emission. However, mitigation efforts beyond energy efficiency improvement is required to reduce GHG emission in the long run as an energy efficient refinery still consumes a lot of energy and produces considerable amounts of emissions.

Renewable Energy and Low-Carbon Fuels as Alternative Energy

The demand for energy is continuously growing, therefore, alternative solutions of replacing fossil fuels with renewable energy as a source of energy such as nuclear, solar, wind, geothermal and hydro (IEA, 1999) and research on alternative, greener products to reduce the reliance of fossil resources, which is increasing in price, and minimize environmental concerns, have been explored. The fuel used in the combustion processes in the refineries can be replaced with lower carbon to hydrogen ratio fuels such as LNG, LPG, fuel gas, and hydrogen (IEA, 1999) to produce lower GHG emissions.

To accommodate the growing demand of the fuels, there have been several studies on GHG emission reduction including fuel switching as GHG emission mitigation potentials in transport sector (Pongthanaisawan & Sorapipatana, 2011) including GHG emission reduction for substituting gasoline with ethanol (Nguyen et al., 2007) and substituting diesel with biodiesel (Pleanjai et al., 2009) as fuel for automobiles.

1.1.5 Thailand Ratifies Paris Climate Accord Which Considers CCS Technology in Mitigation Strategy

The United Nations Framework Convention on Climate Change (UNFCCC) with the aim to protect the climate, has developed a climate agreement, the 'Paris Agreement', which targets to prevent the serious consequences of global warming by limiting the global temperature rise below 2 degrees Celsius above pre-industrial levels.

It is stated that CCS is required to be in the mitigation strategy to achieve the climate policy targets to limit the temperatures to 2 degrees and that the world needs 2,732 CCS facilities by 2050 to cut down the emission by the 14 per cent quota towards the Paris Climate Accord (Global Carbon Capture & Storage Institute, 2018). Currently, there are only 17 CCS facilities, and many countries including the UK and U.S. are seeing it as a vital technology that needs to be invested in to achieve the targets.

Thailand is one of the Parties that ratified the Paris Agreement and developed the Nationally Appropriate Mitigation Actions (NAMAs) to drive the country towards a low-carbon society. According to Thailand's Second Biennial Report (Office of Natural Resources and Environmental Policy and Planning, 2017), Thailand is striving towards reducing GHGs emission by 20% below BAU level by 2020. The key mitigation plans according to the NAMAs that Thailand is implementing includes i) Development of renewable and alternative energy sources, ii) Improvement of energy efficiency in power generation, industries, buildings, and transportation iii) Substitution of fossil fuels with bio-fuels in the transport sector and iv) Advancement of the transport infrastructure development plan. However, CCS technology has not been considered as a GHG mitigation strategy and not included in the current climate change master plan despite the fact that the petroleum industry could benefit from CCS (Hardisty et al., 2011). There is still limited studies on the potential of GHG emission reductions from processes at petroleum refineries in Thailand in the literature, when the oil refining industry is one of the highest energy consuming industries with high potential to reduce emissions.

1.1.6 Thailand's Readiness Towards Deployment of CCS

The Global CCS Institute (2018) has assessed the readiness of different nations towards deployment of CCS (Figure 4). The readiness of the nations to deploy CCS is measured by several indicators including: Inherent CCS interest, policy developments, legal and regulatory frameworks and geological CO_2 storage development. Countries with high dependency on fossil fuels have high scores of the inherent interest indicator, demonstrating the potential of high impact from climate change and high dependency on CCS deployment to reduce their emissions. According to the indicators mentioned, Thailand has a low CCS Readiness Index and a high Inherent Interest Indicator which raises concerns as the nation has a large gap in policy framework and legislation to support the deployment of CCS.

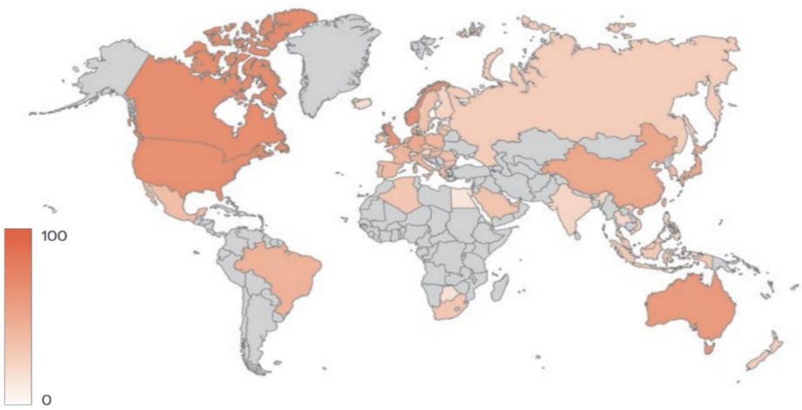

Figure 2: CCS Readiness Index 2018

Source: Havercroft and Consoli (2018)

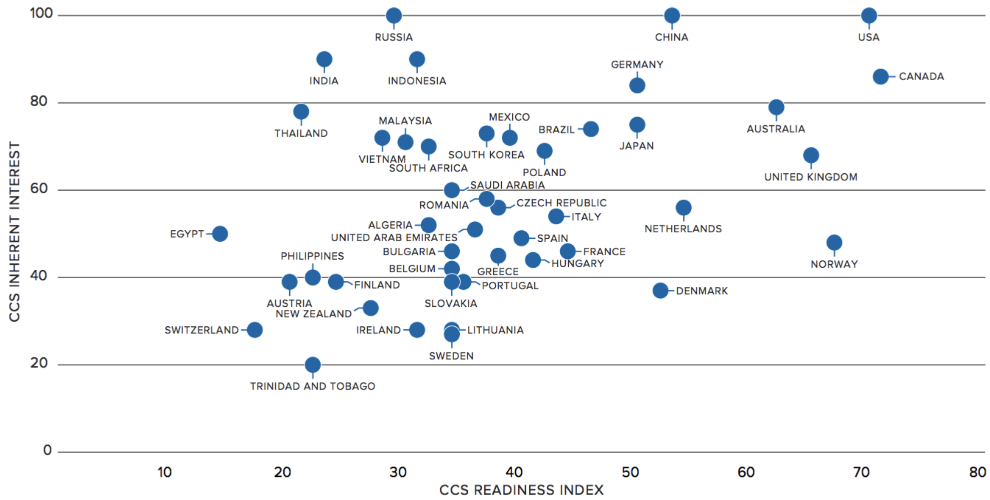

Figure 3: CCS Readiness Index vs Inherent Interest Indicator (2018)

Source: Havercroft and Consoli (2018)

1.1.7 Concerns Regarding the CCS Technology

The idea of CCS technology in the media and research has been very optimistic in the years and potentials of the technology as a GHG emissions mitigation strategy has been praised in the literature (Yao et al., 2018; Asian Development Bank, 2013; Sara et al., 2015). However, many scholars criticized the technology due to its technical, economic and social uncertainties (Markusson et al., 2011; Raza et al., 2019). According to IEA (2010), commercial power plants and industrial facilities may not be planning to invest in CCS due to the fact that the benefits it provides does not outweigh the costs.

As the CCS technology is new and there is not much experience, the scholars have been uncertain with different aspects of the technology. The literature has concerns regarding the CCS technology and listed uncertainties of the innovation:

- The uncertainty due to the diversity of the capture, transport and storage options raises the question of which technology will win out and which to invest in.

- The uncertainty regarding the storage facility to whether it is safe over a long term.
- The uncertainty with the speed of development and deployment of the technology.
- The uncertainty with the technicality of the technology due to lack of experience.
- The uncertainty with the economic and financial viability of the technology.
- The uncertainty from no framework for deploying the technology.
- The uncertainty with the level of public acceptance.

1.1.8 Challenges Influencing the Adoption of CCS Technology in Thailand

There are several challenges in terms of capacity, regulations, incentives and engagement that need to be addressed to deploy CCS in Thailand (Witsarut et al., 2012). The potential of CCS technology and its role to mitigate climate change is not well recognized and there is no national level planning in terms of resources required to pilot a CCS project which is a barrier to deploying the technology. As CCS technology is still in an early phase of development, the skills and training required to implement the technology successfully needs to be attained. To promote the adoption of CCS, an appropriate policy is required. There are several barriers that need to be addressed to deploy CCS, which requires a legal and regulatory framework to support its development.

1.2 Problem Statement

Petroleum refineries have been contributing to global warming by producing direct emissions of greenhouse gases including carbon dioxide, methane, nitrous oxide etc. from their operations. Due to the increase in emissions produced by the refineries worldwide, there has been an interest in developing different technologies to mitigate emissions. CCS technology is one of the new technologies that has been given importance in the literature in recent years in many industrial sectors including the petroleum industry.

Petroleum refineries in Thailand have been implementing different energy efficiency improvement projects which are believed to reduce GHG emissions as it is considered to be the most cost-effective mitigation option (Gabr et al., 2016; Morrow et al., 2015). According to Intergovernmental Panel Climate Change (IPCC) (cited in Stangeland, 2007), the potential for reducing CO_2 emission through energy efficiency improvements and renewable energy is limited and the refineries need to consider new strategies such as CCS to mitigate the emission to avoid the consequences of global warming. CCS technology has been documented in the roadmap to low-carbon scenario in many literatures, however, according to the two master plans developed by the Ministry of Energy, unfortunately, CCS technology is still not being actively considered as a GHG emission mitigation strategy in Thailand. The high Inherent Interest Index (Figure 3) indicates that Thailand should consider CCS technology as an emission mitigation strategy, and this research will study the barriers preventing the deployment of the technology in one of the major petroleum refineries in Thailand (Figure 1), and develop a roadmap to demonstrate how refineries can overcome those barriers and deploy the technology.

1.3 Research Objectives

The primary objective of this study includes:

1. To determine and organize the potential barriers and challenges of deploying CCS at a Thai petroleum refinery.
2. To apply FMEA approach to evaluate the criticality of the barriers and prioritize them.

3. To develop a roadmap with action plans required to overcome the challenges to implement CCS technology.

1.4 Research Questions

This research will study the potential of the CCS technology as an emerging technology for mitigation of GHG emissions. This thesis will answer the following research questions:

1. What are the main barriers in implementing CCS technology at Thai petroleum refinery?
2. What are the actions required to overcome the barriers to implement CCS technology at petroleum refineries?
3. Can the barriers be overcome to deploy the technology at the petroleum refineries in Thailand?

1.5 Scope of Research

In this research, the barriers to deploying CCS technology as a GHG emission reduction strategy in Thai petroleum refineries will be evaluated using the FMEA approach. The recommendations to overcome those barriers will be discussed. The literature on barriers to deployment of CCS technology is vast and the complete analysis of the existing literature is beyond the scope of this research. The literature review was restricted to national level research that involved collecting opinions from experts in the field of CCS deployment in one of the leading petroleum refineries in Thailand using survey and interview on their views on barriers to deploy CCS. The barriers will be prioritized according to their severity and occurrence using the FMEA approach to plan actions to mitigate them. A roadmap will be developed to suggest actions to overcome the barriers that prevent the deployment of the technology as the emission mitigation strategy for a Thai petroleum refinery.

1.6 Expected Outcomes

1. The significant barriers of deploying CCS technology as an emission mitigation strategy at petroleum refinery will be understood.
2. The suggestions to policymakers to solve the obstacles to deploying CCS and design strategies to promote CCS technology at petroleum refineries.
3. Academic contribution of the potential of CCS technology in Thailand to literature.

1.7 Limitations of the Study

The findings from the interviews represent opinions of experts in one of the petroleum refineries in Thailand and therefore not the entire sector. The research on barriers to deploying the CCS technology in the literature is vast and therefore there are many more barriers specific to different organizations and countries, and not all have been included in the study. The perspective of the experts from the case company on the barriers, especially the organization barriers, may be different from other companies as different companies would be faced with unique challenges. Engagement of other stakeholders including appropriate people from the financial sector, academics and government body along with people from the petroleum refining sector to contribute their perspectives and interpret the analysis while developing the roadmap was not included in this study. The limitation of the quantitative analysis used in this research also needs to be considered while reading this report.

1.8 Overview of Dissertation Structure

The structure of this dissertation is as follows:

Chapter 1 introduces the research topic and the objectives of the dissertation.

Chapter 2 reviews the literature on CCS technology, TOE framework, FMEA approach and roadmap development.

Chapter 3 discusses the Methodology used in this research.

Chapter 4 analyzes the results of the research of the barriers of deploying CCS in a Thai petroleum refinery and discusses the recommendations to overcome those barriers on a roadmap.

Chapter 5 closes the dissertation with conclusion and recommendations for further research.

Chapter 2 Literature Review

2.1 Carbon Capture and Storage

The CCS technology has three processes, capture, transportation and storage and can be looked at as a system of three integrated technologies. It has the potential to reduce 85-95% of CO_2 emission in the atmosphere (Maneeintr et al., 2017). The IEA has estimated that the capital cost of meeting the emission reduction target would increase by 40% without CCS. This section will discuss CCS based on its procedure: 1) CO_2 capture 2) CO_2 transportation 3) CO_2 storage.

2.1.1 CO_2 Capture

CO_2 can be captured from sources including fluid catalytic cracking units, hydrogen production units, flares and other stationary combustion sources in the refinery.

There are three ways to capture CO_2 (Freund, 2005, cited in Chan et al., 2016):

a) Post-combustion capture: CO_2 is captured from flue gas before emitted to the atmosphere.

b) Oxyfuel combustion capture: Use pure oxygen instead of air for combustion to produce flue gas with high purity CO_2.

c) Pre-combustion capture: hydrocarbon fuel is pretreated to produce CO_2 and H_2 and CO_2 separated (fuel gas is decarbonized before sent to combustion units).

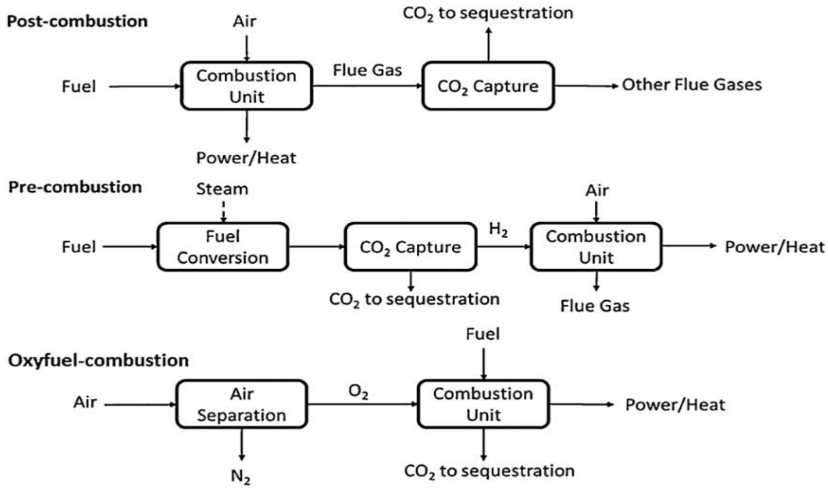

Figure 4: Three CO_2 Capture Systems

Source: Yao et al. (2018).

According to IPCC, the choice of capture system used depends on factors like the concentration of CO_2 in the gas stream, the pressure of the gas stream and the fuel type. Chemical absorption is the best method to be used to capture CO_2 at refineries (Das and Kumar, 2016). Solvents like monoethanal amine (MEA) are used for CO_2 adsorption.

2.1.2 CO_2 Transport

The captured CO_2 is compressed into supercritical form and transported as liquid CO_2 for storage. The captured CO_2 can be transported through pipelines to storage sites or transported via ships to the ocean storage site.

