A Life Cycle Cost Analysis of Pertamina Refinery Carbon Capture & Utilization [1, 2]

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Abstract

Indonesia's Government has agreed to support CO2 emission reduction below 1,683 MTon CO2e in 2030, according to the National Determined Contribution (NDC). There are many ways to achieve the following target, CCUS (Carbon Capture Utilization & Storage) is one of them. With this kind of technology, Carbon is captured to reduce emissions and carbon utilization to improve the economic value. This study aims to analyze the Life Cycle Cost of Carbon Capture Utilization & Storage technology applied to the Pertamina Refinery. Furthermore, the most economical Carbon capturing and utilization method will be selected.

The method used in this study includes the life cycle cost analysis of several CO2 capture technology such as chemical absorption, physical absorption, and oxyfuel combustion, along with the utilization technology in particular for Methanol production, Enhanced Oil Recovery, and Greenhouses. Subsequently, Multi-Attribute Decision Making will be utilized to determine the best technology arrangement. In conclusion, this study has shown that utilizing CO2 captured with physical absorption technology for the greenhouse is the most economical option.

Keywords: Life Cycle Cost, Pertamina Refinery Unit, Carbon Capture & Utilization, Carbon Emission, Net-Zero Emission, Indonesia Carbon Tax Regulation

Introduction

"There is a growing concern about global warming and its impact on people and the ecosystem they depend on. Temperatures have already risen 1.4^{0}F since the start of the 20th century"[1]. "Average global surface temperatures will likely rise by an additional 2.0-

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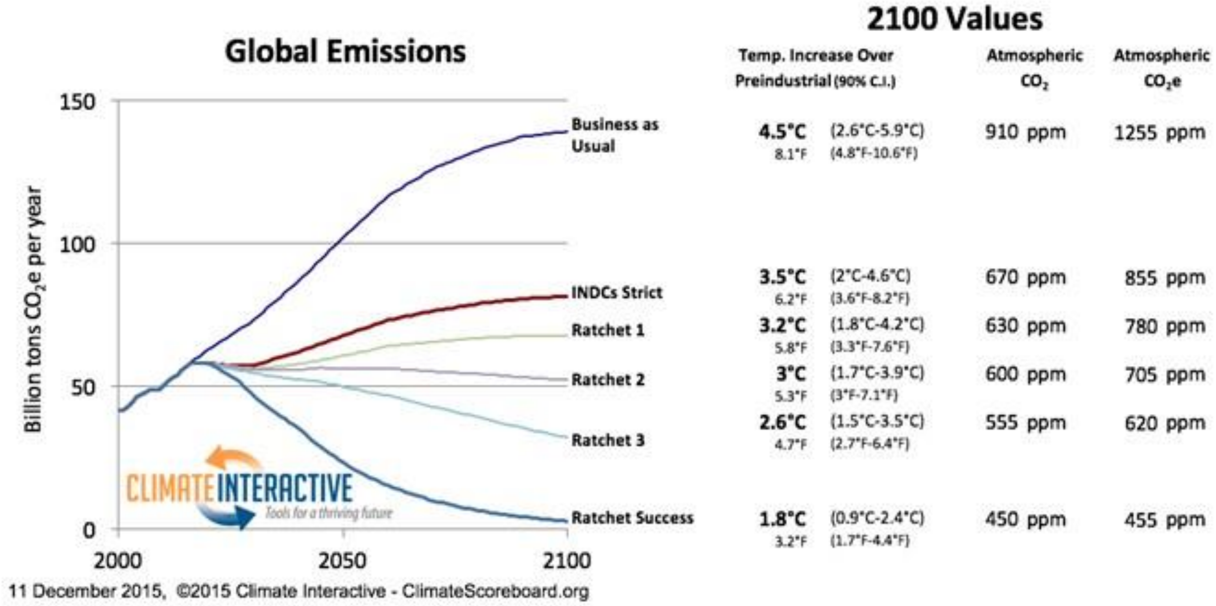
11.5^{0}F (1.1-6.4^{0}C) by 2100. Most of the observed increase in global average temperatures is likely due to the increase in anthropogenic greenhouse gas concentrations"[2]. Several greenhouse gases warm the planet, such as carbon dioxide, methane, nitrous oxide, ozone, and halocarbons. "Among these emissions, carbon dioxide (CO2) is the critical anthropogenic greenhouse gas due to its abundance and ability to remain in the atmosphere for thousands of years"[3]. "The role of carbon dioxide in warming the earth's surface was first proposed by Swedish scientist Svante Arrhenius more than 100 years ago, who suggested that changes in carbon dioxide might explain the large temperature variations over the past several hundred thousand years known as the ice age"[1]. Furthermore, "Greenhouse gases like carbon dioxide and methane absorb the infrared energy, re-emitting some of it back toward Earth and some of it out into space."[4]



2100 Values

Temp. Increase Over Preindustrial (90% C.I.)		Atmospheric CO$_2$	Atmospheric CO$_2$e
4.5°C 8.1°F	(2.6°C-5.9°C) (4.8°F-10.6°F)	910 ppm	1255 ppm
3.5°C 6.2°F	(2°C-4.6°C) (3.6°F-8.2°F)	670 ppm	855 ppm
3.2°C 5.8°F	(1.8°C-4.2°C) (3.3°F-7.6°F)	630 ppm	780 ppm
3°C 5.3°F	(1.7°C-3.9°C) (3°F-7.1°F)	600 ppm	705 ppm
2.6°C 4.7°F	(1.5°C-3.5°C) (2.7°F-6.4°F)	555 ppm	620 ppm
1.8°C 3.2°F	(0.9°C-2.4°C) (1.7°F-4.4°F)	450 ppm	455 ppm

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Figure 1 Total World CO2 Emission[5]

As per data in figure 1, the world's total CO2 emission exceeds 35 billion tons at a time.

However, other literature has emerged that offers contradictory findings on the Green House Gas emission and the impact of CO2 on the earth. Some theories state that "the earth's temperature is affected by many other factors. Among these are solar activity, the distribution of atmospheric water vapor and clouds, atmospheric and ocean circulation patterns, volcanic activity, and slow changes in the earth's orbital parameters.

Atmospheric CO2 also contributes to greenhouse warming but much less than H2O"[6,7]. Several studies also show that a warmer world will benefit human beings. "Global rewarming since the 18th century, plus better housing, sanitation, food and water supplies has greatly benefited human health and prosperity"[8]. "Despite warming from 1964 to 1998, a 74.4% decline in heat-related mortality in 28 of the largest U.S. cities is found. They estimated that another 1ºC increase would reduce the net mortality rate"[9]. In addition, another reference also states that "CO2 levels need to be elevated to more than eight times the current average ambient outdoor level of 407 ppmv (0.04%) to be harmless to humans and animals."[10]

