CARBON DIOXIDE MANAGEMENT FOR PRODUCT SUPPLY CHAIN AND TOTAL SITE UTILISATION AND STORAGE

WAN NORLINDA ROSHANA BINTI MOHD NAWI

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Prof. Dr. Denny Kok Sum Ng
Room CA 25, Block C, Malaysia Campus, Jalan Broga,
University of Nottingham Malaysia,
43500 Semenyih, Selangor.

Nama dan Alamat Pemeriksa Dalam :
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CARBON DIOXIDE MANAGEMENT FOR PRODUCT SUPPLY CHAIN AND TOTAL SITE UTILISATION AND STORAGE

WAN NORLINDA ROSHANA BINTI MOHD NAWI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Chemical Engineering)

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

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To my beloved husband, Muhammad Faizal

Umairah, Umaiza,Uzayr

Ibu, Bapak, Mak, Abah and family members

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ABSTRACT

The development of insight-based graphical and algebraic techniques in process integration (PI) for carbon dioxide (CO_2) emission targeting, design, and planning based on pinch analysis (PA) has evolved in line with the developments of other PI tools for the conservation of resources including heat, mass, gas, power, and electricity. Complementary PA-based tools can provide graphical and visualisation insights that are vital for better conceptual understanding of problems, particularly at the onset of CO_2 emission systems planning and design, have been developed over the last ten years. Therefore, a comprehensive and systematic CO_2 emission reduction planning and management using PA-based methods are proposed in this research to provide a systematic and vital insights towards CO_2 emission reduction. This research proposes a methodology for CO_2 emission reduction throughout product supply chain and end-of-pipe management of CO_2 via total site integration. A palm cooking oil product is used to demonstrate the proposed methodology development. In the first step, CO_2 emission hotspot which contributes the highest emission phase in the supply chain is identified. Next, the most suitable and economically viable CO_2 reduction strategies are identified and screened by using CO_2 management hierarchy as a guide, and SHARPS as a cost screening technique. At this stage, a total of 1,077 tonnes per year (t/y) CO_2 emissions for a basis of 100 t/y of palm cooking oil production are successfully reduced to 402 t/y which is approximately 63% reduction based on the implementation of CO_2 emission reduction strategies that achieved target payback period (TPP $\leq$ 2 years) and investment cost (INV $\leq$ USD 150,000). In the third step, the remaining CO_2 emission could be further reduced with end-of-pipe emission management considering multiple sites which can act as CO_2 sources or demands. A methodology for total site CO_2 integration is introduced to integrate and fully utilise the CO_2 emissions among industries and/or plants via single and multiple centralised header before being sent to storage to permanently store and zero CO_2 emissions can be achieved via single header. Finally, CO_2 purification and pressure drop are considered during CO_2 transportation in the total site CO_2 integration system's design. An algebraic approach called CO_2 utilisation and storage-problem table algorithm is proposed to obtain total site target for integration of CO_2 utilisation and storage. In conclusion, a new integrated methodology of CO_2 emission reduction for product supply chain and CO_2 end-of-pipe management has been successfully developed. This new methodology is expected to enable planners, policy makers or designers to plan and manage their CO_2 emissions reduction effectively as well as systematically planning for resource conservation.

ABSTRAK

Pembangunan proses bersepadu (PI) berdasarkan teknik grafik dan algebra untuk sasaran pelepasan karbon dioksida (CO_2), reka bentuk dan perancangan berdasarkan analisa jepit (PA) telah berkembang sejajar dengan perkembangan metodologi PI yang melibatkan pemuliharaan sumber termasuk haba, jisim, gas, kuasa dan elektrik. Metodologi pelengkap berasaskan PA yang telah dibangunkan sejak sepuluh tahun lepas menyediakan grafik dan pandangan visual yang mana penting untuk pemahaman konsep permasalahan reka bentuk dan perancangan bagi sistem pelepasan CO_2. Oleh itu, perancangan dan pengurusan pelepasan CO_2 yang komprehensif dan sistematik berasaskan PA dicadangkan dalam kajian ini bagi menyediakan pengamatan penting dan sistematik terhadap pengurangan pelepasan CO_2. Kajian ini memperkenalkan metodologi pengurangan pelepasan CO_2 menerusi produk rantai bekalan serta pengurusan akhir-paip pelepasan CO_2 melalui CO_2 seluruh tapak bersepadu. Pembangunan metodologi dilaksanakan menerusi produk minyak masak kelapa sawit. Pada mulanya, fasa titik panas pelepasan CO_2 iaitu fasa pelepasan CO_2 yang tertinggi dalam rantai bekalan dikenalpasti. Seterusnya, strategi-strategi pengurangan CO_2 yang paling sesuai dan ekonomik dikenalpasti dan disaring berdasarkan hierarki pengurusan CO_2 sebagai panduan dan teknik penyaringan kos SHARPS. Pada peringkat ini, pelepasan CO_2 sebanyak 1,077 tan per tahun (t/t) dari 100 t/t asas produk minyak masak kelapa sawit telah berjaya dikurangkan kepada 402 t/t dengan anggaran pengurangan sebanyak 63% berdasarkan pelaksanaan strategi pengurangan pelepasan CO_2 yang mencapai sasaran tempoh pulangan balik (TPP $\leq$ 2 tahun) dan kos pelaburan (INV $\leq$ USD 150,000). Pada langkah ketiga, baki daripada jumlah pelepasan CO_2 setelah metodologi pengurangan CO_2 dilaksanakan, dapat dikurangkan lagi dengan pengurusan akhir-paip pelepasan CO_2 yang mempertimbangkan tapak-tapak industri sebagai sumber pelepasan CO_2 atau permintaan penggunaan CO_2. Metodologi CO_2 seluruh tapak bersepadu telah diperkenalkan untuk menyepadukan dan menggunakan pelepasan CO_2 dengan sepenuhnya di kalangan industri dan/atau loji-loji melalui sistem terusan tunggal dan pelbagai berpusat sebelum dihantar ke simpanan secara kekal dan sifar pelepasan CO_2 boleh dicapai menerusi sistem terusan tunggal. Akhirnya, proses ketulenan CO_2 dan susutan tekanan sepanjang pengangkutan CO_2 dalam reka bentuk sistem CO_2 seluruh tapak bersepadu telah dipertimbangkan. Pendekatan algebra penggunaan dan simpanan CO_2 masalah jadual algoritma telah diperkenalkan untuk mendapatkan sasaran seluruh tapak bagi penggunaan dan simpanan CO_2 bersepadu. Sebagai kesimpulan, kaedah bersepadu baru pengurangan pelepasan CO_2 untuk rantaian bekalan produk dan pengurusan akhir paip CO_2 telah berjaya dibangunkan. Metodologi baru ini dijangka dapat membolehkan perancang, pembuat dasar atau pereka untuk merancang dan mengurus pengurangan pelepasan CO_2 mereka dengan berkesan serta merancang pemuliharaan sumber dengan sistematik.

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Set

i	-	Index for supply chain phase
j	-	Index for CO_2 reduction strategy
k	-	Index for CO_2 source
q	-	Index for CO_2 demand

Variable

CO_2^R	-	Value of CO_2 emission reduction
ES_{CO2}	-	CO_2 emission
F_{CO2}		CO_2 flowrate
$FC\text{-}D$	-	Fresh CO_2 flowrate to demand
$FC\text{-}H1$	-	Fresh CO_2 flowrate to header 1
F^D	-	After purified flowrate
F^G	-	Tail gas flowrate
F_{OG}	-	Other gas flowrate
FP_{in}	-	Feed flowrate to purify
F_T	-	Flue gas flowrate
INV^{after}	-	Investment after SHARPS
$INV^{initial}$	-	Investment before SHARPS
INV^{set}	-	Desired investment
$INV^{strategy}$	-	Individual investment for each of the strategy
m	-	Gradient of strategy
$P_{CO2}{}^{H1}$	-	CO_2 purity of the header 1
$P_{CO2}{}^{H2}$	-	CO_2 purity of the header 2
P^D	-	Purified product purity
$Q^{base\ case}$	-	CO_2 emission before reduction
$R^{strategy}$	-	Individual contribution of CO_2 emission reduction for each of the strategy
$S^{implement}$	-	CO_2 emission reduction when a strategy is implemented
$TPP^{initial}$	-	Initial total payback period
TPP^{set}	-	Desired TPP
TPP^{after}	-	Total payback period after SHARPS

Parameter

CC	-	Estimated capital cost (USD/unit)
D	-	Demand
Dt	-	Distance
E	-	Utilised amount of strategy proposed (result in CO_2 emission reduction)
EF	-	Emission factor

H1	-	Header 1
H2	-	Header 2
H1-D	-	Header 1 to demand
H2-D	-	Header 1 to demand
H2-H1	-	Header 2 to Header 1
H1-H2	-	Header 1 to Header 2
P_{CO2}	-	CO_2 purity
R^{ER}	-	Recovery efficiency
S	-	Source
x	-	Consumption activity

Other

CC	-	Composite curve
CCC	-	Cost composite curve
CCS	-	Carbon capture and storage
CCU	-	Carbon capture and utilisation
CCUS	-	Carbon capture, utilisation and storage
CECR	-	Cost effective carbon reduction
CEPA	-	Carbon emission Pinch Analysis
CMH	-	Carbon management hierarchy
CO_2CC	-	Carbon dioxide composite curve
CSCA	-	Carbon storage cascade analysis
CSCC	-	Carbon storage composite curve
CSPO	-	Certified sustainable palm oil
CUM	-	Cumulative
CUS-PTA	-	CO_2 Utilisation and Storage–Problem Table Algorithm
EOR	-	Enhanced oil recovery
EROI	-	Energy return on energy investment
FiT	-	Feed-in-Tariff
GCA	-	Gas cascade analysis
GCC	-	Grand composite curve
GCCA	-	Generic carbon cascade analysis
GHG	-	Greenhouse gas
HEN	-	Heat exchanger network
HI	-	Heat integration
ICO_2R	-	Investment versus CO_2 reduction
LCoE	-	Levelised cost of electricity
LIES	-	Locally integrated energy system
LP	-	Linear programming
MED	-	Ministry of Economic Development
PI	-	Process integration
PTA	-	Problem table algorithm
RCN	-	Resource conservation network
RE	-	Renewable energy
REC	-	Regional energy clustering
RESDC	-	Regional energy surplus deficit curve
RSPO	-	Roundtable on Sustainable Palm Oil
RRMCC	-	Regional resource management composite curve
SDC	-	Source demand curve
SHARPS	-	Systematic hierarchical approach for process screening

SUGCC	-	Site utility grand composite curve
TS	-	Total site
TSCI	-	Total site CO_2 integration
WAMPA	-	Waste management Pinch Analysis

LIST OF SYMBOLS

%	-	Percentage
ΔP_d	-	Pressure drop
°C	-	Degree celcius
D	-	Pipe diameter
$\mathcal{E}$	-	Roughness value
EF	-	Emission factor
E_s	-	Utilised amount
f	-	Friction factor
in	-	Inch
kg	-	Kilogram
km	-	Kilometre
kW	-	Kilowatt
L	-	Pipe length
m	-	Mass flow rate
M	-	Million
m^3	-	Meter cubic
m_n	-	Slope for each strategy
MPa	-	Megapascal
MWh	-	Megawatt hour
Re	-	Reynolds number
t	-	Tonne
TJ	-	Terajoule
y	-	year
Π	-	Pi
ρ	-	Fluid density
Σ	-	Summation

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Greenhouse gas (GHG) emission contributes the main cause of global climate warming and has received much attention in recent years due to its environmental, social, and economic impacts. Power plants, petroleum refineries, cement factories, steel plants, and chemical process industries are major contributors of GHG emission. Heightened global warming issues have led the governments, industries, businesses, and consumers becoming increasingly aware the importance of environmental conservation. Figure 1.1 indicates the global GHG emissions according to various types of gas in 2010 (IPCC, 2014).