2.1.3 CO_2 Storage

a.1) Geological Storage

The two storage options that are adopted on a commercial scale includes the storage in formations containing nonpotable water and in oil and gas reservoirs (Rackley, 2017). Injection of CO_2 into the oil reservoir provides the benefit from the application of EOR.

a.2) CCS and EOR

Most of the operating CCS facilities utilizes the captured CO_2 in enhanced oil recovery operations. The refineries in the US have been injecting CO_2 into reservoirs to improve oil recovery instead of emitting it out into the atmosphere, this process is called enhanced oil recovery (EOR) (Aycaguer et al., 2001). Thermal recovery is one of the most widely used EOR methods but the CO_2 injection EOR has been rising. Apart from extraction of additional oil, captured CO_2 could be injected and stored in the reservoirs.

b) Ocean Storage

The captured CO_2 is injected at depth into the ocean for long-term storage. The injection can be done into the water column through pipelines or onto the seafloor to form a lake. This form of storage is still in the research phase (IPCC, cited in Stangeland, 2007). The acidity of the ocean would increase from the absorbed emission slightly.

2.2 CCS Projects Worldwide

The technical feasibility of the CCS technology can be reflected by the operating projects worldwide. CCS technology has been gaining recognition over the years and has been included in Clean Development Mechanism (CDM) as a necessary technology to develop a low-carbon economy. CCS projects around the world include, Century Plant in Texas, Shute Creek Gas Processing Plant in Wyoming, Great Plains Synfuels Plant in Dakota, Petra Nova Carbon Capture in Texas and Boundary Dam Carbon Capture and Storage in Saskatchewan etc. which are capturing approximately 40 million tons per year (Mt/yr) of CO_2 (Global CCS Institute, cited in NS Energy, 2019). A CCS facility at Shute Creek gas processing plant, owned by ExxonMobil, alone captures CO_2 equivalent to removing 1.5 million cars off the road. According to the Carbon Capture and Sequestration project database at MIT (2016), most of the commercial CCS projects are based in the USA with Century Plant being the largest plant capturing 8.4 Mt/yr. The plant was led by Occidental Petroleum, an international oil and gas exploration and production company, since 2010.

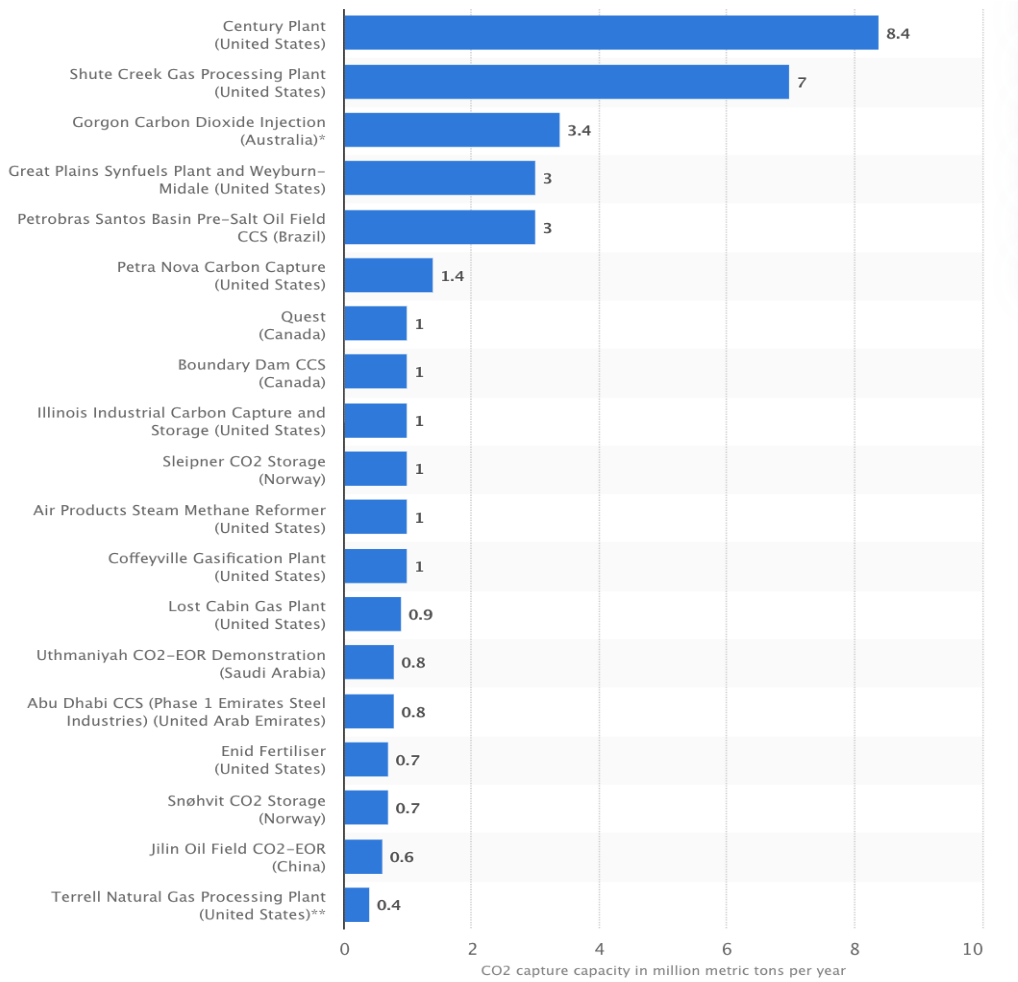

Figure 5: Capacity of Operational Large-Scale Carbon Capture and Storage Facilities Worldwide as of 2019 (in million tons per year).

Source: Statista (2020)

2.3 The Studies on Barriers to Implementing CCS Technology in the Literature

Despite the fact that CCS technology is gaining recognition to mitigate climate change and that it must be deployed to achieve the envisioned GHG emission reduction levels, the integrated CCS technology is still under development and there are challenges that limit the deployment of the technology.

The challenges involved in implementing the CCS technology has been studied by many scholars; The assessment of commercial-scale CCS technology barriers in U.S.

(Davies and Ruple, 2013), The perspectives and barriers for implementation of CCS in Poland (Uliasz-Misiak and Przybycin, 2015), Barriers and incentives of CCS deployment in China (Dapeng and Weiwei, 2009), The public acceptance of CCS technology (Itaoka et al., 2005), The non-technical barriers for CCS implementation in Finland (Pihkola et al., 2017). Different scholars have recognized different barriers that influence the deployment decision of the CCS technology in terms of economics, legal regulations, technological and political. The barriers to deploying CCS technology mentioned in several literature is summarized in the table below:

Table 2: Literature Review on Barriers to Deploy CCS Technology

Journal	Barriers to Deploy CCS Technology
Davies, L. L., Uchitel, K., & Ruple, J. (2013) Understanding barriers to commercial-scale carbon capture and sequestration in the United States: An empirical assessment, Energy Policy, 59, pp. 745–761.	• Cost and cost recovery • Lack of financial incentives • Long-term liability risk • Lack of comprehensive regulation
Uliasz-Misiak, B., & Przybycin, A. (2015) The perspectives and barriers for the implementation of CCS in Poland. Greenhouse Gases, Science and Technology, 6(1), pp. 7–18.	• Lack of legal regulations • Lack of public acceptance • Cost - Lack of financial resources
Nguyen-Trinh, H. A., & Ha-Duong, M. (2015) Perspective of CO2 capture & storage (CCS)	• Technical risks due to lack of experience • High Cost • Financial risks

development in Vietnam: Results from expert interviews, International Journal of Greenhouse Gas Control, 37, pp. 220–227.	• Lack of appropriate policies • Additional energy consumption for CCS
Dapeng, L., & Weiwei, W. (2009) Barriers and incentives of CCS deployment in China: Results from semi-structured interviews, Energy Policy, 37(6), pp. 2421–2432.	• High cost • Technological uncertainties • Regulatory framework
Kapila, R. V., Chalmers, H., Haszeldine, S., & Leach, M. (2011) CCS prospects in India: Results from an expert stakeholder survey, Energy Procedia, 4, pp. 6280–6287.	• Technology readiness • High capital and operating cost • Political acceptability • Financing support • No framework to support the deployment in terms of safety and storage
Pihkola, H., Tsupari, E., Kojo, M., Kujanpää, L., Nissilä, M., Sokka, L., & Behm, K. (2017) Integrated Sustainability Assessment of CCS – Identifying Non-technical Barriers and Drivers for CCS Implementation in Finland, Energy Procedia, 114, pp. 7625–7637.	• Legislative barriers • High investment cost and low profitability due to energy penalty • Lack of national storage sites • CCS does not eliminate the dependency of fossil fuels • Investing in CCS would reduce the budget on renewable energy funding • Safety concerns on possible leakage of CO_2 to human and environment

	• Competitive technologies with higher efficiency
Lai, X., Ye, Z., Xu, Z., Husar Holmes, M., & Henry Lambright, W. (2012) Carbon capture and sequestration (CCS) technological innovation system in China: Structure, function evaluation and policy implication, Energy Policy, 50, pp. 635–646.	• High capital and operational costs • CO_2 leakage risks • Energy penalty • Other environmental emissions from CCS technology implementation • Absence of explicit carbon pricing • No regulation or framework • Public acceptance

2.4 Technology-Organization-Environment (TOE) Framework

This framework was developed by Tornatzky and Fleischer in 1990. The framework allows the factors under three principle contexts, the technological context, the organizational context and the environmental context, that influences the technology adoption decision by a firm to be studied. It has been recognized that both the internal and external factors of the organization drive the decision-making of the adoption of a new innovation by any firm. The technological context refers to the availability and the characteristics of technologies, internal and external to the firm. The organization context considers the size and structure of the firm along with the resources available to accept the innovation. The inclusion of environment constructs in the TOE framework has made it superior to other frameworks that studies technology adoption. The incorporation of the environment that the firm operates; the market and the industry characteristics and the government regulations, allows the evaluation of constraints and opportunities external to the firm that may affect the adoption of innovation.

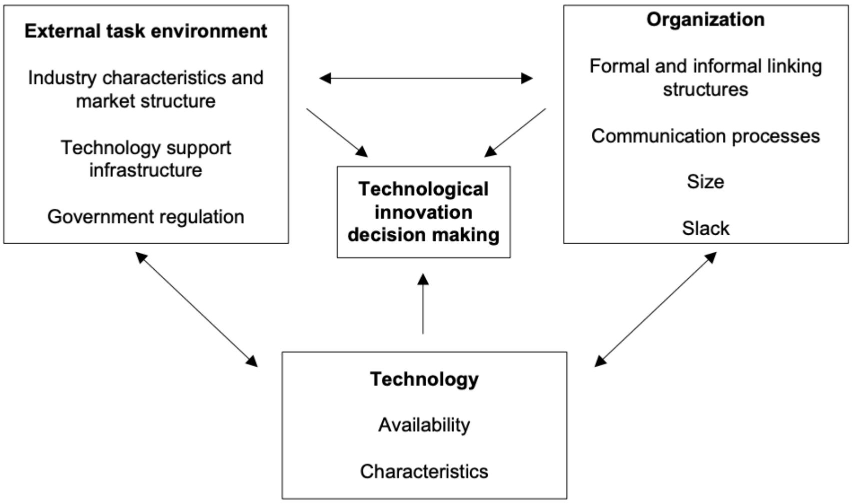

Figure 6: The Technological-Organizational-Environmental (TOE) Framework

Source: Tornatzky and Fleischer (1990)

The TOE framework is applicable to a broad range of industry due to its adaptability and the scholarly evidence has shown that. The framework has been adapted by many researchers to study IT innovation adoption. TOE framework was used by many scholars for e-business adoption (Zhu et al., 2003, Oliveira and Martins, 2010, Zhu and Kraemer, 2005, Lin and Lin, 2008, cited in Oliveira and Martins, 2011), EDI adoption (Kuan and Chau, 2001cited in Oliveira and Martins, 2011) and e-commerce (Oliveira and Martin, 2009, Liu, 2008, Teo et al., 2006, cited in Oliveira and Martins, 2011).

According to Consoli and Havercroft (2018), Thailand has a low CCS Readiness Index score and high Inherent Interest score, and to evaluate the different factors that results in those scoring, the Technology-Organization-Environment Framework will be used. In this research, the study of barriers to deploying CCS technology will be done using the TOE framework that allows the analysis of the barriers under three contexts, the technological context, the organizational context and the environmental context.

2.5 The Failure Mode and Effect Analysis (FMEA)

The FMEA method has been used for many applications to identify and prioritize potential causes of failures of products and processes. According to literature, the FMEA is applied to: identify modes of failures and the effects of those failures, assess the possibilities of the fault occurring and the severity of their consequences. Andersen and Fagerhaug (2006) stated that the failure mode analysis is a tool that allows the organization to think forward of the problems that could occur to eliminate possible failures. The modes of failures that have occurred previously with a similar process can be studied using this methodology to learn the severity and the likelihood of potential failures with minimum resource expenditure analytically, to aid the organization to identify the failures and their causes before they occur and eliminate them.

This procedure has been used in practice for many years to analyze the potential failure modes. Apollo Space program, Toyota and Ford Motor all applied FMEA to analyze their processes for potential process induced failures to mitigate risk. Pantazopoulos and Tsinopoulos (2005, cited in Ambekar et al., 2013) stated that FMEA is a tool that can study the weaknesses in a system to minimize the risk occurrence. According to Ambekar et al. (2013), the objectives of FMEA are:

- To identify potential failures in the design and process before they occur.
- Identify potential causes of failure modes.
- Evaluate the effects of each failure mode.
- Identify measures to reduce or eliminate risks of each failure mode.

Almannai et al. (2008) referred to FMEA approach as a “bottom up” approach that identifies potential failures of a product or service as well as determine the severity of the failure impact and the frequency of the failure occurrence. It is a useful tool in risk management to assess the risk associated with investments.

Afshari et al. (2016) demonstrated how FMEA could identify the potential failure modes along with their causes and effects to understand the barriers preventing the greening of existing buildings. FMEA is considered as one of the risk analysis tools that uses the bottom-up approach to study the failure modes, causes and effects of each component by relying on the opinions of experts in the field. The contribution of the experts validates the results of the analysis.

This tool can also be used to prioritize the criticality of the failure cause; The criteria used are:

1. Severity (S)
2. Occurrence (O)
3. Detection (D)

Traditionally, FMEA analysis is used to calculate Risk Priority Number (RPN) by multiplying Severity, Occurrence and Detection to demonstrate the risk priority level of each failure mode and plan corrective actions according to the criticality of the failure modes.

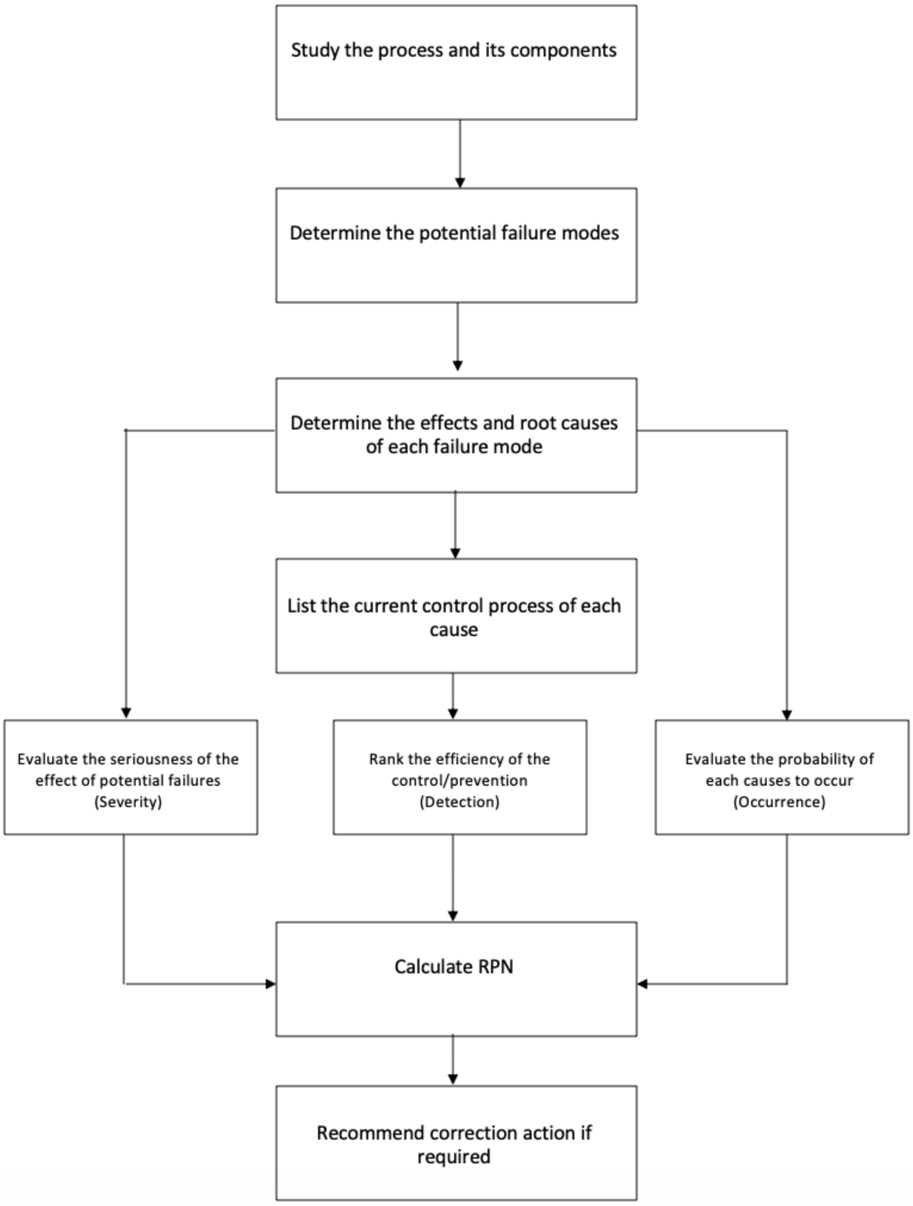

Figure 7: The Traditional FMEA Procedure

Source: Adapted from Tay and Lim (2006).