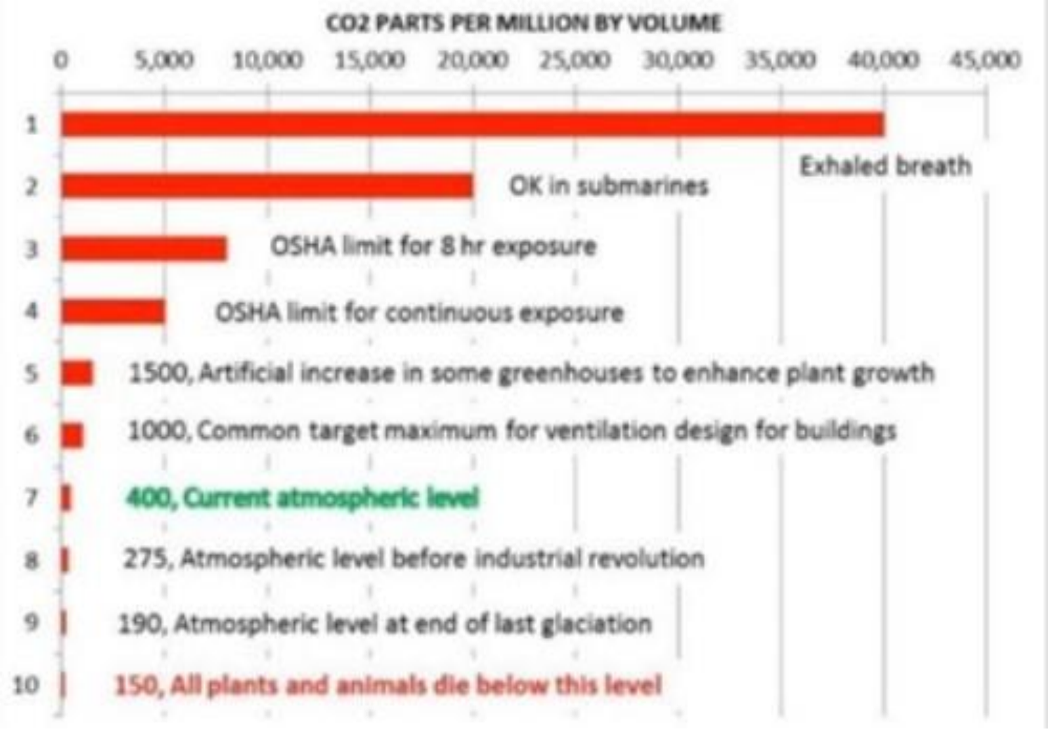
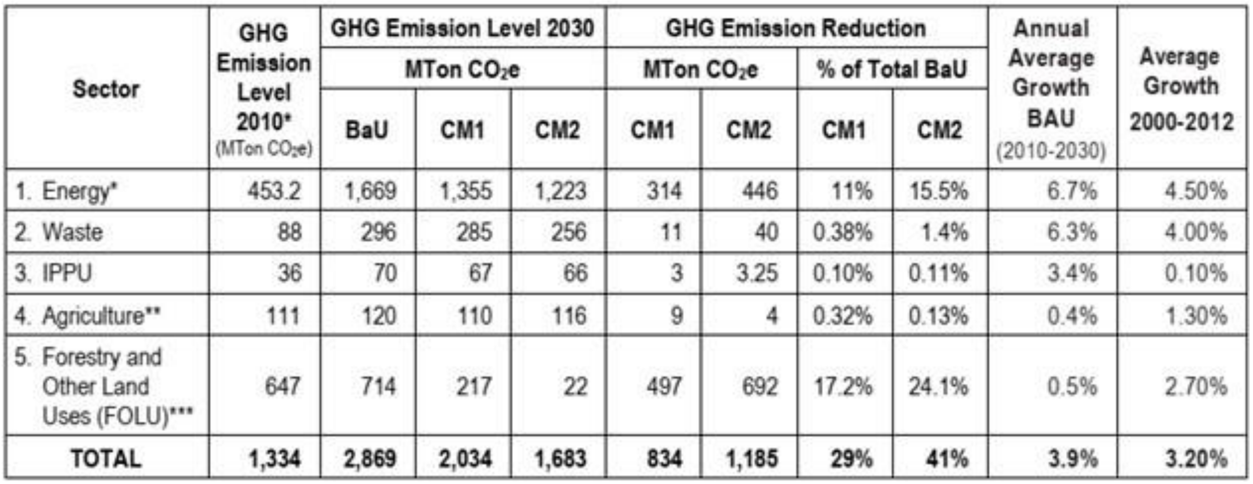


Figure 2 CO2 impact by percentage (ppm)[10]

Amid those controversies, the Indonesian Government through the Nationally Determined Contribution is committed to withstand the Total GHG Emission Level below 1,683 MTon CO2e in 2030"[11]. To support this mission to reduce CO2 emissions, the Indonesian Government establishes the Carbon Tax Regulation as per Indonesia regulation UU No. 7 Tahun 2021.

Table 1 Indonesia Projected BAU and GHG Reduction Emission[9]



Sector	GHG Emission Level 2010* (MTon CO₂e)	GHG Emission Level 2030			GHG Emission Reduction				Annual Average Growth BAU (2010-2030)	Average Growth 2000-2012
		MTon CO₂e			MTon CO₂e		% of Total BaU			
		BaU	CM1	CM2	CM1	CM2	CM1	CM2		
1. Energy*	453.2	1,669	1,355	1,223	314	446	11%	15.5%	6.7%	4.50%
2. Waste	88	296	285	256	11	40	0.38%	1.4%	6.3%	4.00%
3. IPPU	36	70	67	66	3	3.25	0.10%	0.11%	3.4%	0.10%
4. Agriculture**	111	120	110	116	9	4	0.32%	0.13%	0.4%	1.30%
5. Forestry and Other Land Uses (FOLU)***	647	714	217	22	497	692	17.2%	24.1%	0.5%	2.70%
TOTAL	**1,334**	**2,869**	**2,034**	**1,683**	**834**	**1,185**	**29%**	**41%**	**3.9%**	**3.20%**

Emphasizing emissions in the energy sector, "5-6% of total CO2 emissions are contributed by oil refinery activity"[12]. In particular, Pertamina, "as a national oil company which is facilitated with six refinery units operating all over Indonesia from RU-II Dumai, Riau, to RU-VII Kasim, Papua, with the total capacity reaches 1.046,70 thousand barrels per day and consists of refinery configuration covering several process units such as CDU, HVU, Naphta Treater, Hydro Cracker Unit, Platformer, RFCC"[13], is responsible for "total CO2 emission exceeds 20 Mt CO2e, Keeping in mind that most of the emission comes from electricity generation"[14].