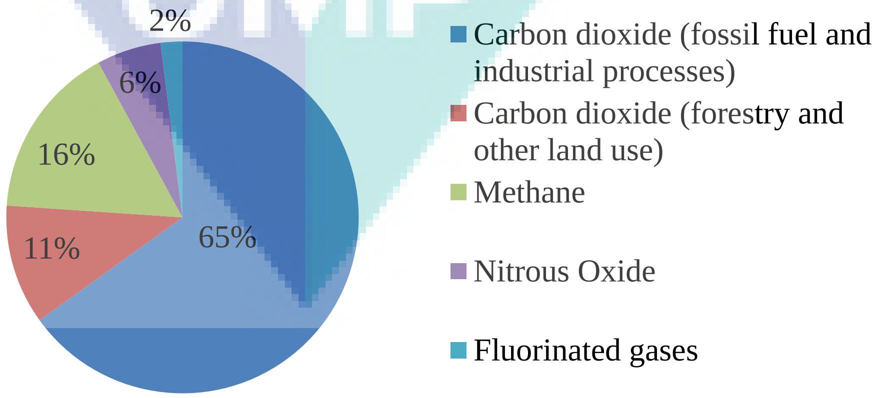


Figure 1.1: Global GHG emission according to gas type (IPCC, 2014)

CO_2 emission contributed 76% of total GHG worldwide, mainly from the consumption of fossil fuel and industrial processes. Rapid economic growth increases the energy consumption, hence increases the emission. In 2014, China and The United States (US) ranked the top CO_2 emitters globally that includes CO_2 emissions from fossil fuel burning, cement production, and gas flaring (Boden et al., 2016). Yang and Chen (2014) have reported different proportions of CO_2 emission based on various energy sources as illustrated in Figure 1.2.

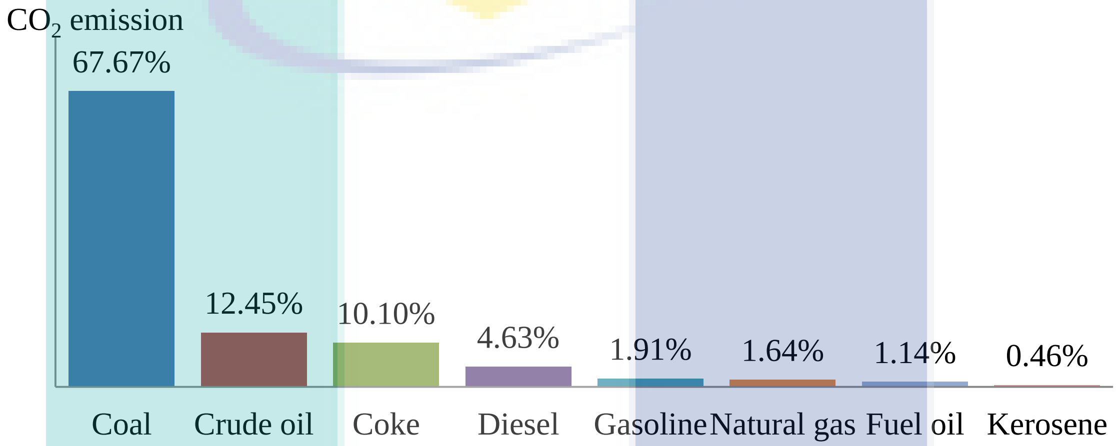


Figure 1.2: Proportion of CO_2 emission from energy sources (2014)

Energy source from burning coal contributed to the highest of total global CO_2 emission. The most widely used source for electricity production is coal due to its high energy content as well as its low price compared to others (Yang and Chen, 2014). However, electricity generation in Malaysia is mostly fossil-based, in particular natural gas and crude oil. In 2013, Malaysia's primary energy supply is natural gas (65.5%), crude oil (29.1%), hydropower (2.7%), coal and coke (1.9%), biodiesel (0.5%) and biomass (0.3%) (Suruhanjaya Tenaga, 2015). Electricity generation and industrial sectors that used coal as an energy source has contributed more than half (52%) of total GHG emissions in 1990 to 2013 (US EPA, 2015). The high energy consumption however, is mainly contributed from major losses in electricity generation, transmission, and distribution (US DOE, 2015) meanwhile about 70% of total electricity production has been used to satisfy the industrial demand that is being attributed for steel industries, chemicals, cement, and automobiles production (Olivier *et al.*, 2014).

Due to Malaysia's CO_2 emission scenario, Renewable Energy Act 2011 and Sustainable Energy Development Authority Act 2011 have been introduced to encounter this. On top of that, the Feed-in-Tariff (FiT) system was initiated in 2011 as one of the sustainable policy and act as a supporting measure to accelerate renewable energy growth (Aghamohammadi *et al.*, 2016). Under a FiT, utilities are legally contracted to purchase electricity generated from any renewable sources such as biomass, small hydro, biogas and solar power at a fixed rate and period as outlined in the law. Therefore under this scheme, every kilowatt-hour (kWh) exported to the main grid, a guaranteed payment is made to the FiT energy developer.

The development and implementation of various methodologies and strategies through Process Integration (PI) could provide a sustainable alternative to control the rising emissions. PI is a set of methodologies used for the conservation of resources and reduction of harmful emissions via integration of several parts of processes, coupled processes, and processes within Total Sites (Klemeš *et al.*, 1997) or industrial areas within a region (Perry *et al.*, 2008). PI-based on Pinch Analysis (PA) has emerged as an insight-based tool for the design of energy efficient process system during the oil crisis of the 1970s (Linnhoff and Flower, 1978). PA was first developed for the optimal design of heat exchanger networks (HEN) by Hohmann (1971) and further developed by Linnhoff and Flower (1978) − see Klemeš *et al.* (2014) for detail description.

The term 'Pinch' represents the thermodynamic limit for the maximum heat recovery of a process. PA has successfully emerged as an effective design tool for various resource conservation systems, such as optimal hydrogen system (Alves and Towler, 2002), heat and power (Perry *et al.*, 2008), extended Water Pinch and wastewater minimisation networks (Wan Alwi *et al.*, 2008), design gas network (Wan Alwi *et al.*, 2009), Total Site Heat Integration (TSHI) (Varbanov and Klemeš, 2010), biomass supply chain (Lam *et al.*, 2010) and Power Pinch (Wan Alwi *et al.*, 2012). Over forty-five years, PI-based on PA methodology has a remarkable progress and has evolved into a suite of graphical, algebraic, and numerical tools used in the conservation of various types of resources.

Increasing CO_2 emission reduction in energy generation and utilisation has received growing attention due to its negative environmental impacts and there is a need to address global sustainability challenges for future works. To date, extensive researches have been done on the development of conceptual methodologies and optimisation tools for efficient energy management, sustainable process design and retrofit addressing the environmental concerns. These are aimed to increase the profitability and sustainability of industrial activities. Systematic planning and management of emissions are one of the sustainable potential alternatives to address the increasing anthropogenic CO_2 emissions from various major industries, including power plants, chemical plants, refineries, cement production factories, and iron and steel industries (Kravanja *et al.*, 2015). This issue has led to extensive research into proper planning and policy formulation for the past decades and remains a need for effective approaches that can systematically plan CO_2 emission reduction through PI-based on PA methodology.

Palm oil production is among the biggest vegetable oil production contributing to 35.5% of total annual production in the world, and Malaysia is the second largest producer and exporter of palm oil (Hosseini *et al.*, 2013). According to Reijnders and Huijbregts (2008) the CO_2 emissions contributed by palm oil industry is estimated in the range of 2.8 to 19.7 kg CO_2 equivalent per kg palm oil. The main sources were from land conversion (60%), methane emissions from palm oil mill effluent treatment via anaerobic digestion (13%), fossil-fuel combustion (13%) and fertilizer use (4%) (Hassan et al., 2011). Roundtable on Sustainable Palm Oil (RSPO) has developed a set of environmental and social criteria which palm oil supply chain companies must comply in order to produce Certified Sustainable Palm Oil (CSPO). It is important to ensure the credibility of the sustainability claim at the end of the palm oil supply chain. Based on CSPO, there is a need to develop systematic tools to evaluate CO_2 emissions throughout palm oil supply chain, from raw materials, until the transport to consumer.

There are numerous graphical, algebraic, and numerical tools that have been used for PI-based on PA CO_2 emission reduction and planning. Tan and Foo (2007) were the first who proposed PI-based on PA for CO_2 emission reduction planning. They introduced a graphical Carbon Emission Pinch Analysis (CEPA) approach to satisfy both regional energy demand and region-specified emission limits in the power sector. The CEPA methodology was extended to include CO_2 emission reduction for region electricity sector (Atkins *et al.*, 2010), chemical processes (Tjan *et al.*, 2010), industrial park CO_2 planning (Munir *et al.*, 2012), CO_2 emission reduction for New Zealand transport sector (Walmsley *et al.*, 2015), waste management Pinch Analysis (Ho *et al.*, 2015), and Greenhouse Emission Pinch Analysis (Kim *et al.*, 2016). It has also been further extended for end-of-pipe CO_2 reduction management and planning through carbon capture and storage (CCS) planning (Ooi *et al.*, 2013) and CO_2 storage planning problems (Diamante *et al.*, 2014).

Despite numerous methodologies have been developed for CO_2 emission planning and management, yet the optimal strategies to plan and manage CO_2 emissions efficiently have not been adequately investigated. Therefore, this study proposes a comprehensive and systematic CO_2 emission reduction planning and management methodologies using PI-based on PA to provide systematic, visualisation advantages as well as introduce a coherent planning and management strategies for CO_2 emission reduction from the view of product supply chain and end-of-pipe CO_2 emission solution. Product supply chain that consists of multiple levels of product development may contribute a myriad amount of CO_2 emission. On top of that, growing power and fuel usage due to increasing industrial demands could also contribute to the largest share of emissions if there is no systematic planning or management implemented in future.