2.6 The FMEA-TOE Approach

Study by Oliveira and Martins (2011) has shown that TOE framework can be combined with other theories. The TOE framework was combined with DOI theory (Chong et al., 2009, Zhu et al., 2006, cited in Oliveira and Martins, 2011). In addition, Almannai et al. (2008) also demonstrated that FMEA can be combined with other techniques. In the study, FMEA was used with Quality Function Deployment (QFM) technique as a decision tool to identify the most suitable manufacturing automation system considering the interaction between technology, organization and people and the risks associated with the system to prevent them. The literature has proven that both these techniques are compatible with other techniques and can be used in combination. The FMEA approach will be done under the TOE framework in this research.

2.7 The Root Cause Analysis (RCA)

Risk is a cause of failure and if not managed properly, a business can be adversely affected. Risk management is widely known to minimize barriers and a general framework for risk management involves risk identification, risk analysis and risk treatment.

Andersen and Fagerhaug (2006) defined RCA as an "investigation that aims to identify the true cause of a problem and the actions necessary to eliminate it". There are several tools and techniques that can be used to identify the causes of problems and they can be classified according to their purpose:

- Problem understanding
- Problem cause brainstorming
- Problem cause data collection
- Problem cause data analysis
- Root cause identification
- Root cause elimination
- Solution implementation

2.7.1 The Ishikawa Diagram

Ishikawa diagram or cause-and-effect diagram which was invented by Dr. Kaoru Ishikawa, is a tool that aids looking at effects and the causes that contribute to those effects systematically (Arvanitoyannis and Varzakas, 2007). According to Hekmatpanah (2011), this analytical tool is very useful in risk management as it identifies and groups into categories potential root causes of problems in an organization. Reid (2012) used the diagram to sort the barriers that prevent adoption of instructional technology into categories and as a framework to depict the barriers within each category.

The four steps in developing a cause-and-effect diagram includes (Dey, 2004, cited in Hekmatoanah, 2011):

- Identifying the problem
- Analyzing the major factors involved
- Determining possible causes
- Analyzing the cause-and-effect diagram

2.7.2 The Pareto Diagram

The principle of Pareto, according to Anderson and Fagerhaug (2006), follows the 80/20 rules where “most effects, often 80%, are the result of a small number of causes, often only 20%”. The important causes, “the vital few”, has a skewed distribution and the Pareto Diagram depicts them sorted by the frequency of occurrence. The recognition of “the vital few” from the chart eases the problem mitigation planning process by ranking the causes according to their importance that lead to the problem.

2.8 Literature Review on How to Overcome the Barriers to Promote CCS Deployment

Table 3: Recommendations to Overcome the Barriers to Deploy CCS Technology

Journal	Recommendations to overcome the barriers
Davies, L. L., Uchitel, K., & Ruple, J. (2013) Understanding barriers to commercial-scale carbon capture and sequestration in the United States: An empirical assessment, Energy Policy, 59, pp. 745–761.	• Create market demand (demand-pull mechanism) (Folger, 2009, cited in Davies et al., 2013) • Increase cost effectiveness of CCS • Liability strategies such as insurance and mandating federal ownership for stored CO_2 • Develop a regulatory framework for monitoring following CO_2 injection • Government loans, financial incentives, private funding and international collaboration to fund the deployment
Uliasz-Misiak, B., & Przybycin, A. (2015) The perspectives and barriers for the implementation of CCS in Poland, Greenhouse Gases: Science and Technology, 6(1), pp. 7–18.	• Government loans and guarantees • Development of law and regulation for effective and safe implementation of CCS • Conduct information campaigns on CCS for the public
Nguyen-Trinh, H. A., & Ha-Duong, M. (2015) Perspective of CO2 capture & storage (CCS) development in Vietnam: Results from expert interviews,	• Develop environment and safety standards • Long-term policies and regulations • Improve knowledge and awareness of CCS • Government supports and loans • Framework for carbon monitoring and

International Journal of Greenhouse Gas Control, 37, pp. 220–227.	trading
Dapeng, L., & Weiwei, W. (2009) Barriers and incentives of CCS deployment in China: Results from semi-structured interviews, Energy Policy, 37(6), pp. 2421–2432.	• Carbon taxes • Carbon trading market • Financial incentives • CO_2 legislation system • Training and education
Kapila, R. V., Chalmers, H., Haszeldine, S., & Leach, M. (2011) CCS prospects in India: Results from an expert stakeholder survey, Energy Procedia, 4, pp. 6280–6287.	• Government support on financing and training initial project • International financing support • Development of policies and framework
Pihkola, H., Tsupari, E., Kojo, M., Kujanpää, L., Nissilä, M., Sokka, L., & Behm, K. (2017) Integrated Sustainability Assessment of CCS – Identifying Non-technical Barriers and Drivers for CCS Implementationin Finland, Energy Procedia, 114, pp. 7625–7637.	• Increase in R&D efforts and commercial demonstration • National climate policies to drive the deployment • Engagement with legislative bodies • Increase in the price of CO_2 emission allowances • Utilization of captured carbon to produce income
De Coninck, H., Flach, T., Curnow, P., Richardson, P., Anderson, J., Shackley, S., Reiner, D. (2009) The acceptability of CO_2 capture and	• Emission Trading Schemes • Legislation support • Demonstration projects • Subsidies for CCS-based electricity supply

storage (CCS) in Europe: An assessment of the key determining factors, International Journal of Greenhouse Gas Control, 3(3), pp. 333–343.	• Public-private partnership for CO_2 network

The EU recognized the potential role of CCS technology in GHG reduction and committed to promote it along with renewable energies. The measures for promotion of CCS technology in the EU includes strengthening RD&D and developing the required technical, economic, and regulatory frameworks. De Coninck et al. (2012) demonstrated that the European Energy Action Plan included CCS technology as one of the Sustainable Fossil Fuels Technologies that is needed to produce Near-Zero Emissions from Coal. The EU has also ratified the Paris Climate Agreement to limit the global temperature increase to a maximum of 2 degrees Celsius by 2050, which they have recognized that 80% in reduction of CO_2 is required and C02 capture capacities installation to power plants are necessary. The funding towards CCS R&D to support large-scale demonstrations of the facilities has been declared by the EU Commission (De Coninck et al., 2012). CCS technology has also been supported in the UK energy policy debates (Scrase and Watson, 2009). The EU Commission also proposed a legal framework for regulation of the captured CO_2 storage to help overcome the legislation barriers preventing the large-scale CCS facility development (De Coninck et al., 2012).

China has recognized that CCS technology can contribute to more CO_2 emission reductions than transitioning to renewable energy and launched a national research and development program to support the technology (Lai et al., 2012). CCS technology has been recognized as a GHG emission mitigation option in China and has been granted funding for R&D by National Research Programs where China has managed to engage oil companies, energy-related communities, institutes, government agencies and international collaborations in CCS R&D and demonstration projects. From the research done by Lai et al. (2012), funding from the government can accelerate CCS deployment. Lai et al. suggested that a public-private partnership on CCS technology consortiums, government incentives to initiate collaboration among different sectors to share resources and knowledge, standard regulation policies for CCS activities such as carbon tax and increasing publicity of the technology to increase public acceptance can facilitate CCS technology commercialization.

2.9 The Roadmap

Following the identification and analysis of the risks, according to the general risk management framework, a roadmap suggesting the actions to overcome the barriers will be developed as a risk treatment; The actions required to eliminate the failure modes.

Roadmaps are visual communication tools developed to demonstrate the strategies that the organization is going to follow to tackle the barriers of deploying a technology (Gough et al. 2010). The roadmap approach integrates knowledge and experience.

A roadmap is like a 'consensual blueprint' stated in a report by Parsons Brinckerhoff (2015) presenting required actions, strategies and policies, business investments, R&D etc. to achieve set goals. According to report prepared by Department of Energy and Climate Change and Department for Business, Innovation and Skills on Industrial Decarbonization and Energy Efficiency Roadmaps to 2050 for Oil Refining Sector, there are three phases in developing a roadmap:

1. Conduct literature review, interviews, surveys, workshops and analyze available data on barriers and enablers to investing in the technology of study.
2. Develop 'pathways' to identify and investigate technology mix to achieve emission reductions.

3. Analysis of the evidence to identify the actions to be taken to overcome the barriers to delivery of technologies within the pathways.

The roadmap approach has been employed vastly, both at national and international levels, with the same vision to accelerate the deployment of CCS technology. According to literature review, many countries are facing similar barriers that need to be addressed to deploy CCS technology, but there are also country specific issues that need to be considered. For instance, Gough et al. (2010) stated that national energy and climate change legislation, land-use planning, and liberalized electricity markets are few UK specific issues that impact the deployment of CCS technology.

China has also proposed a CCS Roadmap with action plans (ADB, 2015). The action plans on the roadmap were divided into short, medium and long-term. The short-term plans include incentive programs, policies, national funding, increasing public awareness to implement demonstration programs to study and overcome barriers to deployment of the technology. The medium-term plans include introduction of more incentives such as carbon tax and development of regulatory framework to promote commercial deployment of CCS technology. Many countries have adjusted their legal and regulatory frameworks to develop a market for CCS to be implemented. For instance, Europe has included CCS in the Emissions Trading System (ETS) to provide complementary financing support for demonstration, US has amended the Resource Conservation and Recovery Act to exclude CO_2 streams as hazardous waste if captured and stored underground under certain guidelines, Alberta introduced The Carbon Capture and Storage Statutes Amendment Act and launched CCS Regulatory Framework Assessment to address barriers to deploy CCS (Lupion et al., 2015). Guidelines to recommend how the barriers can be tackled should be developed and CCS-ready criteria needs to be defined to ease the process of technology deployment by the organizations. The long-term plans include introduction of economic and regulatory policies consistent with global climate change policies to further promote the adoption of the technology to reach the target of emission reduction set.

The study of pathways to adopt CCS in India, Narain (2007), has listed challenges to deploying CCS technology and developed short, medium and long-term action plans to recommend adopting CCS technology. The barriers discussed include high cost of CCS, lack of skills and understanding of the technology, lack of incentives by the government. The short-term actions include groundwork by the authorities responsible to reduce GHG emissions to promote CCS adoption, including the CCS into R&D efforts in different industries, increase cooperative training to develop trained human capacity, creating legislative mandate to guide CCS adoption and assessment of carbon storage capacity. The medium and long-term recommendations include, demonstration of CCS projects as proof of technology, improve the efficiency of project permitting process and compensation mechanism to pay for the costs of CCS.

According to literature, developing a CCS regulatory framework does not have to start from scratch but can be done by amending existing laws and regulations to meet the requirements to promote the deployment of CCS technology. The existing frameworks available in Thailand will be studied to identify the gaps that need to be tackled to promote deployment. The existing legal and regulatory framework in Thailand and the possible amends that can be implemented are summarized in the table below:

Table 4: Existing and Suggestion of Amended Legal and Regulatory Framework for CCS

Issue	Existing Legal and Regulatory Framework for Carbon Capture and Storage	Amends Required to Legal and Framework to Deploy Carbon Capture and Storage
Classification of CO_2	CO_2 is defined as a by-product of petroleum and not as a pollutant	CO_2 should be defined as waste and pollution by Environmental protection laws

Surface and subsurface rights for CO_2 transport and storage	Currently no laws for ownership, grant, or lease of surface or subsurface pore space for CCS.	The grant, lease to surface and subsurface rights and pore space for storage must be given for CCS.
Legal liability of CCS operations and for stored CO_2	No current framework for legal liability exists for CCS.	The liability rules need to be adapted as liability can arise relating to environment and health risks from leakage.
Environmental protection	No current environmental protection rules relating to CO_2 capture, transport or storage.	Environmental Protection and Promotion Act, Groundwater Protection Act, Industrial Waste Regulations, Environmental Impact Assessment need to be adapted to include CCS.
CO_2 transport	No existing regulator for CO_2 pipeline. The upstream pipelines covered by Petroleum Act under Department of Mineral Fuels and the downstream distribution pipelines are regulated by ERC.	Legal framework defining who can build, own and operate pipelines for CO_2 transport for CCS needs to be developed.
Health and safety	No standards specific to CCS that currently exist. Only general occupational	A clear definition of health and safety for workers and of operations in CCS will be

	health and safety is governed by the Ministry of Energy.	required. Some adaptation to existing rules as well.
Enhanced oil recovery (EOR)	The Ministry of Energy has jurisdiction over petroleum-related CO_2 streams under the Petroleum Act.	A clear approach to how CCS-EOR will be integrated into production-sharing arrangements and built into oil-gas field development programs is required.
Foreign direct investment for CCS	Electricity, oil and gas, and mining are subjected to foreign ownership restrictions.	A clear investment climate to support foreign direct investment to raise funds for commercial-scale CCS projects is required.

Source: Adapted from ADB (2015)

Chapter 3 Research Methodology

3.1 Methodology Overview

The study employed to study the critical barriers of CCS technology in a Thai petroleum refinery will be constructed as follows:

This study will adapt the conventional framework of risk management: Risk identification, risk analysis and risk treatment discussed in Section 2.7, to identify the critical barriers and find an action plan to mitigate the barriers to deploying the CCS technology in Thai petroleum refineries.

Firstly, literature review on technologies and practices used in refineries worldwide to reduce GHG emissions was done by the author as a preliminary research. This allowed the identification of problems encountered by refineries regarding the practices used to mitigate emission and formulation of research questions. The flowchart of the processes in the refinery and of the CCS technology is studied in the literature as a technique to understand the problem that may occur if the technology was to be implemented in the refinery in Thailand; The status of CCS technology as a new mitigation strategy is studied from literature as an initial stage of the RCA in this research to identify the possible barriers to implementing the technology. The author has then categorized the barriers under the TOE framework through comprehensive analysis to ease the process of RCA. The potential barriers to deploying CCS technology at petroleum refineries are systematically grouped and depicted on Ishikawa Diagram. After the literature has been reviewed, a survey is developed as a tool for root cause identification. This allows the collection of data or opinions of experts for identification of critical barriers preventing the adoption of CCS as a GHG emission mitigation strategy by one of the refineries in Thailand. The barriers are analyzed by finding the Criticality Number (CN) and prioritized under the FMEA-TOE framework. A Pareto Chart is used as a tool to illustrate the critical barriers preventing the deployment of the technology according to the results of the survey. Interviews are then conducted to study the possible ways to overcome the major barriers preventing the adoption of CCS technology at the refinery. A roadmap of actions required to overcome the critical barriers is developed as a technique to demonstrate the pathway of actions to eliminate the barriers that prevent the implementation of CCS technology at Thai petroleum refineries with milestones set according to the criticality of the different barriers.