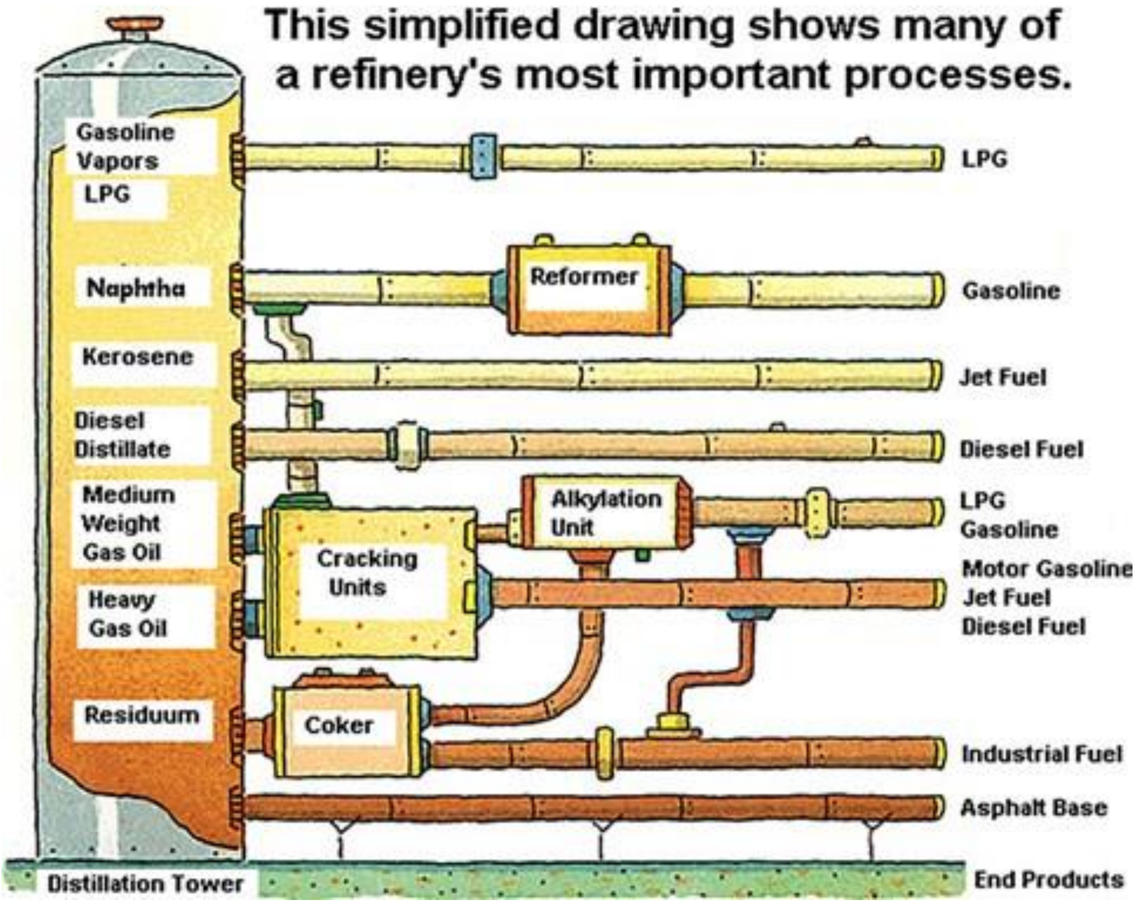
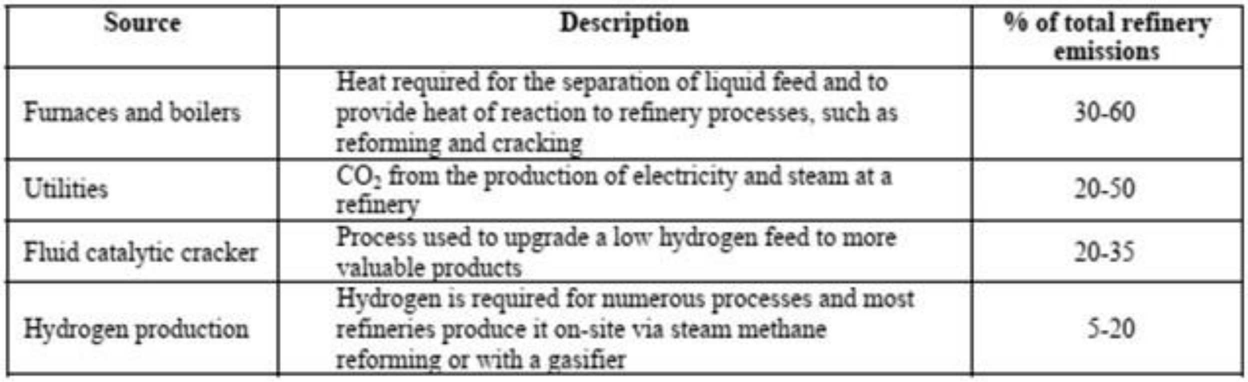


Figure 3 Important Processes of a refinery[15]

Dealing with CO2 emission from oil refinery process units, the majority of CO2 emission comes from furnaces and boilers due to the high energy and heat required for the separation process, reforming, and cracking. CO2 is emitted in flue gas and combustion in process sections.

Table 2 CO2 emission from typical refinery unit[16]



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

Overcoming those CO2 emission problems in an oil refinery, Carbon capture storage & utilization is one of the best practices to be considered"[17]. Notably, "there are several technologies of Carbon Capture"[18] such as

1. **"Absorption based CO_2 Capture"[19]**
   CO2 capture involves absorption by chemical or physical solvents. Chemical absorption uses MEA, DEA, and MDEA liquid, whereas well-established commercial physical absorption technologies for precombustion CO2 capture include "selexol" and "rectisol."

2. **CO2 capture by membrane separator**
   We are using membranes for gas-separation applications to capture CO2.

3. **Oxyfuel separation**
   CO2 is captured by utilizing the combustion of pure oxygen fuel, resulting in CO2 and water vapor. This process is finalized by separating the CO2 and the water vapor.

4. **Adsorption based CO2 capture**
   Using low or high temperature (e.g., zeolite, carbon nanotubes, graphene, etc.) adsorbents to capture CO2

"Absorption, membrane, and adsorption separation could take place before (pre) or after (post) combustion. In the case of pre-combustion, hydrocarbon fuel is pretreated to produce CO2. Meanwhile, in the post-combustion, CO2 is captured at the end-of-pipe solution."[20] Furthermore, "to add more value from CO2 that has been captured, the CO2 could be utilized as classified below"[21].

1. **CO2 for Enhanced Oil Recovery**
   generated from Carbon Capture is injected into oil and gas reservoirs to repressurize the oil or gas trapped in the rock formation.

2. **CO2 for fuels and chemicals feedstock**
   CO2 is converted into fuels (methane, Methanol, syngas) and chemicals (urea, inorganic carbonates, polyurethane). The conversion process needs a large amount of heat and energy to consider the stability of the CO2 molecule.

3. **CO2 for water production**
   CO2 could be utilized to remove dissolved solids in brine water to be transformed into water.

4. **CO2 in Greenhouses**
   "CO2 could be utilized for farmers' greenhouses as CO2 is an essential component of photosynthesis. For most greenhouse crops, net photosynthesis increases as CO2 levels increase from 340-1,000 ppm (parts per million)"[22].

As described above, there are many prospects for CO2 utilization that could be combined with CO2 capture technologies to create a sustainable system and lower the CO2 emission.

As described below, IEA has developed a Net-Zero Emission target to reduce CO2 emissions as the Sustainable Development Scenario that takes a role from 2020 to 2050.