1.2 Problem Statement

Product supply chain involved multiple processes in a product development, which emitted a lot of CO_2 emission throughout several phases starting from material acquisition phase to product disposal phase. It is crucial to reduce CO_2 emission for all phases of the supply chain, but this is optional and yet to be determined either the options are economically feasible or infeasible. Established methodologies of PI-based on PA have contributed substantial reduction in CO_2 emission, however most of the methodologies proposed focussing on a single process without aiming for the emission hotspot phase of the supply chain. Furthermore, the cost-effective screening technique to prioritise emission reduction options as to reduce CO_2 emission within a set of economic criteria such as investment limit target or payback period are not yet explored.

Meanwhile, CO_2 capture, utilisation, and storage have emerged as an end-of-pipe solution for CO_2 emission. Remaining CO_2 emission from any process in product supply chain would be further reduced by integrating CO_2 sources and demand in Total Site CO_2 utilisation and storage. The integrated methodology for end-of-pipe CO_2 emission is still limited and most of the works concentrated on CCS development. The emission reduction planning to maximise the recovery of CO_2 capture as well as to minimise the CO_2 to be sent for storage via centralise header system has not yet been considered.

The overview of the problem statement for this research can be summarised as below.

Given that CO_2 emission are being produced throughout a product supply chain. It is desired to determine which phase of the product supply chain that contributes to the highest CO_2 emission (hotspot) and design suitable strategies based on CO_2 emission management hierarchy consisting of conservation, source switching, and sequestration to reduce the CO_2 emissions based on economic criteria. In addition, there is a need to develop new targeting technique to determine the maximum amount of CO_2 emitted by the industries (CO_2 sources) which can be captured, purified and utilised by certain industries as CO_2 demands. The remaining CO_2 which is not possible to be utilised will be send to the storage reservoir as a final end-of-pipe solution. The exchange of CO_2 will be done via centralised headers with the end of the header is the CO_2 storage. The goal is to minimise as much as possible the amount of CO_2 send to the storage by maximising CO_2 utilisation, and at the same time this can also lead to the reduction of pure CO_2 requirement.

1.3 Research Objective

The main objective of this research is to develop PI-based on PA methodologies for CO_2 emission reduction planning and management. The developed methodologies are insight-based graphical and algebraic approaches. The research objectives are as follows:

(1) To develop a holistic framework for CO_2 emission reduction planning and management throughout a product supply chain and CO_2 Total Site.

(2) To develop a systematic cost screening technique for CO_2 emission reduction strategy in a supply chain phase.

(3) To develop a targeting methodology for maximising CO_2 utilisation in an industrial site and minimise fresh CO_2 consumption and emission by considering with and without CO_2 purification and transportation.

1.4 Research Scope

The scope of this research includes:

(1) Developing a holistic framework for CO_2 emission reduction planning and management:

(i) Identify supply chain phases of a product target and set a boundary for CO_2 emission analysis.

(ii) Estimate CO_2 emission of each of the supply chain phase

(iii) Develop a graphical tool to identify the product supply chain emission hotspot phase.

(iv) Test the methodology on the case study

(2) Developing a systematic screening technique for CO_2 emission reduction strategies:

(i) Identify available CO_2 emission reduction strategies and cost of investment.

(ii) Estimate potential CO_2 reduction for each of the strategy.

(iii) Construct a plot of selected emission reduction strategies with hierarchical guideline combination for heat and electrical energy source to meet desired investment limit or payback period (cost effective).

(iv) Perform cost-effective screening using Systematic Hierarchy Approach for Resilient Process Screening (SHARPS).

(3) Developing a targeting methodology for Total Site CO_2 utilisation and storage:

(i) Introduce a new concept of centralising header system to integrate CO_2 sources and demands within a certain area.

(ii) Identify data needed to be collected for the analysis.

(iii) Develop targeting methodology for Total Site CO_2 utilisation and storage.

(iv) Test the methodology on a case study.

(4) Developing a targeting methodology for maximising CO_2 utilisation considering purification and transportation.

   (i) Study the purification technology of CO_2 and the important parameter for CO_2 transportation.

   (ii) Identify data needed to be collected for the analysis.

   (iii) Develop targeting methodology for Total Site CO_2 utilisation and storage considering purification and pressure drop.

   (iv) Test the methodology on a case study.

1.5 Research Contribution

Four main contributions have emerged from this work. A new methodology for CO_2 reduction planning throughout product supply can equip product planners, designers or policymakers with valuable insights into CO_2 emission reduction. A combination of cost-effective screening graphical approach and a hierarchical guideline can systematically plan the CO_2 emission reduction options and emission can be managed whilst still keeping within the investment and emission reduction target.

Besides, remaining CO_2 emission from any process throughout the supply chain can be further reduced in CO_2 Total Site planning. This methodology could integrate CO_2 emission sources (supply) with CO_2 demands (CO_2 utilisation) using a centralised header system before it is being sent into storage permanently. As an overview, this research involves CO_2 emission reduction planning and management from the beginning of CO_2 emission of product development to CO_2 end-of-pipe solution (e.g CO_2 storage).

1.6 Thesis Outline

This thesis consists of seven chapters. Chapter 1 provides an introduction to the research background including an overview of global emissions, research problem statements, research objectives, and scope of research. A review on the development of PI-based on PA in CO_2 emission planning and management involving previous works is presented in Chapter 2, which ends with a highlight on state-of-the-art PI-based on PA in CO_2 emission reduction planning and management.

Chapter 3 presents an overall framework for the study. Subsequent chapters describe the step-wise methodology construction used to develop the CO_2 emission reduction planning and management methodologies in this study.

Chapter 4 describes a methodology development for CO_2 emission planning and management throughout a product supply chain. A combination of graphical and heuristic approaches that extend upon SHARPS was proposed to evaluate the CO_2 emissions of a product throughout its supply chain and to select the most suitable, and economically viable CO_2 reduction strategies. The methodology was developed within the desired investment criteria that could still yield economic and environmental benefits to improve the profitability and sustainability. Case Study 1 and 2 were demonstrated with modified data from literature study to validate the developed methodology.

In Chapter 5, methodology development of CO_2 integration targeting technique for optimal targeting CO_2 utilisation and storage was developed. The methodology involved the integration of CO_2 captured to utilise across industries and/or plants that are linked via centralised headers before the remaining CO_2 are permanently stored. This methodology was demonstrated throughout Case Study 3.

Chapter 6 describes methodology development for targeting CO_2 transportation via pipeline header system. Purification process for high purity CO_2 demand and pressure drop along CO_2 transportation were considered to further improve the design of a centralised header system for CO_2 utilisation, and storage. This methodology was further demonstrated in Case Study 4.

Finally, Chapter 7 concludes overall findings for this study and proposed a few recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Growing global concern on the environmental, social, and economic impacts of GHG emissions has been the main motivation that leads towards the development and implementation of various methodologies and strategies for CO_2 emission reduction (Fais *et al.*, 2016). Systematic CO_2 emission planning and management via PI has potential to provide a sustainable alternative to control the continuous rise of anthropogenic CO_2 emissions from various energy-intensive industries including power plants, chemical plants, refineries, cement production plants, and iron and steel industries (Khan *et al.*, 2014). This chapter starts with a critical review of the development of PI methodologies for emission reduction planning and management. The research gaps identified in PI-CO_2 emission planning and management are addressed at the end of this chapter.

2.2 Process Integration based on Pinch Analysis

Over forty-five years since its introduction, PI-based on PA has shown a remarkable progress and has evolved into a suite of graphical, algebraic, and numerical tools addressing conservation of various types of resources. To date, the tools have been extensively developed and implemented beyond heat or power integration that accounts new dimensions of sustainability in the industry such as cleaner utilisation of fossil fuel or renewable energy sources, waste management, utilising renewable and waste materials for the production of energy and goods (Varbanov and Seferlis, 2014).

PA or Pinch point specifically has been extensively used in the chemical engineering area and is defined as the most constrained point in the process. It is used to improve the process of energy use and gives a significant result on energy saving. Hohmann (1971) followed by Linnhoff and Flower (1978) introduced the temperature versus enthalpy diagram, which provided the basis for PA tools development. Figure 2.1 shows the Pinch point and heat recovery target in a Composite Curves plot. Heat and Cold Composite Curves that represent process heat source and heat sink are presented for energy targeting.

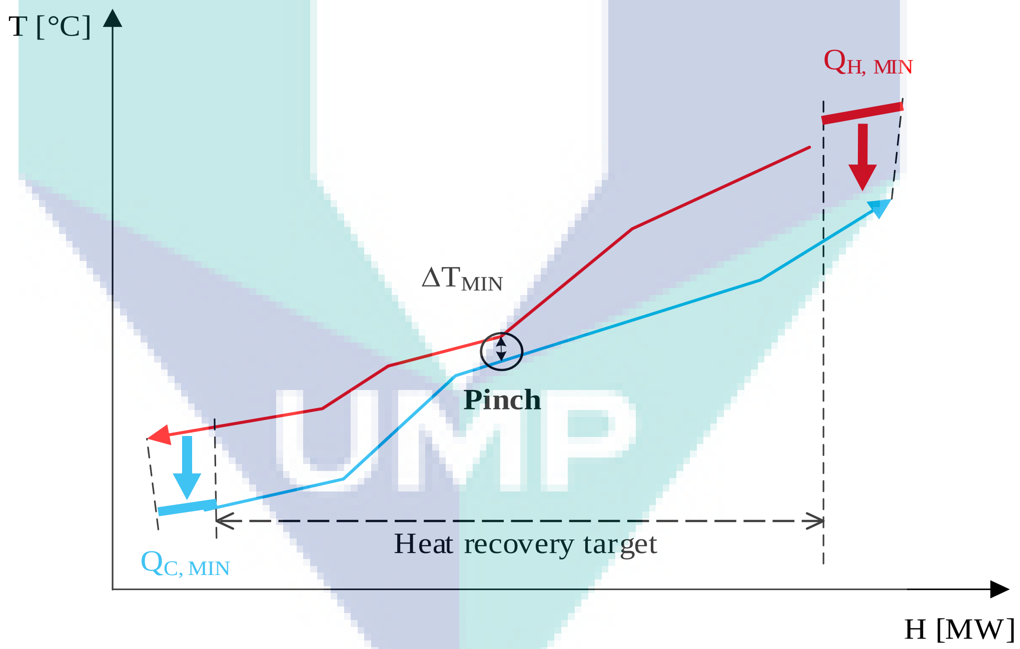


Figure 2.1: Composite Curves for minimum energy targeting (Klemeš *et al.*, 2010)

The Composite Curves provide a visual insight of overall process heat availability and requirements as well as the maximum possible heat recovery. The Composite Curves are constructed by combining hot and cold streams of few processes to yield the Hot Composite Curve (a single composite of hot streams representing the overall heat sources within the process) and the Cold Composite Curve (a single composite of cold streams representing the overall heat demands within the process) (Linnhoff and Flower, 1978). The overlap between the Hot and Cold Composite Curves at the minimum allowable temperature difference (ΔT_{min}) represents the target for maximum heat recovery (MER). As the ΔT_{min} increases, the maximum heat recovery potential and the heat transfer area decreases. The term 'Pinch' represents the thermodynamic limit for the MER while Qc and Q_h represent the minimum cold utility and hot utility needed by the process.