The general framework used in this research is summarized below:

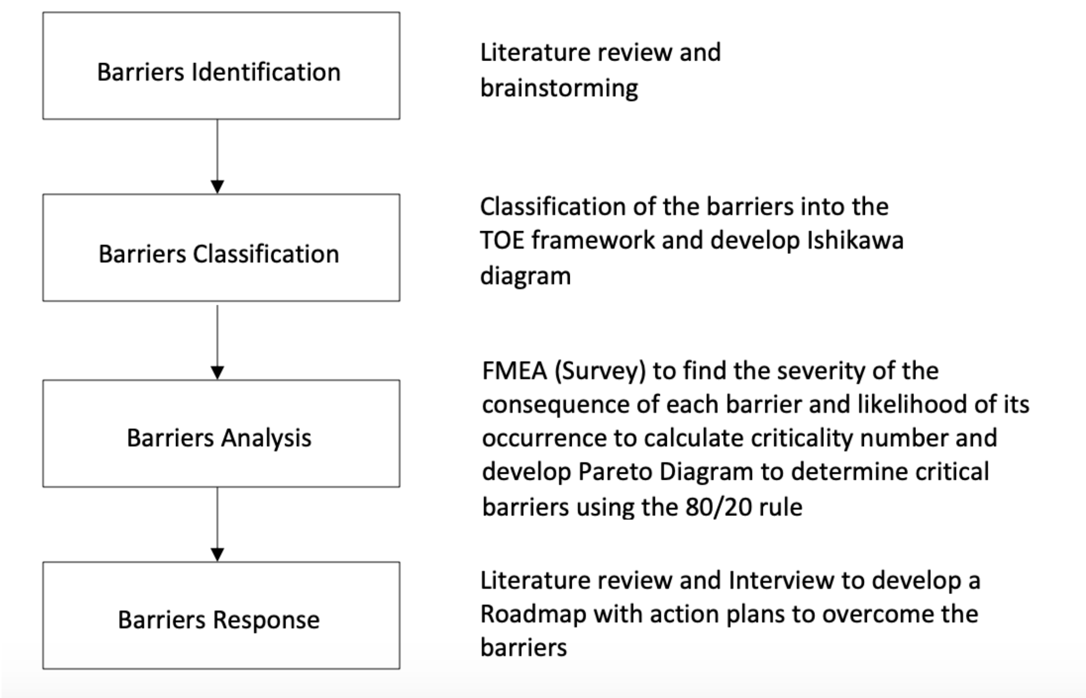

Figure 8: General Framework of This Research

Source: Adapted from Flanagan and Norman (1993).

3.1.1 Barriers Identification

The barriers discussed in the journals studied by the author is summarized in section 2.2. The barriers that are widely mentioned include economical barriers, technical uncertainties and concerns of the technology, and gaps in the national and international legal regulations that need to be addressed to commercialize the technology etc.

3.1.2 Barriers Classification

The Technological, Organizational and Environmental will be the three contexts that the barriers to deploying CCS technology at Thai petroleum refineries will be classified into. The barriers identified from literature review and brainstorming are categorized under the TOE framework. This systematic compilation of the barriers by grouping them under one of the three contexts eases up the analysis and the development of a roadmap to overcome them.

The Barriers under Technological Context: The barriers in terms of technology, including barriers in carbon capture, transport and storage technology that prevents its deployment.

The Barriers under Organizational Context: The conditions in the organization in terms of resources and strategy that would affect the adoption of the CCS technology.

The Barriers under Environmental Context: The barriers in the external environment including the political, economic, social and legal that may have effects on the decision of CCS deployment by the petroleum refineries.

3.1.3 Barriers Analysis

After the barriers have been identified and classified under the TOE framework, the barriers are then assessed. The objective of this step is to prioritize the barriers to identify the critical barriers that are preventing the deployment of CCS technology at petroleum refineries in Thailand under technological, organizational and environmental contexts.

The FMEA approach, one of the commonly used risk analysis techniques, is adapted to be used to analyze the criticality of the potential barriers. The criticality of the barriers is dependent on their likelihood of occurrence and severity of their consequence. In this research, the potential failure modes are the barriers which obstruct the deployment of CCS technology at the petroleum refinery. The objective is to analyze the degree of the risks involved with each barrier by finding the severity and probability of its occurrence.

The data were collected by conducting a survey with experts in the field at one of the leading petroleum refineries in Thailand. The experts were briefed about the research prior to the survey. This group of people was chosen as a sample because they would have knowledge of the technology and the urgency of global warming and give honest opinion regarding the barriers of adopting CCS technology. In total, three experts were invited to perform the survey. The respondents of the survey were asked to rate the severity and occurrence of different barriers belonging under the TOE framework using a five-point Likert scale, a common rating format for surveys. The survey is a Likert scale format to gain quantitative results of the severity of the consequence of each barrier and the likelihood of their occurrence that would influence the uptake of the CCS technology as emission reduction strategy.

The survey consists of three tables; The barriers under technological, organizational and environmental contexts. There were 9 technological barriers, 9 organizational barriers and 11 environmental barriers that experts had to assign the severity and occurrence scores using the 1-5 Likert scale; 1 (least critical) to 5 (most critical). Severity is the effect of the potential failure mode on the refinery and Occurrence is the likelihood that the failure cause will occur at the refinery. These two factors are scored on a scale from “1” to “5” for each barrier. The criteria for ranking the severity and occurrence of the barriers have been adapted from Afshari et al. (2016) by the author for the experts to rank the Severity and Occurrence based on the same measures. The criteria of ranking the severity and occurrence are described in below:

Table 5: The Criteria for Ranking the Severity and Occurrence for FMEA Survey

Severity (S)		
Rating	Description	Definition
1	Very Low	This barrier will have a very low effect on the refinery.
2	Low	This barrier will have a minor effect on the refinery.
3	Moderate	This barrier will have an apparent effect on the refinery.
4	High	This barrier will have a serious effect on the refinery.
5	Very High	This barrier will have a catastrophic effect on the refinery.
Occurrence (O)		
Rating	Description	Definition
1	Very Low	This barrier will possibily not occur.
2	Low	This barrier will rarely occur.
3	Moderate	This barrier sometimes occur.
4	High	This barrier often occur.
5	Very High	This barrier always occur.

Source: Adapted from Afshari et al. (2016).

In this study, the FMEA analysis is adapted to find the Criticality Number which is calculated by multiplying Severity and Occurrence. The Detection is not considered as the purpose of this study is to determine the criticality of the barriers, and criticality is a function of the likeliness and the severity of the consequence of the failure. The results from the survey are transferred into Excel spreadsheet as Severity (S) and Occurrence (O) ratings. The average of the S and O are calculated for each failure mode and the averages were multiplied to determine the Criticality Number (CN) of each barrier. The analysis of the barriers was done separately under Technological, Organizational and Environmental contexts based on the TOE framework. The barriers with high CN under each context would be identified as critical barriers to deploying CCS technology. The calculated CN was used to prioritize the barriers to identify the critical barriers preventing the petroleum refinery from deploying the CCS technology. The highest possible criticality number is 25 and the lowest is 1. This research is based on qualitative and quantitative analysis of the barriers. The calculation of the CN gives a quantitative analysis of the risk involved with each barrier and prioritization of the risks is a qualitative analysis which allows them to be further studied. The Pareto diagram will be developed, and the 80/20 rule will be used to identify the critical barriers. The prioritization of the barriers will allow the efforts to be directed to the most critical barrier which requires highest priority (Catelani et al., 2015). The survey results are presented in Section 4.

3.1.4 Barriers Response: The Roadmap

In this research, the critical barriers to deploying CCS technology at Thai petroleum refineries identified from the survey results were used to develop a roadmap with action plans to overcome the barriers. The critical barriers were classified as short, medium and long-term milestones to facilitate the deployment of the technology more strategically like how the CCS technology roadmaps were proposed in literature (ADB, 2015; Narain, 2007). The roadmap would not just focus on the technological barriers but also the organizational and environmental barriers to include legislation, policy and resource planning.

The objective of the barrier treatment is to develop a response to the identified barriers by developing action plans to mitigate the risks involved with those barriers to make the technology more attractive to deployment. The aim of this study is to identify feasible ways to reduce the likelihood of occurrence and minimize the severity of the consequences that could occur from different possible barriers of deploying CCS technology at Thai petroleum refineries and not just suggest general action plans to promote the deployment of the technology like most studies in literature. The three phases as suggested Parsons Brinckerhoff's report (2015) will be adapted to develop the roadmap in this study.

After the completion of the data collection from literature review and identification of critical barriers to deploy CCS technology at petroleum refineries from FMEA, the ways to overcome those barriers are studied from literature. Section 2.8 explains the different ways to overcome barriers and promote CCS technology deployment. A semi-structured interview will also be conducted with the same group of experts that ranked the severity and occurrence of the barriers to discuss the action plans to overcome the barriers to promote the deployment of CCS technology at Thai petroleum refineries based on the identified critical barriers from the FMEA. Some of the interview questions were adapted from Dapeng and Weiwei (2009) to understand the position of CCS technology in Thailand's petroleum refinery industry, the concerns that the experts have on the technology specific to the country and the organization that are preventing the deployment of CCS technology, and to discuss the validity of the strategies and policies suggested in the literature if they were to be adopted to overcome the barriers of CCS technology deployment at the case petroleum refinery.

Parsons Brinckerhoff's report (2015) suggested that in the second phase of roadmap development, different pathways of different technology mix should be developed, but as the objective of this research is to study the deployment of CCS technology to mitigate GHG emission reduction in Thai petroleum refineries, therefore, only one pathway suggesting short, medium and long-term action plans to overcome the technological, organizational and environmental critical barriers will be developed. According to ADB (2015), a pathway, irrespective of the country planning to deploy CCS technology, follows pilot projects, demonstration projects and commercial projects stages, and this will be adopted in this research where the action plans will correlate to development of pilot, demonstration and commercial projects in the short, medium and long-term respectively.

The third phase summarizes the enablers to promote deployment of CCS technology and strategies and policies that will overcome different critical barriers into short, medium and long-term actions plans to develop a pathway of pilot, demonstration and commercial projects stages respectively. The aim of the actions on the roadmap is to build capacity: technical, financial, environmental, community engagement, regulatory and legal, to develop and implement CCS (ADB, 2015). The critical barriers are classified into short, medium and long-term milestones strategically just like proposed by ADB (2015) and Narain (2007) in the literature.

3.2 Research Process Summary

Table 6: Research Process Summary

Research Objective	Source of Data	Research Instrument/Method
To determine and organize the potential barriers and challenges of deploying CCS at a Thai petroleum refinery.	Literature review and brainstorming	• TOE Framework • Ishikawa Diagram
To apply FMEA approach to evaluate the criticality of the barriers and prioritize them.	Experts' opinion	• Survey • FMEA to calculate Criticality Number (CN) on Microsoft Excel • Pareto Diagram
To develop a roadmap with action plans required to overcome the challenges to implement CCS technology.	Literature review and experts' opinion	• Semi-Structured Interview • Roadmap

Chapter 4 Result and Analysis

In this chapter, the findings of this research will be presented. The purpose of this research was to identify the critical barriers to deploying carbon capture and storage technology at a Thai petroleum refinery using an analysis tool, FMEA, and develop a roadmap with short, medium and long-term action plans to overcome those barriers to promote the deployment of the CCS technology at the refinery.

4.1 General Overview of Case Company and Background of the Experts

The case company is one the leading petroleum refineries in Thailand. The company is committed to minimizing environmental effect and sustainability. The company has been executing an Environmental Master Plan by initiating projects to maximize energy efficiency and reduce emission of greenhouse gases. The projects initiated include improvement of heat insulation, improvement of heat exchange efficiency, monitor for leakage, improvement of combustion efficiency etc. which has allowed them to meet their emission reduction goals. This petroleum refinery has not included CCS technology as a GHG mitigation strategy in their Environmental Master Plan, which is why representatives from the organization are asked to participate in the survey and semi-structured interview to gain their perspectives on the barriers which are preventing the deployment of the technology as an emission abatement option at the refinery.

The background of the three experts that participated in the survey and the interview are as follows:

- Expert 1: The Vice President of Corporate Strategic Risk in the Risk Management Department of the refinery.
- Expert 2: The Manager of Sustainability Development in the Corporate Governance and Sustainability Department of the refinery.

- Expert 3: The Environmental Specialist in Planning and Strategy Department of the refinery.

4.2 Demonstration of the Research Findings Based on Research Objectives

4.2.1 Research Objective 1: The Potential Barriers are Classified Under TOE Framework

The first objective of this research is to determine and organize the potential barriers and challenges of deploying CCS technology at a Thai petroleum refinery. The potential barriers to deploying CCS technology identified from literature review and brainstorming are classified under the TOE Framework into technological, organizational and environmental contexts. The barriers are classified into each category by their nature:

The barriers identified as Technological Barriers are the challenges involved with the availability, readiness, characteristics, diversity, knowledge and safety of the CCS technology that is preventing the deployment of the technology.

The barriers identified as Organizational Barriers are the challenges involved with the resources, strategy, efficiency, financial and other capacities of the refinery that is preventing the deployment of the CCS technology.

The barriers identified as Environmental Barriers are the challenges involved with the industry, technology support infrastructure, safety of the environment, regulations and government support that affects the decision of deploying the CCS technology by the refinery.

The Ishikawa diagram is used to depict the barriers under each category below (Figure 8).

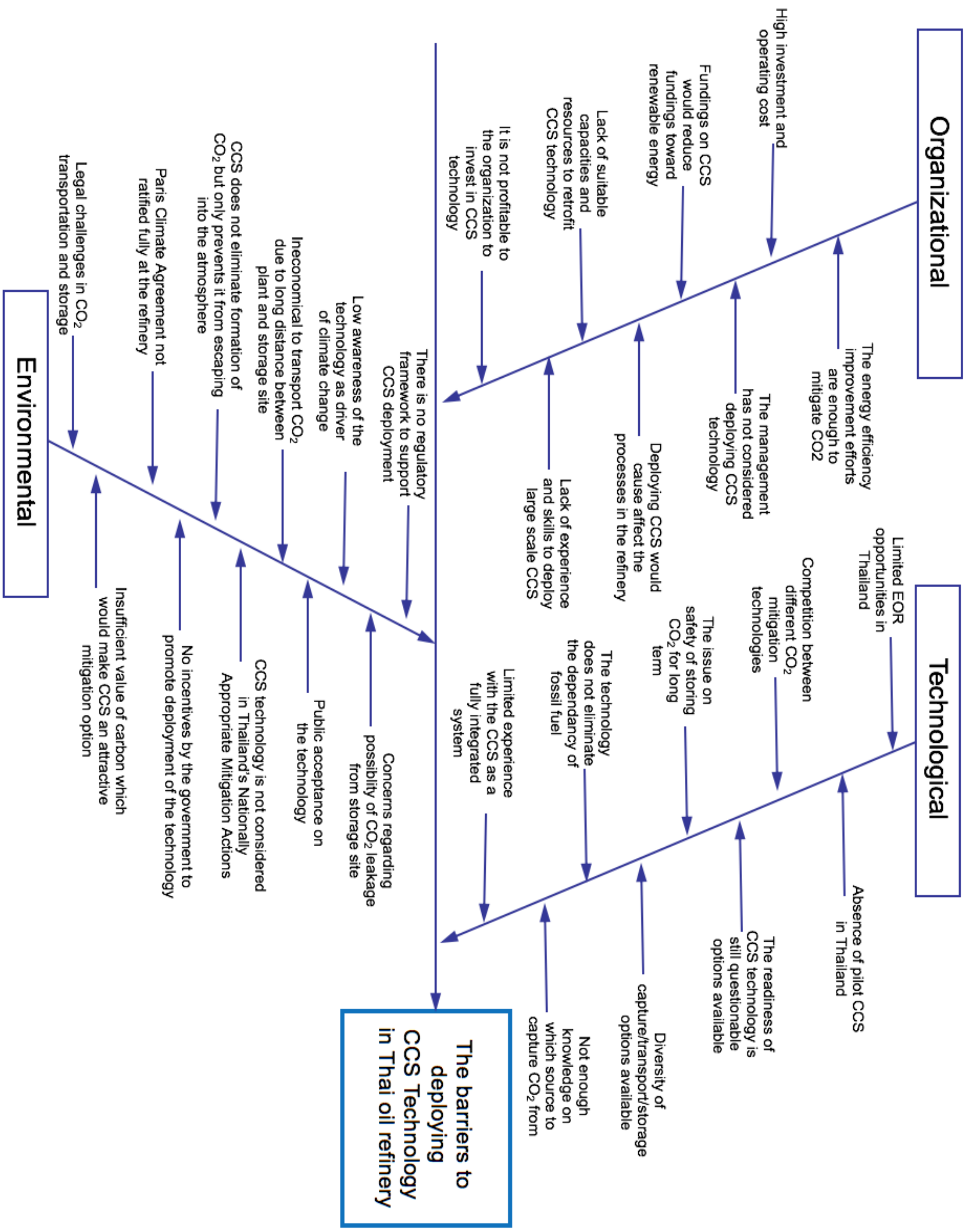

Figure 9: The Ishikawa Diagram Depicting Barriers to Deploy CCS Technology at Thai Petroleum Refinery Under TOE Framework

4.2.2 Research Objective 2: Application of FMEA Approach to Evaluate the Criticality of the Barriers and Prioritize Them.