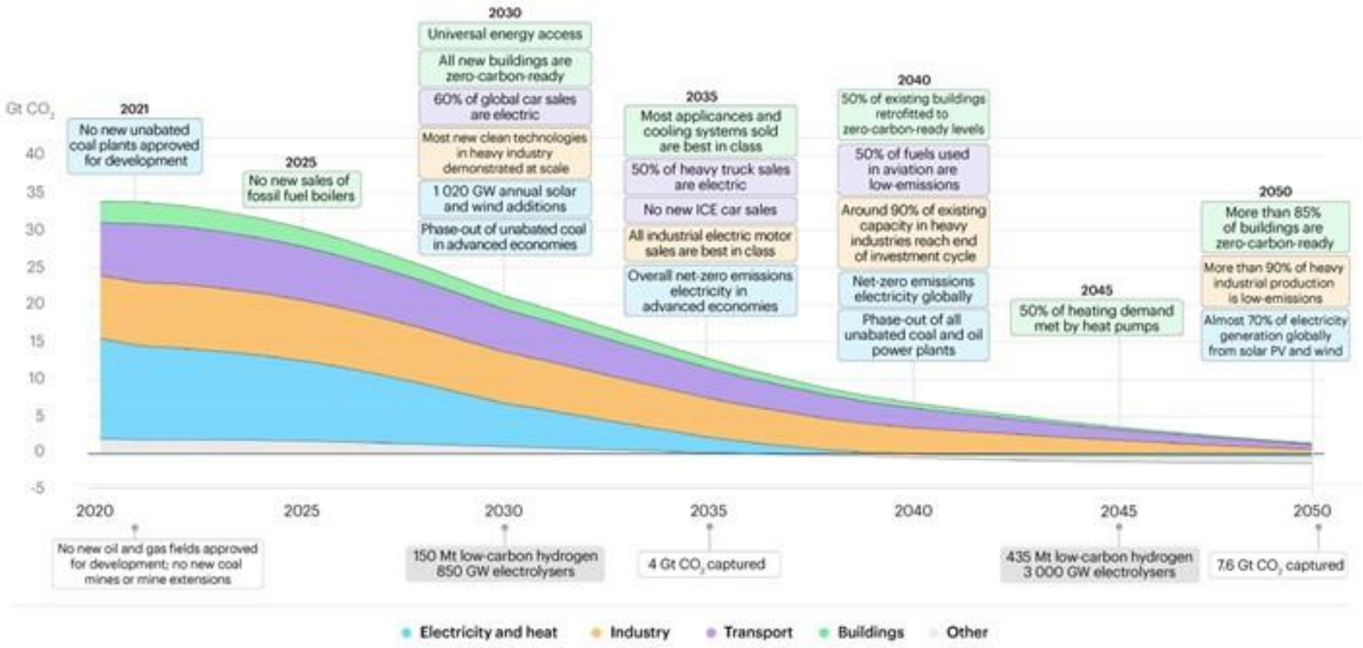


Figure 4 Target world CO2 emission and capture[23]

Starting from around 37 Gt CO2 in 2020 and by utilizing zero-emission technology, the emission kept decreasing until 2050.

This study systematically reviews the data from potential CO2 that could be captured until CO2 utilization, aiming to provide the Life Cycle Cost Analysis (LCCA) of Carbon Capture and Utilization. "LCCA is an evaluation of the economic performance of a system within its lifetime."[24,25] This analysis encompasses the project cost consisting of construction cost, operation, maintenance, replacement, utilities, and the time value of money. With this analysis, the cost-effectiveness of the projects could be evaluated.

Performing LCCA is composed of:

1. Define the analysis objective
2. Define the evaluating criteria
3. Identifying and developing design alternatives
4. Gathering cost information
5. Life Cycle Cost Analysis

The scope of this study was limited in terms of Life Cycle Cost Analysis that covers the implementation of Carbon Capture Utilization in the Pertamina Refinery Unit. Moreover, "the quantitative and qualitative scoring attributes will also be considered."[26]
To summarize, in this paper, I want to research and find answers to the following questions:

1. What kind of Carbon Capture could be utilized in Pertamina Refinery?
2. How to implement Carbon Capture technology in Pertamina Refinery?
3. How much does it cost to employ carbon capture technology in Pertamina Refinery?
4. What is the Life Cycle Cost Analysis result of carbon capture technology alternatives?

Methodology

Problem Recognition, Definition, and Evaluation

1. Problem Definition

"Carbon Capture and Storage is removing or reducing the CO2 content of streams normally released to the atmosphere and transporting that captured CO2 to a location for permanent storage"[27]. The term that we use to mention those technologies is "CCS." CCS has been acknowledged as an essential option to reduce CO2 emissions in recent decades. Several vast projects of CCS are deployed around the world, such as "Shute Creek Gas Processing Plant and Century Plant in the United States with the capacity of 7 Mton/year and 5 Mt/year, Petrobras Santos Basin Pre-Salt Oil Field CCS at Brazil with 4.6 Mton/year, and Gorgon Carbon Dioxide Injection at Australia with 4 Mt/year"[28]. The "CCS" term was still being used right until "The carbon Sequestration Leadership Forum (CSLF) on September 23rd, 2011 has changed the term into CCUS (Carbon Capture, Utilization, and Storage). This CO2 utilization will lead to achieving two main goals: reducing atmospheric CO2 emissions and creating new products, jobs, and profits"[29].

"Generally, if the economic value of captured CO2 is high enough to cover its capture and transportation costs, CCUS projects can be profitable. Therefore, the key to CCUS projects is now the CO2 value chain, which requires a feasible business model because it is an emission reduction activity and a business activity"[30].

Notably, the "industrial sector accounts for 30% of the total anthropogenic emission of carbon dioxide, with the largest emission from iron and steelmaking industry (31%), petroleum refineries (10%), pulp & paper (2%), and cement industries (27%)"[31].

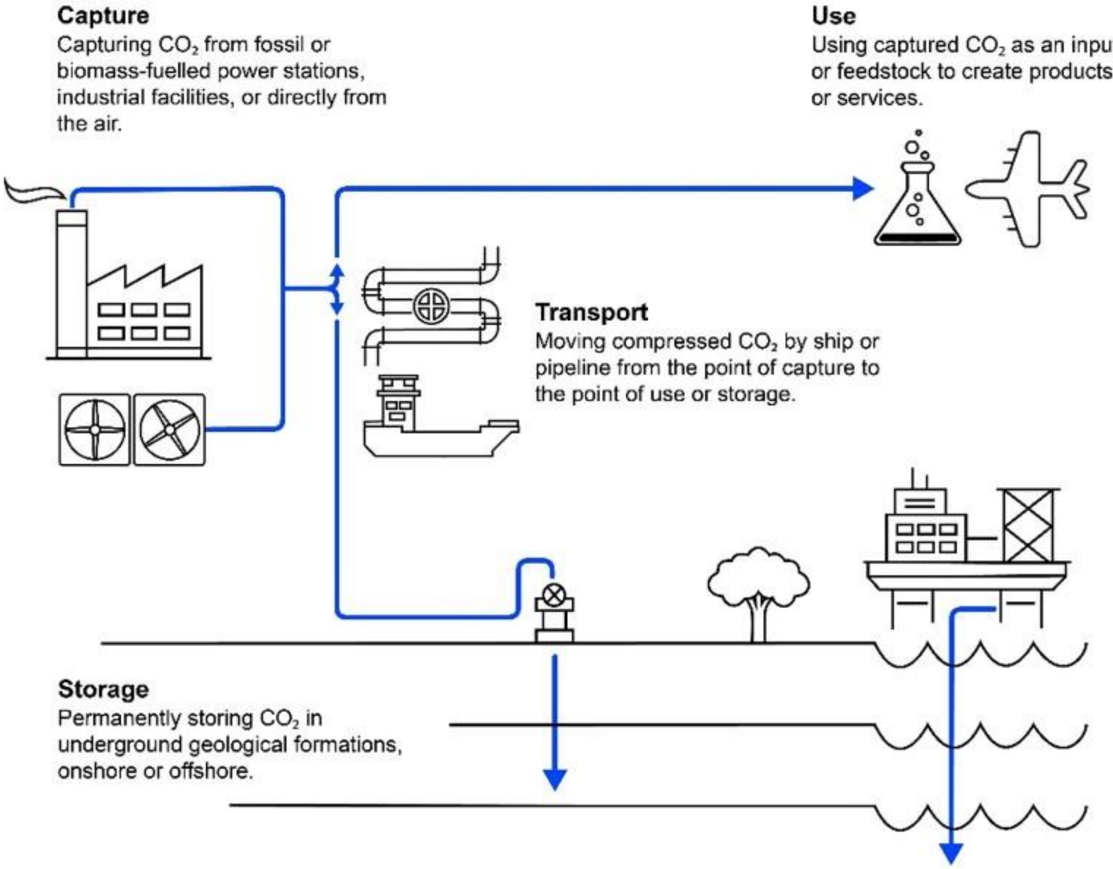


Figure 5 Carbon Capture Utilisation & Storage[20]

