ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF CARBON CAPTURE AND UTILIZATION AT COAL-FIRED POWER PLANT IN THAILAND

BY

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ABSTRACT

Greenhouse gas reduction from large point sources has been of interest for global warming mitigation. Coal-fired power plants with carbon capture and utilization (CCU) technology can minimize carbon emissions. In this study, Life Cycle Assessment (LCA) methodology is applied to evaluate the potential environmental risks of capturing carbon dioxide at the coal-fired power plant in Thailand and utilizing it in alternative methanol (CO_2_MeOH) and formic acid (CO_2_FA) productions through direct CO_2 hydrogenation. The study aims to achieve low carbon growth and sustainable development success in Thailand. According to the analyses, the negative carbon feedstock provides larger decarbonization in the CO_2-based productions than the conventional productions (i.e., -862 vs. 712 kgCO_2-eq in a ton of MeOH production while 1.96E3 vs. 4.11E3 kgCO_2-eq in a ton of FA production). Despite the net negative carbon emissions, CO_2_MeOH production can rise 6 out of 8 investigated environmental impact indicators, when 2 out of those would increase in CO_2_FA production. The maximum impact scores as a result of the energy demand of the carbon capture can be reduced by integrating the waste heat recovery from the carbon removal process. Consequently, the higher impacts would

be 4 out of 8 indicators in the CO_2_MeOH production, whereas the CO_2_FA production remains the same pattern.

Furthermore, the investment costs of CCU projects are estimated on a unit price basis to strengthen an economy with a clean energy transition. The findings revealed that the process with the waste heat integration could decrease not only the related environmental risks but also the investment cost. However, total production costs (1227 \$/tCO_2_MeOH & 1044 \$/tCO_2_FA) are still expensive to compete with the conventional production prices (295-368 \$/tMeOH & 546 \$/tFA) and the current global market prices (750 \$/tMeOH & 500-800 \$/tFA), that could be lowered if low electricity cost was available. Selling by-product oxygen from CO_2_MeOH production and cheaper catalysts from local or global market can reduce the total production cost.

Keywords: LCA, Economic assessment, Carbon capture and utilization (CCU), Methanol, Formic Acid

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	Terms
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
ASEAN	The Association of Southeast Asian Nations
EGAT	Electricity Generating Authority of Thailand
tCO_2e	ton of carbon dioxide equivalent
GHG_s	Greenhouse gases
USC	Ultra-supercritical
NETL	National Energy Technology Laboratory
COP-26	The UN Climate Change Conference
FGD	Flue Gas Desulphurization
SCR	Selective Catalytic Reduction
ESP	Electrostatic Precipitator
MEA	Monoethanol Amine
IGCC	Integrated Gasification Combined Cycles
PC	Pulverized Coal
GWP	Global Warming Potential
MDEA	Methyl Di-ethanol Amine
HTP	Human Toxicity Potential
kg 1,4 DCB eq	Kilogram 1,4-Dichlorobenzene-equivalent
USC PC	Ultra-Supercritical Pulverized coal
SC PC	Super-Critical Pulverized coal
KS-1™	Hindered amine
$CaCO_3$	Calcium Carbonate
Ru-Ph	Ruthenium-Phosphino
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
CO_2_MeOH	CO_2-based Methanol
CO_2_FA	CO_2-based Formic Acid
AOX	Adsorbable Organic Halogen
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
TOC	Total Organic Carbon
DOC	Dissolved Organic Carbon
GW	Global Warming
TA	Terrestrial Acidification
FWEu	Freshwater Eutrophication
HCT	Human Carcinogenic Toxicity

HnCT	Human non-Carcinogenic Toxicity
FPMF	Fine Particulate Matter Formation
MRS	Mineral Resource Scarcity
FRS	Fossil Resource Scarcity
CEPCI	Chemical Engineering Plant Cost Index
EPCC	Engineering, construction management, home office and fees
TPC	Total Plant Cost
BEC	Bare Erected Cost
TOC	Total Overnight Cost
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
Fixed O & M	Fixed operating and maintenance
Var O & M	Variable operating and maintenance
CBM	Cost of bare model
COE	Cost of Electricity
LCOP	Levelized Cost of Production
CRF	Capital Recovery Factor
GJ	Giga joule
MPa	Mega Pascal
SMR	Steam Methane Reforming
ELCD	European reference Life Cycle Database
NaOH	Sodium hydroxide
TEG	Triethylene Glycol
USLCI	U.S Life Cycle Inventory
$NHeX_3$ / $C_{18}H_{39}N$	tertiary amine or trihexyl amine
IPCC	Intergovernmental Panel on Climate Change

CHAPTER 1
INTRODUCTION

1.1 Background of the study

Electricity generation from coal burned power plants has been relying on the world to meet the energy demand due to its stable supply and the remaining coal reverses in other nations such as China. Coal-fired power plants, however, are identified as a severe threat to the environment and human beings due to the massive pollutant emissions, mainly from the power plant operation. In the process of daily power production, carbon dioxide (CO_2), toxic gases (e.g., SO_2, NO_X), particulate matters (PM, sometimes called "soot"), volatile organic compounds (VOCs), and other chemical substances directly or indirectly spread into the atmosphere, soil and water by burning fuel in coal-fired power plants through chemical reactions that cause environmental degradation, as well as detrimental health problems to the living things including humans in a variety of ways. Carbon dioxide, among those various pollutants, is regarded as the most serious concern because of the most considerable contribution to the greenhouse effect leading to environmental consequences such as global warming. The concentration of carbon dioxide in the atmosphere will rise gradually without effective emission reduction strategies. At the same time, the world nations have been striving to limit global warming within 1.5˚C set out in the Paris Agreement, 2015 to avoid further devastating effects of climate change. Curbing the enormous amount of carbon emission from large point sources such as power generation and industrial plants (i.e., steel, iron, cement, and ammonia productions) through carbon capture technology is a great solution to cope with the global warming. At present, CO_2 capture and utilization (CCU) technology helps to minimize the doubling step of carbon release; on the one hand, it has challenges of higher energy penalty and increasing material and fuel consumption that can maximize not only the scores of environmental impacts but also total capital costs compared to the conventional productions.

Thailand is a developing country among ASEAN members in Southeast Asia. Electricity production plays a vital role in all-around development and coal-fired power plants are essential for enough electricity supply, especially in the northern part

of Thailand. As the outcome of the available coal source from the Mae Moh lignite mine-mouth mining area, coal burned power plants have been running for electricity distribution. According to the energy statistics of the Ministry of Energy, as the whole kingdom, total electricity consumption had risen to 187,046 GWh in 2020 compared to 149,301 GWh in 2010. However, the production and consumption of lignite can be reduced from 17,785,747 tons and 17,843,097 tons in 2010 to 13,250,574 tons and 13,437,692 tons in 2020, all of the lignite production came from the Electricity Generating Authority of Thailand (EGAT) (Energy Policy and Planning Office (EPPO), 2021).

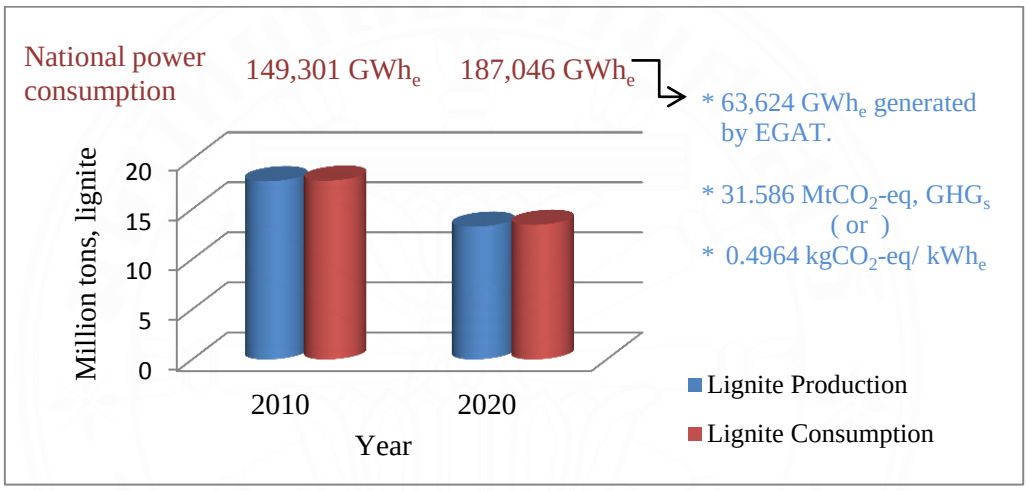

Figure 1.1 Lignite production and consumption in Thailand

EGAT, the large state-owned power enterprise, has taken responsibility for electricity production and transmission to the length and breadth of the nation. It is a large-scale electricity enterprise owned 52 power plants with a total installed capacity of 16,037.32 MW (35.26% of total contracted capacity, 45,480.37 MW), of which 2,220 MW (4.88%) were from Mae Moh lignite power plant (EGAT Sustainability Report (2020)). In 2020, EGAT generated up to 63,624,302 MWh net electricity and released 31,586,257.97 tCO_2-eq of GHG_s, corresponding to the emission intensity of 0.4964 $kgCO_2$-eq per kWh electricity generated that was the reduction of GHG_s emissions up to 8,758,780 tCO_2-eq exceeding 4,000,000 tCO_2-eq abatement mission (EGAT Sustainability Report (2020)). Meanwhile, Thailand is making an effort to minimize much more GHGs by preparing its climate change act relevant to the country and EGAT is collaborating together with it.

Thailand's Climate Change Master Plan (2015–2050) is aimed to assist the sustainable development goal of Thailand, low carbon growth, and climate change resilience by 2050, by following the plans: (i) building climate resilience by integrating policies and measures in all sectors, (ii) creating mechanisms to reduce GHG emissions, leading to sustainable low carbon growth, (iii) building readiness of master plan implementation by enhancing potential and awareness of stakeholders, and (iv) developing a database, knowledge, and technology to support climate change adaptation and mitigation (Misila, Winyuchakrit, & Limmeechokchai, 2020). As long as larger pollutant emission fuel resources are burned for electricity generation, carbon abatement plans and technology will be required to avoid intense environmental impacts and related human health problems.

1.2 Statement of problem

Carbon capture and storage (CCS) or utilization (CCU) technology is an effective strategy to eliminate the GHGs accumulation, transform into the net-zero transition targets, and mitigate and adapt to climate change. However, the utilization of the captured CO_2 is not completely secure, safe, and efficient like other advanced technologies as it has other environmental consequences such as acidification, eutrophication, human toxicity, more or less on nature and human health. Life-cycle assessment (LCA) is an appropriate tool for finding out and reviewing those potential environmental risks, partly or wholly from the entire process but unsuitable for long-term aspects integration (Petra Zappa, 2012).

1.3 Objectives and scopes

The major objectives of this study are:

(1) To evaluate the potential environmental risks of the CCU plants for alternative methanol and formic acid productions through direct CO_2 hydrogenation technology compared to the conventional productions. Carbon dioxide is assumed to be captured from the current existing 655 MW capacity, Ultra-Supercritical (USC) boiler of Mae Moh coal-fired power plant in Thailand.

(2) To analyze the cost-benefit estimations of the CO_2 capture process and CO_2-based products.

The total budgets of all plants are estimated using similar NETL methods (Battaglia, Buffo, Ferrero, Santarelli, & Lanzini, 2021; Vincent Chou, 2016). The main impact boundary assumption of this study is summarized in Table 1.1:

Table 1.1 Impact assessment boundary

Process	CO_2 capture	CCU	Remark
Raw material (without fuel) and energy production, transportation and consumption	Yes[(a)]	Yes[(b)]	Energy from Mae Moh plant & MEA[(a)], CO_2 & H_2[(b)]
Transportation (Via Pipeline)	Yes[(c)]	No	CO_2[(c)]
Plant construction and dismantling	Yes	Yes	Include in Infrastructure
Process operation	Yes	Yes	
End usage	Yes[(d)]	No	Methanol & Formic Acid productions[(d)]

1.4 Significance of study

CCU technology is targeted to minimize the double-steps of CO_2 emissions from the CO_2 capture process to carbon utilization plants by substituting the conventional products in the market with the CO_2-based high-value commercial products, which can create a win-win situation between the environment and the human beings for economic benefits. Although this kind of technology provides better environmental performance, especially GHG_s savings, it has the consequences and trade-offs such as intensive material and energy demand that can raise the questions of associated environmental impact changes and higher production costs that are conducted in this study. The results are aimed to use for future technological developments in the same research field, to minimize or avoid the adverse environmental impacts, to emerge and strengthen a carbon-based product market with lower production costs in the near future, as well as to make the right decision when applying coal burned power plant with CCU.

CHAPTER 2
LITERATURE REVIEW

2.1 Carbon capture technology emerging

To substantially curb or combat the effects of global warming and environmental crisis, deploying carbon capture technology is one of the best solutions. Sustainable development goals (SDGs), COP-26, Net Zero targets by 2050, and the Paris Agreement are marching toward carbon neutrality with active and innovative collaborations from both private and industrial sectors worldwide. Emerging CCU technology in the industrial and energy roles helps immense decarbonization. Applying the carbon capture system to power generation plants can reduce our serious concerns rather than the traditional power production method despite a challenging solution due to its trade-offs that are needed to solve gradually through the research and development (R & D) findings. To achieve a carbon clean world, every county will need to participate with the same effort relevant to their county's standards; simultaneously, equitable access to all affordable carbon abatement technology is required to create at pace for long-term sustainability.

2.2 Global Warming Potential (GWP) or Greenhouse Gases (GHG_s) reduction in the carbon capture process

In a carbon capture scenario, the CO_2 capture efficiency and GHG_s reduction vary depending on the power plant type, boiler type, and capture system. Deploying carbon capture technology to coal burned power plants can minimize the CO_2 emissions on average by 90% from power generation process which reduced the global warming potential (GWP) to 71-80% in the Post-combustion system, 76-86% in the Oxy-fuel combustion system and 78-86% in the Pre-combustion system based on the kind of capture solvent when compared to the power plant without carbon capture process (Koornneef, van Keulen, Faaij, & Turkenburg, 2008; Odeh & Cockerill, 2008; Singh, Strømman, & Hertwich, 2011; Tang, Yokoyama, Kubota, & Shimota, 2014; Zhou et al., 2014). However, applying the carbon capture process to power plants increased coal use from 15% to 30% on a gram per kilo watt hours fundamental unit (Odeh & Cockerill, 2008) that contributed to an increase in the total

GHG emissions from 3.3% to 10.7% in the pre-combustion system, 25.5% in the post combustion, and 39% in the oxy-fuel combustion respectively (Zhou et al., 2014). Due to the carbon capture scenario, pulverized coal (PC) power plant increased coal use 24-40%, while 14-25% in the Integrated Gasification Combined Cycle (IGCC) plant (Metz, 2005). The average GWP of a normal power generation plant is 876 kg CO_2eq./MWh in PC plant type, while 1009 kg CO_2eq./MWh in IGCC type (Rosa M. Cue´ llar-Franca, 2015). When the power plant is installed carbon capture system, the GWP value per MWh unit basis was 203 kg CO_2eq. (post combustion with MEA) and 154 kg CO_2eq. (oxy-fuel combustion) in PC plant; whereas 190 kg CO_2eq. (pre-combustion) and 200 kg CO_2eq. (oxy-fuel combustion) in IGCC plant (Rosa M. Cue´ llar-Franca, 2015).

Almost all of the GWP impact in a traditional power plant without CO_2 capture mainly came from plant operation, followed by coal mining, productions of ammonia and the limestone involved in the Selective Catalytic Reduction (SCR) and Flue Gas Desulphurization (FGD); while in a power plant with Methyl Di-ethanol Amine (MDEA) or Calcium Looping (CaL) or ammonia based carbon capture case, the majority of GWP contribution were from coal mining followed by power generation process, CO_2 transport & storage, MDEA production or aqueous ammonia for the SCR process, and CO_2 pipelines commissioning (Petrescu, Bonalumi, Valenti, Cormos, & Cormos, 2017). The impacts of materials production, infrastructures, decommissioning, CO_2 storage leakage and transportation are insignificant because those impacts are minimal when compared to the power generation and the carbon capture scenarios.

Integrated Gasification Combined Cycle (IGCC) power plant (45.9% net electrical efficiency) with Calcium looping or Chemical looping capture process resulted in higher CO_2 capture efficiency: 91.56% or 99.45% (Petrescu & Cormos, 2017), while in the pulverized coal (PC) power plant, the capture efficiency was 90.49% with amine-based MDEA, 85% with aqueous ammonia and 92.66% with calcium looping (Petrescu et al., 2017). When choosing the IGCC plant, the efficiency of the GWP reduction was higher than the PC plant; as a result, consequent hazards were lower. As the disadvantage, the IGCC plant with a pre-combustion system

occupied greater material requirement that was 1.5 times higher than the same demand of the oxy-fuel or post combustion in the PC plant (Wu Yujia, 2014).

For larger carbon removal efficiency and the effective impact reduction, not only carbon capture process but also additional co-capture or pollutants removal systems such as Selective Catalytic Reduction (SCR), Electrostatic Precipitator (ESP), and Flue Gas Desulphurization (FGD) installed in the power plant can remove the discharges of CO_2, NO_x, PM, SO_2 and so on (Koornneef et al., 2008; Zhou et al., 2014). Unless FGD was installed prior to carbon capturing, duplex total carbon dioxide emissions could increase (Odeh & Cockerill, 2008).

2.3 Human Toxicity Potential (HTP) / Human Health Impact in the carbon capture process

In all IGCC and PC coal-fired power plants, HTP impact due to infrastructure requirements accounted for 43% in the pre-capture, 27% in the post-capture, and 26% in oxyfuel-capture compared to no-capture case (Singh et al., 2011). The majority of its impact came directly from power plant emissions.