The second objective of this study was to evaluate the criticality of the potential barriers that could be preventing the deployment of CCS technology at the petroleum refineries. The FMEA method is used to analyze the potential barriers. The organized barriers are transformed into a survey for severity and occurrence ranking by the experts. The criticality number (CN) calculated from the severity of the effects and the likelihood of the barriers' occurrence would be used to determine whether the barrier is critical and needs to be considered in the roadmap.

Assigning Severity and Occurrence Ranking

The survey (Appendix A) is used to obtain the severity and occurrence ranking of the potential barriers by the experts from the case petroleum refinery in Thailand. The ranking is based on a 5-point Likert Scale. The description for each point of the scale (Table 5) was established before the ranking process and was given with the survey for the experts to have the same understanding of the rankings. The rankings of severity and occurrence given by the experts to each of the barriers are transferred onto the FMEA worksheet in Microsoft Excel. The barriers are categorized under the TOE framework into Technological, Organizational and Environmental barriers in the worksheet as well. The average of severity 'S' and average occurrence 'O' are calculated and the product of these two values are the CN of each barrier.

The CN of each potential barrier is calculated in the Microsoft Excel. The concept behind calculating the numerical CN, which is determined by multiplying the ranking of the severity of the barriers' effects and the likelihood of their occurrence, is fairly simple. The obtained CN represents the degree of risk associated with each barrier. According to Bowles (1998), it is not the numerical procedure of determining the criticality number, but the knowledge gained from it about the system that is important; In this study, it is the qualitative result or the priority of the barriers and not the quantitative result or the CN that is given importance. Therefore, the average 'S' and 'O' is used to calculate the CN despite the controversies regarding applying parametric tests for analyzing ordinal data (Sullivan and Artino, 2013; Mircioiu and Atkinson, 2017). The barriers are prioritized to determine the critical barriers in each of the contexts under the TOE framework. The barriers under different contexts of the TOE framework are studied independently as this research does not consider the dependency of the barriers across the category and analyzing them together would not have been accurate. In reality, the barriers under these categories are dependent on one another and weights could be given according to the importance of each category to further analyze the barriers, but this is beyond the scope of this research.

The result of the severity and occurrence ranking of the barriers from three experts (1,2 and 3) in no particular order under Technological, Organizational and Environmental contexts along with the calculated average severity 'S', average occurrence 'O', and criticality number 'CN' obtained from the survey are presented in the tables below:

Table 7: The FMEA Worksheet for Technological Barriers

Technological Barriers	Severity				Occurrence				Criticality Number (CN)
	1	2	3	S	1	2	3	O	S x O
Limited experience with the CCS as a fully integrated system	4	4	4	4.00	4	4	4	4.00	16.00

Not enough knowledge on which source to capture CO_2 from	1	4	2	2.33	1	4	2	2.33	5.44
The technology does not eliminate the dependency of fossil fuel	1	4	3	2.67	1	4	3	2.67	7.11
The issue on safety of storing CO_2 for long term	1	5	4	3.33	1	5	4	3.33	11.11
Diversity of capture/transport/storage options available	2	3	4	3.00	2	3	4	3.00	9.00
The readiness of CCS technology is still questionable	3	4	4	3.67	3	5	4	4.00	14.67
Competition between different CO_2 mitigation technologies	2	5	3	3.33	2	5	3	3.33	11.11
Absence of pilot CCS in Thailand	2	4	4	3.33	2	5	4	3.67	12.22
Limited EOR opportunities in Thailand	4	4	4	4.00	4	4	4	4.00	16.00

Table 8: The FMEA Worksheet for Organizational Barriers

Organizational Barriers	Severity				Occurrence				Criticality Number (CN)
	1	2	3	S	1	2	3	O	S x O
It is not profitable to the organization to invest in CCS technology	5	4	5	4.67	5	5	5	5.00	23.33
High investment and operating cost	5	4	5	4.67	5	4	5	4.67	21.78
Funding on CCS would reduce funding toward renewable energy	1	5	2	2.67	1	5	2	2.67	7.11
Lack of suitable capacities and resources to retrofit CCS technology	1	4	4	3.00	1	4	4	3.00	9.00
Lack of experience and skills to deploy large scale CCS	2	4	4	3.33	2	4	4	3.33	11.11
The energy efficiency improvement efforts	2	4	2	2.67	2	5	2	3.00	8.00

are enough to mitigate CO_2									
The management has not considered deploying CCS technology	1	4	4	3.00	1	4	4	3.00	9.00
The deployment of CCS technology would affect the efficiency of the refinery	1	4	4	3.00	1	5	4	3.33	10.00
Deploying CCS would cause affect the processes in the refinery	1	4	4	3.00	1	5	4	3.33	10.00

Table 9: The FMEA Worksheet for Environmental Barriers

Environmental Barriers	**Severity**				**Occurrence**				**Criticality Number (CN)**
	1	**2**	**3**	**S**	**1**	**2**	**3**	**O**	**S x O**
Paris Climate Agreement not ratified fully at the	5	5	4	4.67	5	5	4	4.67	21.78

refinery									
No incentives by the government to promote deployment of the technology	5	4	4	4.33	5	5	4	4.67	20.22
CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions	5	4	4	4.33	5	5	4	4.67	20.22
CCS does not eliminate formation of CO_2 but only prevents it from escaping into the atmosphere	5	4	3	4.00	5	4	3	4.00	16.00
Uneconomical to transport CO_2 due to long distance between plant and storage site	2	4	4	3.33	2	4	4	3.33	11.11
Public acceptance on the technology	2	4	5	3.67	2	5	5	4.00	14.67
Low awareness of the technology as	3	3	3	3.00	3	4	3	3.33	10.00

driver of climate change									
Concerns regarding possibility of CO_2 leakage from storage site	3	4	3	3.33	3	5	3	3.67	12.22
There is no regulatory framework to support CCS deployment	5	4	4	4.33	5	4	4	4.33	18.78
Insufficient value of carbon which would make CCS an attractive mitigation option	5	4	4	4.33	5	5	4	4.67	20.22
Legal challenges in CO_2 transportation and storage	2	4	4	3.33	2	5	4	3.67	12.22

The qualitative information obtained from calculating CN of the barriers is used to prioritize the barriers to determine the critical barriers that are preventing the deployment of the CCS technology at the petroleum refinery. The correlation between the criticality of the different barriers under different contexts of the TOE framework are not being considered in this research, therefore, the barriers are ranked in descending order of critical number under each context individually. The barriers with higher CN mean that they have higher risk of preventing the deployment of the CCS technology.

Table 10: Technological Barriers Ranked in Descending Order of CN

Technological Barriers	Criticality Number
Limited experience with the CCS as a fully integrated system	16.00
Limited EOR opportunities in Thailand	16.00
The readiness of CCS technology is still questionable	14.67
Absence of pilot CCS in Thailand	12.22
The issue on safety of storing CO_2 for long term	11.11
Competition between different CO_2 mitigation technologies	11.11
Diversity of capture/transport/storage options available	9.00
The technology does not eliminate the dependence of fossil fuel	7.11
Not enough knowledge on which source to capture CO_2 from	5.44

Table 11: Organizational Barriers Ranked in Descending Order of CN

Organizational Barriers	Criticality Number
It is not profitable to the organization to invest in CCS technology	23.33
High investment and operating cost	21.78
Lack of experience and skills to deploy large scale CCS	11.11
The deployment of CCS technology would affect the efficiency of the refinery	10.00
Deploying CCS would cause affect the processes in the refinery	10.00
Lack of suitable capacities and resources to retrofit CCS technology	9.00
The management has not considered deploying CCS technology	9.00
The energy efficiency improvement efforts are enough to mitigate CO_2	8.00
Funding on CCS would reduce funding toward renewable energy	7.11

Table 12: Environmental Barriers Ranked in Descending Order of CN

Environmental Barriers	Criticality Number
Paris Climate Agreement not ratified fully at the refinery	21.78
No incentives by the government to promote deployment of the technology	20.22
CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions	20.22
Insufficient value of carbon which would make CCS an attractive mitigation option	20.22
There is no regulatory framework to support CCS deployment	18.78
CCS does not eliminate formation of CO_2 but only prevents it from escaping into the atmosphere	16.00
Public acceptance on the technology	14.67
Concerns regarding possibility of CO_2 leakage from storage site	12.22
Legal challenges in CO_2 transportation and storage	12.22
Uneconomical to transport CO_2 due to long distance between plant and storage site	11.11
Low awareness of the technology as driver	10.00

of climate change	

The barriers under different categories as well as the barriers within the same category are studied independent of one another as the relationship between each barrier on one another and the relative importance of the barriers in relation to their impact on CCS deployment was not considered in the study. The purpose of studying the barriers under different categories is because it is more organized, and it makes it easier to understand where most efforts need to be put to reduce the risk to promote the deployment of the technology. Looking at the result obtained from the FMEA, the Organizational and Environmental Barriers were ranked higher CN than the Technological Barriers. The barrier that had the highest CN was an Organizational Barrier: Investing in CCS technology is not profitable to the organization. The barriers belonging to the Environmental category have the highest number of barriers that scored high CN as compared to the barriers in other two categories. From the risk associated with the barriers, it can be seen that more than the concerns with the technology that is preventing the adoption of the CCS technology, it is the lack of capacities in the organization and the lack of support from the government that has higher power in preventing the deployment of the CCS technology at Thai petroleum refineries. The barriers to adoption of CCS at Thai petroleum refineries determined in this study correlates with the challenges to deploy CCS technology in Thailand suggested by Witsarut et al. (2012) in Section 1.1.8. This has proven the claim made that Thailand is not ready for CCS deployment by Global CCS Institute (2018), Section 1.1.6.

After the barriers were scored using the FMEA scoring system to determine the criticality number and prioritized from highest to lowest CN, the critical barriers can be identified. The technological barriers that scored high CN include the limited experience with CCS technology as a fully integrated system, the limited EOR opportunities, the readiness of the technology, the absence of pilot CCS projects in Thailand and the safety concerns of storing CO_2 for long term. The critical organizational barriers include the profitability of investing in the technology, high cost, lack of experience and skills and the issues with efficiency of the refinery after retrofitting the technology. The critical environmental barriers include the refinery not fully ratifying Paris Climate Agreement, no government incentives to promote CCS deployment, CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions, no carbon market and no regulatory framework for the technology.

Pareto Analysis to Evaluate the Critical Barriers

The barriers that were analyzed using FMEA were then further evaluated using Pareto analysis. Pareto diagram and the 80/20 rule were used to evaluate and identify the critical barriers of each category: Technological, Organizational and Environmental. According to theory, 20% of the barriers are accountable for 80% of the criticality number.

After the barriers were rearranged in descending order of CN, the following steps are followed in this research to do the Pareto analysis:

1. The cumulative CN of all the barriers in each category were calculated separately.
2. The cumulative percentage of the barriers were determined for barriers under each category.

$$\text{Cumulative \%} = \frac{\text{Cumulative CN}}{\text{Total Cumulative CN}} \times 100$$

3. Determine number of barriers that made up 80% of the cumulative % for each category.
4. These barriers are considered as critical barriers according to the 80/20 rule and should be 20% of total cumulative number of barriers.

There are 9 Technological Barriers, 9 Organizational Barriers and 11 Environmental Barriers that have been analyzed in this study. The Pareto analysis of the barriers was done for each category, Technological, Organizational and Environmental, separately just like how the FMEA and the scoring of the severity and occurrence of the barriers were also done separately for each category. The Pareto analysis of the barriers are demonstrated below:

Table 13: Cumulative CN of Technological Barriers

Technological Barriers	Criticality Number	Cumulative CN	Cumulative %
Limited experience with the CCS as a fully integrated system	16.00	16.00	15.58
Limited EOR opportunities in Thailand	16.00	32.00	31.17
The readiness of CCS technology is still questionable	14.67	46.67	45.45
Absence of pilot CCS in Thailand	12.22	58.89	57.36
The issue on safety of storing CO_2 for long term	11.11	70.00	68.18
Competition between different CO_2 mitigation technologies	11.11	81.11	79.00
Diversity of	9.00	90.11	87.77

capture/transport/storage options available			
The technology does not eliminate the dependency of fossil fuel	7.11	97.22	94.70
Not enough knowledge on which source to capture CO_2 from	5.44	102.67	100.00

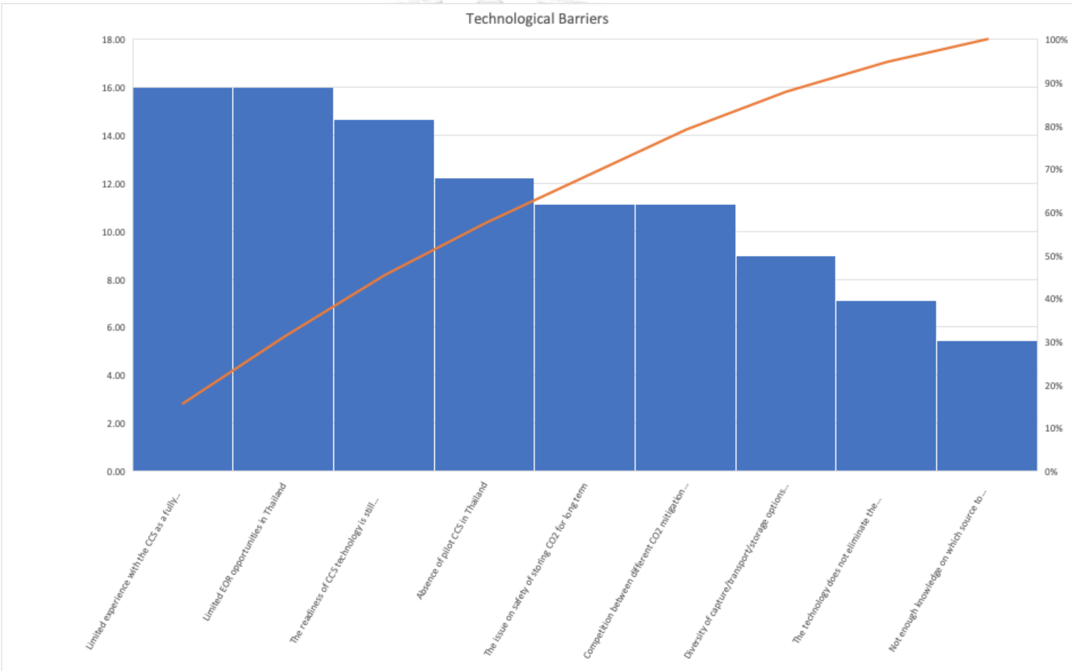

Figure 10: Pareto Diagram of Technological Barriers to Deploying CCS Technology at Thai Petroleum Refinery

The total cumulative CN of all Technological Barriers is 102.67 and 80% of that is 83.14. According to the 80/20 rule, the accumulating CN of 20% of the total number of Technological Barriers should be 80% which is 83.14. Considering that 20% of 9 is 1.8, accumulative CN of 2 of the highest ranked Technological Barriers should make up 80% of the cumulative CN. According to the calculations, the accumulative CN of the top 2

Technological Barriers is 32.00 which is only 31.17% of the total cumulative CN of the Technological Barriers and not 80%.