CCUS technology covers capturing, transport, and utilization. "Carbon capture has been thus recognized by many as a mitigation tool for global warming. In terms of carbon capture and storage (CCS) can reduce carbon dioxide (CO2) emissions by capturing and storing CO2 underground. Carbon capture and utilization (CCU) is an alternative way of reducing CO2 emissions via recycling, by capturing CO2 and purifying it to the required standards of industries"[32].

Development of the Feasible Alternatives

2. CO2 Capture Technology

Technically, there are three main classifications of capturing CO2 technologies, pre-combustion, post-combustion, and oxyfuel combustions.

- **Post-combustion CO2 capture**

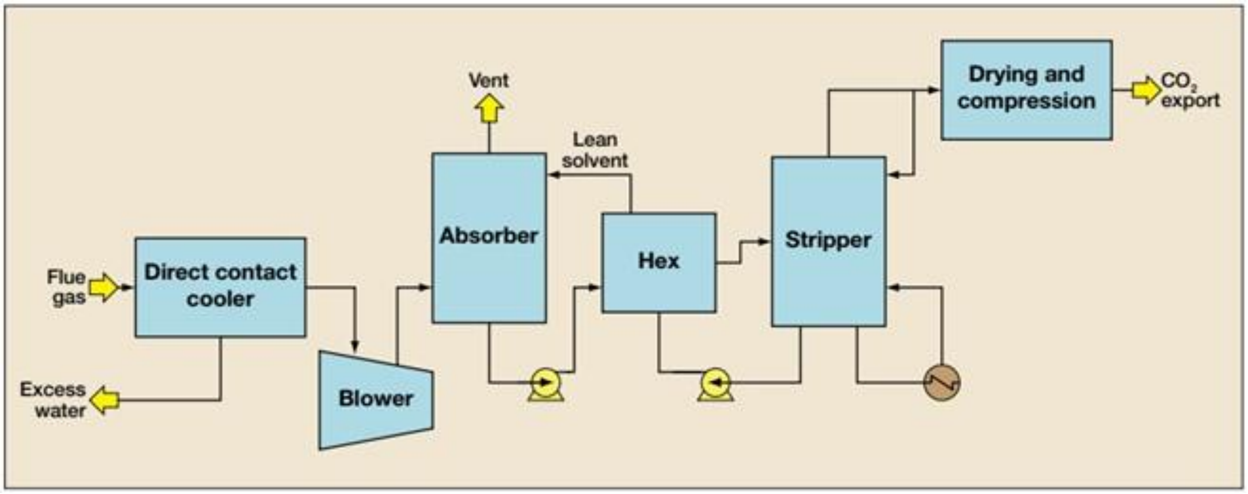


Figure 6 Post-Combustion CO2 Capture[31]

End pipe solution, Flue gas containing CO2 goes through a direct contact cooler and is cooled by water before being washed by physical content (MEA-Monoethanolamine). 90% of CO2 is absorbed by MEA and directed to the stripper. CO2 is released, compressed, and dried before being exported. "Post-combustion is a simpler system than pre-combustion and can be combined with almost any type of combustion system"[15]. This system allows the CO2 at a low partial pressure to be captured from several refinery single point source emissions, including fired heaters, FCC, and hydrogen production units.

- **Pre-combustion CO2 capture**

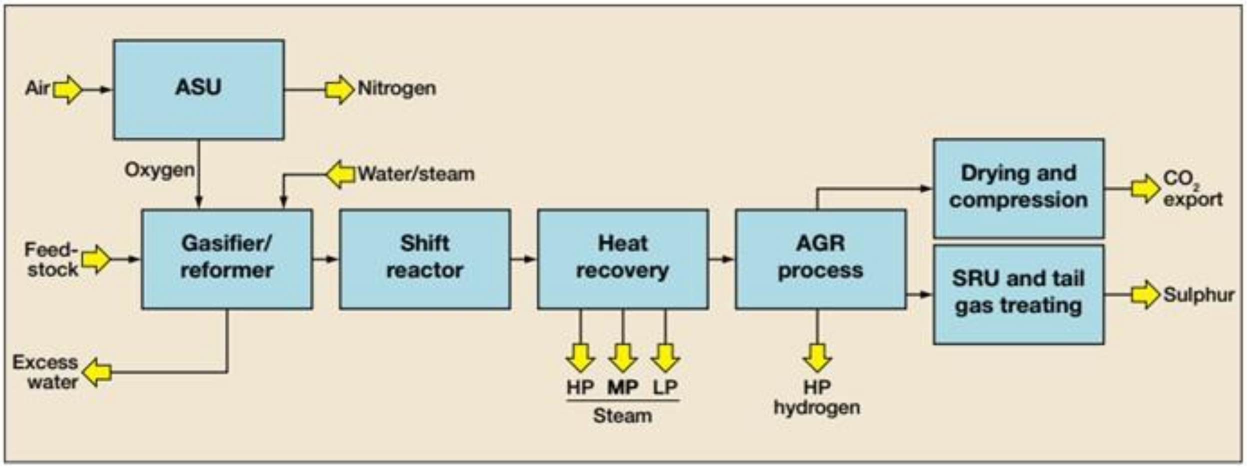


Figure 7 Pre-Combustion CO2 Capture[31]

"With this pre-combustion system, feedstock (fuel) is converted to syngas through gasifier/reformer and reacted with pure O2 from ASU (Air Separation Unit). Syngas directed to Shift Reactor to increase the Hydrogen and CO2 content"[31]. This process is generated pure high-pressure Hydrogen, heat, and pure CO2. High to low-pressure steam can be produced by utilizing heat. Coals, "petcoke," and solid waste use gasifier. In contrast, natural gas and light liquid utilize reformer. Pre-combustion system is capable of capturing CO2 from refinery's utilities. However, to time, "there is no study that assessed the performance of the pre-combustion system in oil refinery unit"[30].