Before the carbon capture system, particulate matters (PM_{10}, $PM_{2.5}$, and secondary PM), VOCs, the heavy metals, and different inorganic emissions from plant operation can be reduced by the pollutant removal methods such as ESP, FGD, and SCR without discharge into the air; consequently, air related impact and human health would be decreased too. If the wastes with bottom ash from the power plant were piled up into the landfill, the land impact can rise, then gradually cause higher the aquatic human toxicity potential come from the groundwater leakage (Zhou et al., 2014). In comparison with the traditional power production scenario, the plant with the pre-, post-, or oxy-fuel- combustion decreased HTP and human health impacts related to an air source; in addition, the pre-combustion system was mostly lower than post- and oxy-fuel combustions in HTP (carcinogenic and non-carcinogenic) affected by air, soil, and water except for slightly bigger than the oxy-fuel combustion in HTP (carcinogenic) affected by soil (Zhou et al., 2014).

The HTP score of Ultra-Supercritical, pulverized coal (USC PC) plant showed a decrease compared to that of Supercritical, pulverized coal (SC PC) plant thanks to both generating and capture efficiency improvements; however, USC PC plants

applying MEA-based carbon capture system indicated the significant higher HTP score than the cases without capture (i.e., 54% than SC PC and 181% than USC PC) because of MEA production (51% of total HTP score) and consumption in the carbon capture scenario (Koornneef et al., 2008) and also the MEA hazardous waste and heavy metal emission in water (Odeh & Cockerill, 2008).

In summary, dangerous pollutants such as particulate matter, SO_2, and NOx can be alleviated by installing pollutant control technologies such as SCR, FGD, and ESP. Furthermore, deploying CO_2 capture to coal-fired power plant can reduce CO_2 emissions so as not to increase GHGs into the atmosphere. It can be proved from the above literature findings that the IGCC plant with carbon capture system occupies the higher capture efficiency with lesser global warming impact compared to the PC plant with the capture process, but its material demand is more than the PC. However, on the other hand, PC plants with MEA solvent need more advanced investigation in the future because most of the impact categories, especially HTP, come from the MEA process rather than power plant operation and the cause of higher energy demand together with more coal and material consumptions for capture system. It is suggested that the increasing amount of emissions from MEA production and consumption can be limited by lowering acid gases in the additional pollutant removal systems before carbon capturing or by using NaOH to reclaim some of the MEA solvent (Koornneef et al., 2008).

2.4 Captured CO_2 Utilization (CCU) Processes

After capturing CO_2 from the different power plants or processes, it can be utilized to produce various carbon-based value-added products on an industrial scale that can substitute the conventional products.

All CO_2 valorization products lower GWP either by the process itself or by comparing with the conventional production as shown in table 2.1; however, there were more or less other environmental impacts increases depending on each CCU process. Firstly, carbon-based polyol production decreased all investigated environmental impacts; the more the CO_2 content (maximum, 30%wt) in the polyol synthesis, the larger the impacts reduction, but it can utilize the smallest amount of CO_2 among all compared carbon-containing products (Niklas von der Assen, 2014).

Similar to the polyol production, if CO_2 content in the carbon-containing rubber product becomes higher, 1.1-2.49 kg CO_2eq per functional unit product of GWP reduction would be achieved despite being not a GHG sink process; in contrast, it can raise other impact categories such as freshwater eutrophication and ionization radiation (Raoul Meys, 2019).

CO_2-based formic acid production gave lower scores in 16 out of 18 observed impact categories except for slight increases in water depletion and ozone depletion compared to the conventional one (Yuchan Ahn & Han, 2019). In the investigated research, by changing the water electrolysis process such as hydrogen cracking, or reformer for hydrogen production in the place of current membrane cell electrolysis, climate change (GWP) and fossil depletion impacts can be minimized significantly. More than that, the best solution is to use the wood chip for process heat requirement and/or hydropower for electricity demand to produce the desired product with the least impact.

Regardless of being higher in the impact categories such as the total resource use (Wieland Hoppe, 2017), cumulative energy demand, acidification potential, eutrophication potential, and ozone depletion potential (Marian Rosental, 2020), the greater the CO_2 utilization amount in the methane and methanol productions gave an advantage of negative GWP values among all compared CO_2 source plants (Wieland Hoppe, 2017) that is due to the negative carbon uptake and also the negligence to the effects of heat because the required heat for carbon capture was assumed to be recovered from each synthesis process and/or the carbon source plant. The thermal energy requirement with MEA-based carbon scrubbing system was 3.13 GJ per 1 ton of carbon capture; however, methanol synthesis can compensate for 1.4 GJ per 1 ton of methanol product (Marian Rosental, 2020). Unless waste heat was integrated from the carbon source plant for carbon capture, seven out of sixteen analyzed environmental indicators occupied the greatest score in the CO_2 based synthesis gas (SNG) production, and all impacts showed the positive sign (Eleonora Bargiacchi, 2020; Wieland Hoppe, 2017). To cut down more the impacts, renewable energy such as wind power was the appropriate energy source to supply electricity.

The highest GHG saving and much lower environmental impacts were available by permanently storing carbon dioxide through carbonation processes (Sara

Ghasemi, 2017), which can utilize the larger amount of CO_2. Moreover, extracting CO_2 from the underground storage to reuse as enhanced oil recovery can meet the future oil demand. Two-thirds of GWP (297.5 vs. 106.5 $kgCO_2e$/bbl) could be decreased; moreover, when the conventional MEA solvent was changed to KS-1^{TM} (Hindered amine) solvent which required less solvent and energy, or potassium carbonate 30% solution with energy recovery from the base plant, the significant reduction (from 106.5 $kgCO_2e$/bbl to 91 $kgCO_2e$/bbl in KS-1^{TM} & 58 $kgCO_2e$/bbl in potassium carbonate) was found due to lower energy duty (M.A. Morales Mora & Rosa-Domínguez, 2016).

An attractive CCU process at present is the CO_2-based construction materials. The larger amount of CO_2 utilization scenario provided by mineral carbonation is the production of CO_2 concrete blocks. However, the intensive energy and fuel consumptions for the required pressure and temperature increased other environmental impacts such as Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity potential (HTP), Photochemical Ozone Creation Potential (POCP), Abiotic depletion Potential (ADP), Ozone Depletion Potential (ODP) and Cumulative energy demand (CED); yet some CO_2-cured concrete blocks such as slag-portland cement (SPC) block and wollastonite-portland cement (WPC) block were still environmentally advantageous (Hao Huang, 2019). Another construction material ($CaCO_3$ nanoparticles) production used as cement filler compared two types of carbon capture technology (MEA & Ionic liquid (IL)) with three different CO_2 reaction scenarios (CO_2 + $CaO/CaCL_2/CaCL_2$ with waste heat). Due to the intensive energy consumption in the MEA process, 14 out of 16 impact categories, except for freshwater eutrophication, human toxicity with cancer effect were higher in MEA than IL (E. Batuecas 2021). When the internal waste heat (CO_2) from $CaCO_3$ precipitation was combined in the synthesis reaction as system optimization, the impacts were the lowest amid the compared three scenarios. In the comparison results of the $CaCO_3$ filled cement and the traditional cement, the first one achieved a 69% GWP reduction over the latter one and also minimized other investigated environmental impacts.

To sum up, all CCU processes enable lower CO_2 emissions from various point sources; however, the use of captured CO_2 in the limited small-scale chemical

productions does not achieve the net life cycle emission reduction despite lesser all environmental impacts. For net-zero carbon emission mitigation, the carbon sink CCU process would be more beneficial and attractive from the environmental and economic perspectives. It is to be noted that all CCU processes need to combine the waste heat released by the carbon capture process to compensate for the energy penalty of carbon capture and/or to extract the required energy from renewable energy so that all related environmental effects, including embodied carbon to be the least when considering an in-depth LCA. The question of whether CCU is an environmentally friendly solution or not depends largely on where the fuel and the resource requirements in the upstream process and the amount of energy in the production stage will be extracted, as well as the captured CO_2 would be deployed in which process.

Table 2.1 CO_2 utilization amount and GWP reduction in each CCU process

Case study	CO_2 based product/ process	Functional unit (FU)	Total CO_2 contents per FU	GWP reduction
(Niklas von der Assen, 2014)	Polyol	1 kg	0.1 kg (10wt%)/ 0.2 kg (20wt%)/ 0.3 kg (30wt%)	1-5% (0.1kg)*/ 11-18%(0.2kg)*/ 18-30%(0.3 kg)*
(Raoul Meys, 2019)	Rubber	1 kg	0.2 kg	18-34%*
(Yuchan Ahn & Han, 2019)	Formic acid	1 kg	0.978 kg	53.6%*
(Wieland Hoppe, 2017)	Methane, Methanol, Synthesis Gas (SNG)	1 kg	2.75 kg (methane) 1.374 kg (Methanol)	negative values
(Marian Rosental, 2020)	Methanol, Ethylene, Propylene, Benzene, Toluene, Mixed Xylenes	1 ton	1441 kg (Methanol)	88-97%*
(Eleonora Bargiacchi, 2020)	Synthetic Natural Gas (SNG)	1 kg	2.69 kg	30-35%
(Sara Ghasemi, 2017)	Carbonation Product	1 MWh (608 kg CO_2 emission)	548 kg	65-79%
(M.A. Morales Mora & Rosa-Domínguez, 2016)	Enhanced Oil Recovery (EOR)	1 barrel (bbl)	110 kg	64.2%
(Hao Huang, 2019)	Concrete blocks	1 m^3	40.9-68.5 kg	24.3-56.6%*
(E. Batuecas 2021)	$CaCO_3$ nanoparticles	1 kg	0.54-2.45 kg	11.3-126.8%
	Cement		0.593 kg	69%*

* GWP reduction results compared to conventional process

2.5 Financial evaluation of CCU Projects

2.5.1 Electricity prices and the CO_2 avoided costs

The electricity prices without or with carbon capture and the CO_2 avoided costs fluctuate depending on the type of power plant, coal price, capture solvent, and capture technology. The general cost variations are described in Table 2.2 as follows:

Table 2.2 Ranges of electricity price and CO_2 avoided cost.

Cost	PC type	IGCC type	Reference
Electricity Price without carbon capture (US$/kWh)	0.043-0.052	0.041-0.061	IPCC Special Report, 2005 (Metz, 2005)
Electricity Price with carbon captured (US$/kWh)	0.82-0.97	0.67-0.94	
Electricity Price with CO_2 avoided (US$/kWh)	0.62-0.70	0.59-0.73	
Electricity Price with carbon capture and Enhanced Oil Recovery (EOR) (US$/kWh)	0.049-0.081	0.040-0.075	
CO_2 avoided cost with CCS (US$/t CO_2 avoided)	30-70	20-70	
CO_2 avoided cost with CO_2 capture and Enhanced Oil Recovery (US$/t CO_2 avoided)	10-40	0-40	
CO_2 price (US$/t CO_2)	5-180		(Zimmermann et al., 2020)
Levelized Cost of Electricity (LCOE) without CCS (US$/MWh)	61-87		(Tramošljika, Blecich, Bonefačić, & Glažar, 2021)
Levelized Cost of Electricity (LCOE) with CCS (US$/MWh)	94-163		
CO_2 capture (US$/t CO_2)	33-58		
CO_2 avoided cost (US$/t CO_2)	44-86		

2.5.2 Production cost analysis of CCU processes

After the first step of CO_2 capture at the power plant, it can be utilized for various industrial-scale productions, such as the products shown in Table 2.1. Utilization of the waste or pollutant CO_2 for numerous products is attractive for businesses because they can be substituted in our daily commodities; however, the total investment costs are higher than the conventional ones (see Table 2.3). In terms

of the different calculation methods, various assumptions, geological conditions, literature data, electricity price, and the limited economic boundary, there is a barrier to estimate the final production cost of CCU projects. The higher prices in consumables (e.g., chemicals, catalysts, and raw materials) are unavoidable to deploy the CCU projects. Raw materials prices of captured CO_2 and H_2 are not economically feasible (Pérez-Fortes, Schöneberger, Boulamanti, & Tzimas, 2016). In addition, CO_2 consume intensive energy because its bond structure is very strong and stable to decompose or synthesize with other chemical substances.

When the larger energy demand handles the CO_2-oriented projects, electricity prices play an essential role in financial profit and environmental impacts reductions. Supplying the vast energy requirements of CCU plants with renewable energy can meet the lower carbon neutrality goal; on the other hand, it can increase the total production cost from an economic perspective. Referring to relying only on renewable power may not be an effective and practical approach because there will come up the questions on its technological readiness, the availability of current generation capacity, and power transportation feasibility. Although energy generation from fossil fuel resources offers lower production costs, higher carbon emissions cannot be neglected (see production prices and carbon emissions in the study (Khamhaeng, Laosiripojana, Assabumrungrat, & Kim-Lohsoontorn, 2021)). Therefore, CCU projects with system optimization are required to consider for a sustainable society with the long-term benefit from both environmental and economic assessments.

To minimize the higher energy demand, the CO_2 capture price increase, and the consequent environmental effects, the two studies (Cheng Xu, 2020; Minh T Ho, Allinson, & Wiley, 2009) demonstrated that applying the waste heat recovery from the carbon removal process was a solution; in that case, the alternative solvents (KS1 and the potassium carbonate) are more efficient than the MEA solvent (Minh T Ho et al., 2009). But that represented only the CO_2 capture process. Further research and development (R&D) investigations are crucial to developing the whole CCU process.

With respect to the economic analysis, the influence factors on the total investment cost are different depending on the CCU process. For example, 61-80% of total plasterboard production cost comes from alkali use to keep the alkalinity in the carbon precipitation process and 17% from fixed operating cost (labor) (Gálvez-

Martos, Elhoweris, Hakki, & Al-horr, 2020). The lowest production price (410 $/ton) can compete with the conventional one in the market described in Table 2.3.

Concerning synthesis natural gas (SNG) production, capital and operating costs constituted 9.6% & 90.4% at the production capacity of 30 m^3/hr, while 4.7% & 95.3% for the capacity of 700 m^3/hr (Boreum Lee, 2019). The expenditures of H_2 with renewable energy and CO_2 highly influenced the operating cost (71.4% at 30 m^3/hr, 91.7% at 700 m^3/hr). The increased production capacity decreased the unit price of SNG. The next similar case revealed that the total SNG production cost-shared 41% capital, 22% operational & 38% energy supply, which was mainly associated with the electricity price and the operation time. The lesser the operation hour, the lower the SNG production and the higher the capital cost per unit (Jordi Guiler, 2018). Selling Oxygen via water electrolysis can lessen the unit price by 30%. Yet carbon-based SNG could not compare the lower price of the conventional SNG.

Since formic acid was produced through direct CO_2 hydrogenation technology with H_2 produced by water electrolysis, consumables (catalysts), the electricity of the electrolyzer, and steam contributed highly to the total production expense (Mar Perez-Fortes, 2016). When a similar technology was applied to the methanol process, the electrolyzer was the biggest contributor (55%) to the capital cost. In contrast, the electricity (process and electrolysis) significantly dominated the operating cost (Pérez-Fortes et al., 2016). Electricity price vastly affected the methanol unit price variations that can be minimized by selling by-product oxygen or integrating process waste heat compensated by 81% heating & 47% cooling of total energy demand (Battaglia et al., 2021). Both formic acid and methanol processes are roughly four times higher than the conventional ones, as shown in Table 2.3. The advantage is a ton of carbon-containing formic acid and methanol can save 0.4 ton of heavy fuel oil and 0.6 ton of natural gas, respectively (Mar Perez-Fortes, 2016; Pérez-Fortes et al., 2016).

The next study (Dongin Kim, 2020) investigated the formic acid (FA) production with two types of catalysts: Ru-Ph and Au/TiO_2. The following results were obtained;

FA production	with Ru-Ph catalyst	with Au/TiO_2 catalyst
FA conversion yield	81% mol	84% mol
Energy efficiency	22.9%	60.9%
Reaction time	1 hr	72 hr
Energy demand	Higher	Lower
Production cost	Lower	Higher
Purity	85 wt%	85 wt%
Emissions (tCO_2/tFA)	0.36	0.07

Although both types of productions utilized a similar input amount of CO_2 and H_2, the process heat requirement for vapor-liquid distillation was 75% higher in the former than in the latter because of different mass balances. The first method should not be implemented if steam production is expensive. As for cost breakdown relating to the minimum selling price per ton, H_2 was the maximum expenditure (26.7%), followed by tertiary amine (22.3%), catalyst (20%), utility (9.6%), methanol (7.3%), etc., in the FA with Ru-Ph; whereas the FA with Au/TiO_2 allocated capital cost (45.2%), butylimidazole (22.3%), H_2 (16.5%) and so on (Dongin Kim, 2020). CO_2 price (6.6%) does have much fluctuation in both projects. The reaction time caused the production cost difference. If the first project is implemented, the lower production cost is available, but the second one can achieve lesser carbon emissions from the synthesis process.

Finally, the total investment costs of CCU projects differ based on the assumptions, methodology, and technology. Thus, it is crucial to take the data or method from strong literature unless on-site data is available because that will affect the large variation in the estimated result. Mostly, CCU products are more expensive than the conventional or current market products. Although some products such as polyol (Cora Fernández-Dacosta, 2017) and polyurethane rubber (Georg A. Buchner, 2020) occupy lower investment and smaller environmental impact scores than the traditional ones without CO_2, the limited CO_2 input amount cannot meet large-scale commercial productions. Following the local and global demand, the CCU plants should be implemented for economic advantage.