Table 14: Cumulative CN of Organizational Barriers

Organizational Barriers	Criticality Number	Cumulative CN	Cumulative %
It is not profitable to the organization to invest in CCS technology	23.33	23.33	21.34
High investment and operating cost	21.78	45.11	41.26
Lack of experience and skills to deploy large scale CCS	11.11	56.22	51.42
The deployment of CCS technology would affect the efficiency of the refinery	10.00	66.22	60.57
Deploying CCS would cause affect the processes in the refinery	10.00	76.22	69.72
Lack of suitable capacities and	9.00	85.22	77.95

resources to retrofit CCS technology			
The management has not considered deploying CCS technology	9.00	94.22	86.18
The energy efficiency improvement efforts are enough to mitigate CO_2	8.00	102.22	93.50
Funding on CCS would reduce funding toward renewable energy	7.11	109.33	100.00

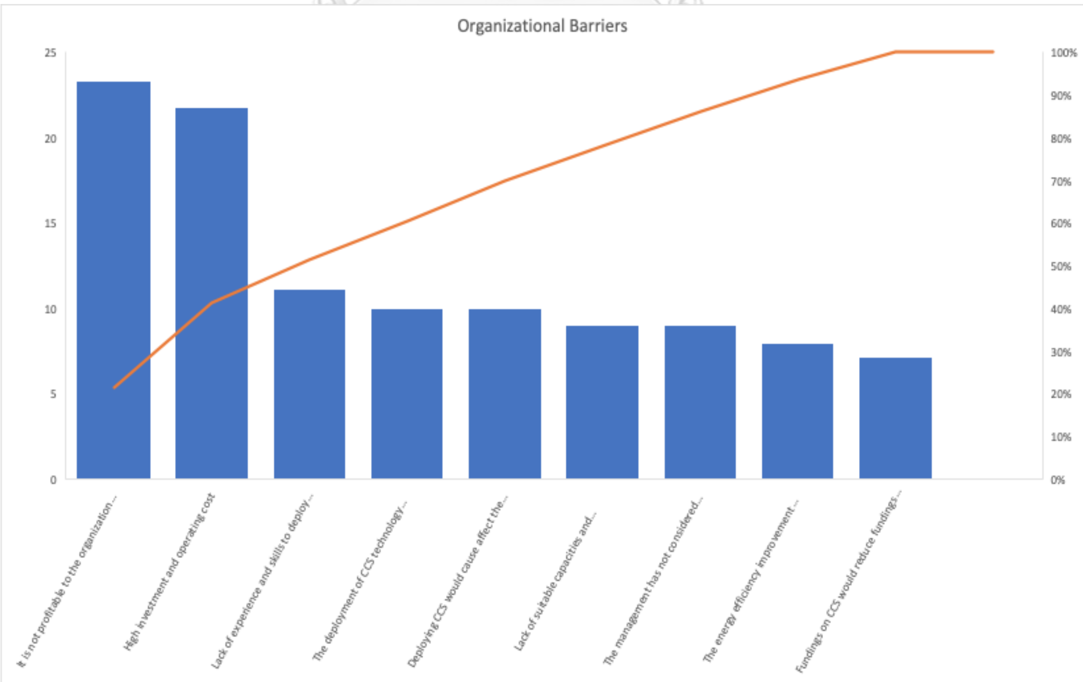

Figure 11: Pareto Diagram of Organizational Barriers to Deploying CCS Technology at Thai Petroleum Refinery

The total cumulative CN of all Organizational Barriers is 109.33 and 80% of that is 87.46. According to the 80/20 rule, the accumulating CN of 20% of the total number of Organizational Barriers should be 80% which is 87.46. Considering that 20% of 9 is 1.8, accumulative CN of 2 of the highest ranked Organizational Barriers should make up the 80% of the cumulative CN. According to the calculations, the accumulative CN of the top 2 Organizational Barriers is 45.11 which is only 41.26% of the total cumulative CN of the Organizational Barriers and not 80%.

Table 15: Cumulative CN of Environmental Barriers

Environmental Barriers	Criticality Number	Cumulative CN	Cumulative %
Paris Climate Agreement not ratified fully at the refinery	21.78	21.78	12.27
No incentives by the government to promote deployment of the technology	20.22	42.00	23.67
CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions	20.22	62.22	35.07
Insufficient value of carbon which would make CCS an	20.22	82.44	46.46

attractive mitigation option			
There is no regulatory framework to support CCS deployment	18.78	101.22	57.04
CCS does not eliminate formation of CO_2 but only prevents it from escaping into the atmosphere	16.00	117.22	66.06
Public acceptance on the technology	14.67	131.89	74.33
Concerns regarding possibility of CO_2 leakage from storage site	12.22	144.11	81.21
Legal challenges in CO_2 transportation and storage	12.22	156.33	88.10
Uneconomical to transport CO_2 due to long distance between plant and storage site	11.11	167.44	94.36
Low awareness of the technology as driver	10.00	177.44	100.00

of climate change			

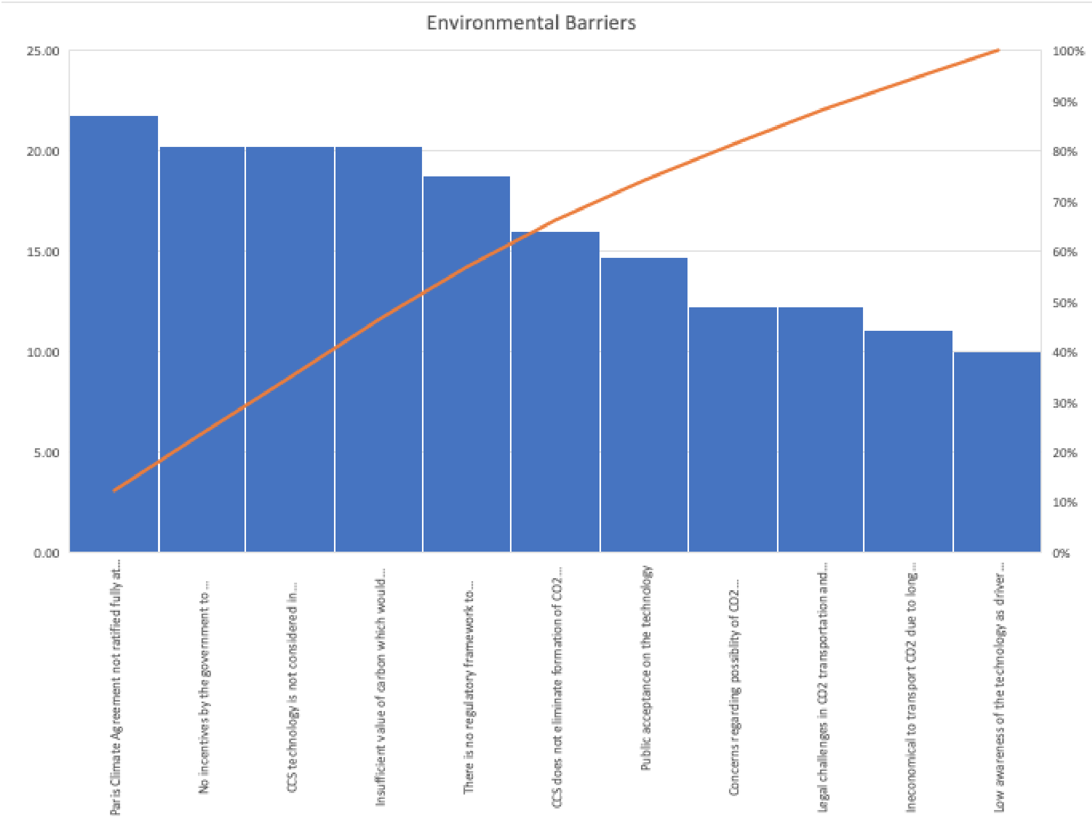

Figure 12: Pareto Diagram of Environmental Barriers to Deploying CCS Technology at Thai Petroleum Refinery

The total cumulative CN of all Environmental Barriers is 177.44 and 80% of that is 141.95. According to the 80/20 rule, the accumulating CN of 20% of the total number of Environmental Barriers should be 80% which is 141.95. Considering that 20% of 11 is 2.2, accumulative CN of 3 of the highest ranked Environmental Barriers should make up the 80% of the cumulative CN. According to the calculations, the accumulative CN of the top 3 Environmental Barriers is 62.22 which is only 35.07% of the total cumulative CN of the Environmental Barriers and not 80%.

According to the results, 20% of the barriers make up less than 80% of the cumulative CN for all of the categories of barriers. Therefore, the 80/20 rule cannot be applied in this study to determine the critical barriers. According to analysis, most of the barriers that scored high CN are correlated, which is why all of the barriers that make up 80% of the cumulative % will be considered as critical barriers in this research and are addressed in the next section while developing action plans to mitigate the risk associated with CCS technology deployment at petroleum refineries. The critical barriers that make up 80% of cumulative CN % are summarized in the table below:

Table 16: The Critical Barriers to Deploying CCS Technology at a Thai Petroleum Refinery Under TOE Framework

Critical Barriers		
Technological	Organizational	Environmental
Limited experience with the CCS as a fully integrated system	It is not profitable to the organization to invest in CCS technology	Paris Climate Agreement not ratified fully at the refinery
Limited EOR opportunities in Thailand	High investment and operating cost	No incentives by the government to promote deployment of the technology
The readiness of CCS technology is still questionable	Lack of experience and skills to deploy large scale CCS	CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions
Absence of pilot CCS in Thailand	The deployment of CCS technology would affect the efficiency of the refinery	Insufficient value of carbon which would make CCS an attractive mitigation option
The issue on safety of storing CO_2 for long term	Deploying CCS would cause affect the processes in the	There is no regulatory framework to support CCS

	refinery	deployment
Competition between different CO_2 mitigation technologies	Lack of suitable capacities and resources to retrofit CCS technology	CCS does not eliminate formation of CO_2 but only prevents it from escaping into the atmosphere
Diversity of capture/transport/storage options available	The management has not considered deploying CCS technology	Public acceptance on the technology
		Concerns regarding possibility of CO_2 leakage from storage site

4.2.3 Research Objective 3: Development of a roadmap with action plans required to overcome the challenges to implement CCS technology.

The objective of conducting FMEA in this research is to analyze the critical barriers that could potentially cause failure to the deployment of CCS technology at a Thai petroleum refinery and develop an action plan that would mitigate those risks. According to literature, one of the purposes of FMEA is to identify measures to reduce or eliminate the risks associated with the failure modes to minimize the risk occurrence. This section will discuss the last process of the risk management, the risk treatment, where possible actions to eliminate the risks or, in this case, the criticality of the barriers to deploy CCS technology will be suggested.

In order to minimize the criticality of the barriers, either the severity score, occurrence score or both of the scores need to be reduced. The barriers that were identified as critical barriers from the 80/20 rule are carried forward to study the possible ways to mitigate them to increase the chance of successfully deploying CCS technology at a Thai petroleum refinery. The frameworks for roadmap development have also been studied, and this research followed the three phases of roadmap development suggested in Parsons Brinckerhoff's report (2015). The first phase of developing a roadmap in this research after the critical barriers were determined is the analysis of available data on barriers and literature review on ways to mitigate those barriers to promote CCS technology and conducting interviews to discuss the validity of the actions suggested in the literature if they were to be adapted to overcome the barriers of CCS technology deployment at the petroleum refinery. The second phase was developing a pathway that will be followed while developing the roadmap. The third phase involves identifying actions into short, medium and long-term plans to overcome the barriers to deliver the pathway.

The potential solutions to reduce the criticality number to minimize the criticality of the barriers are suggested in the tables below:

Table 17: Action Plans to Overcome the Critical Technological Barriers

Critical Technological Barriers	Action Plans to Overcome the Critical Technological Barriers
Limited experience with the CCS as a fully integrated system	• Develop a pilot-scale demonstration project • Increase training
Limited EOR opportunities in Thailand	• Assess EOR opportunities in Thailand
The readiness of CCS technology is still questionable	• Increase R&D efforts
Absence of pilot CCS in Thailand	• Search for financial assistance to fund the development and operate the pilot project of the CO_2 capture and storage for

	demonstration
The issue on safety of storing CO_2 for long term	• Develop monitor and control for stored CO_2 to assess for any leakage
Competition between different CO_2 mitigation technologies	• Include CCS in the NAMA and increase R&D efforts
Diversity of capture/transport/storage options available	• Assess different capture modes/ transportation modes and storage methods to select the most appropriate one

Table 18: Action Plans to Overcome the Critical Organizational Barriers

Critical Organizational Barriers	Action Plans to Overcome the Critical Organizational Barriers
It is not profitable to the organization to invest in CCS technology	• Introduce carbon trading schemes and incentives to promote CCS deployment • CCS-EOR to produce income • Find ways to generate income from the captured CO_2
High investment and operating cost	• CCS-EOR to produce income • Search for financial assistance
Lack of experience and skills to deploy large scale CCS	• Learn from the pilot project • Increase training of staffs • Develop environment and safety standards

The deployment of CCS technology would affect the efficiency of the refinery	• Continuous R&D to improve the efficiency of the technology
Deploying CCS would affect the processes in the refinery	• Study the ways to retrofit CCS technology
Lack of suitable capacities and resources to retrofit CCS technology	• Prepare for required resources to deploy CCS technology • Assess if the technology can be retrofitted into the refinery
The management has not considered deploying CCS technology	• Find opportunities to gain income from captured CCS

Table 19: Action Plans to Overcome the Critical Environmental Barriers

Critical Environmental Barriers	Action Plans to Overcome the Critical Environmental Barriers
Paris Climate Agreement not ratified fully at the refinery	• Fully ratify Paris Climate Agreement at refineries and add CCS technology as organization's GHG mitigation strategy
No incentives by the government to promote deployment of the technology	• Search for support from the government (incentives and legislations)
CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions	• Include CCS in the NAMAs and increase R&D efforts

Insufficient value of carbon which would make CCS an attractive mitigation option	• Develop market for carbon • Find ways to earn income from the captured CO_2
There is no regulatory framework to support CCS deployment	• Establish regulatory framework for CCS to guide the adoption of the technology by adjusting the existing legal and regulatory framework.
CCS does not eliminate formation of CO_2 but only prevents it from escaping into the atmosphere	• R&D on ways to beneficially utilize the carbon captured
Public acceptance on the technology	• Increase public awareness by providing knowledge about the environmental impact
Concerns regarding possibility of CO_2 leakage from storage site	• Monitor and control for stored CO_2 to assess for any leakage

A semi-structured interview has been conducted with the same panel of experts that ranked the severity and occurrence of the barriers to discuss the strategies and policies that could overcome the barriers to deploy CCS technology at the petroleum refinery. The interview questions allowed the author to further gain the views of the experts on emission abatement potential of the refinery using CCS technology. The discussion included the major concerns with the deployment of CCS technology at the petroleum refinery that need to be considered while planning possible action plans and whether the plans on the roadmaps for CCS deployment published in the literature would be applicable to refineries in Thailand.