- **Oxyfuel combustion capture**

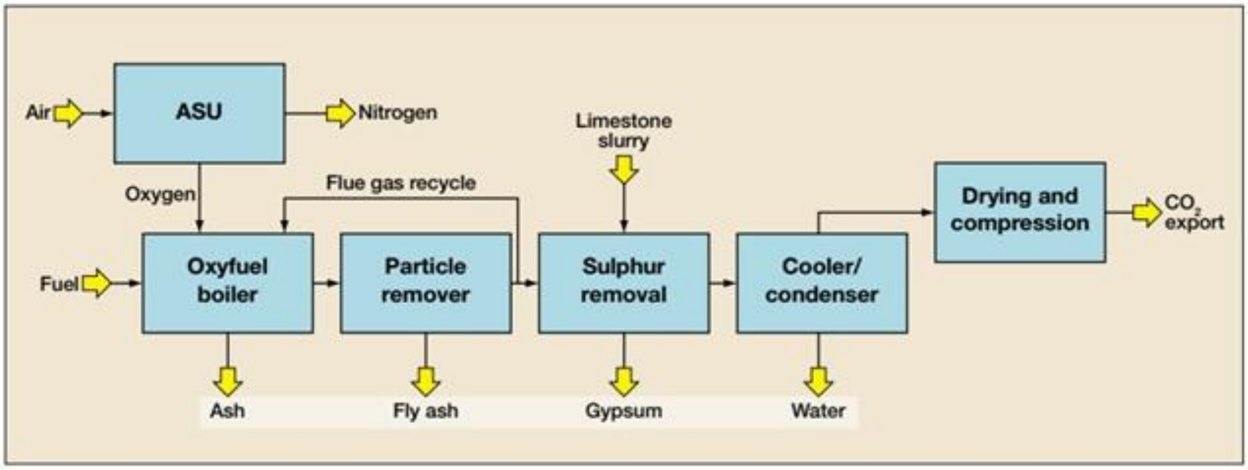


Figure 8 Oxyfuel Combustion CO2 Capture[31]

"Fuel is combusted through the oxyfuel boiler by utilizing pure Oxygen from ASU. The flue gas is filtered through the particle remover and further sulfur removal. The cooler and condenser will benefit from CO2 purification before being dried and compressed to be exported later. Oxyfuel carbon capture aims to increase the partial pressure of the combustion flue gas by effectively eliminating the large volume flow of nitrogen found in systems fired using air as their oxidant, producing a stream containing only CO2 and water"[31]. "This system applies to boilers or furnaces on refinery plant"[30]. "It is expected that oxyfuel CO2 capture may compete with or outperform post-combustion capture in the mid-term future as a retrofit option with an additional advantage of significantly lower SO2 and NOx emissions"[33].

3. CO2 Utilization

CO2 captured can be utilized in several options that could be beneficial and add economic value to the avoided CO2. The term Avoided CO2 is used instead of Captured CO2 as "avoided CO2 cost quantifies the average cost of avoiding a unit of CO2 per unit of a useful product by comparing a plant with capture to a reference plant of similar type and size, without a capture unit"[31]. On the other hand, "The cost of CO2 captured is a similar indicator with the only difference that it covers only the cost of capturing and producing CO2 as a chemical product. Unlike the cost of CO2 avoided metric, it excludes transportation and storage/utilization"[31].

The current study has examined several CO2 utilization that could be detailed as follows,

- **Methanol production by CO2 Hydrogenation**

"CO2 can be utilized chemically for the production of fuels and chemicals including methanol, ethanol, dimethyl ether (DME), dimethyl carbonate (DMC), syngas, methane, and carbonates"[34]. For that reason, "Methanol as one of the alternatives of Power to Liquid ("PtL") is considered an attractive option to convert industrial CO2 to liquid fuels"[35]. "Methanol is one of the most promising target products of "PtL" processes owing to its ability to be used as a gasoline alternative fuel."[36] Methanol can be produced from CO2 by either one-step or two-step processes. "In a one-step process, direct hydrogenation of CO2 to Methanol occurs. In the two steps process, CO2 is first converted to CO by reverse water gas shift reaction (RWGS), which is then hydrogenated to methanol"[37].

CO2 Hydrogenation : $CO_2 + 3H_2 \leftrightharpoons CH_3OH + H_2O$
RWGS : $CO_2 + H_2 \leftrightharpoons CO + H_2O$
CO Hydrogenation : $CO_2 + H_2 \leftrightharpoons CO + H_2O$

Hydrogen can also be produced by splitting water molecules by either thermolysis or electrolysis processes, and this process could be categorized into (1) alkaline water electrolysis (AEL), (2) PEM, and (3) solid oxide electrolyzer (SOE). "AEL is a

well-developed process; however, owing to huge electricity requirements, operating cost associated with this process is very high. PEM water electrolysis can reduce the operating cost by increasing the current operational densities, but the main barrier in implementing this technology is the cell material selection"[38]. "Among those alternatives, SOE is favorable due to low operating cost."[39]

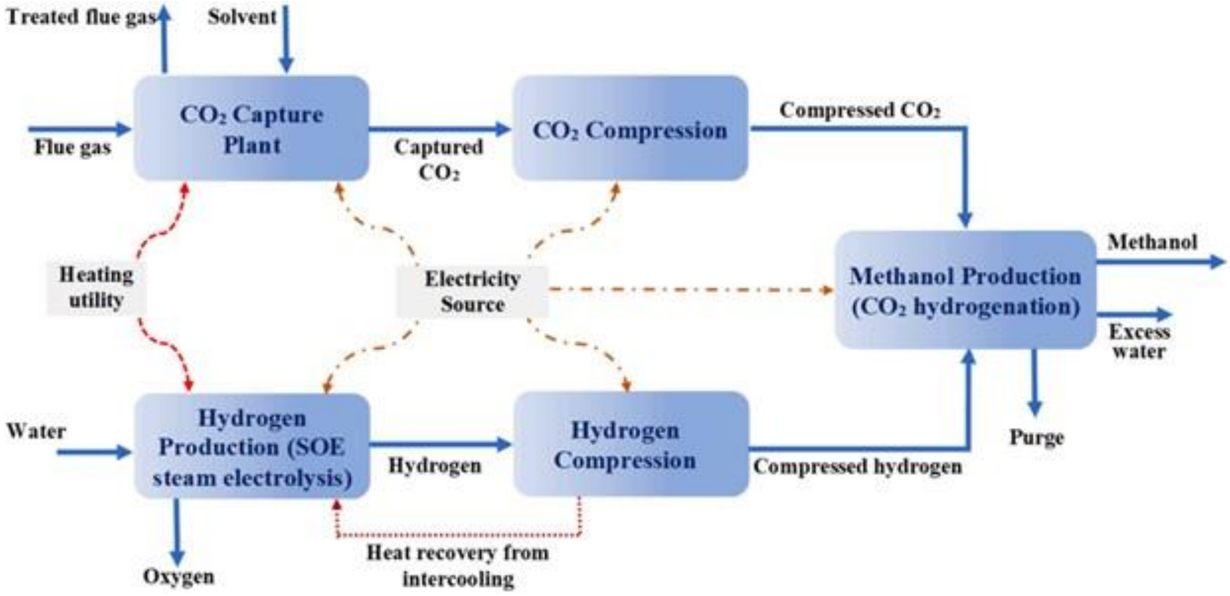


Figure 9 Schematic of Methanol Production with CO2 Hydrogenation[37]

CO2 generated from the capturing process prior to methanol production is reacted with Hydrogen generated from the SOE process. In addition to Methanol, this process also results in the Oxygen as a by-product of the electrolysis. As a note, "Hydrogen production was identified as the major cost burden on the methanol economy with more than 83%. It should be realized that this hydrogen cost includes the operating and capital expenses associated with it"[37].