The heat pinch approach was later extended to combine heat and power network design and Total Site analysis. The Grand Composite Curve (GCC) is introduced by Linnhoff *et al.* (1982) as a tool for heat and power systems integration. The tool was modified for adaption into a Total Site that targets fuel, cogeneration, emissions, and cooling by integrating the heating and cooling system with the site utility system. Klemeš *et al.* (1997) later developed a novel method known as Site Utility Grand Composite Curve (SUGCC) targeting method for the reduction of fuel, power, CO_2 emissions and cogeneration potential in Total Site. The approach was later extended for site-wide heat and power integration such as Locally Integrated Energy Sector (LIES) (Perry *et al.*, 2008) and Total Site Combined Heat and Power (CHP) energy system (Varbanov and Klemeš, 2010).

Subsequent generic PA methodologies were also developed for resources other than energy including synthesis of mass exchange network or known as Mass Pinch by El-Halwagi and Manousiouthakis (1989), Water Pinch (Wang and Smith, 1994), production planning pinch (Singhvi and Shenoy, 2002), batch process system (Foo *et al.*, 2004) and Gas Pinch Analysis (Foo and Manan, 2006). Earlier researches on Gas Pinch have led to the development of Oxygen Pinch (Zhelev and Ntlhakana, 1999) and Hydrogen Pinch Analysis (Alves and Towler, 2002) that are applicable to specific types of gas recovery networks. The progress of PI-based on PA research for industrial implementation has been closely followed by the development of integrated methodologies for emission reduction (Friedler, 2010) and waste management. Table 2.1 shows previous developed methodologies PI-based on PA related to research area such as energy, hydrogen, water, emission, and waste. Most of the methodologies relied on the optimal network design and targeting approach that recognised Pinch as the most constrained region of the design.

Table 2.1: PI-based on PA methodology research area

Research Area	**Examples of previous work in PI based on PA**
Energy	Energy planning targeting (Tan and Foo, 2007), clean energy resources (Shenoy, 2010), fuel switching (Tiew et al., 2012), design of energy-efficient batch process systems (Chaturvedi and Bandyopadhyay, 2012), energy resource planning (Al-Mayyahi et al., 2013), heat integration for utility system (Liew et al., 2013), integrated centralised and decentralised energy system (Liu et al., 2017)
Gas/Hydrogen	Targeting for purification and reuse (Zhang et al., 2011), optimal hydrogen systems (Zhenmin, 2003), hydrogen allocation network (Bandyopadhyay et al., 2014), hydrogen network with purification reuse (Yang et al., 2016)
Water	Urban facilities and buildings (Manan et al., 2006), wastewater minimisation (Majozi et al., 2006), wastewater treatment plants (Kim et al., 2016) , water network retrofit with regeneration (Tan et al., 2007), design of water networks (Wan Alwi and Manan, 2008), interplant water integration (Chew and Foo, 2009)
Emission/CO_2	Reduction of CO_2 footprint in chemical processes (Tjan et al., 2010), CO_2 emission exchange using modified sources and demands (Munir et al., 2012), targeting CCS (Ooi et al., 2013), transport sector (Walmsley et al., 2015), CO_2 and heat integration (Hassiba et al., 2017)
Waste	Waste management PA (Ho et al., 2015), carbon-constrained municipal solid waste management system (Jia et al., 2018)

PI-based on PA methodologies have evolved along two popular routes that are graphical insight-based and numerical or mathematical programming approaches. The graphical method is a visual basis that apply thermodynamic insight-based approach by using PA which is easier to master. Meanwhile, the mathematical programming is advantageous in handling complex problems of higher dimensionality. Both routes have their complementary ability to be applied both in academia and industry.

2.3 CO_2 Emission Management and Integration

The energy generation and industrial sectors are among the major contributors to the increment of global CO_2 emissions. It is responsible for 60% of total anthropogenic CO_2 emissions globally that is mainly from power plants, cement production plants, refineries, iron and steel industries, and gas processing and petrochemical industries (Čuček et al., 2015). Working towards for sustainable industrial sector, an industrial symbiotic relationship by integrating processes and systematic emission management could potentially reduce CO_2 emission (Boix *et al.*, 2015).

The earlier concept of integration that involved CO_2 emission reduction is developed by Linnhoff and Dhole (1993). In the late 1990s, Klemeš *et al.* (1997) proposed a methodology to reduce the energy demands and CO_2 emissions in a number of sites (Total Site) focusing on heat integration. Zhelev and Semkov (2004) have proposed a cleaner flue gas via the industrial application of PA that integrated heat recovery with mass transfer. The methodology for Total Site targeting was later used to plan for the efficient utilisation of conventional and renewable energy sources, and the consequent reduction of CO_2 emissions for numerous energy sectors (Perry *et al.*, 2008). Varbanov and Klemeš (2010) introduced an approach for the recovery of waste heat and reduction of CO_2 footprints via the optimal planning of energy demands from locally generated energy supplies for a given area, while effectively integrating renewable energy into the Total Site cogeneration system. The potential of these approaches are the key driver for the positive outlook in the CO_2 management. Figure 2.2 presents the overview development of PI-based graphical and numerical PA methodologies related to CO_2 emission management in various publication platforms from 1993 until 2016.

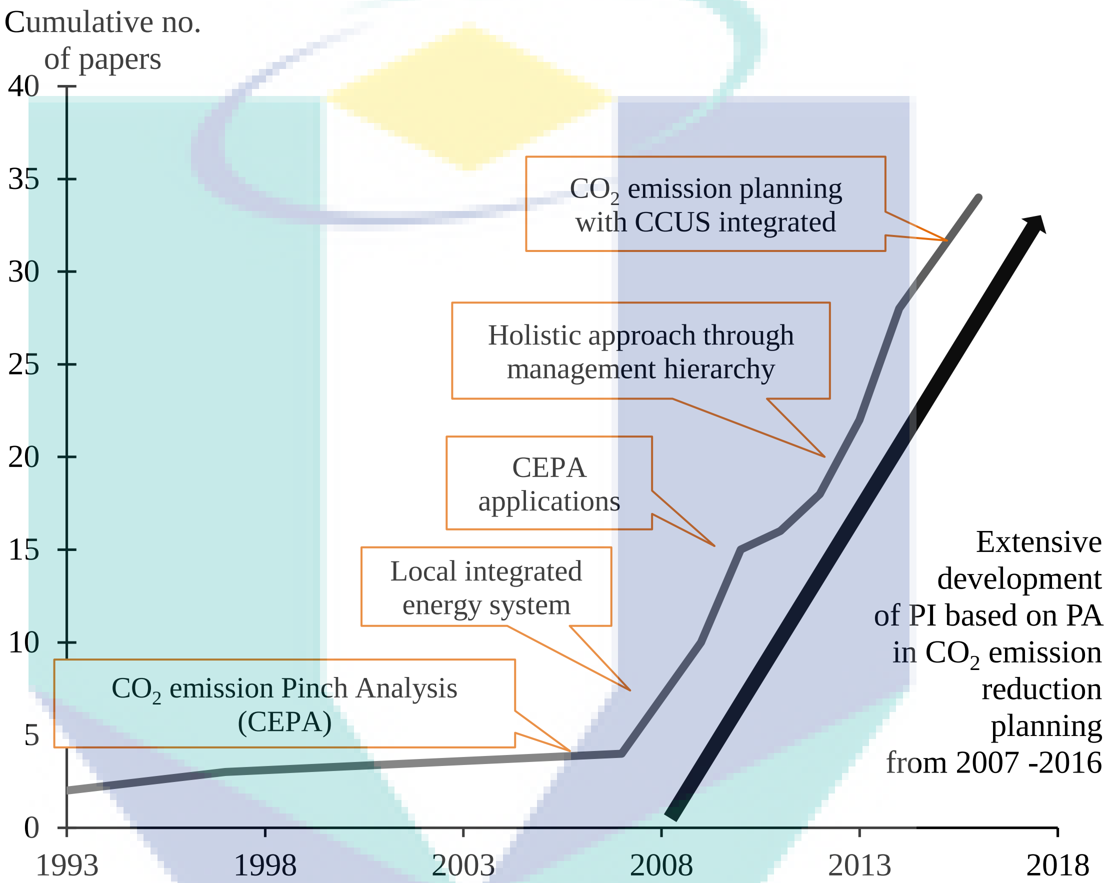


Figure 2.2: Development of PI based on PA methodology in CO_2 emission reduction

Extensive growth in various publications have shown the importance of the implication of CO_2 emission management. The increasing pattern from 2007 until 2016 indicated that PI-based on PA methodologies have the ability and potential to plan and manage the available CO_2 emission reduction strategies. Therefore, overall CO_2 emission management has been reviewed from the perspectives of PI-based on PA in the supply chain, supply or demand side energy and end-of-pipe management in order to address the potential gaps of the research.

In the next sub-sections, available literature of PI-based on PA on CO_2 emission management are presented into several categories, followed by a detailed description of the key focus area of each work, their contributions, as well as the potential for improvement. A few recommendations on research directions and potential for future works that account for CO_2 emission management are concluded at the end session of this chapter.

2.3.1 Supply Chain for CO_2 Management

Supply chain is activities that involve several phases of material acquisition, manufacturing, material/product distribution, and disposal across the product development. There is a practical path to manage CO_2 emission at each phase of the interdependent activities in sequence and cooperates by handling, improving and controlling products by moving them from one to another location, or to perform modification processes (Hidayat and Marimin, 2014). Supply chain also can be classified as the integrating environmental involved product design, material sourcing and selection, manufacturing processes, delivery of the final product to consumers as well as end-of-life management of the product after its useful life (Srivastava, 2007). Therefore, economic potential, environmental impacts, and efficiency of energy use are three main focuses for green supply chain management (GSCM). It has been extended using several techniques such as integration of green technologies and process optimisation, green network analysis and synthesis, life cycle analysis (LCA), green enterprise resources planning and regulatory considerations and sustainability strategies. All of the techniques mentioned above are the main pillars that support in the development of GSCM (Lam *et al.*, 2015).