Table 2.3 Various production prices without or with CO_2

Study	Production/ Process	Unit Price	CO_2-based price	Conventional / Market price
(Battaglia et al., 2021)	Methanol	€/ton	2624–2706 (concentrated solar power) 1867–1949 (offshore wind) 1319–1401 (solar PV) 1150–1232 (geothermal) 1019–1101 (bioenergy) 941–1023 (onshore wind) 823–906 (hydropower)	400-800*
(Pérez-Fortes et al., 2016)	Methanol	€/ton	2472	1270
(Gálvez-Martos et al., 2020)	Plaster board	$/ton	410-5000	570
(Boreum Lee, 2019)	Synthetic Natural Gas (SNG)	$/MWh	121 (30 m^3/hr) 94 (700 m^3/hr)	38-69*
(Jordi Guiler, 2018)	Synthetic Natural Gas (SNG)	€/MWh	70 (Electricity 25€/MWh) 125 (Electricity 40€/MWh)	22 26
(Mar Perez-Fortes, 2016)	Formic acid	€/ton	1524 (Ru-Ph catalyst)	475
(Dongin Kim, 2020)	Formic acid	$/ton	1029 (Ru-Ph catalyst) 1037 (Au/TiO_2 catalyst)	931*
(Cora Fernández-Dacosta, 2017)	Polyol	€/kg	1.2	1.4
(Georg A. Buchner, 2020)	Polyurethane Rubber	$/kg	2.32	2.81
(Bong Jae Lee 2020)	$CaCO_3$ nanoparticles	$/MWh	26	N/A
(Sebastian Teir, 2016)		€/ton	150	

* = market price

CHAPTER 3
METHODOLOGY AND MATERIALS

3.1 Life Cycle Assessment (LCA)

For environmental sustainability, the potential environmental impacts from various processes, products, or services can be evaluated with Life Cycle Assessment (LCA) method partly or wholly from the entire life cycle stage. According to ISO 14040 (Kun-Mo Lee, 2004), the generally defined four steps of LCA are set in this study:

(I) Goal and Scope,

(II) Life Cycle Inventory (LCI) analysis,

(III) Life Cycle Impact Assessment (LCIA), and

(IV) Life Cycle Interpretation.

3.1.1 Goal and Scope

Concerning the scope defined from cradle to gate boundary, the potential environmental impacts of retrofitting carbon capture technology in the current operating 655 MW, USC boiler, pulverized coal Mae Moh power plant and of the industrial-scale captured CO_2 utilization processes are assessed. The results are aimed to reduce GHG emissions, avoid severe environmental effects, and deploy in similar technology improvements.

As illustrated in figure 3.1, the system boundary is initiated with MEA manufacturing, followed by capturing CO_2 released from the Mae Moh power plant, then compressing and transporting it through the onshore pipeline to the carbon utilization plants producing alternative commercial methanol and formic acid. The required energy for the carbon capture is assumed to be extracted from the base power plant. The utilities and consumables imported from the global or local market would be available at the gate of the CCU plants. The functional unit is defined as a ton of CO_2-based product (1 ton CO_2_MeOH or 1 ton CO_2_FA) for each CCU plant.

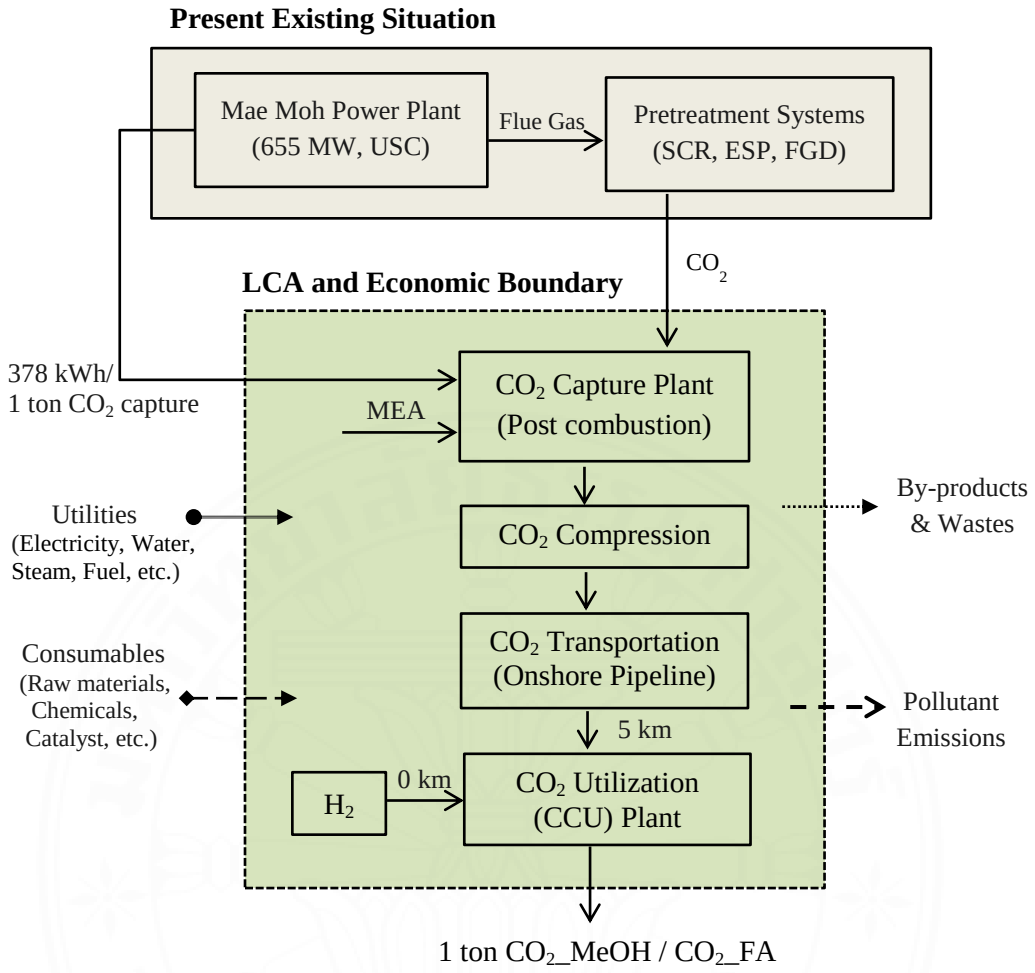

Figure 3.1 Conceptual system boundary of Mae Moh lignite burned power plant with CCU process.

3.1.2 Life Cycle Inventory (LCI) analysis

Detailed impact assessment assumptions from raw material manufacturers to the final carbon utilization stage in the conceptual boundary are described in Table 1.1. The inventory data of the electricity generation of the benchmark power plant is received from the previous literature (Koornneef et al., 2008), including MEA manufacturing (Table 3.5), the infrastructures of the CO_2 capture process (Table 3.6, 3.7 & 3.8), plus again combined with the report data from Mae Moh lignite plant and the ecoinvent dataset from Simapro software. LCI data of the alternative productions are taken from previous case studies (see Table 3.10 & 3.11) and made the general approximate assumptions for this case (see Table 3.12). LCI data of the conventional methanol and formic acid productions are also available from the ecoinvent database

and the study (Rodríguez-Vallejo, Valente, Guillén-Gosálbez, & Chachuat, 2021) (see Table 3.13) to compete with the alternative ones. Additional detailed LCI data assumptions and limitations are described later in the result and discussion section.

3.1.3 Life Cycle Impact Assessment (LCIA)

Eight environmental impact indicators within the emissions of the system boundary are assessed in LCIA because those are the significant impact indicators in the power generation system and the important factors for the society according to Thailand standards. The observed impact indicators are Global Warming (GW), Terrestrial Acidification (TA), Freshwater Eutrophication (FWEu), Human Carcinogenic Toxicity (HCT), Human non-Carcinogenic Toxicity (HnCT), Fine Particulate Matter Formation (FPMF), Mineral Resource Scarcity (MRS) and Fossil Resource Scarcity (FRS). SimaPro free faculty license software with version 9.3.0.3 and the ReCiPe 2016 Midpoint (H) method is applied to characterize and interpret those impacts.

3.1.4 Life Cycle Interpretation

Interpretation results assist the investigators in drawing the conclusion, decision making, and recommendation of the present research and future decision in the related field as well. In this life cycle interpretation, the impacts of CCU products are compared and evaluated with the conventional or traditional products without CO_2. Besides, the sensitivity analyses are performed to decrease the potential environmental hazards much more.

3.2 Economic analysis

To estimate the total costs of both carbon capture and CCU plants, ‘‘0.6 power factor rule’’ is used to scale up the installed equipment cost; moreover, the chemical engineering plant cost index (CEPCI) is used to update the base year cost (2020$) estimation. The currency exchange rate in this paper is 1 Baht = 0.03 $, 1 Euro = 1.15 $, and a dollar is defined as an American dollar.

$$\mathrm{Cost_{Res}} = \mathrm{Cost_{Ref}} \times \left(\frac{\mathrm{Capcity_{Res}}}{\mathrm{Capacity_{Ref}}}\right)^{\mathrm{PF}} \times \frac{\mathrm{CEPCI_{Res}}}{\mathrm{CEPCI_{Ref}}}$$

$\mathrm{Cost_{Res}}$ = Cost in research case

Cost_{Ref} = Cost in reference case
$\text{Capacity}_{\text{Res}}$ = Capacity in research case
$\text{Capacity}_{\text{Ref}}$ = Capacity in reference case
PF = Power factor = 0.6
$\text{CEPCI}_{\text{Ref}}$ = Chemical Engineering Plant Cost Index in reference year
$\text{CEPCI}_{\text{Res}}$ = Chemical Engineering Plant Cost Index in research year
CEPCI (2011) = 585.7, CEPCI (2017) = 567.5, CEPCI (2020) = 596.2

Total overnight cost (TOC) or capital expenditure (CAPEX) and operating cost (OPEX) calculations were estimated as NETL cost analysis methods (Battaglia et al., 2021; Vincent Chou, 2016). CAPEX or TOC has two parts: (1) direct TOC or bare erected cost (BEC) and (2) indirect TOC including EPCC (engineering, procurement, and construction cost), contingencies and owner's cost. OPEX is divided into fixed operating and maintenance cost (Fixed O & M) and variable operating and maintenance cost (Var O & M). Fixed O & M cost is associated with the numbers of operating labor, maintenance, taxes, and insurance. Var O & M cost includes utilities such as electricity, water, steam, fuel, etc., and consumables, for instance, raw materials, chemicals, and catalyst. Detailed cost assumptions for this study are as below:

Carbon Capture Plant Cost [after (Vincent Chou, 2016)]	**CCU Plant Cost (Battaglia et al., 2021)**
Capital Cost (CAPEX/ TOC)	
(A) BEC = Equipment + Labor + Material + Construction+ Installation (B) EPCC = 12 % (A) (C) Process contingencies =10 % (A) (D) Project contingencies = 20 % (A) TPC = (A) + (B)+ (C)+ (D)	(1) Total Equipment Cost (TEC) = 68% (2) Pipe, valves and fittings = 20% (3) Process instruments & control = 7% (4) Electric equipment and materials = 5% (5) Total of the bare module costs (CBM) = (1)+(2)+(3)+(4) = 100% (5) CBM = 68% (6) Erection and installation labor = 24% (7) Buildings, materials and labor = 8% (A) BEC = (5) + (6) + (7) = 100% (B) EPCC = 17.5% (A) (C) Process contingencies = 5% (A)

→

	(D) Project contingencies = 15% (B+C) TPC = (A) + (B)+ (C)+ (D)
(E) Start-up cost = 2%TPC (F) Inventory = 0.5%TPC (G) Financing cost = 2.7%TPC (H) Other owner's cost = 15%TPC TOC = TPC + (E)+ (F)+ (G)+ (H)	
Fixed Operating and Maintenance Cost (Fixed O & M) [after (Vincent Chou, 2016)]	
(I) Total labor Cost in a year ($/yr) (II) Operating Labor Burden = 30% (I) (III) Over Head Charge Rate = 25% ((I)+(II)) (IV) Annual Operating Labor Cost (AOL) ($/yr) = (I) + (II)+ (III) (V) Maintenance Labor Cost = 2% TPC (VI) Administrative & Support Labor = 35% AOL (VII) Property Taxes and Insurance= 2 % TPC Total fix O & M ($/yr) = (IV)+(V)+(VI)+(VII)	
Variable Operating and Maintenance Cost (Var O & M) = Consumables + Utilities + Catalysts	
OPEX = Fixed O & M + Var O & M	

Onshore natural gas pipeline transport cost without including in the NETL report was taken from the previous Thailand case study (Somkiat Khwanpruk, 2015) and added it in the BEC of carbon capture. The working hours of each labor were assumed to be 8 hrs/day. The operators were grouped into 3 shifts/day. To estimate the operating cost (OPEX), electricity, water, and labor prices were referenced from the website (Thailand Board of Investment, 2021) by making the cost assumption from average business or industrial cases. The chemicals and catalysts used in Var O & M were available from the global chemical supply market (Alibaba.com) for large-scale industrial application and also combined with the values from other literature. MEA price was taken from production cost study (Mohammed B Alqaragully, 2015). Detailed cost assumptions can be found in Appendix A. The total energy demand of the carbon capture retrofit case would be extracted from the baseline power plant

without installing a supplementary boiler and coal extraction increase; however its electricity price was considered in the COE calculation.

For the economic evaluation, the discount rate 8%, plant lifetime (30 years for carbon capture plant, 25 years for carbon utilization plants), operation hours (8760 hrs/yr with 80% capacity factor for the carbon capture plant, 8000 hrs/yr for carbon utilization plants), ± 15% for the uncertainty cost analysis of all plants were assumed respectively. The cost of electricity (COE) of the carbon capture retrofit plant or Levelized Cost of Production (LCOP) for CCU plants can be calculated as follows:

$$\textbf{COE / LCOP} = \sum_{t=1}^{N} \frac{(TOC * CRF) + Fix\ O\&M + Var\ O\&M}{Annual\ Production\ (\frac{MWh}{yr}/\frac{t}{yr})}$$

$$CRF = \frac{r(1+r)^N}{(1+r)^N - 1}$$

$$CO_2\ avoided\ cost\ (\$/t\ CO_2) = \frac{COE_{with\ Capture} - COE_{without\ capture}}{CO2emission_{without\ capture} - CO2\ emission_{with\ capture}}$$

COE = Cost of Electricity ($/MWh)

LCOP = Levelized Cost of Production ($/t)

TOC = Total Overnight Cost ($)

CRF = Capital Recovery Factor (%)

Fix O & M = Fixed Operating & Maintenance cost($/yr)

Var O & M = Variable Operating & Maintenance cost ($/yr)

t = lifetime in each year

N = defined total economic lifetime in years

r = interest rate

3.3 Carbon capture technology

In the three classifications of carbon capture systems: pre-combustion, post-combustion, and oxy-fuel combustion, the green-field power plant can deploy any system, whereas oxy-fuel combustion and post-combustion are appropriate only for the existing power plant. In the oxy-fuel combustion technology, oxygen is high-priced and larger energy demand of air separation system in the operation stage can raise carbon dioxide emissions and other environmental effects (Cuéllar-Franca &

Azapagic, 2015). Therefore, post-combustion technology with monoethanolamine (MEA) solvent is opted for capturing carbon dioxide from the current 655 MW, USC boiler of Mae Moh coal-fired power plant because the amine solvent is extensively available in the market and lots of research on this solvent have already been published in spite of being higher energy demand in the MEA regeneration process. The CO_2 capture process for the retrofit case can be studied in (Edward S. Rubin, 2002). The technical parameters of ultra-supercritical power plant (Table 3.1), carbon capture (Table 3.2), and compression & transportation (Table 3.3) are as below:

Table 3.1 Main performance parameters of ultra-supercritical (USC) power plant and energy requirement of CO_2 capture system

Parameter	Value	Reference
USC steam cycle, temperature	600/620˚C	(Tramošljika et al., 2021)
USC steam cycle, pressure	285/60 Bar	(Tramošljika et al., 2021)
Gross power output	655 MW	Mae Moh Plant
Initial operation year	2019	Mae Moh Plant
Net power output with MEA carbon capture retrofit	447.3 MW	Assumption & Calculated
Balance of baseline plant	45 MW	Assumption
Total energy demand for CO_2 capture	122.7 MW	After (Nie, 2009)
CO_2 Compression	40 MW	(Koornneef et al., 2008)
Net efficiency without carbon capture	45%	Assumption
Net efficiency with carbon capture	33%	
Energy penalty for carbon capture retrofit (% point)	12%-pts	(Metz, 2005)
Plant operation time	8760 hrs/yr	Assumption
Capacity Factor	80%	Assumption
Annual electricity production	3,134,678 MWh/yr	Assumption & Calculated
CO_2 emissions	730.5 kg/MWh	(Tramošljika et al., 2021)

Table 3.2 Main performance parameters of CO_2 capture system

Parameter	Unit	Value	Reference
NO_x reduction efficiency	%	1.25	(Koornneef et al., 2008)
HF reduction efficiency	%	90	
CO_2 reduction efficiency	%	90	(Edward S. Rubin, 2002)
SO_2 reduction efficiency	%	99.5	
NO_2 reduction efficiency	%	25	
HCL reduction efficiency	%	95	
PM reduction efficiency	%	50	
SO_3 reduction efficiency	%	100	(Nie, 2009)
CO_2 (lean solvent) loading	mole CO_2/mole MEA	0.05-0.3	(Tramošljika et al., 2021)
CO_2 (rich solvent) loading	mole CO_2/mole MEA	0.3-0.6	
Absorber temperature	°C	30-50	
Absorber pressure	Bar	~1	
Stripper (desorber) temperature	°C	80-160	
Stripper (desorber) pressure	Bar	1-10	
L/G (liquid-to-gas) ratio	kg/kg	2-6	
MEA solution mass fraction	wt%	30	(Edward S. Rubin, 2002)
CO_2 pressure	kpa	50	(Metz, 2005)
CO_2 product purity	wt%	99.5 - ≥99.9	(Edward S. Rubin, 2002)-(Metz, 2005)

Table 3.3 Main performance parameters of CO_2 compression and transportation

Parameter	Unit	Value	Reference
Pipeline length	km	5	Assumption
Pipeline diameter	inch	36	
CO_2 inlet pressure	MPa	0.1	(Koornneef et al., 2008)
CO_2 outlet pressure	Mpa	11	
Pressure loss in distance	Mpa/km	0.006	
Fugitive CO_2 emission pipeline	tCO_2/(km year)	2.32	
Fugitive CO_2 emission compressor	tCO_2/MW/yr	23.2	