- **Enhance Oil Recovery by CO2**

"One of the most attractive uses of the captured CO2 is Enhanced Oil Recovery (EOR). This technology utilizes the captured CO2 and injects it to mature oil fields to boost oil production. The sale of the incremental oil, if high enough, can offset the capture and transportation cost and can even result in net profits."[40].

- **CO2 for Greenhouses**

Carbon dioxide is the essential substance for photosynthesis in the form of a chemical reaction involving the light and CO2 that will provide food for the trees. "For most greenhouses crops, net photosynthesis increases as CO2 levels increase from 340-1000 ppm. Most crops show that for any given level of photosynthesis, increasing the CO2 level to 1000 ppm will increase the photosynthesis by about 50%"[21]. Another reference also shows that "Another model for soybean crops attempted to quantify the yield change about O3 and SO2 uptake and found an increase of 14.7% in yield when an enrichment level CO2 of 680 ppm is applied"[41].

Step 3 Development of the Outcomes and Cash Flows for each Alternative

4. Life Cycle Cost

"LCCA is a process of evaluating the economic performance of a building over its entire life"[21]. This term, also called Total Cost of Ownership (TCO), is an "analysis meant to uncover all the lifetime costs that follow from owning certain kinds of assets."[42] The end of the life cycle may be projected on a functional or an economic basis."[43] The cost elements of the life cycle that need to be considered will vary with the situation. However, several basic life-cycle cost categories will now be defined because of their common use. The Life Cycle Cost Element includes:

- The Investment Cost: the capital required for most of the activities in the acquisition phase.
- Operation & Maintenance Cost: includes many of the recurring annual expense items associated with the operation phase of the life cycle.
- Disposal Cost: nonrecurring costs of shutting down the operation and the retirement and disposal of assets at the end of the life cycle.

This research will extend our knowledge of implementation Carbon Capture Utilisation in Pertamina Refinery. In this case, CO2 emission from Cilacap Refinery Unit will take into account. Historical CO2 emission from the last 5 years will be detailed as follow

Table 3 RU IV Cilacap CO2 Emission 2017-2021

Parameter	2017	2018	2019	2020	2021	Average
CO2 (Ton)	2,982,149	2,460,425	2,691,421	2,903,564	2,854,228	**2,778,358**

From the data above, 2,778,358 TonCO2 (2.78 MTonCO2) will be the basis for the life cycle cost analysis.

- **Capex and Opex for Carbon Capture Technologies**

Capex for this analysis will be represented by "TCR (Total Capital Requirement) or Total Capital Cost, which is the sum of all the direct, indirect cost along with contractor fees"[31]. While the OPEX will cover the fixed and variable costs. Following statistical data, with variations of carbon capture technology as mentioned in the prior section, TCR and O&M costs can be calculated as follows,

Table 4 TCR & O&M Cost Formula[31]

Type	Cost	Model	R^2	Result
Chemical Absorption	TCR (M$)	$y = 270.3x^{0.668}$	0.531	534.93
	O&M (M$/year)	$y = 14.089x^{0.690}$	0.669	28.52
Physical Absorption	TCR (M$)	$y = 206.2x^{0.731}$	0.415	435.21
	O&M (M$/year)	$y = 10.698x^{0.781}$	0.584	23.76
Oxyfuel Combustion	TCR (M$)	$y = 101.9x^{1.533}$	0.652	488.09
	O&M (M$/year)	$y = 9.503x^{1.014}$	0.650	26.78

The formula for the model above consists of x (CO2 emission) and y (related cost). The result shown above is calculated based on data from the average Cilacap Refinery Unit's CO2 emission (2.78 MTonCO2)

- **CO2 Utilization: Methanol Production**

The calculation for the CAPEX and OPEX for the methanol converter unit and hydrogen generation unit using SOE are referred to in a case study with CO2 flow utilization is 88.73 tons/hr[41]. "Scaling method"[40] is practiced in this case to determine the cost for following CO2 emission (2.78 MTonCO2/317.16 Ton/hr).

$$\frac{C}{Cr} = \left[\frac{S}{Sr}\right]^n$$

With n equal to 0.6 (Six-Tenth rule), the calculation results will be

Table 5 Capex & Opex for Methanol Project

Parameter	Benchmark Plant[41]	Cilacap Plant	Unit
CO2 emission	88.73	317.16	Ton/hr
Capital Cost	371.15	797.04	M$
O&M Cost	359.25	771.48	M$/year
Methanol Product	59.49	127.75	Ton/hr
Oxygen Product	96.21	206.61	Ton/hr

With a 10% hurdle rate and the project will last for 20 years, the life cycle cost could be generated as follow,

Table 6 Life Cycle Cost for Methanol Project

Breakdown Cost	CO2 Capture		
	Chemical Abs.	Physical Abs.	Oxyfuel Comb.
Capital Cost (M$)	534.93	435.21	488.09
Capital Cost ($)	534,929,460	435,208,915	488,091,659
Operating Cost (M$/yr)	28.52	23.76	26.78
Operating Cost ($/yr)	28,516,353	23,762,992	26,783,165
	CO2 Utilization: Methanol		
Capital Cost ($)	797,035,361	797,035,361	797,035,361
Operating Cost ($/yr)	77,148,041	77,148,041	77,148,041
	Life Cycle Cost Analysis		
Capital Recovery ($/yr)	$156,452,088	$144,738,950	$150,950,538
Equiv. Ann Cost ($/yr)	$262,116,482	$245,649,983	$254,881,743
Cost ($/tonCO2)	94.34	88.42	91.74

- **CO2 Utilization: Enhanced Oil Recovery**

The calculation for CO2 utilization, notably for Enhanced Oil Recovery, will be accomplished by estimation of Capex for the pipeline with the basic assumption that the pipeline shall be provided from the CO2 point source (Cilacap Refinery Unit) to Oil & Gas Field at Cepu Block, East Java (estimated distance around 300 km). Moreover, other assumptions (CO2 Storage Cost, pipeline size) will use the data from EOR Case Study[40].

Table 7 Table 6 Life Cycle Cost for EOR Project

Breakdown Cost	**CO2 Capture**		
	Chemical Abs.	**Physical Abs.**	**Oxyfuel Comb.**
Capital Cost (M$)	534.93	435.21	488.09
Capital Cost ($)	534,929,460	435,208,915	488,091,659
Operating Cost (M$/yr)	28.52	23.76	26.78
Operating Cost ($/yr)	28,516,353	23,762,992	26,783,165
	CO2 Transportation		
Cap.Cost Pipeline ($)	27,512,400	27,512,400	27,512,400
Operating Cost ($/yr)	1,100,496	1,100,496	1,100,496
Capital Recovery ($/yr)	$66,064,210	$54,351,072	$60,562,659
Equiv. Ann.l Cost ($/yr)	$67,164,734	$55,451,592	$61,663,182
Cost ($/tonCO2)	24.17	19.96	22.19
	CO2 Utilization: EOR Cost of Storage		
Cost of Storage (USD/tCO2)	43	43	43
Cost ($/tonCO2)	67.17	62.96	65.19

- **CO2 Utilization: Greenhouses**

Greenhouse CO2 utilization will cover yearly needs as per case study[21] with 179,919 kg/ha. With 2.7 MTonCO2 per year from Cilacap Refinery Unit, it will be sufficient to provide a 15,424 ha Greenhouses area. Moreover, CAPEX to build a greenhouse also need to be considered as per case study[41]. Transportation will be covered by trucks to support the operation daily.