All of the experts agreed that the two major barriers for CCS deployment are the high cost involved in the technology with no evident economic benefits from the captured carbon, and the safety issues of storing the CO_2. From the interview, all of the experts were optimistic about the CCS technology as a GHG mitigation strategy, but they do not see the technology being implemented in the near future. In terms of the economic concerns, Expert 1 stated that CCS-EOR opportunities in Thailand is limited and without the opportunities to gain income from deploying CCS at the refinery, the refinery would not consider implementing the technology just yet. There are also no government actions or laws to encourage investments on emission abatement technologies as the oil sector is not recognized as an important source for emission reduction. The technology does not seem to be a sustainable way to reduce emissions, stated the expert. The experts believe that the projects being invested in the refinery, including operational efficiency improvement, changing the product mix to produce light oil, recovery of hydrocarbon, replacing fuel oil with natural gas as fuel and green business, were enough to achieve the set targets of GHG emission reduction set by the refinery. Expert 2 even suggested that buying carbon credit or paying tax would be cheaper than investing in CCS technology considering the current status of the technology with no immediate financial benefits. In terms of safety issues, there are concerns regarding the possible contamination of injecting CO_2 with impurities under water, the possibility of CO_2 stored being leaked into the atmosphere, and safety of transporting CO_2 from the capture site to the storage site. These barriers are also included when developing a roadmap.

The actions along with the associated policies, strategies and investment plans that would enable the treatment of the corresponding barriers are further explained below:

Action Plans to Overcome the Critical Technological Barriers

1. Limited experiences with the CCS as a fully integrated system: The way to overcome this barrier is to develop a pilot-scale demonstration project of the CCS system of capture, transport and storage facilities to gain experience with the fully integrated system.

2. Limited EOR opportunities in Thailand: The CCS-EOR opportunities should be assessed and promoted in Thailand as EOR is one of the methods to beneficially utilize the captured CO_2. One of the major concerns that is preventing the deployment of CCS technology is that there is limited use of the captured carbon to generate revenue from deploying the CCS technology.

3. The readiness of CCS technology is still questionable: The amount of R&D on CCS technology at refineries in Thailand has been minimal as the budgets are mostly given to studies to improve energy efficiency and renewable energy projects. There are many possible ways to capture, transport and store carbon and there are limited studies done on the technology to fully understand the most appropriate technology to deploy at different sources, raising questions about the readiness of the most economic and efficient technology to implement at the refinery. Increasing research on the technology would aid the development process of the technology and make it ready for deployment.

4. Absence of pilot CCS in Thailand: A pilot-scale project needs to be developed in Thailand. Developing a prototype or a pilot project will allow data collection of possible causes of failures that may occur from actual implementation of the technology which would allow the refineries to better plan technical and economic resources to prepare for the deployment of the technology. Refineries should search for financial assistance from the government or international investors to fund the development of the pilot CCS technology project. Involvement of different sectors including refineries, institutes and government is

required in the R&D process to assess the technology, share resources and knowledge and develop policies before proceeding with commercial-scale projects, therefore, these sectors should be involved in developing the project.

5. The issue on safety of storing CO_2 for long-term: A monitor and control system for leakage of stored CO_2 needs to be developed. A safety standard guideline regarding stored CO_2 must be developed as according to the experts, safety issue is one of the major barriers of CCS technology deployment.

6. Competition between different CO_2 mitigation technologies: According to Expert 2, CCS technology has been discussed as a long-term GHG mitigation strategy. Budgets are allocated to other GHG mitigation technologies, such as energy efficiency improvement technologies and not towards R&D of CCS technology because it is still not actively considered as a beneficial mitigation strategy. To overcome this barrier, refineries need to increase efforts towards R&D of the CCS technology.

7. Diversity of capture/transport/storage options available: The strategy to overcome this barrier is to assess the different modes of capture, transport and storage to understand the benefits of different modes and choose the most appropriate facilities and develop an effective integrated CCS system for the refinery.

Action Plans to Overcome the Critical Organizational Barriers

1. It is not profitable to the organization to invest in CCS technology: CCS technology is an expensive GHG mitigation strategy and for refineries to invest in it, there should either be a policy developed by the government for the refineries to deploy the technology or the benefits of implementing the technology towards

the refinery needs to be understood. Carbon trading schemes can be introduced in Thailand, or cost effectiveness of CCS technology needs to be improved for the technology to be considered.

2. High investment and operating cost: The high cost of the technology is one of the major barriers preventing the refineries from deploying it as a GHG mitigation strategy. According to Expert 2, the cost of reducing CO_2 via CCS technology is approximately three times that of energy efficiency improvement. Funding needs to be obtained by the refinery to deploy the technology and opportunities to generate income from the captured CO_2 needs to be explored to make CCS technology an attractive option as there are uncertainties about the return on capital.

3. Lack of experience and skills to deploy large scale CCS: Partnership with experts regarding the technology who has experience and skills will ease the deployment of the technology. Training needs to be provided to the staff, and environment and safety standards need to be developed to guide the deployment of large-scale CCS technology.

4. The deployment of CCS technology would affect the efficiency of the refinery: The projects of energy efficiency needs to be continued along with R&D of the CCS technology to continuously improve the efficiency of the technology and the processes in the refinery. The effect of retrofitting the CCS technology into the refinery needs to be studied to explore whether there are any negative impacts on the efficiency of the refinery as the refinery still needs to remain competitive without compromising on its efficiency.

5. Deploying CCS technology would affect processes in the refinery: The different modes of capture needs to be studied to choose the most appropriate one that

can be fitted with the existing plant with the least modification. The source of carbon capture in the refinery should be thoroughly studied to choose which method would have the minimum effect on the processes in the refinery.

6. Lack of suitable capacities and resources to retrofit CCS technology: From the interview, one of the main concerns with Expert 3 was the limited resources such as space in the existing refinery that would make the deployment of the technology challenging. In order to overcome this barrier and to better plan resources required for the deployment of the technology at the refineries, the experience with the technology needs to be increased.

7. The management has not considered deploying CCS technology: The management should make climate change a priority and include CCS technology in their R&D efforts and commit to promoting it along with energy efficiency improvements and renewable energy as a GHG reduction strategy. The refineries need to consider collaborating with public institutes to gain funding for R&D of the CCS technology. According to the interview with the experts from the case study petroleum refinery, Expert 2 mentioned that the management has been talking about exploring the technology as a GHG mitigation strategy but the lack of benefits that can be created from deploying the technology is making it less attractive, therefore, there needs to be factors that would create a market pull.

Action Plans to Overcome the Critical Environmental Barriers

1. Paris climate agreement not ratified fully at the refinery: The government needs to pass out more laws to motivate the refineries to take GHG emission reduction more strictly. Refineries need to work towards continuously reducing the GHG

emission and consider different emission abatement technologies to help achieve the target of GHG reduction set.

2. No incentives by the government to promote deployment of the technology: The government needs to provide incentives and develop legislative frameworks to promote the refineries to deploy CCS technology. The support from the government in providing the required resources to develop a pilot demonstration plant is necessary. An ambitious GHG emission reduction target is required for CCS technology to be deployed.

3. CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions: Thailand needs to recognize that CCS technology needs to be considered as GHG emission mitigation option and support funding for launching of national research and development programs like the EU and China to catalyze the adoption of the technology. If the technology is considered in the NAMAs there would be domestic and international financial and policy support.

4. Insufficient value of carbon which would make CCS an attractive mitigation option: A market for carbon needs to be created with a defined value for carbon, and carbon trading and carbon tax programs need to be introduced. The existing laws about the ownership rights of the captured CO_2 and stored CO_2 also needs to be updated.

5. There is no regulatory framework to support CCS deployment: The regulations need to be adapted to overcome the legislation barriers such as demonstrated in Table 4 that are preventing the CCS technology deployment. Development of the regulatory framework will support the commercial deployment of CCS technology.

6. CCS does not eliminate formation of CO_2 but only prevents it from escaping into the atmosphere: The different ways to utilize the captured CO_2 needs to be explored to generate income for the refinery. The CCS technology allows fossil fuel to be used as fuel while reducing the CO_2 escaping into the atmosphere, not like renewable energy that is trying to find alternative forms of energy, which is why the technology is not that attractive to the refineries. If the benefits can be created to the refineries from the captured CO_2, the attractiveness of the technology would increase as it would not only benefit the environment by preventing the CO_2 from escaping into the atmosphere but also generate income for the refinery.

7. Public acceptance on the technology: The public is still unaware of the CCS technology and its role in mitigating GHG emissions. The public needs to be educated about the technology to gain acceptance.

8. Concerns regarding possibility of CO_2 leakage from the storage site: Safety concerns is one of the top priorities when it comes to dealing with GHG emissions. The leakage of CO_2 can bring a lot of damages therefore a monitor and control system needs to be developed to track the stored CO_2 underground. If the captured CO_2 can be utilized instead of just stored underground, there would not be any concerns with the possibility of the leakage of CO_2 from the storage site which is one of the main barriers preventing the deployment of the technology.

The development of the roadmap included the division of strategies and policies to treat the barriers, and other investments into short, medium and long-term action plans over the period from 2020 to 2050. The plans suggested in the roadmap to overcome the barriers integrated the knowledge and experiences of the experts along with the information from previous studies in the literature. The strategy used to develop the roadmap would follow the pathway of pilot, demonstration and commercial-scale projects stages suggested by ADB (2015) where the action plans must include capacity building of technical, financial, legal and regulatory to align them with the stages and overcome the barriers. The actions on the roadmap were planned based on two criteria in this study to facilitate strategic development of the roadmap. Firstly, the criticality of the barriers was used to determine whether the barrier needed immediate response; Barriers with high criticality numbers were considered requiring immediate response, and the actions to overcome those barriers are proposed as short-term plans if it aligned with the strategy. Secondly, the opinions of the experts were also considered while dividing the actions into short, medium and long-term plans. The implementation of the suggested action plans on the roadmap is beyond the scope of this research due to the economic, laws and regulations limitations, and time constraints.

Table 20: Short, Medium and Long-Term Action Plans to Overcome Critical Barriers to Deploying CCS Technology and Thai Petroleum Refineries

Pilot Stage	Demonstration Stage	Commercial Stage
Short-term Action Plan (2020-2030)	Medium-term Action Plan (2030-2040)	Long-term Action Plan (2040-2050)
• Pilot-scale operation of the CO_2 capture, transport and storage development • Assess EOR opportunities in Thailand • Search for financial assistance to fund	• Commercial scale demonstration project of 500-2,700 metric tons CO_2 captured and stored per day • CCS-EOR to produce income • Continuous R&D to improve the	• Multiple CCS operations at commercial scale projects (2,700 - 30,000 metric tons per day) • Established policy that supports CCS adoption • Continuous

the development and operate the pilot project • Train staffs • Include CCS technology into refinery's GHG emission reduction strategy • Support from the government (incentives and legislations) • Include CCS in the NAMAs and increase R&D efforts • Develop monitor and control system for stored CO_2 to assess for any leakage	efficiency of the technology and assess different capture, transport and storage modes • Explore different ways to gain income from the captured CO_2 • Establish regulatory framework for CCS commercial scale to guide the adoption of the technology by adjusting the existing legal and regulatory framework. • Establish environmental and safety standards for deploying CCS technology • Introduce carbon trading schemes and incentives to promote CCS deployment • Develop guideline	development on the technology to further improve the efficiency and reduce operating cost • Explore different ways to generate income from the captured carbon

	to overcome barriers to deploying CCS technology • Increase public awareness by providing knowledge about the environmental impact and the role of CCS technology	

Suggestions for Short, Medium and Long-Term Projects to Implement to Mitigate the Risks Involved with The Critical Barriers to Promote the Deployment of CCS Technology at Thai Petroleum Refinery:

<u>Short-Term Plans</u>

- Government Needs to Amend the Legal and Regulatory Framework and Include CCS Technology in the NAMAs

To support the deployment of the CCS technology at Thai petroleum refineries, firstly, the government needs to adapt the legal and regulatory framework as suggested on Table 4. Development of the CCS project would not be possible with the existing legal and regulatory framework. The government needs to pass more laws to drive the GHG emitters to better deal with the pollution and wastes they produce and fully ratify Paris Climate Agreement. The rights to transport and store the captured carbon subsurface needs to be given for CCS purposes. The Environmental Protection laws should be adapted, and monitor & control system needs to be developed to prepare for technology deployment. Laws regarding the ownership of the captured carbon, who can build and operate CCS, who will benefit from the CCS-EOR as well as the health and safety laws for operating CCS needs to be defined. Secondly, after the legal and regulatory framework has been amended, the government needs to include CCS technology into the NAMAs to increase the importance of the technology as a GHG emission mitigation strategy and increase the R&D efforts towards the technology to make it more attractive for deployment by the refineries. Inclusion of the technology in the national emission abatement strategy shows that the government is willing to support the development of the technology to explore it as a GHG emission mitigation strategy.

- Private-Public Collaboration to Develop Pilot-Scale CCS Project

The first milestone of this roadmap is the development of a pilot-scale project of CCS. The aim at this stage is to gain knowledge of how to deploy the CCS technology successfully. The actions required to deliver this includes searching for a low-cost site for pilot project development, designing the project with estimation of costs, obtaining the required funding, and training of pilot project operating staffs. The government needs to provide incentives to the refinery that is willing to include CCS technology in their GHG emission reduction strategy and collaborate in the project of constructing a pilot-scale CCS operation to promote the deployment of the technology. The financial support may come from domestic or international sources. The resources need to be shared between the refinery, the government, and other stakeholders to plan and build the pilot CCS project.

<u>Medium-Term Plans</u>

- Develop a Commercial-Scale CCS Project

The second milestone is the development of a commercial-scale project that can capture more CO_2 compared to the pilot project. The knowledge and experience gained from operating the pilot is used to design and construct the demonstration project along with the pipeline to transport CO_2 from capture to storage site and establish regulatory framework and environmental and safety standards. The legal frameworks are further adjusted to facilitate the deployment of the CCS technology at a larger scale as per required to reduce the risk involved with the technology. The knowledge gained can also be used to develop a guideline on how to overcome the barriers of deploying the technology at the refineries.

- Introduction of Government Incentives

After the success of the pilot-scale CCS project, the next step is to build more CCS facilities to capture CO_2 from more sources in the petroleum refineries in Thailand. The aim at this stage has shifted from expanding knowledge on the technology to increasing emission reduction. Government support such as grants, policies and incentives such as carbon trading schemes needs to be introduced to further promote the deployment of the technology by the refineries. The government needs to place a cost on emission and refineries should be allowed to emit only a certain amount of emission. If the CO_2 emission is higher than the allowed value, the refinery will have to buy the allowance or may use CCS technology to prevent the emission of CO_2 into the atmosphere.

- Generate Income from CCS Technology Deployment and Improve Efficiency of the Technology

The objective at this stage is to try to reduce the cost of deploying the technology and produce income into the refinery from capturing the CO_2. After the EOR opportunities have been explored, CCS-EOR should be implemented to produce income for the refinery. The additional oil recovered would result in extra revenue for the refinery. The research into different ways to utilize the captured CO_2 for to generate revenue for the refinery such is in chemical industry. Continuous R&D to improve the efficiency of the CCS technology to reduce the cost of operation is necessary. The different capture techniques can be assessed for different emission sources of the refinery to expand knowledge about the most efficient method to capture, transport and utilize $CO_{2.}$

- Increase Public Awareness of CCS Technology

The awareness of CCS technology is low considering the technology is still at an early adoption stage. Awareness is considered a basic condition to improve attractiveness of the technology (Tcvetkov et al., 2019). The public, one of the important stakeholders of CCS projects, should be educated about global warming and the growing CO_2 emissions trend in the industry to build a background before giving them knowledge about the role of CCS technology.

<u>Long-Term Plans</u>

- Deploy CCS Technology at Multiple Sources at Thai Petroleum Refineries

The third milestone on this roadmap is the deployment of CCS technology at multiple petroleum refineries in Thailand. The commercial demonstration project is modified to design a more efficient commercial-scale CCS project. CCS legislation and regulation frameworks are further updated as per requirement to accommodate any other barriers that surfaces as the technology is implemented at larger scale. To support the deployment of CCS technology further, government needs to set ambitious GHG reduction targets and establish more policies to promote CCS. There are CCS commercialization barriers that would further need to be addressed including the cost-effectiveness of the technology, long-term liability of the stored CO_2, lack of financial incentives and comprehensive regulation that will be needed for different refineries to deploy the technology. The aim is to continuously look for ways to improve the efficiency of the technology, minimize the cost, both capital and operational, and reduce the risks involved in barriers to deploy CCS technology of CCS technology that would help make it a competitive emission reduction technology.