3.3.1 Energy demand

The total energy demand in MEA-based CO_2 capture process is the sum of (1) the steam or thermal consumption in the stripper for CO_2 scrubbing and solvent regeneration and (2) the electricity used for pumps, gas blowers, a multi-stage CO_2 compressor, and the other running devices; in which the thermal energy extracted from the IP/LP steam turbine of the baseline plant is the majority (Zhang et al., 2014). In this case, the total thermal energy loss (12% points) equivalent to 378 kWh per ton of the carbon capture retrofit process is suggested to supply from the base power plant without additional coal consumption. The detailed energy penalty, the chemical consumptions in 1 ton CO_2 capture (Table 3.4), the LCI data of 1 kg MEA production (Table 3.5), and the LCI data of 1 ton CO_2 capture infrastructure (Table 3.6) are described as follows:

Total energy penalty in 1 ton CO_2 capture retrofit case with MEA solvent

Total energy demand = 378 kWh	(12%-pts)
Total heat demand = $4GJ_{steam}$ (Koornneef et al., 2008) (or) 222 kWh	(7.05%-pts)
Total electricity demand (I+II+III) = 156 kWh	(4.95%-pts)
I. 23.6 kWh for fans and pumps (Koornneef et al., 2008)	(0.75%-pts)
II. 21.4 kWh for other equipment and system	(0.68%-pts)*
III. 111 kWh for Compressor (Koornneef et al., 2008)	(3.52%-pts)

* Own calculation based on boiler capacity

Table 3.4 Consumptions in 1 ton CO_2 capture

Consumption	Value	Reference
Triethylene Glycol, TEG	0.2 kg	(Vincent Chou, 2016)
NaOH	0.13 kg	(Edward S. Rubin, 2002)
Activated Carbon	0.075 kg	
Cooling water makeup	0.8 m^3	
MEA makeup	2.04 kg	(Nie, 2009)

Table 3.5 LCI data for MEA (1 kg) production (Koornneef et al., 2008)

Material/ process	Unit	Value
Input		
Natural gas	MJ	2
Electricity	kWh	0.333
Ammonia	g	788
Ethylene oxide	g	816
Infrastructure chemical plant	P	4×10^{-10}
Transport (truck and train)	tx km	11.23
Output		
Monoethanolamine	kg	1
Ethylene oxide to air	g	1.63
Ethylene oxide to water	g	1.47
Waste heat	MJ	1.2
Ammonia to air	g	1.58
Ammonium to water	g	3.04
CO_2	g	26.5
Nitrate (NO_3) to water	g	6.97
COD, BOD	g	21.3
TOC, DOC	g	8.02

Table 3.6 LCI data for 1 ton CO_2 capture infrastructure (Koornneef et al., 2008))

Material/ process	Unit	Value
Steel (Chromium steel)	kg	0.00258
Steel (Chromium steel pipe)	kg	0.000901
Concrete	m^3	0.011E-6

3.3.2 CO_2 compression and transportation to CCU plant

After CO_2 capturing, it would be compressed and dehydrated using the capacity of 40 MW, a four-stage compressor to reach the desired pressure from the atmospheric condition, 0.1 MPa to 11 MPa for onshore pipeline transportation. Finally, it is sent to the CCU plant for commercial carbon-containing chemical products. The pipeline transportation from the carbon capture plant to the CCU plant is assumed to be 5 km long with a 36-inch pipeline diameter. LCI data of 1 ton CO_2 compressor infrastructure (Table 3.7) and LCI data of 1 ton CO_2 onshore pipeline transport infrastructure (Table 3.8) are as follows:

Table 3.7 LCI data for 1 ton CO_2 compressor infrastructure (Koornneef et al., 2008)

Material/ process	Unit	Value
Concrete	m^3	1.048E-6
Diesel	ton	0.75284E-6
Electricity from 655 MW, Mae Moh Plant	MWh	0.98387E-3
Steel (low-alloyed)	t	1.048E-6
Copper (Cathode)	t	0.1129E-6
Polyethylene (Low density)	t	0.3226E-6
Compressor capacity	MW	40
CO_2 leakage	kg	0.29

Table 3.8 LCI data of 1 ton CO_2 onshore pipeline transport infrastructure [After (Koornneef et al., 2008)]

Material/ process	Unit	Value
Sand	kg	0.107
Diesel	kg	4.2716E-3
Reinforcing steel	kg	0.01277
Drawing of steel pipes	kg	0.01277
Bitumen	kg	0.127E-3
Polyethylene	kg	0.225E-3
Transport total	t x km	0.01254
CO_2 leakage	kg	0.0038

3.4 CCU (CO_2_MeOH & CO_2_FA) Plants

After carbon capture, compress, and transportation stages, the captured CO_2 is purified up to 99.99% to use as the feedstock and avoid catalyst poisoning in the methanol and formic acid productions. The CO_2 product stream of this study is assumed to get at the desired purity condition. Therefore, an additional purification process is excluded. Hydrogen, being accessible from diverse sources and used as the feedstock in CCU plants, is crucial to converting into carbon-based products. For this research, two types of hydrogen production are considered for each CO_2-containing product: green hydrogen produced from renewable energy for methanol and gray hydrogen from fossil fuel for formic acid. Both offer advantages and disadvantages,

such as higher production cost with less emission impact in green hydrogen and lower production cost with higher emission impact in gray hydrogen (Khamhaeng et al., 2021).

3.4.1 Hydrogen productions for CO_2-based Methanol and Formic Acid products

In methanol production, the reactant H_2, which reacts with CO_2, is produced through water electrolysis technology (see LCI data in Table 3.9). The required electricity is supplied by renewable energy, wind power to cure massive CO_2 emissions. LCI dataset of wind power electricity is directly chosen from Agri-footprint 5 project, ELCD in the software.

Although hydrogen production through water electrolysis offers the advantage of lesser CO_2 emission, the higher price amidst various hydrogen processes might be unattractive to entrepreneurs. Therefore, the lower hydrogen production cost of stream reforming technology is chosen for formic acid, the price is taken from the paper (Khamhaeng et al., 2021), and the electricity is supplied by the medium voltage of the national grid. LCI database of hydrogen (reformer) production is selected from Industry data 2.0. The hydrogen plants are assumed to be located near or inside the same on-site of the CCU plants, so as not to consider additional transport costs and the emissions effects.

Table 3.9 LCI data for 1 kg of Hydrogen (H_2) production via water electrolysis technology. (González-Garay et al., 2019)

Inputs	Value
Water, deionized	18.04 kg
Electricity	52.26 kWh
Outputs	Value
H_2	1 kg
O_2	8 kg

3.4.2 Methanol production from CO_2 hydrogenation

At first, the pure and compressed CO_2 and H_2 are combined with the recycled stream to heat up in the heat exchanger before feeding with the copper-based commercial solid catalyst ($Cu/ZnO/Al_2O_3$) into the reactor operating at the 76 bar and 210˚C (Mar Pérez-Fortes, 2016). The outflow is divided into two streams: one is employed to preheat the feed to the reactor, while another is used to support the reboiler and preheat the feed to the distillation column (Tuan B.H. Nguyen, 2015). The excess heat generated from the heat exchanger can compensate for the process heat or generate electricity, or be used in the carbon capture process. In this study, the process heat required during the reaction is assumed to be used from the recovered heat. For every 1 kg of methanol production, input electricity, 1.2 MJ is needed, while thermal energy, 1.4 MJ is produced back via the synthesis process (Marian Rosental, 2020). The main chemical reactions in the process are:

$$CO_2 + 3H_2 \overset{water}{\longleftrightarrow} CH_3OH + H_2O \qquad (3.1)\ \text{(Mar Pérez-Fortes, 2016)}$$

$$CO_2 + H_2 \overset{water}{\longleftrightarrow} CO + H_2O \qquad (3.2)\ \text{(Mar Pérez-Fortes, 2016)}$$

After the heat integration process, methanol and water through chemical reactions are condensed at the cooling temperature of 35˚C, followed by the gas and liquid separation process in the flash vessel. After that, the mixer of liquid methanol and water is preheated and evaporated in the heat exchanger to insert into the distillation column where water and methanol are separated, while the gas stream passes through the partial condenser enters into the heat exchanger are expanded to 1.2 bar (Pérez-Fortes et al., 2016). Finally, liquid methanol (99.9 wt% with the whole conversion yield, 94%) is produced. In this research, 1 Mt/yr of Methanol production is assumed, and the process simulation data of CHEMCAD software model including equipment and water electrolyser costs was extracted from (Pérez-Fortes et al., 2016). LCI data are taken from the previous case studies (González-Garay et al., 2019; Marian Rosental, 2020; Pérez-Fortes et al., 2016; Sternberg, Jens, & Bardow, 2017; Wieland Hoppe, 2017) to make the LCI assumption for this case (see Table 3.10).

Table 3.10 LCI data assumption for 1 ton methanol (MeOH) production

Research Case Study	Inputs per 1 ton MeOH				Emissions
	CO_2 (ton)	H_2 (ton)	Electricity (MWh)	Steam (MWh)	
(Wieland Hoppe, 2017)	1.374	0.189	1.271	-	N/A
(Marian Rosental, 2020)	1.441	0.203	0.330	-	66 kg CO_2, 578 kg H_2O, 1.4 GJ heat
(Pérez-Fortes et al., 2016)	1.460	0.199	0.177	0.439	90 kg CO_2, 768 kg H_2O
(González-Garay et al., 2019)	1.46	0.200	0.21	-	80 kg CO_2, 571 kg H_2O, 0.178 kg NO_2, 10 kg MeOH
(Sternberg et al., 2017)	1.436	0.197	1.340	-	62 kg CO_2
	1.484	0.204	0.69(0.3)	-	112 kg CO_2
	1.376	0.189	0.67(0.55)	0.37	2 kg CO_2
This research	**1.460**	**0.200**	**0.25**	**0.40**	**90 kg CO_2, 580 kg H_2O, 0.178 kg NO_2, 10 kg MeOH**

3.4.3 Formic acid production from CO_2 hydrogenation

After compressing and cooling CO_2 and H_2 to 105 bar and 30˚C, both are fed into the reactor at 90˚C for synthesis. Formic acid is produced from methanol; thus, it needs additional two main stages: (1) catalysts and methanol recovery, and (2) FA formation and purification. The chemical reaction and separation stages of FA are as below:

$CO_2 + H_2 + C_{18}H_{39}N \leftrightarrow C_{18}H_{39}N\text{-}HCOOH$ (3.3) (Mar Perez-Fortes, 2016)

$C_{18}H_{39}N\text{-}HCOOH \leftrightarrow C_{18}H_{39}N + HCOO$ (3.4) (Mar Perez-Fortes, 2016)

The two main streams react in the presence of ruthenium and phosphine-based catalysts, a tertiary amine, and a polar solvent (a mixture of MeOH and water) in the reactor, later forming an FA-amine adduct which has to be thermally separated to provide FA in the last distillation (Mar Pérez-Fortes, 2016). In the middle of the process, catalyst recovery from the separation of the light phase in a decanter and

methanol recovery in a stripping column working at 3 bar is recycled back to the rector (Mar Pérez-Fortes, 2016). In the final stage, the vapor-liquid distillation process separates and produces pure formic acid with 85 wt% from the formic acid and tertiary amine compound (Dongin Kim, 2020). Formic acid production amount, 250 kt/yr is adopted in this research. Aspen Plus process simulation data assumption from (Dongin Kim, 2020), equipment costs using 0.6 rule to scale up from (Mar Perez-Fortes, 2016), hydrogen production expense from (Khamhaeng et al., 2021), and CO_2 price from Mae Moh power plant were collected respectively for financial evaluation. LCI data assumptions can be found in Table 3.11.

Table 3.11 LCI data assumption for 1 ton formic acid (FA) production

Research Case	Inputs per 1 ton FA				Emissions
	CO_2 (ton)	H_2 (ton)	Electricity (MWh)	Steam (MWh)	
(Yuchan Ahn & Han, 2019)	0.978	0.045	0.207	1.038	21 kg CO_2
(Sternberg et al., 2017)	0.988	0.071	0.48(0.35)	3.27	32 kg CO_2
	0.985	0.045	0.530	2.51	29 kg CO_2
(Mar Pérez-Fortes, 2016)	0.834	0.059	0.296	2.786	166 kg CO_2, 60 kg H_2O
This research	**0.98**	**0.06**	**0.31**	**2.78**	**30 kg CO_2, 60 kg H_2O**

The final LCI data assumption results of both alternative and conventional productions for this study are described in Table 3.12 and Table 3.13 as follow:

Table 3.12 LCI data for 1 ton of alternative productions

a. CO_2_MeOH (1 ton) Production		b. CO_2_FA (1 ton) Production	
Inputs	Amount	Inputs	Amount
CO_2 (t)	1.46	CO_2 (t)	0.98
H_2(t) via water electrolysis	0.2	H_2 (t) via steam reformer	0.06
Electricity (MWh)	0.25	Electricity(MWh)	0.31
Heat (MWh)	0.40	Heat (MWh)	2.78
Cooling Water (m^3)	90	Cooling Water (m^3)	250
		Methanol (t) (Dongin Kim, 2020)	0.15
		Amine (t) (Dongin Kim, 2020)	0.12
Catalysts & Infrastructure		Catalysts & Infrastructure	
CuO (kg) (Pérez-Fortes et al., 2016)	63.26E-3	Ruthenium-based catalyst(kg) (Mar Pérez-Fortes, 2016)	2.5E-3
ZnO (kg) (Pérez-Fortes et al., 2016)	23.76E-3	Phosphino-based catalyst(kg) (Mar Pérez-Fortes, 2016)	1.25E-3
Al_2O_3 (kg) (Pérez-Fortes et al., 2016)	11.88E-3		
Infrastructure(P) (Marian Rosental, 2020)	2.35E-7	Infrastructure(P) (Nils Thonemann, 2019)	5E-7
Outputs	Amount	Outputs	Amount
Methanol(t)	1	Formic Acid (t)	1
CO_2 (t)	0.09	CO_2 (t)	0.03
H_2O (t)	0.58	H_2O (t)	0.06
Methanol(air) (t) (Rodríguez-Vallejo et al., 2021)	0.01		

Table 3.13 LCI data for 1 ton of the conventional productions

[Ecoinvent dataset from Simapro software and the study (Rodríguez-Vallejo et al., 2021)]

a. Methanol (1 ton) production via stream methane reforming (SMR)		b. Formic Acid (1 ton) production via methyl formate route	
Inputs	Amount	Inputs	Amount
Natural gas, high pressure (m^3)	651.79	Carbon monoxide (t)	0.6144
Process Water (t)	0.85	Heat (GJ)	22.795
Cooling water (m^3)	8.16	Electricity (MWh)	0.2878
Copper oxide (kg)	0.09	Methanol (kg)	40
Molybdenum (kg)	0.01	Water, deionised (kg)	600
Zinc (kg)	0.03	Cooling water (m^3)	375.5
Nickel, class1 (kg)	0.02		
Aluminium oxide (kg)	0.24		
Electricity (MWh)	0.074		
Heat (GJ)	6.93		
Infrastructure		Infrastructure	
Methanol factory (P)	3.72E-08	Chemical factory (P)	4E-07
Outputs	Amount	Outputs	Amount
Methanol (t)	1	Formic Acid (t)	1
Emissions to air		*Emissions to air*	
Carbon dioxide (kg) (Rodríguez-Vallejo et al., 2021)	80	Carbon dioxide (kg)	13.91
Nitrogen dioxide (kg) (Rodríguez-Vallejo et al., 2021)	0.178	Carbon monoxide, fossil (kg)	6.14
Methane, Fossil (kg)	0.98	Methyl formate (kg)	2.64
Nitrogen monoxide (kg)	0.15	Water (m^3)	145.63
Sulfur dioxide (kg)	0.0138		
Methanol (kg)	0.53		
Water/m^3 (m^3)	3.336		
Emissions to water		*Emissions to water*	
AOX as Cl (kg)	0.001	BOD5 (kg)	1.0784
BOD5 (kg)	0.18	COD (kg)	1.0784
COD (kg)	0.49	DOC (kg)	0.4212
Chlorine (kg)	0.002	Methyl formate (kg)	1.0540
DOC (kg)	0.24	TOC (kg)	0.4212
Methanol (kg)	0.03	Water (m^3)	230.47
Formaldehyde (kg)	0.1		
Phosphorus (kg)	0.01		
Phenol (kg)	0.01		
Suspended solids (kg)	0.02		
TOC (kg)	0.24		
Water (m^3)	5.674		

CHAPTER 4
RESULTS AND DISCUSSION

4.1 General LCI data assumptions and limitations

The data of the required electricity for each stage was taken from Thailand electricity, medium voltage market, whereas CO_2 capture energy was from Mae Moh (USC) plant, and electricity of H_2 & CO_2-MeOH productions from wind power, ELCD project.

All datasets were based on ecoinvent 3, Cut-off, U except for

- Transportation data, combination truck with average fuel mix/US from USLCI project for MEA manufacture,
- Hydrogen (reformer) production data from Industry data 2.0 project for CO_2- based formic acid product.

LCI data of tertiary amine ($NHeX_3$) was replaced with trimethyl amine due to no precise data in the Simapro software. The LCIA results in Table 4.1& 4.2 with the investigated potential environmental impact indicators include complete life cycle data from raw materials production, electricity generation, the whole CO_2 capture process, infrastructures, catalysts, chemicals to final captured CO_2 utilization products. The observed results are discussed in detail in subsections.

Although this study assessed the complete LCI data assumptions from MEA manufacture to final CO_2 utilization including plant infrastructure of each stage, there were limitations in the scope due to no available on-site data. Thus, we did not conduct the effects of before and after carbon capture in the power plant by using and comparing a functional unit, upstream activities such as coal extraction and transport, downstream activities such as recycling stages and waste managements, the big uncertainty of taken MEA manufacturing data, lack of detailed pollutant emission data of alternative productions, as well as the final end-users (the grave stage in LCA). These may have changed to the current impact scores from the entire LCA point of view.