In general, LCA method is selective and commonly used for evaluating the whole life cycle analysis including all relevant material acquisition and end-of-life processes (Middleton *et al.*, 2014). Many studies have been established referring to the LCA method such as three-tier model analysis for evaluation of direct energy consumption, purchased energy and combination of fuel combustion and industrial processes (Yang and Chen, 2014), hybrid LCA approach for industrial park (Dong *et al.*, 2013) and biodiesel supply chain product (Acquaye *et al.*, 2011). However, they provide little insight on the supply chain planning as well as lack of user involvement through CO_2 reduction strategies decision-making.

Lee (2011) highlighted the important components in supply chain management to integrate the issue of carbon footprint into supply chain management which is a measurement of direct and indirect carbon footprint, setting of system boundary and mapping of a product carbon footprint development. These will enabled the identification and measurement of carbon emissions across the supply chain. Hsu et al. (2013) have utilised a fuzzy systematic approach to evaluate the criteria for supplier selection. They acknowledged that management systems of carbon information and training related to carbon management in GSCM are the most two significant influences to improve the overall performance of supplier. Besides, the strategic decision-making of an optimisation model with green constraint and analytic hierarchy process has been successfully developed to identify the vehicles routes with optimal costs and low-carbon emission on the demand side of the supply chain network. While for production supply chain strategy, an aggregate production planning by managing supply and demand to meet the required production is the most important element to ensure business sustainability. A linear programming model to exhibit operational flexibility for multiple supply scenarios and automated targeting model (ATM) for aggregate production planning has been developed (Foo, 2015). These tools, however are operated based on optimisation algorithm and focus on optimising of other production variables in a supply chain optimisation problem. Chaturvedi and Bandyopadhyay (2015) later developed a methodology that equally applicable to aggregate planning of production as well as aggregate planning of input material supply. The algebraic procedure based on the principles of PA is applied to identify the different kinds of production bottlenecks (pinch points) to provide a significant physical understanding. Li et al. (2016b) have developed a methodology to identify an optimal supply chain network while minimise the carbon emissions. This approach enabled to determine the total carbon footprint of transportation for the supply chain based on the location of the thermal plant and biomass resources. In addition, it also enable the identification of optimal target for low-carbon resource and the synthesis of biomass supply chain network.

CO_2 emission during supply chain activities rely on carbon footprint determination and most of the studies have analysed the environmental impacts by identify and quantify the energy and material used and waste released throughout the whole production and use chain (Pereira *et al.*, 2014). Aziz *et al.* (2016) have summarised on material efficiency, product life extension, and product recycling which are the main strategies to help designers in designing a good product and tend to lower the global warming potential and energy resource impact. There are various of potential techniques across a product supply chain that can be applied including energy resource planning, material input planning, supplier selection, energy saving process, renewable energy, waste conversion and product distribution or storage process to lower down CO_2 or GHG emissions. However, investments and innovative operational processes are required to be implemented. Therefore, Shi and Lai (2013) concluded that suitable evaluation and systematic assessment system are needed in order to review the potential of renewable energy, energy efficiency, processes and technologies planning for sustainable development and it was relevant to be applied in a product supply chain.

Based on the aforementioned works, most of the previous CO_2 management via supply chain planning are based on optimisation-mathematical programming approaches. However, there has been limited study which involved an insight-based of PA approach. The approach is easier to be implemented for all types of industry, that take account on various industry background which is to be used later in the supply chain planning. In addition, those developed tools have not included the screening techniques for CO_2 reduction strategies which are highly potential to be implemented throughout supply chain activities.

2.3.2 CO_2 Mitigation in Industry

Perry *et al.* (2008) introduced Local Integrated Energy System (LIES) to reduce the CO_2 emission by integrating the energy systems and has applied the system to integrate renewable energy into the energy source mix to satisfy both energy demand and specific emission limits that has been set by the region. Demands for heating/cooling and electricity can be satisfied locally by renewable energy sources such as wind, solar cells, or heat pumps as well as via excess heat and power available from local industry and hence the CO_2 emission will be reduced. Besides, Tan and Foo (2007) have also developed a tool for energy sector planning within CO_2 emission constraint which is Carbon Emission Pinch Analysis (CEPA). This tool is analogous to the material recovery Pinch Diagram by El-Halwagi *et al.* (2003) and water flow rate targeting by Prakash and Shenoy (2005). They introduced Energy Supply and Demand Composite Curves as a new application of PA, as shown in Figure 2.3. The method allowed the allocation of the energy resources to meet both the overall emissions limit and the individual targets of the different sectors or location.

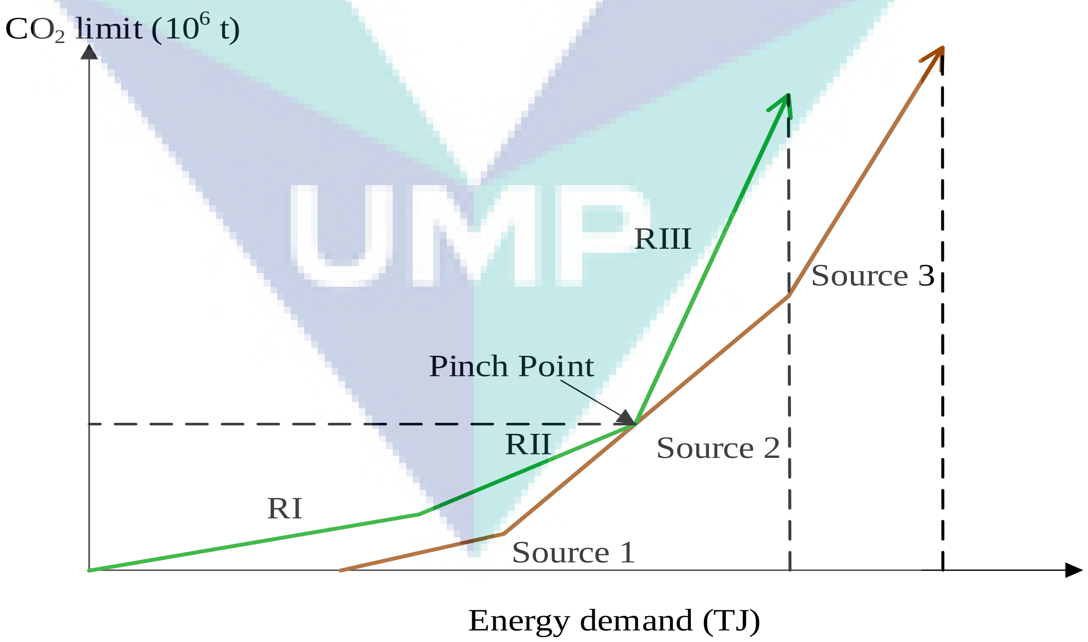


Figure 2.3: Energy Supply and Demand Composite Curves (Tan and Foo, 2007)

As shown in Figure 2.3, the required amount of energy sources needed to satisfy energy demand can be determined by shifting the Source Composite Curve horizontally until it touched the Demand Curve at the pinch point. The required amount of clean energy in the system is given by the horizontal distance between the new position of the Source Composite and its origin. The horizontal distance of the end-point of the Source Composite Curve from the end-point of Demand Composite Curve indicated the amount of high-emission fossil fuels that should be phased out. The authors highlighted the significance of the pinch point as the optimal solution by supplying the zero-carbon energy source to the demands that fall below the pinch while energy demands above the pinch does not required and to be supplied with zero- carbon energy source.

Lee *et al.* (2009) extended upon the Energy Supply and Demand Composite Curves to target a low carbon energy source by exploring changes in the arrangement of the energy mix in order to meet the CO_2 emission limit but with different fuel priority e.g. prioritising coal, which is cheaper and more abundant eventhough it produces high CO_2 emissions. The method was applied for electrical and transportation sector for fuel mix planning as shown below in Figure 2.4.

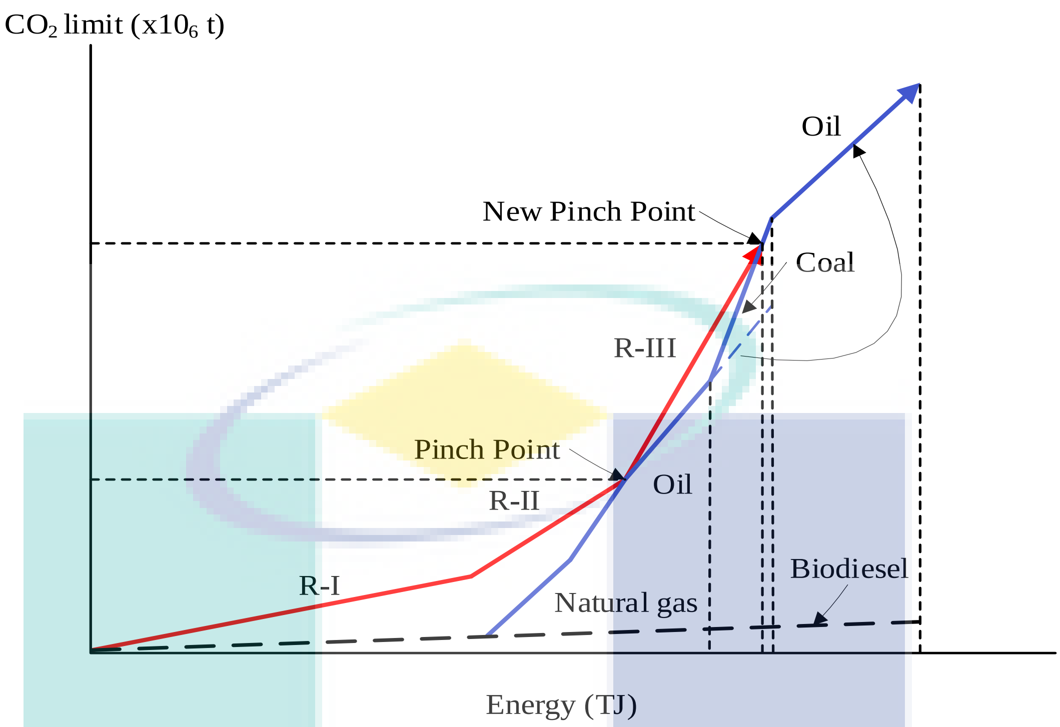


Figure 2.4: Energy supply composite curve for maximise coal usage (Lee *et al.*, 2009)

Furthermore, CEPA methodology has been widely applied in the power sector generation planning such as in Ireland (Crilly and Zhelev, 2008), New Zealand (Atkins *et al.*, 2010), and China (Li *et al.*, 2016b). The adapted methodology was improved and designed for both the energy resource mix and emission targets of the electricity generation sector, influenced by renewable energy emission factors (Crilly and Zhelev, 2010). Jia *et al.* (2010) have also applied the same methodology for the energy mix planning of a chemical industrial park. Foo et al. (2008) later proposed an algebraic cascade analysis technique to represent the Energy Supply and Demand Composite Curves for detailed analysis approximation. As PA-based graphical approach is limited to relatively simple problems with highly aggregated energy sources and demands, a numerical approach can account for the constraints encountered in detailed planning. A generic carbon cascade analysis also has been introduced by Manan *et al.* (2014) to complement the generic graphical approach. The technique was used with the Carbon Management Hierarchy (CMH) to systematically achieve the holistic minimum CO_2.