Chapter 5 Conclusion and Recommendations

The research findings were analyzed based on three objectives of this study in the previous chapter. This chapter will present the conclusion of the study along with recommendations for further studies.

5.1 Conclusion

The purpose of this study is to identify and analyze the critical barriers to deploying CCS technology in Thai petroleum refineries and develop an action plan to overcome those barriers to promote CCS technology deployment to minimize the CO_2 emission from the energy sector, the most energy consuming industry producing highest emission in Thailand.

Despite the fact that there is a growing trend in emissions produced from petroleum industry, there is limited studies in the literature on the potential of GHG emission reductions from the processes at petroleum industry in Thailand which is recognized as having untapped potentials to reduce the emissions. This study aims to close that gap by studying the CCS technology, a new technology which has not been actively considered as a strategy in the master plans developed by the Ministry of Energy for mitigating CO_2, the highest emitted GHG, to understand the barriers preventing it from being adopted by the petroleum industry and develop a roadmap to suggest strategies and policies to promote the deployment of CCS technology by overcoming the critical barriers identified.

The general framework followed in this study is adapted from the conventional risk management framework (Flanagan and Norman, 1993) aiming to identify the barriers and assess the risks associated with the barriers preventing the deployment of CCS technology at Thai petroleum refineries. The first objective was to determine and organize the potential barriers of deploying CCS at a Thai petroleum refinery. To achieve this objective, the potential barriers to deploying the technology were obtained from literature review and brainstorming and organized using the TOE framework to ease the analysis process.

The potential barriers are categorized and demonstrated on the Ishikawa Diagram as following:

- Technological Barriers
- Organizational Barriers
- Environmental Barriers

The second objective was to apply FMEA to evaluate the criticality of the barriers and prioritize them. The FMEA was used to analyze individual barriers according to their likelihood of occurrence and severity of consequence. The FMEA process is used to identify the barriers involved with the process of deploying CCS technology and prioritize the barriers according to the risk associated with them. The process used to study the barriers under each category is the same but the barriers under each category and were studied independently of one another as the relationship between the them were not considered in this research. The risk corresponding to each barrier is represented by the Criticality Number (CN) which is the product of likelihood of occurrence and severity of consequence. Three experts in the field from one of the petroleum refineries in Thailand, have been approached to conduct the FMEA by responding to a survey, ranking the Severity (S) and Occurrence (O) of 29 potential barriers using a 1-5 scale according to the criteria provided.

To answer the first research question of 'What are the main barriers to deploying CCS technology at Thai petroleum refinery?', 29 potential barriers were identified:

- 9 Technological Barriers

- 9 Organizational Barriers
- 11 Environmental Barriers

The critical barriers to deploying CCS technology in Thai petroleum refineries are identified using the 80/20 principle of the Pareto analysis. According to the result obtained from FMEA, 22 out of 29 barriers studied are critical barriers preventing the deployment of CCS technology at Thai petroleum refineries that requires action plans to reduce the associated risks.

The 22 critical barriers to deploying CCS technology in a Thai petroleum refinery consists of:

- 7 Technological Barriers
- 7 Organizational Barriers
- 8 Environmental Barriers

The Organizational and Environmental Barriers were ranked higher CN than the Technological Barriers. The barrier that had the highest CN was an Organizational Barrier: Investing in CCS technology was not profitable to the organization. The Environmental category has the highest number of barriers that scored high CN as compared to the barriers and the barriers belonging to the Technological category scored lower CN compared to the other categories. The critical barriers identified by the FMEA method in this research correlates with the challenges to adopt CCS technology in Thailand in the literature: lack of resources to pilot CCS, no policy and legal framework to support the development, and no national level planning (Wisarut et al., 2012). From this result, it can be seen that it is the lack of capacities in the organization and the lack of support from the government are preventing the deployment of the CCS technology by Thai petroleum refinery more than the technological concerns and that the efforts to overcome the barriers to deploying CCS technology need to come from the petroleum refinery as well as the government to reduce the risk associated with the barriers; the CN of the barriers, to close the gap in policy framework and legislation. The result has proven the claim made by the Global CCS institute (2018) that despite the high Inherent Index Indicator, Thailand still has a large gap in policy framework and legislation causing it to have a low CCS Readiness Index.

The third objective is to develop a roadmap to overcome the challenges to implement CCS technology at Thai petroleum refineries. A roadmap is developed by adapting the three phases suggested in Parsons Brinckerhoff's report (2015). Following the analysis of the barriers, literature review and interviews were conducted to study the strategies and policies to overcome the identified critical barriers to develop a pathway of strategically planned actions. The actions were planned based on two criteria, the criticality of the barriers and the obtained opinions of the experts from the conducted interviews.

The second research question was 'What are the actions required to overcome the barriers to implement CCS technology at Thai petroleum refineries?'. This research has answered that question by suggesting short, medium and long-term action plans to treat the barriers over the period from 2020 to 2050. The roadmap integrated the knowledge and experiences of the experts along with the information from previous studies in the literature to follow the pathway of roadmap development suggested by ADB (2015).

The third research question was 'Can the barriers identified be overcome to deploy the CCS technology at Thai petroleum refineries?'. Based on the results obtained from this research, the critical barriers to deploying CCS technology at Thai petroleum refineries identified are similar to the barriers to implement CCS technology faced by different industries mentioned in the literature. The barriers specific to Thailand and petroleum industry including the limited CCS-EOR opportunities, absence of initiatives to include CCS technology in the national GHG mitigation strategies and lack of capacities does not rule out the possibility of deploying CCS technology as a GHG mitigation strategy in the future. According to the interview, one of the experts has mentioned that the case study refinery has been discussing a possibility of developing a pilot project in collaboration with the government in the year 2025 to study the technology as a GHG mitigation option. But, considering the current situation and the uncertainties with several aspects of the technology such as safety issues with carbon storage and no economic justification to promote the technology are still of high concerns and without actions to minimize the risks involved in these barriers, the deployment of CCS technology in the near future may still be of question.

5.2 Research Contribution

The general method applied in this research can be adapted by different sectors to study the barriers to deploying a new technology at an organization. This research study has contributed to the literature by extending the study of barriers to deploying CCS technology to Thai petroleum refinery. The findings of this research can be extended to assist designing strategies to promote the deployment of the CCS technology by policymakers in the future.

5.3 Recommendations for Future Work

5.3.1 Recommendations for Improving the Success of Deploying CCS Technology in Thai Petroleum Refineries

The actions suggested in the roadmap should be implemented to minimize the risks associated with the barriers to promote the deployment of CCS technology in Thai petroleum refineries. Efforts need to be made from the refineries, institutes and government to follow the strategies on the roadmap and build the required capacities to facilitate the achievement of the milestones in the planned time frame. The results from this research are helpful for the case study petroleum refinery in planning a path to deploy CCS technology in the future.

5.3.2 Extension of the Scope by Covering More Petroleum Refineries and Other Stakeholders

The research can be extended to include all of the petroleum refineries as there are specific barriers to different organizations that need to be considered while developing strategies and policies for the roadmap to deliver CCS. Surveys can be conducted with representatives from different petroleum refineries to gain more information on other possible organizational barriers as well as with other institutes and stakeholders to expand the list of possible barriers that are preventing the deployment of the CCS technology to be included in the roadmap.

Due to the limitations of the research, not all of the barriers that prevent the implementation at the petroleum refinery were discussed and there may be other critical barriers that need to be considered in the roadmap to minimize the risk associated with them to successfully deploy the CCS technology. The way to identify other potential barriers include:

- The Technological Barriers can be identified from current CCS projects and extending the literature review.
- The Organizational Barriers can be identified from conducting interviews with personnel from different departments from different refineries.

Interviews can be conducted with experts from different departments of the refinery including:

- Management, who plans the strategies in the organization
- Engineers, who would understand the processes of retrofitting the technology

- Finance department, who plan the budgeting of the R&D
- Safety department, who would understand the safety concerns of retrofitting the technology into the refinery
- Legal department, who would understand the law restrictions preventing the deployment of the technology

- The Environmental barriers can be identified from interviewing other institutes, government, public etc. to identify the gaps in the legal and regulatory framework, policies, public acceptance and other challenges.

5.3.3 Extension of the Scope by Covering Relative Importance of the Barriers

The relationship between each barrier on one another can also be studied to find the relative importance of the barriers in relation to one another and on their impact on CCS deployment (Davies et al., 2013). The risks associated with each barrier may be changed due to the dynamic environment or implementation of different strategies, and the change in the risk of one barrier may have an effect on the criticality of other relative barriers. Therefore, the relative importance between the barriers within the same category and across the categories need to be assessed.

5.3.4 Extension of the Scope to Include Economic Feasibility of Deploying the CCS Technology

This research did not consider the value of investing in the CCS technology if deploying the technology is economically feasible. Research can be conducted to study the different scenarios to determine the case that is most profitable for the petroleum refinery to invest in the CCS technology. The effectiveness of different government incentives and regulatory frameworks such as carbon taxes, grants support, carbon pricing to assist the deployment of CCS technology can also be assessed to propose the appropriate incentives to support the implementation of the technology most profitably.

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Appendices

Appendix A: The Survey

The Application of FMEA to Study the Critical Barriers to Deploying Carbon Capture and Storage in a Thai Petroleum Refinery

Survey Information Leaflet

This survey is designed to collect data on severity and occurrence of listed barriers to analyze the criticality of each barrier to deploy carbon capture and storage (CCS) in a Thai refinery.

The survey is designed in a rating format, where participants have to rate the severity and occurrence by assigning a number from the scale of 1 to 5 to both the severity and the occurrence for each barrier that are under three categories: Technological, Organizational and Environmental.

The severity ranking will measure the consequences of each barrier, if happened. The occurrence ranking will measure the possibility of the barrier occurring. The guideline to rating the severity and occurrence of the barriers is given below:

Table 21: The Criteria for Ranking the Severity and Occurrence for FMEA Survey

Severity (S)		
Rating	Description	Definition
1	Very Low	This barrier will have a very low effect on the refinery.
2	Low	This barrier will have a minor effect on the refinery.
3	Moderate	This barrier will have an apparent effect on the refinery.
4	High	This barrier will have a serious effect on the refinery.
5	Very High	This barrier will have a catastrophic effect on the refinery.
Occurrence (O)		
Rating	Description	Definition
1	Very Low	This barrier will possibily not occur.
2	Low	This barrier will rarely occur.
3	Moderate	This barrier sometimes occur.
4	High	This barrier often occur.
5	Very High	This barrier always occur.

Rating the Severity and Occurrence of The Barriers to Deploying Carbon Capture and Storage in a Thai Petroleum Refinery

Table 22: Table for Rating Severity and Occurrence of Technological Barriers

Technological Barriers	Severity	Occurrence
Limited experience with the CCS as a fully integrated system		
Not enough knowledge on which source to capture CO_2 from		
The technology does not eliminate the dependence of fossil fuel		

The issue on safety of storing CO_2 for long term		
Diversity of capture/transport/storage options available		
The readiness of CCS technology is still questionable		
Competition between different CO_2 mitigation technologies		
Absence of pilot CCS in Thailand		
Limited EOR opportunities in Thailand		

Table 23: Table for Rating Severity and Occurrence of Organizational Barriers

Organizational Barriers	Severity	Occurrence
It is not profitable to the organization to invest in CCS technology		

High investment and operating cost		
Fundings on CCS would reduce fundings toward renewable energy		
Lack of suitable capacities and resources to retrofit CCS technology		
Lack of experience and skills to deploy large scale CCS		
The energy efficiency improvement efforts are enough to mitigate CO_2		
The management has not considered deploying CCS technology		
The deployment of CCS technology would affect the efficiency of the refinery		
Deploying CCS would cause affect the processes in the refinery		

Table 24: Table for Rating Severity and Occurrence of Environmental Barriers

Environmental Barriers	Severity	Occurrence
Paris Climate Agreement not ratified fully at the refinery		
No incentives by the government to promote deployment of the technology		
CCS technology is not considered in Thailand's Nationally Appropriate Mitigation Actions		
CCS does not eliminate formation of CO_2 but only prevents it from escaping into the atmosphere		
Uneconomical to transport CO_2 due to long distance between plant and storage site		
Public acceptance on the technology		
Low awareness of the technology as driver of climate change		

Concerns regarding possibility of CO_2 leakage from storage site		
There is no regulatory framework to support CCS deployment		
Insufficient value of carbon which would make CCS an attractive mitigation option		
Legal challenges in CO_2 transportation and storage		

Appendix B: Interview Questions

Table 25: Interview Questions and Objectives

Questions	Objective
- Do you think CCS technology is applicable to petroleum refineries in Thailand and Is it possible to deploy the technology? - Is CCS technology being considered as GHG mitigation strategy at the refinery?	To understand the position of CCS in Thailand's energy strategy and case study petroleum refinery's strategy.
- What are the major risks of CCS technology deployment at Thai petroleum refineries? - What are the main influencing factors to deploying CCS technology in Thailand? - What policies would promote CCS deployment in Thailand?	To understand the experts' concerns of deploying CCS technology at the refinery and gain their opinions on policies that will promote the deployment of the technology.
- Are the proposed action plans in the literature applicable to Thai petroleum refineries?	To validate the action plans and gain policy-making suggestions for overcoming the critical barriers to develop the roadmap.

Source: Adapted from Dapeng & Weiwei (2009).

Appendix C: The Consent Form

Participation Information Leaflet and Online consent for Online Questionnaire

PROJECT TITLE: THE APPLICATION OF FMEA TO STUDY THE CRITICAL BARRIERS TO DEPLOYING CARBON CAPTURE AND STORAGE IN A THAI PETROLEUM REFINERY.

NAME OF RESEARCHER: Ms. Amornrat Sethi, amornrat.s@live.com.

This sheet seeks to provide information, and advice, with respect to an individual's participation in support of the specified research project:

1. The project is entitled The application of FMEA to study the critical barriers to deploying carbon capture and storage in a Thai petroleum refinery, which aims to evaluate the barriers of deploying carbon capture and storage at Thai petroleum refineries to develop a roadmap with action plans required to overcome the challenges.

This research is being conducted by Ms. Amornrat Sethi in support of their studies for a dual MSc program in Engineering Business Management at the University of Warwick and Chulalongkorn University, and this research is self-funded by the student. This questionnaire will take 15 minutes.

2. The research is being supervised by Prof. Parames Chutima, parames.c@chula.ac.th, who is a supervisor appointed by the University;

3. Participation in this research is totally voluntary, and assurances are given to the effect that no negative consequences will arise from refusal to participate in the research project;

4. Your consent for your data to be used in this questionnaire will be gained by your ticking the consent question at the end of this page, so by ticking this box you agree that your submitted data can be used in the resulting dissertation;

5. Each individual is advised to fully consider, with others if necessary and prior to participation, any disadvantages, side effects, risks and/or discomforts that may arise from participation in this research;

6. Unless specifically agreed otherwise, all information will be held as confidential and will not be distributed to others;

7. The resulting dissertation, with anonymous data, will be reviewed by a University teaching staff member and/or a University appointed external assessor, by the University moderators, and by external examiners;

8. Whilst an MSc Dissertation does not pass into the public domain, it is possible that the dissertation (with its data) may be used as a source for future research, including research work for publication;

9. Whilst summarised/ analysed data may be used in future research and/ or publications, your individual data responses will be retained only until the student completes their course and then destroyed.

This research has been favourably reviewed by the University's Biomedical and Scientific Research Ethics Committee, Approval Reference: REGO-2020-WMGOS-0006, dated: 6th March 2020. Dissatisfaction with the conduct of this research may be referred to the person below, who is a senior University of Warwick official entirely independent of this study:

Head of Research Governance, Research & Impact Services, University House, University of Warwick, Coventry, CV4 8UW; Tel: 024 76 522746; Email: researchgovernance@warwick.ac.uk

☐ I give my consent to my data submitted within this questionnaire being used for the purposes stated above

VITA

NAME	Amornrat Sethi
DATE OF BIRTH	26 October 1994
PLACE OF BIRTH	Bangkok