4.1.1 Global Warming (GW)

According to the analysis in figure 4.1, the negative global warming (GW) value of -741 kg CO_2-eq is offered for every 1 ton of CO_2 capture. The maximum scores among all inventory inputs are mainly owing to the heat and electricity extractions from the Mae Moh power plant, followed by a small amount from MEA production. The contributions of other chemicals and CO_2 infrastructures (i.e., CO_2 capture infrastructure, CO_2 compressor infrastructure & CO_2 pipeline transport infrastructure) are trivial. In the case of heat duty-free from the waste heat recovery, the carbon emissions into the air could be much more avoided, plus the additional benefit of lowering other impact categories that are discussed in the sensitivity analysis.

When the CO_2-based methanol (CO_2_MeOH) production is compared with the conventional methanol production via natural gas steam-methane reforming technology in figure 4.2, the negative GW value (-862 vs. 712 kg CO_2-eq) is achieved in the CO_2_MeOH resulted from the captured CO_2 feedstock. The maximum GW impact (118 kg CO_2-eq/t CO_2_MeOH) comes from wind power electricity because of the massive electricity requirement (i.e., 10.45 MWh/t CO_2_MeOH) in H_2 production through water electrolysis technology. To supply such vast electricity demand with the least carbon emissions, power generation from wind power (green energy) is the most appropriate supply because of its zero-carbon source rather than other fossil fuel types (gray energy). If electricity was taken from the grid instead of wind power, GW impact would rise to 17.2 kg CO_2-eq/1kg methane, in which methanol was transformed via methanation technology (Wieland Hoppe, 2017). By-product oxygen from water electrolysis is not shared to any environmental burden in this study. Direct CO_2 emissions from the methanol synthesis reaction are the second-largest GW, but the effects of catalysts and infrastructure are lesser (see Table 4.1).

Regarding the formic acid productions illustrated in figure 4.3, CO_2-containing formic acid (CO_2_FA) has a lower GW potential with 1.96E3 kg CO_2-eq than the traditional FA; the difference is double. Around 46% of total GW impact in CO_2_FA is due to the process steam, followed by H_2 (20.2%), amine (12.7%), electricity (8.64%), catalysts (4.9%), methanol (3.9%), and finally infrastructure. Direct CO_2 emissions from the formic acid reaction do not have any noticeable GW

effect. The CO_2 uptake (-27.1%) is able to reduce the total GW of CO_2_FA. Process steam assumption of this case is lower than other studies (Sternberg et al., 2017), (Mar Pérez-Fortes, 2016), but nearly three times higher than the study (Yuchan Ahn & Han, 2019), resulting in 76% of total GW from H_2 and 9% from electricity without complete LCI data analysis such as amine and catalysts consumption effects. However, it presented that the lowest GW impact from the heat requirement can be attainable from wood chip burning among the compared diverse sources.

4.1.2 Terrestrial Acidification (TA)

The terrestrial acidification (TA) result of CO_2_MeOH is slightly higher than the MeOH without CO_2, which obtains 1.68 kg SO_2-eq in the former, while 1.56 kg SO_2-eq in the latter. In contrast, CO_2_FA with 16.5 kg SO_2-eq is less than the conventional FA with 20.4 kg SO_2-eq. The biggest TA impact in CO_2_MeOH comes from CO_2 uptake (77%), in which the heat requirement of the carbon capture is the major stressor, whereas it is primarily from catalyst consumption (54%), followed by process heat requirement (19%) in CO_2_FA.

Even though the impacts received from process heat and electricity demands of the alternative productions can be avoided by changing different source generations, the ones gained from the energy requirements of the carbon capture cannot be prevented by switching to another source production. Because this study is based on the coal-fired power plant in Thailand and the required energy for the carbon removal process is already defined practically to be extracted from the base power plant. Thus, the findings in this scenario reflect the potential environmental impacts of CCU implementation at the USC boiler of Mae Moh coal burned power plant.

4.1.3 Freshwater Eutrophication (FWEu)

The freshwater eutrophication (FWEu) score of CO_2_MeOH surpasses the conventional MeOH (i.e., 0.457 vs. 0.0975 kg P-eq). The difference between the two compared products shown in figure 4.2 is about 79%. The major culprit of the highest impact on CO_2_MeOH is the coal combustion in the power plant for electricity supply (97.1%) to the CO_2 capture process. Methanol infrastructure, copper oxide catalyst

and hydrogen cause a slight increase in FWEu by 2%, 0.5%, and 0.38%, respectively. The effects of electricity from wind power and the remaining catalysts are minute.

On the other hand, the analysis results show that CO_2_FA achieves a lower score in FWEu (i.e., 1.07 vs. 1.92 kg P-eq). The FWEu increase in CO_2_FA is mostly from the electricity of carbon capture (27.7%), process heat (19.7%), catalysts (16%), process electricity (14.5%), amine (11.7%), and infrastructure (8.91%) respectively. If we substitute trihexyl amine ($NHeX_3$) with triethylamine, not trimethylamine, its impact score would be the highest at 27.7%.

4.1.4 Human non-carcinogenic toxicity (HnCT), Human carcinogenic toxicity (HCT)

Human non-carcinogenic toxicity (HnCT) scores are much more serious in CO_2_MeOH (636 kg 1,4-DCB) and CO_2_FA (4.58E3 kg 1,4-DCB) than the conventional products (192 kg 1,4-DCB in MeOH & 3.64E3 kg 1,4-DCB in FA). On the one hand, human carcinogenic toxicity (HCT) is higher in CO_2_MeOH (33.9 kg 1,4-DCB) but lower in CO_2_FA (106 kg 1,4-DCB). The analysis results describe that the two impacts in CO_2_MeOH are caused by the electricity generation from coal for carbon capture, when in CO_2_FA, the metal catalyst used in the reactor dominates the HnCT category. In the software, ruthenium- and phosphino-based catalysts are replaced and analyzed with metal catalysts as the specific types of catalysts cannot be chosen. Although only a tiny amount of catalysts is required in the chemical synthesis, which gives an unexpected higher score in the HnCT of CO_2_FA.

4.1.5 Fine Particulate Matter Formation (FPMF)

The score of fine particulate matter formation (FPMF) exceeds slightly in CO_2_MeOH (0.664 kg $PM_{2.5}$-eq) compared to the conventional production (0.501 kg $PM_{2.5}$-eq); on the contrary, CO_2_FA gets a lower score (5.38 vs. 8.9 kg $PM_{2.5}$-eq). Heat demand of carbon capture attributes largely to FPMF in CO_2_MeOH production. The FPMF result of CO_2_MeOH is uncertain because not only additional co-capture or pollutants removals such as SCR, ESP, and FGD installed in the power plant but also the carbon capture process can remove the discharges of CO_2, NO_x, PM, SO_2, and so on (Koornneef et al., 2008; Zhou et al., 2014) (see. Table 3.2) that was not

involved in this study consideration, but the benefit is expected to reduce the FPMF impact when CCU technology is implemented on-site.

4.1.6 Mineral Resource Scarcity (MRS), Fossil Resource Scarcity (FRS)

The increased mineral resource uses at the production stages and the plant constructions of CO_2-based products increase the mineral resource scarcity (MRS) category in comparison to the conventional productions (i.e., 56.4 vs. 0.932 kg Cu-eq in MeOH, while 22.2 vs. 3.63 kg Cu-eq in FA). The maximum impact comes from hydrogen (96%), more explicitly, from wind power electricity production at the power plant for H_2 feedstock of CO_2_MeOH, while it is due to the metal catalysts (79%) & infrastructure (15%) in CO_2_FA. The electricity of H_2 & MeOH productions was taken from the wind power plant, ELCD project, which assessed the following LCA phases: production, transportation, erection, operation, maintenance, dismantling, and removal of the wind turbines, which cause an increase in MRS category. If the above-described stages of the wind power plant were considered together with recycling of the materials such as iron ore, copper, and aluminum after the end of its lifespan, the environmental degradation would be lesser, especially 70% reduction in abiotic resource depletion (Mozart Tavares da Silva, 2018).

Relating to fossil resource scarcity (FRS) impact, the score is fewer in CO_2 containing products (i.e., 102 vs. 740 kg oil-eq in MeOH, and 958 vs. 1270 kg oil-eq in FA) because the conventional products are vastly based on fossil resources: high-pressure natural gas use (84% impact contributor) and process heat from the natural gas market (13.7% contributor) in the conventional MeOH production. Furthermore, carbon monoxide produced from heavy fuel oil (55.5% impact contributor) and heat from natural gas (37.3% contributor) in conventional FA production. When fossil resource extractions and utilization are able to be reduced in carbon-based products rather than in fossil-based traditional products by reusing carbon dioxide released from fossil fuel (lignite) combustion, the environmental impact becomes lesser.

Table 4.1 Analysis results of 1 ton of alternative Methanol production

Impact category	Total Score	MeOH reaction	H_2	CO_2	CuO	ZnO	Al_2O_3	Infrastructure	Electricity
GW (kg CO_2 eq)	-862.47	90	117.53	-1081.9	0.376	0.018	0.028	8.773	2.770
TA (kg SO_2 eq)	1.68	0.037	0.241	1.293	0.021	0.000	0.000	0.085	0.006
FWE (kg P eq)	0.46	0	0.002	0.444	0.002	0.000	0.000	0.009	0.000
HnCT (kg 1,4-DCB)	635.70	1.56	-19.223	539.449	27.878	0.104	0.059	86.452	-0.577
HCT (kg 1,4-DCB)	33.93	0	0.221	24.683	0.205	0.001	0.022	8.802	0.000
FPMF (kg $PM_{2.5}$ eq)	0.66	0.004	0.070	0.545	0.007	0.000	0.000	0.038	0.002
FRS (kg oil eq)	101.82	0	24.251	74.699	0.095	0.006	0.006	2.197	0.570
MRS (kg Cu eq)	56.37	0	54.241	0.107	0.085	0.000	0.001	0.635	1.297

Table 4.2 Analysis results of 1 ton of alternative Formic Acid production

Impact category	Total Score	FA reaction	CO_2	H_2	Methanol	Heat	Metal catalyst	Infrastructure	Trimethyl amine	Electricity
GW (kg CO_2 eq)	1957.70	30	-726.2	542.75	104.62	1227.4	131.48	75.158	340.6	231.9
TA (kg SO_2 eq)	16.45	0	0.868	0.991	0.273	3.170	9.002	0.626	0.998	0.526
FWE (kg P eq)	1.07	0	0.298	0.000	0.015	0.212	0.172	0.096	0.126	0.156
HnCT (kg 1,4-DCB)	4580.19	0	362.09	0.006	32.7	375.74	2801.5	628.64	193.46	186.1
HCT (kg 1,4-DCB)	106.31	0	16.57	0.001	2.578	15.878	18.706	31.337	11.594	9.645
FPMF (kg PM2.5 eq)	5.38	0	0.366	0.296	0.099	1.182	2.600	0.263	0.374	0.200
FRS (kg oil eq)	957.66	0	50.14	101.14	114.19	360.09	43.703	17.919	204.43	66.04
MRS (kg Cu eq)	22.18	0	0.072	0.025	0.160	0.296	17.495	3.265	0.783	0.084

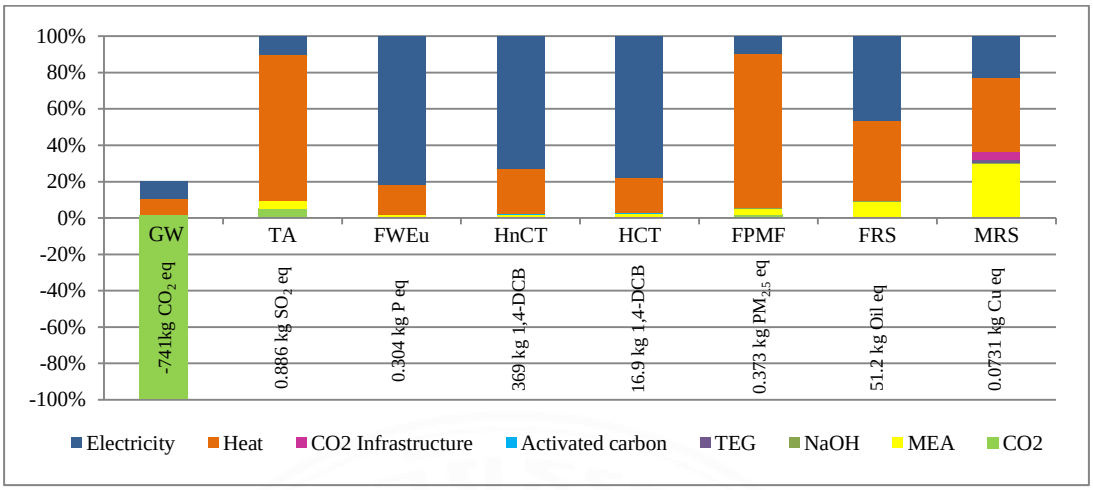

Figure 4.1 Impact assessment result of 1 ton CO_2 capture.
(Total score in each impact is set to 100%)

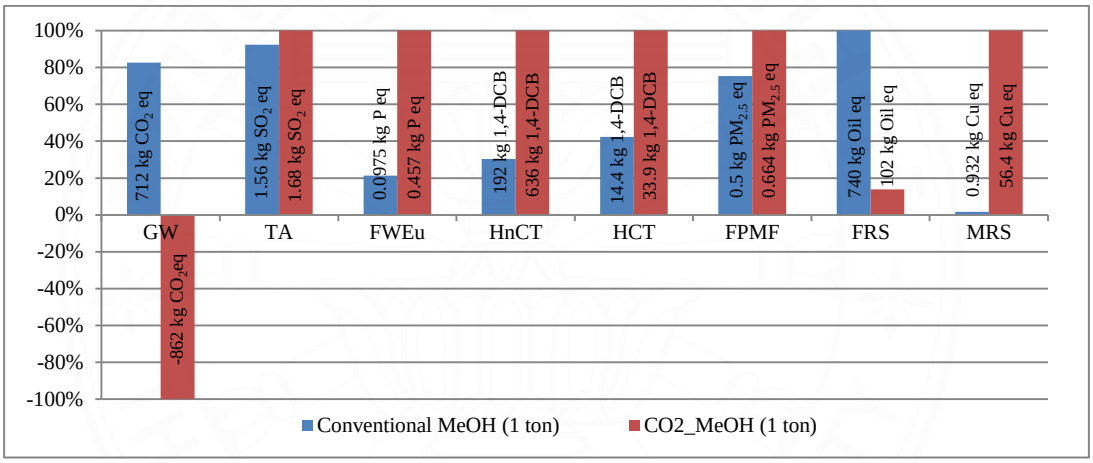

Figure 4.2 Impact assessment comparisons between the two types of methanol production. (Maximum impact score is set to 100%)

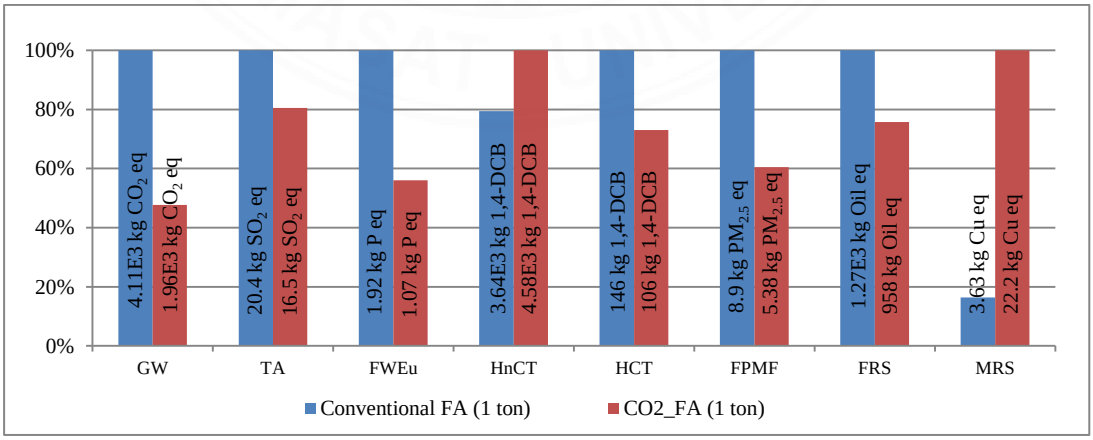

Figure 4.3 Impact assessment comparisons between the two types of formic acid production. (Maximum impact score is set to 100%)

4.1.7 Sensitivity analysis

Sensitivity analyses by impact score reductions in figure 4.4 and by impact percentage reductions in figure 4.5 are carried out based on (0% to 100%) heat compensation from the waste heat recovery of carbon capture to reduce the heat requirement and its related effects. The waste heat extracted from multi-stage compressors with intercoolers and coolers in the MEA-based carbon removal process (see the sample figure 4.6) decrease the total efficiency loss of the power plant due to carbon capture from 3% (Minh T Ho et al., 2009) to 3.86% (Cheng Xu, 2020), which can fulfill half of the heat demand (7.05%).

The sensitivity analysis results illustrated that in terms of the impact score reduction, the noticeable changes are found in the three highest impact indicators: HnCT, FRS, and GW, whereas the very few scores of others do not show significant variations but provide further great benefit to FPMF and TA impacts reductions in CO_2_MeOH production with waste heat rather than the production without waste heat combination. Compared to the scenarios without heat compensation (0%), 50% heat compensation can minimize the impact scores additionally by 10% in GW, 11% in HnCT, 16% in FRS, 30% in TA, 35% in FPMF, 8% in FWEu, 7% in HCT and 0.04% in MRS of the CO_2_MeOH; while by 3% in GW, 1% in HnCT, 1.1% in FRS, 2.1% in TA, 2.9% in FPMF, 2.3% in FWEu, 1.5% in HCT and 0.07% in MRS of CO_2_FA. As a result, four (FWEu, HCT, HnCT, MRS) out of eight observed impacts are higher in CO_2_MeOH with the waste heat integration than the traditional, when CO_2_FA without or with heat integration remains the same pattern.