Due to an increment energy demand for a specified CO_2 emission target in energy resource and utility system planning, Al-Mayyahi *et al.* (2013) targeted minimum cost by using the CO_2 Emissions Composite Curve (CO_2CC) and Cost Composite Curve (CCC). Marginal energy cost and marginal CO_2 emissions are employed to construct two composite curves to be used as targeting tools. Pareto optimal has been demonstrated for visualising and confirming the results of numerical optimisation and simultaneously satisfy both objectives for energy costs and environmental minimisation targets for industrial utility system and national energy sector planning.

Walmsley *et al.* (2014) performed the emissions planning for New Zealand's Energy Sector by using PA and Energy Return on Energy Invested (EROI) analysis. EROI is the ratio of total useful energy generated to total energy used from the point of extraction and processing of the natural resource to the construction and decommissioning of the heat and power plants. High value of EROI is said to be attractive while value of EROI which is less than unity is unattractive because it indicates that a project consumes more energy rather than being generated. The EROI value, however, is a resource and site-dependent and more research need to be conducted in order to establish a proper EROI database. In their paper, EROI was estimated based on relative cost per MWh of generation compared to coal using data from the Ministry of Economic Development (MED) (Ministry of Economic Development, 2013). The cumulative energy expanded to generate electricity was then obtained by plotting the estimated energy expended against electricity generation for each resource, as shown in Figure 2.5. For an example, the energy requirement for CO_2 storage (CCS) increases the energy expended which resulted low value of EROI. This is an unattractive solution as it consumed more energy rather than being generated. This study has demonstrated the relative EROI values of each resource being affected when a resource is phased into the energy generation mix planning.

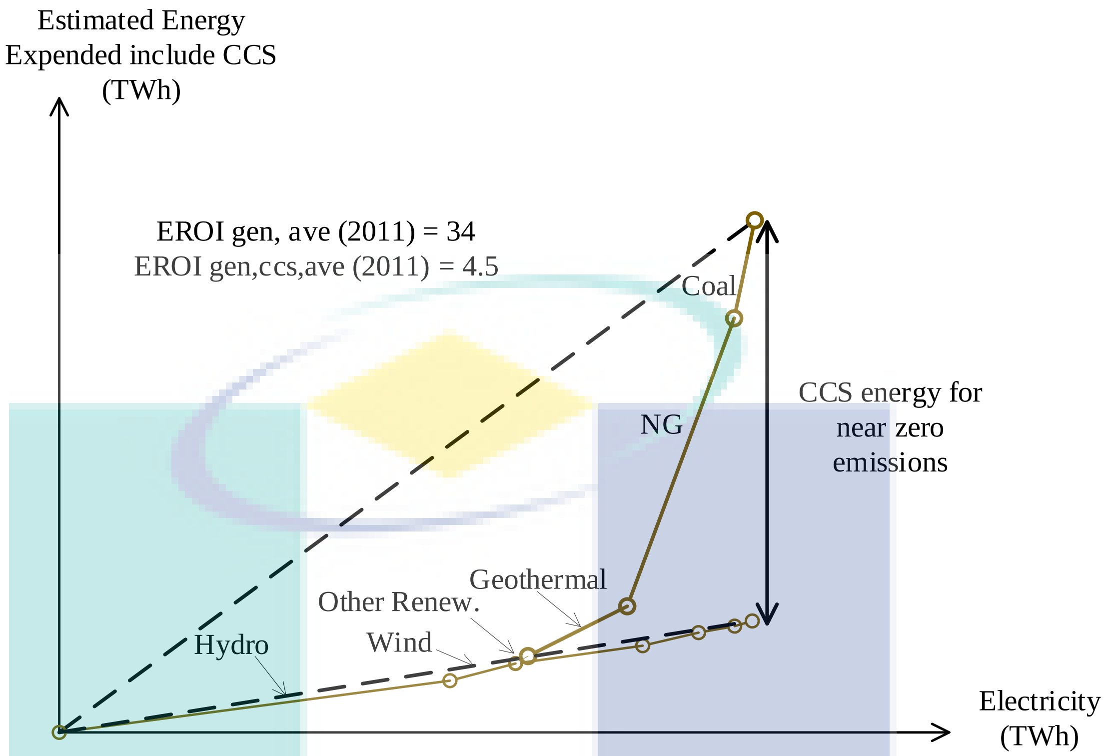


Figure 2.5: The estimated total annual energy consumed for generating electricity in New Zealand in 2011 including the additional energy required for CCS operations to achieve zero carbon emissions (Walmsley et al., 2014)

Priya and Bandyopadhyay (2013) investigated power system planning with emission targeting within overall cost minimisation in the Indian Power Sector, in which numerical and graphical approaches were used. In their case, optimum energy mix need to meet the energy targets and emission constraints at affordable and preferable costs. The developed method combined prioritised cost and the Limiting Composite Curve that can be used to identify optimum power plant mix for any given set of sources and demands. This work is then extended to determine the optimal cost of mixed energy sources planning (renewable and non-renewable energy) through an illustrative case study in Lakshadweep Islands, India (Bandyopadhyay and Desai, 2016). The developed method was proposed to reduce the burden of the government's electricity subsidy by utilising an appropriate available local renewable energy sources.

Tan *et al.* (2009) developed a graphical PA targeting retrofit planning with CCS capability to reduce the carbon footprint within a given geographic region to enhance sustainability in the power generation sector. This technology is widely used as one of the essential interim technologies to mitigate greenhouse gas emissions, while still being able to utilise fossil fuels, that are relatively inexpensive and reliable in comparison to inherent low-carbon renewable resources. A Source Composite Curve was then drawn on a cumulative CO_2 emission versus cumulative energy output diagram, as shown in Figure 2.6.

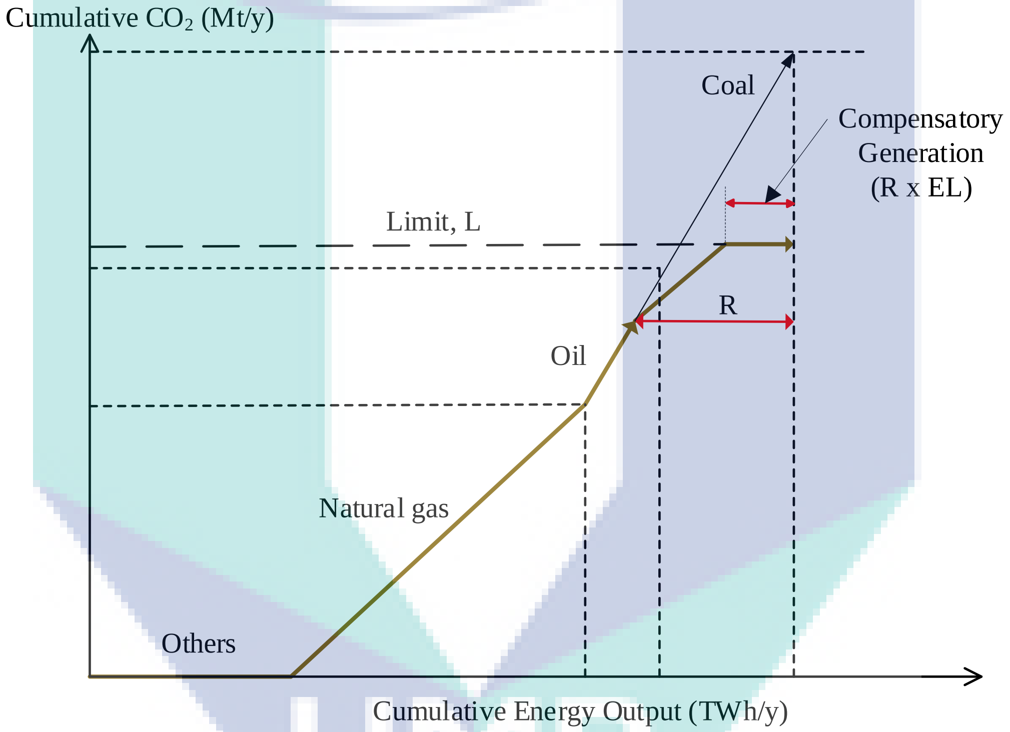


Figure 2.6: Graphical procedure to determine compensatory renewable energy requirement (Tan *et al.*, 2009)

The CEPA later was revised by rearranging the energy source in ascending order of carbon intensity. As a result, the targeting procedure yielded the minimum requirement for a CCS retrofit for a given carbon footprint limit. The approach of Tan *et al.* (2009) resulted in CO_2 emission targets requiring minimal power plant retrofit. Following this, a scheme was proposed to consider additional power demand from carbon emissions capture systems. The scheme included a compensatory electricity generation from renewable energy or from energy efficiency improvements of the existing plant. The required sectoral power output to compensate for the losses and renewable energy compensatory requirement is targeted using the simple graphical approach. An aggregate CO_2 emission targets for the power generation sector can be met while minimising the need for power plants retrofit.

Harkin *et al.* (2010) applied the PA and HI in a power plant. The energy penalty in their study either resulted in the net reduction of electrical energy generation caused by the addition of CCS, or an increase in power plant energy requirement, so as to maintain the same power output after the addition of CCS. The PA was therefore applied to the power plant with new equipment and new heat sources and demands to reduce overall energy penalty and additional cost.

In regional planning, Lam *et al.* (2010) introduced Regional Energy Cluster (REC) to subdivide a region into a number of clusters. The Regional Energy Surplus-Deficit Curves (RESDC) indicated the size of the energy clusters. A Regional Resource Management Composite Curve (RRMCC) was used to visualise the overall energy imbalances in trading-off resources management. A cluster comprises of sub-areas (representing a country/province/community/ industrial park/agricultural area) that is self-sufficient in terms of energy supply (Kostevšek *et al.*, 2015). The energy surpluses and deficits from various zones were then matched and combined to form energy supply clusters. These graphical tools act as an analogy of the PI approach, which provides the energy supply network between the source and sink points within the boundary. The modified Composite Curve within the cumulative area and the energy balance for a system is shown in Figure 2.7.