Table 8 Life Cycle Cost for Greenhouse Project

Breakdown Cost	**CO2 Capture**		
	Chemical Abs.	**Physical Abs.**	**Oxyfuel Comb.**
Capital Cost (M$)	534.93	435.21	488.09
Capital Cost ($)	534,929,460	435,208,915	488,091,659
Operating Cost (M$/yr)	28.52	23.76	26.78
Operating Cost ($/yr)	28,516,353	23,762,992	26,783,165
	CO2 Transportation		
Truck Oper. Cost ($/yr)	$9,931,277	$9,931,277	$9,931,277
Capital Recovery ($/yr)	$62,832,614	$51,119,476	$57,331,063
Equiv. Ann. Cost ($/yr)	$101,280,243	$84,813,745	$94,045,505
	CO2 Utilization: Greenhouse		

Capital Greenhouse ($)	$148,245,778	$148,245,778	$148,245,778
Capital Recovery ($/yr)	$17,412,893	$17,412,893	$17,412,893
Equiv. Ann. Cost ($/yr)	$118,693,137	$102,226,638	$111,458,398
Cost ($/ton)	42.72	36.79	40.12

Step 4 Selection of a Criterion (or Criteria)

5. Multi-Attribute Decision Making

Multi-Attribute Decision Making is a "tool used to combine pure quantitative financial analysis models with the almost purely qualitative models used in the logical framework."[44] With this analysis, several attributes, including nonmonetary, can be considered to be taken into account in the evaluation. Compensatory models will be used to analyze the CCUS case. "The basic principle behind all compensatory models, which involve a single dimension, is that the values for all attributes must be converted to a common measurement scale. The result is that good performance in one attribute can compensate for poor performance in another. This allows trade-offs among attributes to be made"[42]. Several attributes will be considered in this analysis, such as:

- **Life Cycle Cost**

The life cycle cost considered in this MADM analysis will cover capital, operation, up to utilization as analyzed in the prior section.

- **Technology Readiness Level**

"Technology Readiness Level (TRL) is a measure of the maturity of a technology. It uses a scale that runs from 1 to 9, where a figure of 1 represents technology at a very early stage of research. A figure of 9 represents technology operating in a commercial environment over the entire range of conditions it was designed for"[45]. Specifically, TRL for CO2 capture technology, as per the scope of this study, will be as follows

Table 9 Carbon Capture Technology Readiness Level

Technology	TRL (2020)	Projects
Chemical Absorption	9[46]	Sleipner, Snohvit, Boundary Dam
Physical Absorption	9[45]	Val Verde, Shute Creek, Century Plant
Oxyfuel Combustion	6[44]	Under development

- **Energy Required for CO2 capture**

CO2 capture technologies differ in the way CO2 is separated and captured. "Regardless of the type, however, CO2 separation and capture add a considerable penalty to the overall process in both energy and cost. A recent thermodynamic study for post-combustion capture and storage of CO2 from coal-fired plants has estimated the lower bound of the energy penalty to be 24 kJ/molCO2. Meanwhile, PSA and TSA (for O2 separation before Oxyfuel Combustion system) were estimated to be 75 kJ/molCO2"[47].

Table 10 Energy Required

Technology	Energy Required (kJ/molCO2)
Chemical Absorption	24
Physical Absorption	24
Oxyfuel Combustion	75

Based on the data, several attributes could be summarized using nondimensional scaling as follows

Table 11 Non-dimension Scaling

Attribute	Value	Rating Procedure	Dimensionless Value
Life Cycle Cost ($/Ton CO2)	36.79	$\frac{94.34 - cost}{57.55}$	1
	94.34		0
Technology Readiness Level	9	$\frac{TRL - 7}{2}$	1
	7		0
Energy Required (kJ/molCO2)	24	$\frac{75 - energy}{51}$	1
	75		0

Findings

Step 5 Analysis and Comparison of the Alternatives

6. Analysis

By utilizing table 11, referring to the prior section, the value for each alternative could be determined as follows,

Attribute	Methanol Prod.			Enhanced Oil Recovery			Greenhouse Util.		
	Chem. Abs	Phys Abs	Oxy. Comb.	Chem. Abs	Phys Abs	Oxy. Comb.	Chem. Abs	Phys Abs	Oxy. Comb.
LCC	0.00	0.10	0.05	0.47	0.55	0.51	0.90	1.00	0.94
TRL	1	1	0	1	1	0	1	1	0
Energy Req'd	1	1	0	1	1	0	1	1	0
Total	2.00	2.10	0.05	2.47	2.55	0.51	**2.90**	**3.00**	0.94

From the calculation above, Carbon Capture using Physical Absorption technology and being utilized as greenhouse utilization has the highest result among other alternatives. At the same time, the second-best option is chemical absorption technology with a common utilization for greenhouses.

Step 6 Selection of the Preferred Alternatives

7. Alternative Selection

Carbon Capture using physical absorption technology and a greenhouse is the most favorable result. At first, physical absorption is categorized as the most economical way to capture CO2, specifically for single-point sources such as CO2 emitted from the oil refinery. Moreover, utilizing this CO2 emission collected from the refinery and directed into near greenhouses will be valuable and generate potential profit without spending significant capital and operational costs. "Recent study shows that utilizing this CO2 will generate higher crop yields. Another study also shows, with higher CO2 concentrations in the field, from 400 μL L^{-1} as regular concentration up to 800 μL L^{-1} will generate a higher dry weight for trees, more than 100%"[48]. This study's Carbon Capture deployment in Pertamina Cilacap Refinery could cover around 15,000 ha of local greenhouses.

Step 7 Performance Monitoring and Post-Evaluation of Results

This study shows that physical absorption technology for greenhouses is the most beneficial way. Keeping in mind that Indonesia, as an agricultural country, has many agricultural field areas and the enormity of CO2 emissions from many sources, it will potentially benefit many farmers in Indonesia.

Conclusion

Carbon Capture Storage and Utilization covers the technology to capture the CO2 emission, storage, and or utilize it to generate more valuable products. There are several capturing technologies and methods to convert them into new products. In this study, Life Cycle Cost Analysis is carried out to evaluate the economic valuation of each alternative. Since other aspects shall be considered for CCUS deployment, Multi-Attribute Decision Making is done to determine the best CCUS alternative that should be chosen. The result of this study is briefly described as follows

1. What kind of Carbon Capture could be utilized in Pertamina Refinery? Carbon capture with physical absorption is the best way to be utilized, particularly in Pertamina Refinery as a CO2 single point source through refinery stacks and utility units.

2. How to implement Carbon Capture technology in Pertamina Refinery? To add more value to carbon capture technology, utilizing the CO2 emission for the greenhouse is best. With a relatively low cost per ton of CO2 captured, potentially, it will generate more profit for corps yields.

3. How much does it cost to utilize carbon capture technology in Pertamina Refinery? Utilizing carbon capture technology for the greenhouse will cost around 36.79 USD/ton of CO2

4. What is the Life Cycle Cost Analysis result of carbon capture technology alternatives? Of several alternatives, utilizing CO2 captured with physical absorption technology for the greenhouse is the most economical way. Keeping in mind that Indonesia is an agricultural country, it will be precious for Indonesia shortly.

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