To sum up, according to the compared results, the potential environmental impacts become higher in 6 out of 8 indicators at CO_2_MeOH production while 2 out of those at CO_2_FA production. The analysis results were taken into account with the complete LCI data from the primary feedstocks: CO_2 and H_2 productions to catalyst consumptions and infrastructures that were found to increase the scores of the investigated indicators despite GHG_s savings. As system optimization, the maximum impact scores associated with the energy demand of CO_2 capture can be cut down by the waste heat integration gained from the carbon removal process that offered further two impacts reductions to CO_2_MeOH production than the production without waste heat combination.

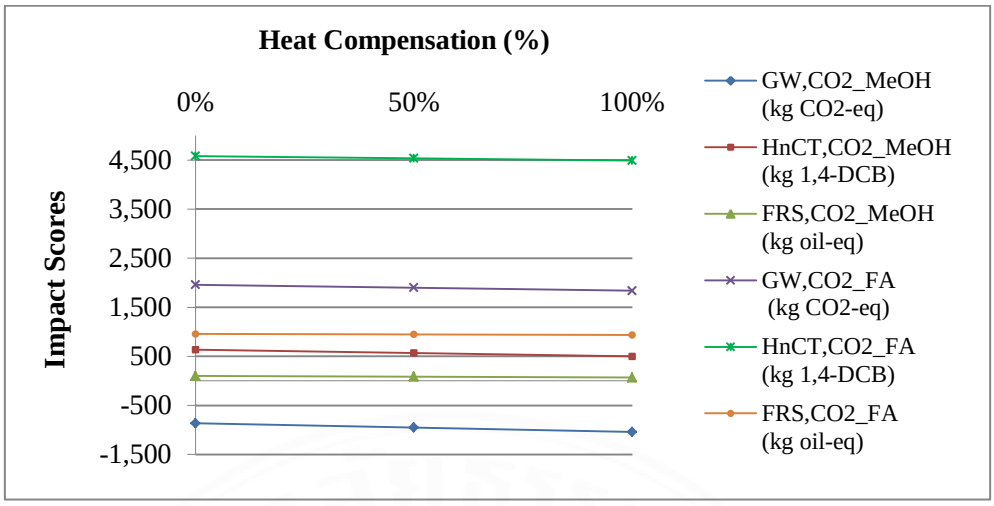

Figure 4.4 Sensitivity analysis of (0% to 100%) heat compensation by integrating waste heat recovery in 1 ton of CO_2_MeOH and CO_2_FA productions. (In terms of impact scores reduction)

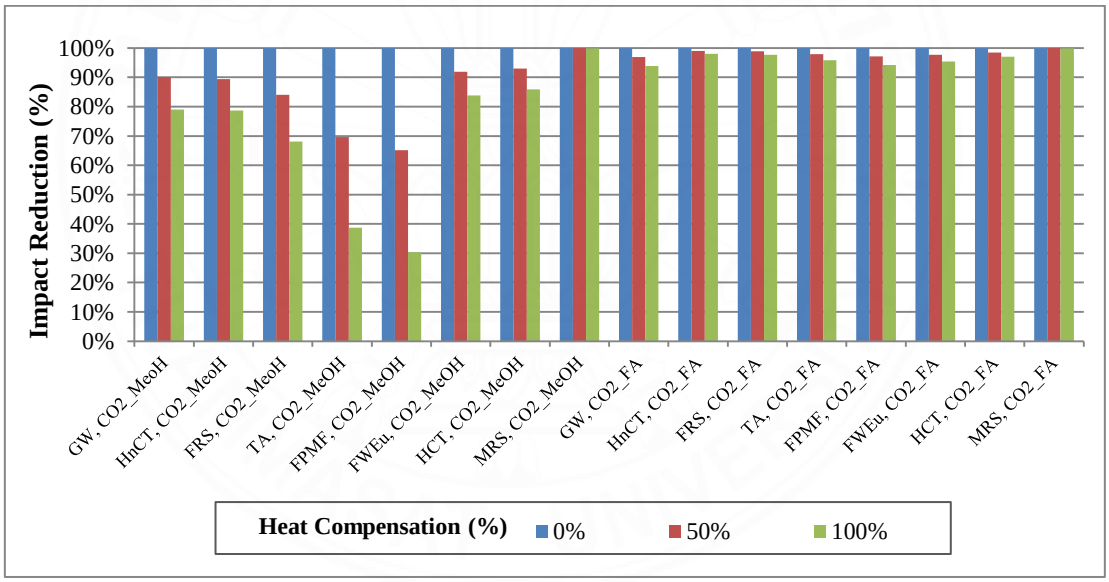

Figure 4.5 Sensitivity analysis of (0% to 100%) heat compensation by integrating waste heat recovery in 1 ton of CO_2_MeOH and CO_2_FA productions. (In terms of impact reduction percentage)

4.2 Economic analysis results

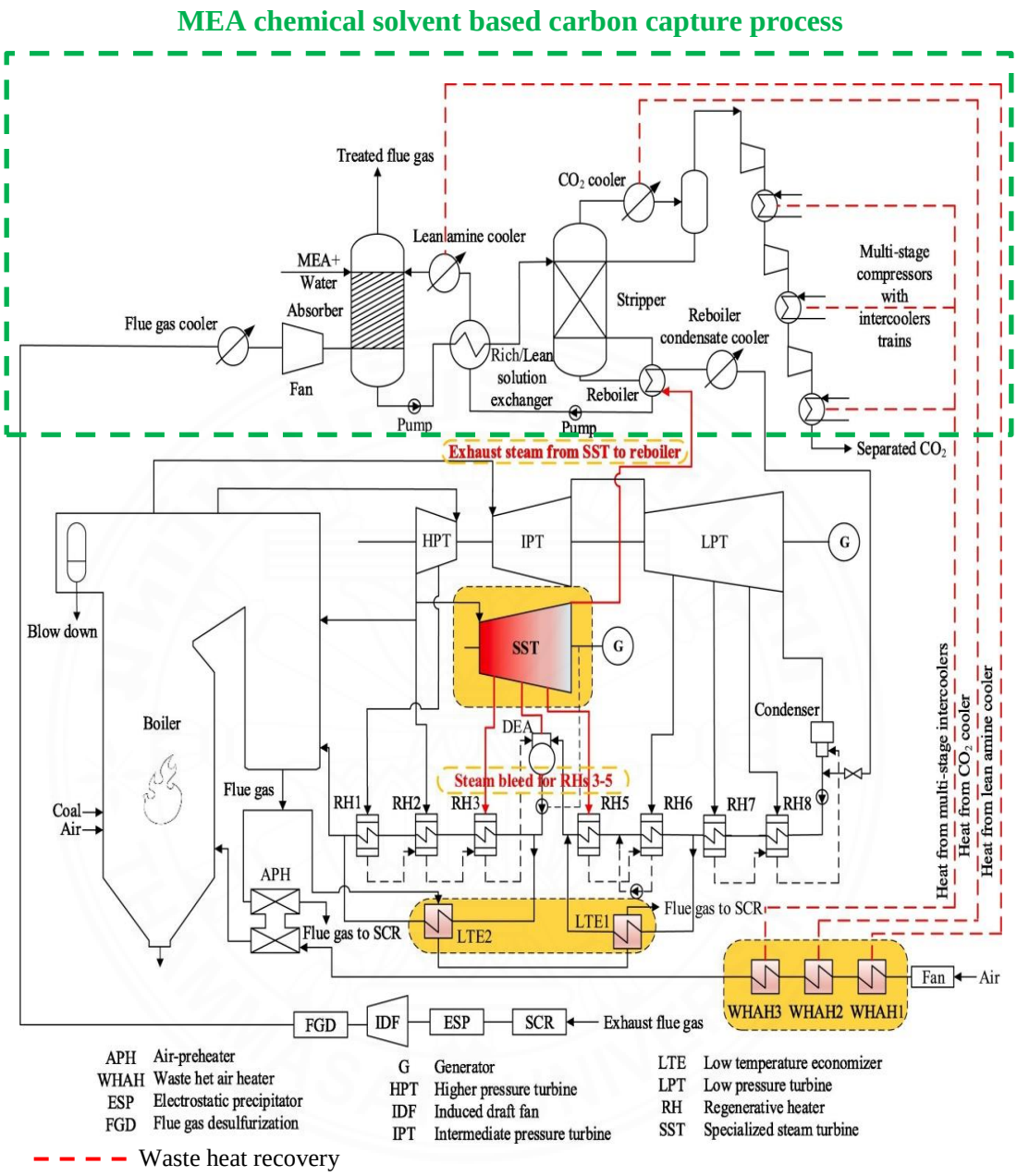

Figure 4.6 Sample figure of MEA-based carbon capture process with waste heat recovery in a coal-fired power plant. (Cheng Xu, 2020)

Table 4.3 CO_2 capture cost comparison to the existing pulverized-coal power plants.

Items	Mae Moh plant with CO_2 capture (2020)	(Minh T Ho et al., 2009)		(Cheng Xu, 2020)		IPCC Report (Min-Max) (Metz, 2005)
		Without heat recovery	With heat recovery	Without heat recovery	With heat recovery	
Plant type	PC	PC		PC		PC
Boiler Type	USC	Subcritical		USC		Subcritical
Coal Type or combustion rate	Lignite, <4600 kcal/kg	Lignite		21.13 MJ/kg (LHV)		Sub-bitu/ Bitu
Reference plant power output (MW, Gross)	655	550		1089		248-470
Power output with carbon capture (MW, Net)	447.3	287	339	782.7	875.5	140-400
Capacity factor (%)	80	85		N/A		67-91
CO_2 emission before capture (tCO_2/MWh)	0.7305	1.09		0.77		0.9-1.0
CO_2 emission after capture (tCO_2/MWh)	0.073	0.19	0.16	0.105	0.091	0.06-0.37
CO_2 capture %	90	90		N/A		90-96
Capture technology	MEA (30 wt%)	MEA (30 wt%)		MEA (30 wt%)		MEA (30 wt%)
Plant efficiency (%)	45	31		45.17		33-37
Plant efficiency with carbon capture (%)	33	18	21	32.52	36.38	19-25
Energy penalty in carbon capture (%-pts)	12	13	10	12.65	8.79	12-14
Plant TOC ($/kW)	N/A	1210		644		0-160
Plant TOC with carbon capture ($/kW)	N/A	3925	3390	1132-1163[a]	1035-1063[a]	647-1941
Incremental cost for carbon capture ($/kW)	2427	2715	2180	488-519[a]	391-419[a]	647-1602
Plant COE ($/MWh)	N/A	33		61.04		18-26
Carbon capture plant COE ($/MWh)	84	98	83	95.19-96.55[a]	86.11-87.33[a]	51-70
Incremental COE for carbon capture ($/MWh)	84	65	50	34.15-35.51[a]	25.07-26.29[a]	31-62
Cost of CO_2 avoided ($/$tCO_2$)	127	73	55	51.1-53.14[a]	36.92-38.72[a]	45-73

a = including CO_2 transport and storage cost

According to the economic evaluation results in Table 4.3, the cost of electricity production (COE) and the CO_2 avoidance price in Mae Moh Plant are higher than the competitive studies due to different cost assumption methods, CO_2 compression and transportation cost consideration, and the different currency base year. For example, the study (Cheng Xu, 2020) had considered only 162 M$ for MEA-based CO_2 capture process and 35.8 M$ for the compression stage in capital cost. In contrast, Mae Moh case assumed 387 M$ for carbon capture and 78.78 M$ for compression and drying. In addition, the carbon capture plant of Mae Moh included plant upgrades, EPCC, process contingencies, project contingencies, other owner costs and so on in the capital cost assumption (see calculation in Appendix B). Compared to the cost analyses of the study (Minh T Ho et al., 2009) and the IPCC 2005 report without CO_2 compression and transportation cost (Metz, 2005), the currency base year of the Mae Moh case was updated to 2020 by using CEPCI.

However, the lower CO_2 emission is achieved in the USC boiler compared to the SC boiler. If enhanced oil recovery projects can utilize the captured CO_2 from the plant, the increased COE could be lowered (Tramošljika et al., 2021). The total energy penalty of integrating the carbon capture process into the existing coal power plants can be found the same, at least 12% in all plants; while for new power plants with CO_2 capture, the losses are 9-12% in IPCC report (Metz, 2005). Concerning the cases of Minh Ho (Minh T Ho et al., 2009) and Cheng Xu (Cheng Xu, 2020), the plant with the waste heat integration gained from the MEA-based carbon removal process provided great benefits such as total energy demand fall, the plant efficiency increase, lower CO_2 emissions, and the cost reductions in the carbon capture, COE, and the avoided CO_2 rather than the plant without heat combination. In Table 4.7, a further 13$ cost reduction in the CO_2 avoided is offered from 50% heat compensation compared to the cost without heat compensation.

Table 4.4 Levelized cost of production (LCOP) of CCU products.

LCOP ($/ ton product)		
Production	a. Methanol	b. Formic acid
CAPEX/ TOC ($)	1,366,313,252	60,563,548
Fixed O & M ($/yr)	47,477,909	3,369,847
Variable O & M ($/yr)	1,052,185,362	251,978,059
n, year	25	25
r, interest rate	0.08	0.08
CRF, Capital Recovery Factor	0.094	0.094
Production (t/yr)	1,000,000	250,000
LCOP ($/ton product)	**1,227**	**1044**

Table 4.5 Methanol production cost comparison

Methanol production technology	Production capacity (t/d)	CO_2 emissions (tCO_2/tFA)	LCOP ($/t)	Currency year
Direct CO_2 Hydrogenation (this study)	3,000	0.136[a], 0.09[b]	1,227	(2020$)
Stream methane reforming (Blumberg, Tsatsaronis, & Morosuk, 2019)	2,590	N/A (0.695[a], 0.073[b])	295	(2016$)
Stream methane reforming (Al-Rowaili et al., 2022)	90	0.08	368	(2021$)
Global Market Price (Alibaba.com)	1 ton = 750 $			(2021$)

a = indirect emissions (Pérez-Fortes et al., 2016),
b = process (direct) emission (Pérez-Fortes et al., 2016)

Table 4.6 Formic Acid production cost comparison

Formic Acid (FA) production technology	Production capacity (t/d)	CO_2 emissions (tCO_2/tFA)	LCOP ($/t)	Currency year
Direct CO_2 Hydrogenation (this study)	750	1.03[a], 0.03[b]	1044	(2020$)
Methyl formate hydrolysis with CO produced from heavy fuel oil (Mar Perez-Fortes, 2016)	N/A	2.18	546	(2014$)
Global Market Price (Alibaba.com)	1 ton = 500-800 $			(2021$)

a = indirect emissions (Dongin Kim, 2020) , b = process (direct) emissions

Table 4.7. Production prices with the waste heat recovery of carbon capture

Price ($/ton)			System Optimization
CO_2 avoided	CO_2_MeOH	CO_2_FA	
127	**1227**	**1044**	0% heat compensation
114	1208	1031	50% heat compensation
101	1190	1019	100% heat compensation

Regarding the cost analyses of CCU plants, the LCOP of the industrial-scale methanol produced from the captured CO_2 valorization for this case is a three- to four-fold increase compared to the conventional production prices from the literature (Al-Rowaili et al., 2022; Blumberg et al., 2019), as indicated in Table 4.5. As for formic acid (FA) production, shown in Table 4.6, the LCOP of the CO_2-containing FA is approximately double the conventional FA derived from carbon monoxide synthesis. Furthermore, it can be observed that the gap between CO_2-based product prices and the global market prices is roughly 1.5 times.

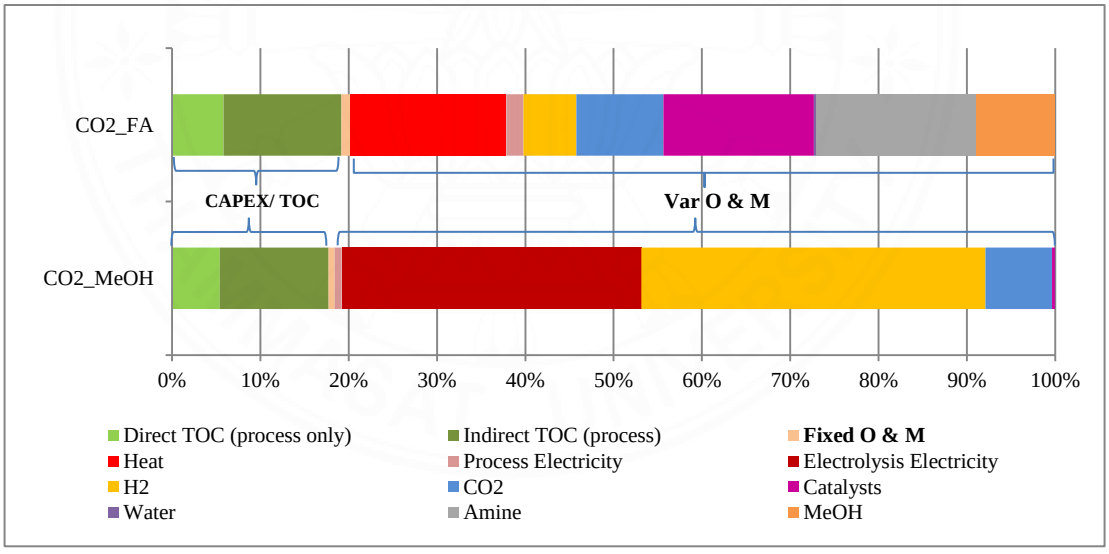

Figure 4.7 Carbon-based Methanol and Formic Acid total production cost breakdown.