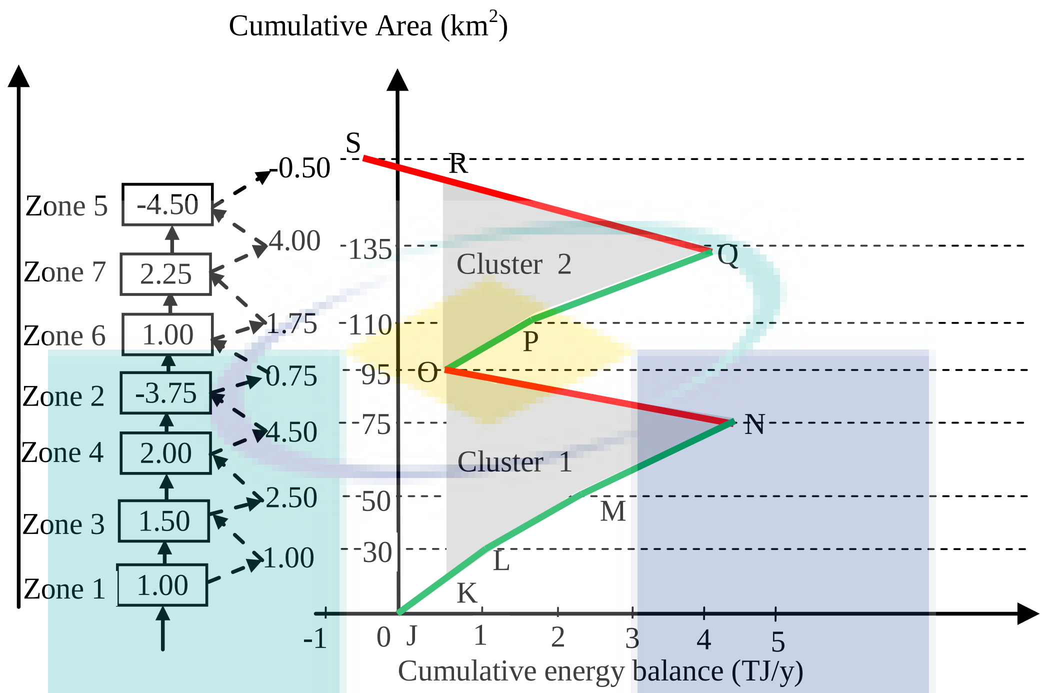


Figure 2.7: RRMCC for minimised carbon emissions footprint (Lam *et al.*, 2010)

In Figure 2.7, the zones with positive slopes supply biomass energy to those with negative slopes (demand zones). An energy balance for a given cluster can be achieved by shifting their lower turning point to the y-axis, where the cumulative energy starts from zero. Retrofit of a new facility in the network can be analysed using the carbon footprint payback analysis to determine the break-even point of an investment and the corresponding construction of the GHG footprint. The methodology provides an insight on which facility options to be prioritised during regional biomass energy planning. Wong *et al.* (2011) have utilised Composite Curves in scheduling the agricultural plantation clearing and replanting. They applied the methodology to determine the land area and identify the most suitable time when a given land plot should be cleared for planting whilst satisfying a targeted CO_2 emission limit. The developed graphical method is generic and applicable for different crops used either conventional or bioenergy applications.

2.3.2.1 Transportation Sector for CO_2 Reduction

CEPA was extended into the transportation sector (Walmsley *et al.*, 2015) for emission targeting and planning in New Zealand by 2050. The graphical was modified and improved for application in the sector. The Supply Curve captured the fuel sources (e.g. petrol, diesel, electricity, compressed natural gas, etc.) used in the various transport operations, which were then stacked beginning with the fuel with the lowest transport fuel emissions factor in ascending order. The Demand Curve represents the transport's primary purposes (e.g. freight or passenger), mode (e.g. marine, air, rail), and class (e.g. buses, ships, trains, light passenger vehicles, etc.). For the Composite Curve, the y-axis indicates the carbon emissions equivalent $_e$ and the x-axis shows the useful transport output in Mt-km, where t could represent the weight of people or freight depending on the purpose of the transport operation, as shown in Figure 2.8.

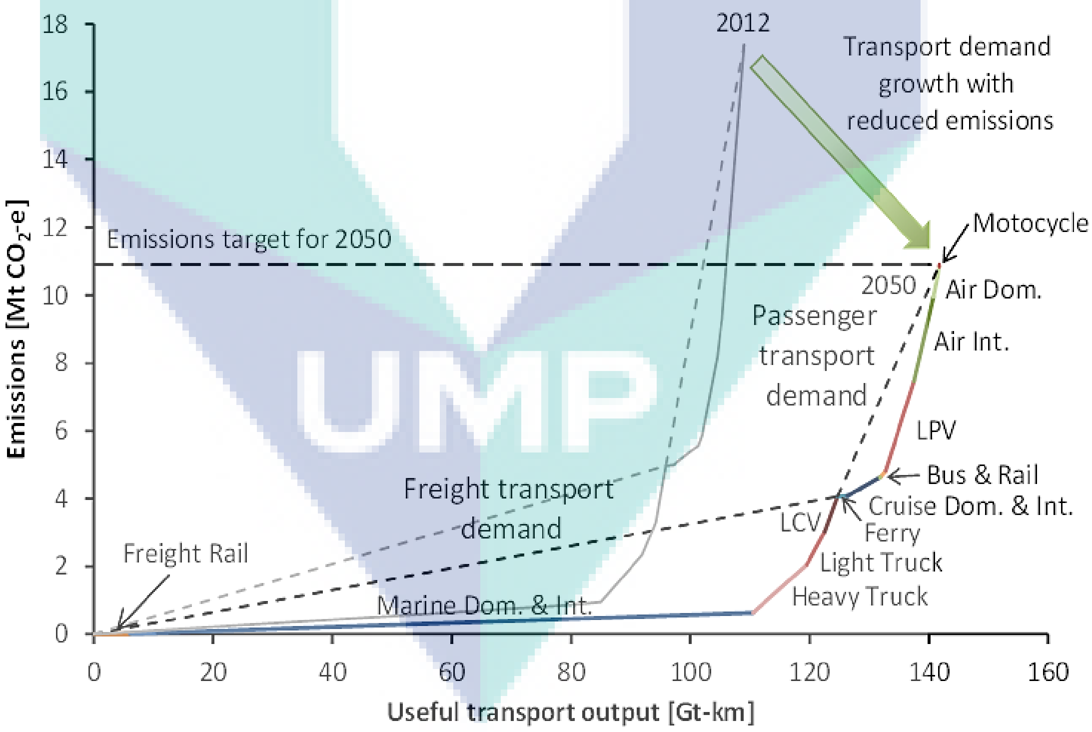


Figure 2.8: Combined emissions Composite Curve for freight and passenger transport demand according to transport purpose and class in New Zealand for 2012, targeting up to 2050 (Walmsley et al., 2015)

It is also useful to plot the transport data on an emission versus fuel use in PI to understand the impact of various emissions reduction options on total fuel use. This developed method is useful for application in other countries and should be further extended to include major GHG emissions footprint including CO_2 and NO_x due to their relationship with human-induced climate change and global warming (Čuček *et al.*, 2015).

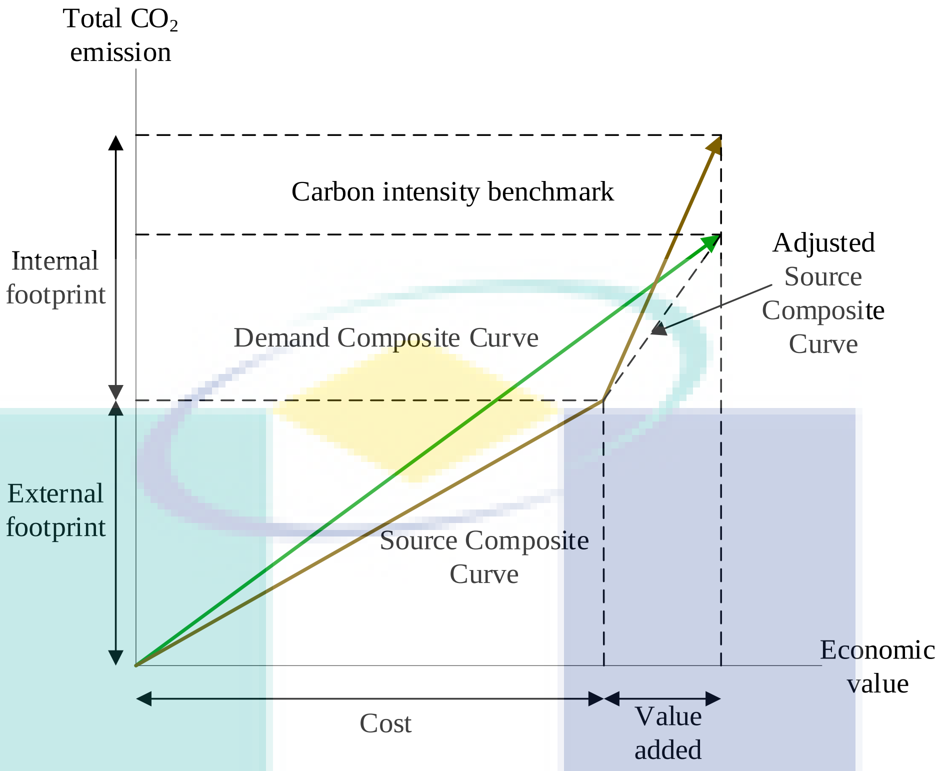
2.3.2.2 Building CO_2 Reduction Planning

Buildings sector is one of the high energy consumers. The major appliances of energy consumption including air-conditioning, computers, printers, lighting, and many more. Lawal *et al.* (2012) have highlighted the importance of systematic and cost-effective electricity and CO_2 emission reduction tools for buildings. A systematic screening method is proposed to maximise the CO_2 reduction. This approach is developed by plotting investment versus CO_2 reduction (ICR) according to CO_2 hierarchy levels and heuristics. Three levels involving conservation, source switching to renewable energy, and sequestration, are arranged in order of increasing priority. Level 1 (conservation) involves the use of energy conservation measures. Level 2 (source switching to renewable energy) considers that the primary source might be switched to renewable energy (e.g., biomass, wind, solar) and Level 3 (sequestration) concerns the removal of carbon from the atmosphere and depositing it in "carbon sinks" such as trees, soil, water, etc. The holistic Cost-Effective Carbon Reduction (CECR) framework was introduced in their study and an extended SHARPS (Wan Alwi and Manan, 2006) was applied to screen cost-effectively CO_2 reduction options in building facilities, however it is limited to only electrical appliances are considered in the developed method.