In the total production cost analyses depicted in Table 4.4 and figure 4.7 (see detailed calculation in Appendix C), the capital expenditure (CAPEX or TOC) associated with the direct and indirect cost contributes to around 20% of both CO_2_FA and CO_2_MeOH productions; fixed operating and maintenance cost (Fixed

O & M) attribute to by far the lowest proportion; variable operating and maintenance expense (Var O & M) accounts for the maximum (80%) contribution. In the detailed cost breakdown, the feedstock hydrogen via water electrolysis and the electrolysis electricity dominate as the majority of total methanol production cost; on the contrary, the maximum expenditure comes from the catalysts (i.e., amine and catalysts), followed by the heat in the formic acid production. The expense of input CO_2 taken from the CO_2 avoided price and water do not have a distinct effect on the total production cost.

Again, sensitivity analysis is performed on the electricity price to evaluate the maximum variable operating and maintenance (Var O & M) cost reduction in figure 4.8. The required process heat and electricity were assumed to be produced from the same power functional unit (MWh), which costs 80$ per unit. The electricity cost from wind power was considered at the same price. The electricity price variation has a significant effect on the LCOP of CO_2_MeOH although the waste heat recovery excludes the process heat demand because the water electrolysis process consumes the larger electricity amount, which is needed to be considered when the CCU plant is implemented. However, the electricity price does not notably influence the LCOP of CO_2_FA because of 20% contribution (heat + electricity) to the total production cost, whereas about 35% involvement (process electricity + electrolysis electricity) in CO_2_MeOH production.

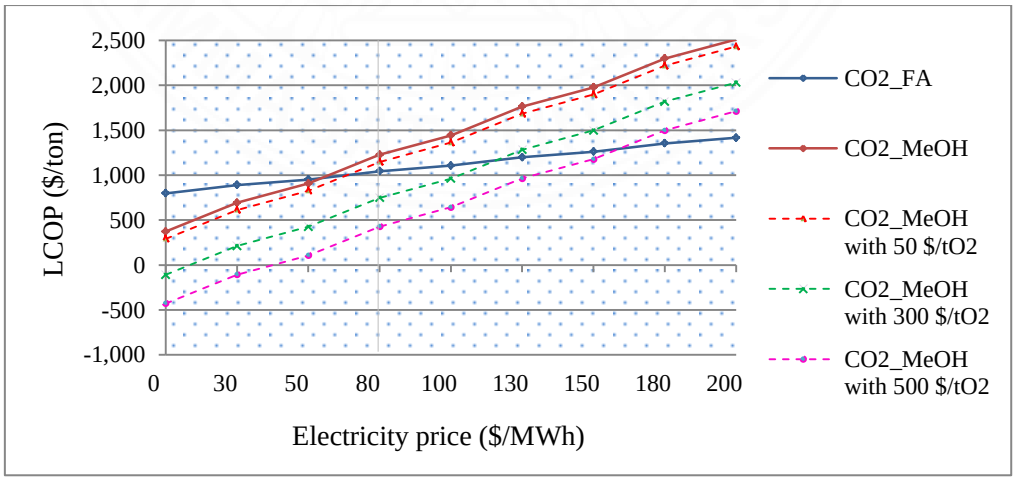

Figure 4.8 Sensitivity analysis of electricity price variation on the LCOP of carbon-based products.

The higher unit price of CO_2_MeOH can be minimized by selling by-product Oxygen (O_2) produced by 1.6 t/t CO_2_MeOH through water electrolysis technology. Depending on the oxygen and electricity selling price range, the LCOP of CO_2_MeOH could be lowered from the maximum 1711~2431 $/t CO_2_MeOH to the minimum 291~(-429) $/t CO_2_MeOH, shown in figure 4.8. Regarding the CO_2_FA production price, the maximum expenditures from catalysts, amine, and heat can be reduced if they are available at lower prices from the local or global supply market. For example, although the ruthenium catalyst type is costly (210,000€/kg) in the reference journal (Mar Pérez-Fortes, 2016), the price is reasonable (1065$/kg) in the global supply market (Alibaba.com) (see Appendix A, page 72). If the cheaper catalyst can be used for CO_2_FA production, the total production cost per unit would be reduced from 1044 $/t CO_2_FA to 866 $/t CO_2_FA, which can compete with the global market price.

Overall, the results demonstrate that the industrial-scale captured CO_2-based methanol and formic acid processes are promising technology to implement in Thailand from an environmental point of view despite being unprofitable from an economic perspective with the competitive conventional productions. Both productions would be the most likely to launch for the financial benefit if the government offered an incentive or a favor, such as low or free electricity cost. In addition, selling by-product oxygen would be profitable for CO_2_MeOH production depending on the current market price of oxygen. The lower catalysts and amine prices would offer a reasonable CO_2_FA production cost when compared with the global market price and the conventional production cost.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, to decrease the CO_2 emissions from power plants or industries, carbon capture and utilization (CCU) technology has become a promising and attractive solution. Besides, CCU provides an incentive to the entrepreneurs who strive to reduce carbon emissions by transforming the waste pollutants into numerous commercial value-added products, which can fulfill the future fuel shortage or demand for commodities.

The risen environmental impact scores and the higher CO_2 price caused by the heat and electricity extractions of the Mae Moh power plant for carbon capture can be lowered by combining the waste heat recovered from the carbon removal process. Furthermore, waste heat integration can minimize the thermal efficiency loss and the electricity production price in the power plant retrofitting the carbon capture system.

Among various CO_2-based chemical products, CO_2_MeOH production is one of the best processes which can reduce the vast GHG emissions due to the negative carbon feedstock from the carbon capture plant and offer lower energy demand owing to the excess heat recovery through the synthesis process. The CO_2_FA production proved that the most impact categories could be reduced compared to the conventional one, whereas others can have the additional environmental impact increases except for GHG savings. Waste heat combination is a better solution to reduce the environmental impacts and the production costs.

Concerning the cost analysis, the CO_2 (avoided) price does not significantly change the total production costs of CO_2_MeOH and CO_2_FA, but they are more costly than the conventional ones because of the hydrogen production and the electrolysis electricity in CO_2_MeOH, while catalysts, amine, and heat in CO_2_FA. Although both CO_2-containing processes are expensive, subsidies or supply from the government would be beneficial to boost the CCU projects in the green transition with zero (lower) carbon emissions by 2030 or 2050 in Thailand.

5.2 Recommendations or Solutions

To achieve a low carbon society in Thailand and to produce both CO_2-based products with minimum impacts and low production cost, the followings are recommended:

(1) The vast electricity generation from wind power (green energy) for H_2 production via water electrolysis technology is the most suitable option in the CO_2_MeOH process due to its lower carbon emissions, rather than other fossil fuels (grey energy) vented larger carbon emissions.

(2) Consequently, the assessed phases of wind power electricity production raise the MRS impact, which should be alleviated by recycling the materials after the plant lifetime.

(3) The highest impact scores and the larger CO_2 avoided cost associated with the energy demand of the CO_2 capture should be minimized by the waste heat recovery from the carbon removal process.

(4) To reduce the maximum global warming impact of process steam, the process heat or steam extraction from the waste heat recovery of methanol synthesis would be recommended for the CO_2_MeOH process, while for CO_2_FA, the steam production from wood chip burning would be better.

(5) By-product, oxygen through water electrolysis should be co-produced and sold to be cost-effective for CO_2_MeOH production.

5.3 Policy suggestion

Carbon pricing shows a signal to the emitters in their financial investments for carbon releases into the atmosphere, but helps shift the severe environmental burdens from human activities. Placing an adequate carbon price with a firm policy on the coal-fired power plants urges businesses to eliminate or avoid greenhouse gas emissions. It is a tool for the government to transform into a decarbonized economy, low-carbon society, and green energy transition. At the same time, investors emphasize this external cost reduction together with an awareness to global warming, plant efficiency improvement, climate-resilient activities, and market innovation.

Introducing carbon capture technology in a coal-fired power plant is an incentive to avoid the carbon tax in the investment portfolios and the potential climate risks to the environment. In accordance with the policy, carbon revenue reduction on the CO_2 emissions of the coal-fired power plants will be profitable for the investors. For example, if the carbon pricing, 25\$/tCO_2 emission is charged in the power generation of the Mae Moh coal plant, the revenue for CO_2 emissions can be minimized from 83,829,250 \$/yr (without carbon capture) to 8,382,925 \$/yr (with carbon capture). It is the consideration only on the power generation process and does not include the emissions of coal extraction, coal mining, rising coal consumption in the carbon capture plant, etc. Policy set up on the carbon capture technology should offer a financial incentive with the lower the carbon tax, which leads to a clean environment or an environmentally-friendly solution in the future.

CHAPTER 6
RESEARCH TIMEFRAME

This research work has been planned for two academic years with the following twelve steps in Table 5.1 from August 2020, until July 2022.

Table 5.1 Research timeframe

Research Plan	First Academic Year (2020-2021)												Second Academic Year (2021-2022)											
	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
1. Literature review																								
2. Set up the goal and scope, system boundary, and methodology																								
3. Data collection																								
4. Economic evaluation or cost analysis																								
5. Prepare proposal																								
6. Proposal presentation and submission																								
7. Impact assessment & Interpretation																								
8. Draft report																								
9. Progress presentation																								
10. International conference attending and presentation																								
11. Final presentation																								
12. Final thesis report submission																								

CHAPTER 7
COMMENTS AND REVIEWS ON THESIS

1. Comments and Reviews on Thesis Proposal

Question from Professor Hidetoshi Sekiguchi.

In which productions will these CO_2-based products be utilized because those are just basic chemicals and are used in various productions? Should prepare further utilization processes in the next step.

Answer

For the further steps of CO_2-based methanol and formic acid utilizations (the grave stage in LCA), there is no additional LCA case study. Although there are technical papers on formic acid and methanol utilizations, no one studied from LCA points of view and economic analysis. So, I defined and limited the LCA system boundary in the figure. (An additional explanation can be read on page 62, answer-2, third comment)

Question from Associate Professor Paiboon Sreearunothai.

Why do not you compare the MEA-based carbon capture process with another CO_2 capture process? What are the criteria in your research?

Answer

Because there is no available on-site data to compare the two CO_2-capture processes, besides the CO_2-capture processes with different solvents or technology have not been well developed in Thailand to collect and compare data. Although I can discuss with the authors who published a new CO_2 capture process in a journal or a paper, their explanations and descriptions had limitations because they used their private/ industrial data in detail and cannot share with me all of their technology and intellectual property.

The main criteria in my case study are LCI data based on a functional unit because LCA assessment and economic analysis are mainly estimated or evaluated by using those LCI data. Without LCI data, I cannot do anything in my Thesis.

2. Comments and Reviews on Research Progress

Question from Professor Hidetoshi Sekiguchi.

When you consider the heat recovery, do you check temperatures of heat sources and sinks between which heat is exchanged? Also, in Fig.4.6, five heat exchangers are installed. Does this case indicate best performance? Are there any possibilities to set heat exchangers?

Answer

My research is only environmental and economic assessment, did not include a technical viewpoint. So, the heat recovery with detailed technical parameters was not required to consider. If included all viewpoints (Techno-Economic and Environmental views), the results would be come out the best. In addition, we will need to be familiar with the various software, as each analysis process has to be used with different software.

The waste heat recovery with five heat exchangers (according to the sample figure 4.6) can not be referred as the best performance when checking with the final results in my case study, but it is a better solution or system optimization to reduce the intensive energy demand of MEA-based carbon capture process and its consequent environmental impacts.

Question from Professor Hidetoshi Sekiguchi.

You assume that methanol synthesis use electrolysis for hydrogen production, however, steam reforming is used for formaldehyde synthesis. Why do you assume different synthesis methods? Also, if electrolysis is used for FA, is the index of GW shown as negative similarly to methanol synthesis?

Answer

I assumed different synthesis methods looking at total production cost, carbon emissions, and H_2 input amount. It would be better producing CO_2_MeOH with H_2 via electrolysis to reach my goal of lower carbon emission despite higher investment. If we consider the CO_2_MeOH process with H_2 via steam reforming, most environmental impacts will increase compared to the conventional production because stream reforming technology is based on fossil fuel resources such as Natural gas. If we produce CO_2_FA with H_2 from steam reforming, it is still lower in environmental

impacts and production cost. The key is the H_2 requirement amount that is lesser in CO_2_FA (0.06t/1t FA) than in CO_2_MeOH (0.2t/1t MeOH), thus CO_2_FA with reforming did not show significant environmental impacts.

If water electrolysis is used for FA, according to the software analysis results below, the negative GW index was not shown because as I explained above, the H_2 input amount is small.

Impact category	**Unit**	**CO_2_FA with steam reforming**	**CO_2_FA with electrolysis**	**Conventional FA**
Global warming	kg CO_2 eq	1957	1450	4110
Terrestrial acidification	kg SO_2 eq	16.5	15.5	20.4
Freshwater eutrophication	kg P eq	1.075	1.08	1.92
Human non-carcinogenic toxicity	kg 1,4-DCB	4580	4570	3640
Human carcinogenic toxicity	kg 1,4-DCB	106	106	146
Fine particulate matter formation	kg $PM_{2.5}$ eq	5.38	5.1	8.9
Fossil resource scarcity	kg oil eq	958	864	1270
Mineral resource scarcity	kg Cu eq	22.18	38.4	3.63

Question from Professor Hidetoshi Sekiguchi.

What is $C_{18}H_{39}N$? Is it catalyst for FA formation?

Answer

$C_{18}H_{39}N$ = $NHeX_3$ = Tertiary amine (or) Trihexyl amine = catalyst for FA formation

For CO_2-FA formation of this case, Tertiary amine catalyst, Ruthenium and phosphino catalysts are used.

Question from Professor Hidetoshi Sekiguchi.

As compared with the results of methanol, the assessment of FA shows better. What is the most important factor for this result?

Answer

Because it is due to CO_2 and H_2 input amount. When we take a look at the results of Tables 4.1 and 4.2, all environmental impacts of MeOH (despite negative global warming value) came from the input CO_2 due to the energy extraction from Mae Moh coal plant for the CO_2 capture process. The higher the input CO_2 amount in CCU processes, the greater the environmental impacts because of fossil fuel use to capture carbon in my study. That is also one of the reasons why I chose the MeOH

project with H_2 from electrolysis, not from steam reforming (fossil fuel use). CO_2 and H_2 input amount of FA is lower than that of MeOH, so the assessment of FA showed better.

Again, I did not try to go synthesis natural gas (SNG) production via methanation technology because it consume the higher CO_2 amount and finally all impacts will raise. That would be beyond the goal of this study.

Question from Professor Hidetoshi Sekiguchi.

Are there any ideas for improvement of the assessment of methanol except for heat recovery? Also for FA such as HnCT and MRS?

Answer

In order to improve the assessment of all CO_2-based productions, it would be better to utilize not only process heat recovery but also all energy requirements from biomass or renewable power for both CO_2 capture and the synthesis process.

Human non-carcinogenic toxicity (HnCT) and mineral resource scarcity (MRS) impacts of CO_2-FA are due to the metal catalysts (used instead of Ruthenium-Phosphina, Ru-Ph), that cannot be avoided as long as it is used. However, we can change the same method with a different catalyst, Au/TiO_2 (Please see the comparison of Ru-Ph and Au/TiO_2 on page 16, financial evaluation on CCU Projects, Literature Review, Chapter-2). If changed to Au/TiO_2 catalyst, a further detailed assessment will be required. When evaluating it in general, Au/TiO_2 would be better than Ru-Ph because of lower energy demand and the smaller amount of catalyst.

Question from Associate Professor Pakorn Opaprakasit.

In the Simapro software, there are total 18 impact categories. Why you choose only 8 impacts? What are the criterias?

Answer

I chose only 8 impacts because those are the significant impact indicators in the power generation system and the important factors for the society according to Thailand standards. Other impacts such as water consumption and land use are less important than the current investigated impacts.

Question from Dr.Seksan Papong.

In chapter 3, you mention about 655 MW pulverized coal Mae Moh power plant, there needs to be an explanation of existing of the power plant and an explanation of the CCS for Mae Moh power plant. How much CO_2 was generated from 655 MW for one year? How much capacity of the carbon capture plant for 655 MW?

Answer

- an explanation of existing of the power plant and an explanation of the CCU for Mae Moh power plant = (Please read Chapter 1, Background of the study, pages 2-3)
- CO_2 generation from 655 MW for one year = Please see Table 3.1, just simply calculate it as follow;

  CO_2 generation in a year = Power output (Gross) x operation time x capacity factor x CO_2 emission before carbon capture

  = 655 MW x 8760 hrs/yr x 80% x 0.7305 tCO_2/MWh

  = 3,353,170 tCO_2/yr
- Capacity of the carbon capture plant for 655 MW = Please see Table 4.3.

Question from Dr.Seksan Papong.

Chapter 4, your research assumes that the electricity of H_2 & CO_2-MeOH productions come from the wind power plant, how much is the capacity of a wind power plant? Are you considering the production cost of a wind power plant? Are you account for the transportation stage for raw material from the production source to the carbon capture and utilization plant?

Answer

The capacity of the wind power plant in my study is 300 MW according to the taken data information from the Simapro software.

I did not consider the production cost of a wind power plant, but the taken data itself was the LCA assessment of the electricity production from a wind power plant. There is no market choice for electricity produced from wind power in the software.

The raw material productions in my study are MEA, CO_2 & H_2 that were taken into account with the transportation stage.

MEA transportation = Plese see at LCI data for MEA (1 kg) production.

CO_2 transportation = 5 km pipeline transportation, please see at LCI data for onshore CO_2 pipeline infrastructure.

H_2 transportation = Assumed to locate the H_2 plant in the same onsite of CCU plant. (No need transportation)

Question from Dr.Seksan Papong.

Where is the location of the Methanol and Formic acid plants in your study?

Answer

Please read in page-27. From the carbon capture plant to the CCU plant was assumed to be 5 km long distance with CO_2 pipeline transportation.

Question from Dr.Seksan Papong.

CO_2 capture cost of Mae Moh plant with CO_2 capture (2020 $) in Table 4.3. Does the result come from your analysis or literature review?

Answer

I did not attach the reference for it in Table 4.3. I calculated it by using the equations, formula and the assumptions from pages 20-23. You can check that calculation in Appendix B.

Question from Dr.Seksan Papong.

I would to know about the cost of a company emitting 100% CO_2 and paying the carbon tax, and a company investing in the CCS to reduce carbon tax.

Answer

For 100% CO_2 emissions, total CO_2 emissions at 655 MW plant = 3,353,170 ton/yr
If you charge carbon tax, 25$/t$CO_2$ emission = 3,353,170 ton* 25$ = 83,829,250 $/yr

If you use carbon capture technology, total CO_2 emissions at 655 MW plant with carbon capture = 335,317 ton/yr.
If you charge carbon tax, 25$/t$CO_2$ emission = 335,317 ton * 25$ = 8,382,925 $/yr

It is only the consideration on the power generation process. Not included the CO_2 emissions on coal mining, increased coal consumption in carbon capture plant, CCU plants, and so on. It depends on your policy how you will charge the carbon tax on a power plant and if introduced carbon capture technology, the carbon tax will be much more reduced or not.

3. Comments and Reviews received from the reviewers at ‘‘PACCON 2022 Conference’’ for full paper conference proceeding.

First Comment - I don't clear some sentence "Despite a net negative carbon emission, CO_2_MeOH production can arise 6 out of 8 investigated environmental impact indicators while 2 out of 8 impacts increase in CO_2_FA production".

Answer

Yes, in that sentence, "net negative carbon emission" is the key of this study. Net negative carbon emission means that we need to add -1 ton CO_2 (air emission) in the Simapro software for every one ton of carbon capture because 1 ton CO_2 emissions into the air is avoided. Minus sign is of importance. However, we got global warming (GW) impact score -741 kg CO_2 eq in the analysis result because of CO_2 emissions from the energy productions and other chemicals in the carbon capture.

After that, we use that negative carbon capture value as the input CO_2 requirements in the CO_2-based productions, so negative value is still achieved in the global warming impact of CO_2_MeOH. Although GW impact is negative thanks to negative carbon emissions, other impacts are higher in the CO_2-based productions than the conventional (i.e., 6 out of 8 investigated impacts increases in CO_2_MeOH, 2 out of 8 impacts increases in CO_2_FA).

Second Comment - "Explain the figure 2, 3, 4 (i.e. Figure 4.1, 4.2, 4.3) in the manuscript, difficult to understand. Should show the score on Environmental impact aspects".

Answer

Yes. I added the figures as the results of LCA software and I hoped every LCA users can understand them, so I removed this description "the Maximum impact score is set to 100%" in the figure due to the limited page numbers for publication. I forgot to target all audience to present clearly. Thank you very much for the comment.

In the figure 2 (Figure 4.1), total score in each impact is set to 100% of which energy production, chemical etc. contribute to how much percentage were revealed.

In the figure 3 (Figure 4.2) and 4 (Figure 4.3), the maximum impact score between the two compared productions (with and without CO_2) is set to 100%. Then, in CO_2-based products, we described which input contributed to how much percentage of total impact score in the manuscript.

Third Comment - "The manuscript was well written with sufficient information. However, there are some points that should be reconsidered as follows;

1. In the second last line of the first paragraph in the Introduction, the statement ...that can "go up"....go up should be replaced with other term.

2. In the second paragraph of the results and discussion, if such limitations were already known to the authors, why they were not included in the assessment? Please clarify.

3. In the conclusion, the discussion should be further clarified in the case of possibility in using wind energy and/or waste heat recovery in Thailand, does the current technology/ infrastructure offer the country to achieve those recommendations?."

Answer

1. I noticed to change this "go up" term, but I did not revise it immediately and forgot it later. Thank you for your alert.

2. Due to Covid-19 situation, I could not go and collect on-site data. For data, I cannot use literature (secondary) data because emission data is different depending on the type of coal, type of power plant and additional pollutant removal installations such as ESP, SCR, FGD in the power plant. Again, there was no complete study which described detailed pollutant emission data of alternative products. Thus, I tried to collect and present the data as much as I can in my study. To go the next step, the final end-user or CO_2-based methanol and formic acid utilization processes (the grave stage in LCA), there is no further case study to collect LCI data, besides as far as I know, these CCU projects have not been implemented in Thailand to use on-site data. I can try CO_2-based Synthesis Natural Gas (SNG) production via methanation technology but at the end, most environmental impacts will become higher, that is not suitable to choose and present. So, those are why there were limitations in my study. According to my literature reviews, above limitations except for final end user stage

may not have too much score difference because coal extraction and transportation will show + sign score, whereas recycling and waste management will show - sign score.

3. I further clarified the possibility of using wind energy and/or waste heat recovery in conclusion and recommendations section as your advice. For the question "Does the current technology/ infrastructure offer the country to achieve those recommendations?" in my view, it is possible to achieve the lower carbon growth with such technology from an environmental point of view, but from an economic benefit perspective, the government's subsidies will be required to implement the CCU projects because CO_2-based products are more expensive than the conventional products.

4. Thesis Preparation

This research work was prepared during two academic years.

In the first year, LCA literature reviews of CCS and CCU were done under the supervision of the co-advisor at NSTDA. General knowledge, lectures related to sustainable development, research preparations, and presentations were well trained by Tokyo Tech professors. LCA data running and results interpretation were taught effectively by a teacher from Kasetsart University. From that LCA training, I became familiar with the LCA software and got to know with my observation that I can request Free license software from the Simapro software team. Thus, I got one-year free license with the latest version from the Simapro software team; furthermore, they provided the necessary training for data simulations. Therefore, I can analyze the LCI data well.

In the second year, I frequently attended the CCU seminars, webinars, and discussions organized online by the western countries such as UK, USA, Canada. Consequently, I gained priceless knowledge and idea to prepare and write my CCU Thesis. Journals, papers, articles, and reports taught me how to write my Theis in detail, for example, which parameter should be analyzed in the sensitivity analysis. If I did not understand an article, I directly discussed it with the authors via email, but their explanations had limitations due to their private onsite data. Mostly, I found the solutions from the appendix or supplementary files attached to their articles. Moreover, Thailand electricity background data was taken from the websites of

EGAT and the Ministry of Energy. LCI data were collected from journals, reports, and Simapro software. The collected data were combined with the findings of literature reviews to meet the research goal of the lower global warming impact of the CCU projects. Then, I practiced and analyzed the detailed data on my own in the software to produce better results for my Thesis and checked my final results with the other CCU papers. The university advisor evaluated my manuscript and commented on it in accordance with the Master's degree graduation requirement standard. Due to my relentless efforts and the advisor's supervisions and arrangements, all graduation requirements were met on time during two academic years.

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APPENDICES

APPENDIX A

PRICES OF UTILITIES AND CONSUMABLES

Utility	**Unit**	**Price**	**Reference**
Electricity	$/kWh	0.08	(Thailand Board of Investment, 2021)
Water	$/$m^3$	0.39	
Cooling Water	$/t	0.0148	(Khamhaeng et al., 2021)
Labor/ job position	**Unit**	**Price**	**Reference**
Operator Salary	$/month	900	(Thailand Board of Investment, 2021)
Engineer/ Supervisor / Lab Technician	$/month	1,500	
Leader/ Chief Officer	$/month	3,000	
Other Basic Position (eg. Security, Cleaner)	$/month	450	
Consumable Cost	**Unit**	**Price**	**Reference**
Activated Carbon	$/t	1,600	(Alibaba.com)
Caustic soda, NaOH	$/t	300	
Triethylene Glycol(TEG)	$/t	500	
Methanol	$/t	750	
MEA	$/t	2,000	(Mohammed B Alqaragully, 2015)
Catalyst ($CuO/ZnO/Al_2O_3$)	$/kg	109	(Mar Pérez-Fortes, 2016)
Ruthenium-based catalyst	$/kg	241,500	
Phosphino-based catalyst	$/kg	97,635	
Trihexylamine, $NHeX_3$	$/kg	833	

Activated Carbon Order Link - https://www.alibaba.com/product-detail/Activated-Carbon-Industry-Waste-Gas Treatment_1600312435736.html?spm=a2700.galleryofferlist.normal_offer.d_title.59699712nPkyKc&s=p

Caustic soda, NaOH Order Link - https://www.alibaba.com/product-detail/99-Caustic-Soda-NaOH-Sodium-Hydroxide_62000082292.html?spm=a2700.galleryofferlist.normal_offer.d_title.46f940aaeHjbll

TEG Order Link - https://www.alibaba.com/product-detail/High-Quality-Triethylene-Glycol-TEG-for_62565163914.html?spm=a2700.galleryofferlist.normal_offer.d_title.3af460dfmcB7Ws

Made-in-China.com would like to let you know that you have just received a business message reply below.

Message Details	
Message Subject	Re:Inquiry about High Quality Industrial Methanol 99.9% Methyl Alcohol CAS 67-56-1
Message Content	**Dear Ms. Shwe Yi :** **Hello,I am Tracy, Thank you inquiry on made in china .This is our best offer.** **Methyl Alcohol :** **CAS#:67-56-1** **Purity:99.9Min.** **Price:USD 750/mt FOB Qingdao.** **Packing:160kg/drum 730Mt/Fcl.(without pallets)** **Best regards** **Tracy** **Shandong Near Chemical Co., Ltd** **Near International Trade Co.,Limited** **Mobile: +86-17862112303** **QQ:3209925076** **Wechat: +17862112303** **Whatsapp:+86 17862112303** **Skype:+8617862112303** **Linkedin:tracy cui** **Websit: https://www.nearchemical.net/** **ADD:Fuqian Street No.55,Dongying City,Shandong Province.,P.R.C.**

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Company	Shandong Near Chemical Co., Ltd.
Email	tracy@nearchemical.net (NOTE: Please REPLY to tracy@nearchemical.net but DO NOT REPLY to en_notification@made-in-china.com)
Telephone	86-546-7277736
Fax	
Country/Region	China
Homepage	https://www.nearchemical.net
Sender's IP Address	119.187.171.*
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This is Susan from Wuhan Golden Kylin Industry & Trade Co., Ltd, China. I got your enquiry of Ruthenium catalyst from Alibaba RFQ.

May I know what's your required metal content? We can supply Ruthenium catalyst with metal content 0.5%-10%.

And is 800kg the order quantity in one shipment?

Today we quote Ruthenium catalyst with metal content 5% first for your reference:

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CAS: 7440-18-8
Quantity: 800KG shipped in LCL
Packing: 8kg/drum with pallet
Payment term: T/T in advance
Price: USD1065/KG FOB Shanghai port, China

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APPENDIX B

CO_2 CAPTURE PLANT COST ESTIMATION

Table B.1 Capital cost estimation of carbon capture plant

Cost Assumptions	**k$_ 2020**
A. Bare Erected Cost	636,051
B. Engineering, construction management, home office and fees (12 % BEC)	76,326
C. Process contingencies (10 % BEC)	63,605
D. Project contingencies (20 % BEC)	127,210
Total Plant Cost (TPC = A. + B. + C. + D.)	**903,192**
E. Start-up cost = 2% TPC	18,063
F. Inventory = 0.5% TPC	4,515
G. Financing cost = 2.7% TPC	24,386
H. Other owner's cost = 15% TPC	135,478
Total Overnight Cost (TOC = TPC + E. + F. + G. + H.)	**1,085,637**

Table B.2 Fixed Operating and Maintenance Cost (Fix O&M) of carbon capture plant

Job Position	**Assumption**	**Total Salary**
Operator	5 Ope* 3 shit = 15	13,500
Skilled labor or Supervisor	3	4,500
Leader	2	6,000
Lab Technician	3	4,500
Other Positions (eg. Security, Cleaner)	12	5,400
Total Cost of labor	($) for a month	33,900
Total Cost of labor	**($) for a year**	**406,800**
Total Fixed Operating and Maintenance Cost ($/yr) **= 37,020,116**		

Table B.3 Variable Operating and Maintenance Cost (Var O&M) of carbon capture plant

Consumables	**per Day**	**Cost ($)**	**$/yr**
Water (m^3)	7,349	0.39	1,046,189
Makeup and Wastewater Treatment Chemicals (lbs):	0	0	0
Limestone (ton)	0	0	0
MEA Solvent (ton)	18.74	2,000	13,680,935
NaOH (tons)	1.19	300	130,774
Triethylene Glycol (ton) for CO_2 Dryer	1.84	500	335,317
Activated Carbon (ton)	0.689	1600	402,380
Ammonia (19% NH_3) (ton)	0	0	0
Subtotal consumable Cost ($)			**15,595,595**
Waste Disposal			
Fly Ash (ton)*	1,057	0	0
Bottom Ash (ton)*	455	0	0
Subtotal Waste Disposal			**0**
By-products & Emissions			
Gypsum (tons)	1,691	0	0
Maintenance Material Cost ($), (2.5% TPC)			**22,579,811**
Coal (ton)	8,504	136	0
Electricity (1,140,202 MWh/yr)		80	**91,216,160**
Total Var O & M cost ($/yr)			**129,391,567**
Var O&M = 41.28 $/MWh			

* Waste disposal and by-product cost are not added in the Var O&M as Mae Moh plant sells them and reuses as feedstock in construction material production according to EGAT's annual report, 2018.

Table B.4 Cost of Electricity (COE) and CO_2 avoided cost of carbon capture plant

Coal Power Plant	Carbon capture cost
Plant Size with capture (MW, Net)	447.3
TOC ($)	1,085,637,332
Fixed O & M ($/yr)	37,020,116
Variable O & M ($/yr)	129,391,567
n, year	30
r, interest rate	0.08
CF, Capacity factor	0.8
Annual Generation(MWh)	3,134,678
Capital Recovery Factor(CRF)	0.0888
Fuel Cost	0
Net Heat Rate	0
COE	**83.85**
CO_2 avoided cost($/MWh)	**127**

APPENDIX C

CCU PLANT COST ESTIMATIONS

Table C.1 Methanol production cost (1 Mt/yr)

	Equipment	M€ (2014 July) 450 kt/yr (Pérez-Fortes et al., 2016)	M$ (2020) 1 Mt/yr
1	Heat Exchanger without use for CO_2 compressor	30.0	57.65
2	Furnace	7.20	13.84
3	Turbines	3.30	6.34
4	Distillation Column	1.60	3.07
5	Pressure Vessels	1.30	2.50
6	Reactor	1.00	1.92
7	Pumps	0.20	0.38
8	Compression for H_2 and recycled gas streams	25.0	48.04
9	CO_2 purification	0	0
10	Hydrogen production from water electrolysis	147.7	283.82
Total Equipment Cost (TEC)			**417.57**
Total of the bare module costs (CBM)			**614.07**
BEC			**903.039**
TPC			**1136.70**
TOC			**1366.31**

Table C.2 Fixed Operating and Maintenance Cost of Methanol production

Job Position	Total Salary	Assumption
Operator	48,600	18 Ope* 3 shit = 54
Skilled labor or Supervisor	9,000	6
Leader	3,000	1
Lab Technician	9,000	6
Other Position (eg. Security, Cleaner)	6,750	15
Total Cost ($/month)	76,350	
Total Cost ($/year)	916,200	
Total fixed O & M ($/yr)	**47,477,909**	

Table C.3 Variable Operating and Maintenance Cost of Methanol production

Consumables	**per 1 ton MeOH**	**Cost ($/unit)**	**$/yr (1 Mt)**
H_2 (t) via water electrolysis	0.2	-	-
CO_2 (t)	1.46	127	185,420,000
Electricity (MWh) for process	0.250	80	20,000,000
Electricity (MWh) for electrolysis	10.452	80	836,160,000
Heat (MWh)	0.4	-	-
Cooling (MWh)	0.862	-	-
Cooling Water (t)	90	0.0148	1,332,000
Water (t) for electrolysis	3.608	0.39	1,407,120
Catalyst (CuO/ZnO/Al2O3) (t/yr)	44.5	109,480	7,866,242
Total Var O & M ($/yr)			**1,052,185,362**

Table C.4 Formic Acid production cost (250 kt/yr)

	Equipment	M€ (2014 July) (Mar Perez-Fortes, 2016)	M$ (2020)
1	Heat Exchanger without use for CO_2 compressor	0.200	1.472
2	Separation Processes	0.731	5.380
3	Reactor	0.446	3.282
4	Pumps	0.138	1.016
5	Compression for H_2 and recycled gas streams	1.000	7.359
6	CO_2 purification	0.212	0
Total Equipment Cost (TEC)			**18.509**
Total of the bare module costs (CBM)			**27.22**
BEC			**40.028**
TPC			**50.386**
TOC			**60.564**

Table C.5 Fixed Operating and Maintenance Cost of Formic Acid (FA) production

Job Position	Total Salary	Assumption
Operator	32,400	12 Ope* 3 shit = 36
Skill labor or Supervisor	6,000	4
Leader	3,000	1
Lab Technician	6,000	4
Other Positions (eg. Security, Cleaner)	4,050	9
Total Cost ($/month)	51,450	
Total Cost ($/year)	617,400	
Total fixed O & M ($/yr)	**3,369,847**	

Table C.6 Variable Operating and Maintenance Cost of Formic Acid (FA) production

Raw Materials	per 1 ton FA	Cost ($/unit)	$/yr (250 kt)
H_2 (t) via stream reformer	0.06	1260	18,900,000
CO_2 (t)	0.98	127	31,115,000
Utility cost			
Electricity (MWh)	0.31	80	6,200,000
Heating (MWh)	2.78	80	55,600,000
Cooling (MWh)	2.96	-	-
Cooling Water (t)	250	0.0148	925,000
Consumables			
MeOH (t)	0.15	750	28,125,000
Ruthenium-based catalyst(kg/yr)	30	241,500	44,801,613
Phosphino-based catalyst(kg/yr)	15	97,635	9,056,325
Amine,$NHeX_3$ (t/yr)*	0.12	833	57,255,121
Total Var O & M Cost ($/yr)			**251,978,059**

* (250/120) x 27,482,458 from (Dongin Kim, 2020) = 57,255,121

BIOGRAPHY

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