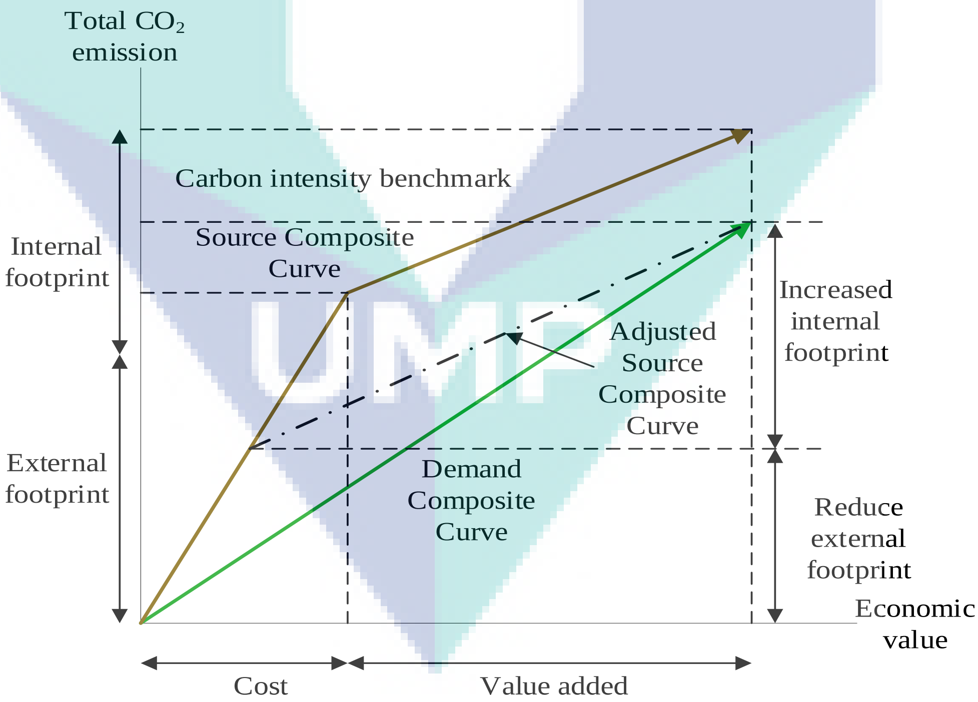
2.3.2.3 Process Plant for CO_2 Reduction

Tjan *et al.* (2010) have developed a graphical technique based on PA to determine few strategies to achieve GHG footprint reduction. A revised methodology is developed to represent the graphical GHG footprints of companies based on CEPA to evaluate and visualise the GHG footprint reduction options in chemical processes. As per Figure 2.9, the plot indicates economic value on the horizontal axis while CO_2 emissions on the vertical axis, and the ratio of carbon footprint to economic value represented as the carbon intensity. The industrial case studies of phytochemical extract and chor-alkali production have been evaluated and illustrated how the simplify graphical PA approach enhances decision-making by prioritising strategies for company-level visualisation and analysis of carbon footprint improvement.

Figure 2.9 shows two scenarios using the plots of carbon footprint composite curves based on internal and external footprints. The internal footprint is contributed mainly by fuel combustion for steam generation (within the plant premises), while the external footprint is contributed mainly by electricity, which is provided by external utility supplier. The carbon footprint composite curves in the graph facilitate the potential of process changes and allow for evaluation and screening of cleaner production options. It allows clear visualisation of key contributors to the minimisation of carbon footprint for both process plants.



(a) Scenario 1: External carbon intensity is lower than the internal one



(b) Scenario 2: External carbon footprint has a much higher intensity than the internal one

Figure 2.9: Carbon footprint composite curves (Tjan *et al.*, 2010)

2.3.2.4 Industrial Site for CO_2 Management

Previous studies on PA-based gas network which involved hydrogen network integration including the hydrogen surplus concept by Alves and Towler (2002) and hydrogen system design by Zhenmin (2003). Foo and Manan (2006) extended the cascade analysis technique and take account on utility gas network. Wan Alwi *et al.* (2009) later introduced a useful visualisation tool to establish minimum gas flow rate targets. Based on classical PA concepts, Munir *et al.* (2012) introduced CO_2 targeting by implementing a holistic waste-to-resources approach involving CO_2 exchange by prioritising options for implementing process changes for industrial park planning. Carbon Management Hierarchy (CMH) is introduced to systematically guide the carbon reduction process toward holistic minimum carbon targets. Figure 2.10 shows an illustration of the CMH priority levels.

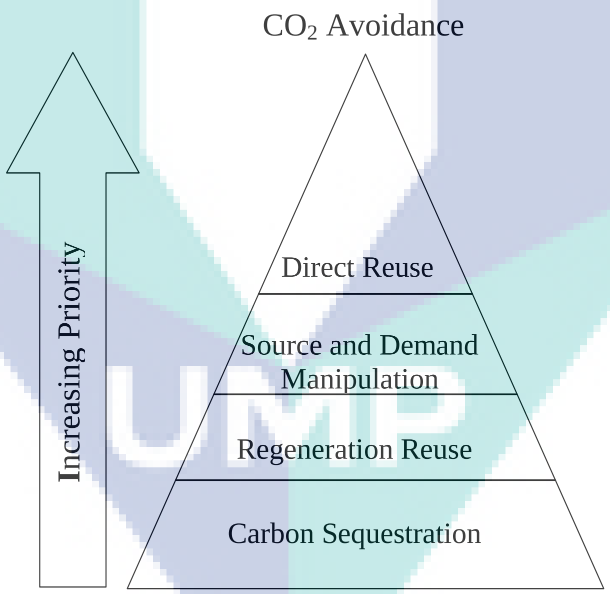


Figure 2.10: Carbon management hierarchy (Munir *et al.*, 2012)

The authors constructed the methodology by identifying the feasible sources of CO_2 emissions and potential CO_2 consuming processes (CO_2 demands). The CO_2 sources and demands were carefully planned and designed to facilitate CO_2 exchange and minimisation in an industrial park. The Source Demand Curve (SDC) was used to establish targets for maximum carbon exchange, minimum carbon emissions, and minimum fresh carbon requirements for the park which is adapted from mass targeting methodology by El-Halwagi *et al.* (2003). The modified plot of primary gas flow rate versus the mass load of contaminants in their study yielded targets for fresh CO_2 flow rate and minimum flue gas emissions (see Figure 2.11). The cumulative flow rate of gases other than CO_2 (F_{OG}) versus the cumulative flowrate of CO_2 (F_{CO2}), was constructed in the form of ascending concentration of sources and demands to enable sources with the highest CO_2 content to be matched with the demands that require high CO_2 content. The CMH can systematically guide users to implement process changes using the SDC. All carbon emissions reduction options for the industrial park were considered and prioritised based on the CMH levels.

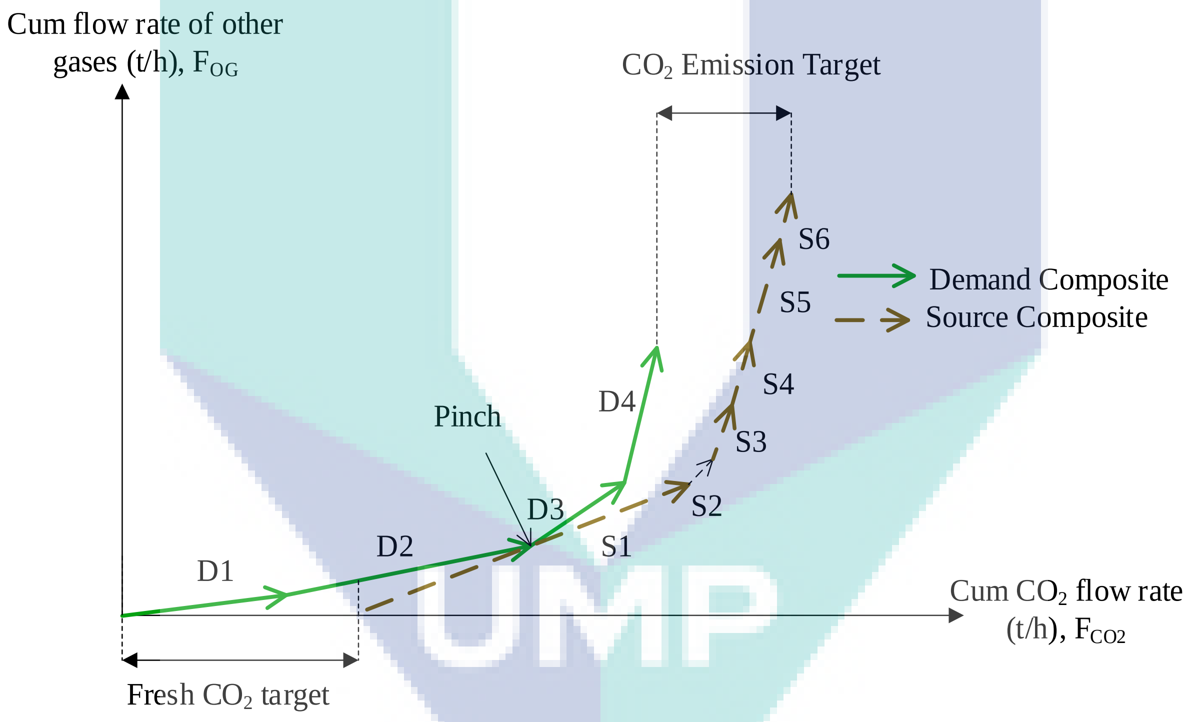


Figure 2.11: Source Demand Curve to facilitate CO_2 exchange and minimisation

The graphical plot of SDC could visualised integrated demands with emission point sources to determine the maximum carbon recovery and the minimum carbon emission targets at the Pinch point. The holistic planning approach at a refinery site has resulted maximum potential in CO_2 emissions reduction.

As electricity play a pivotal role in industrial sites, Wan Alwi *et al.* (2012) have introduced Power Pinch Analysis (PoPA) that could help energy managers, electrical and power engineers as well as designers in determining the minimum targets for out-sourced electricity as well as the amount of excess electricity. Algebraic tools to provide a more rapid and precise electricity targeting are then presented by Mohammad Rozali *et al.* (2013b) and has covered a wide range of applications such as power and storage allocations considering energy losses (Mohammad Rozali *et al.*, 2013a) and optimal hybrid power system sizing (Mohammad Rozali *et al.*, 2014). The (PoPA) methodology has been further extended by Ho *et al.* (2013) to assist in the design of off-grid distributed standalone hybrid power generation systems (SAHPPA), which offers the capability of optimising the capacity of both power generators and energy storage for both intermittent (solar photovoltaic) and non-intermittent (biomass) energy technologies. Integrated diesel plant using PoPA methodology was developed to determine the optimal power output and operational hours for a diesel generator supplemented with renewable energy technologies (Mohammad Rozali *et al.*, 2016).

Many PI-based on PA methodologies have been developed to reduce CO_2 emission in various industries, however has not yet include a systematic screening for emission reduction strategies. As for example, a product development process which comprises a series of stages will emitted a large amount of emissions and there is a need to plan and manage the emissions in order to investigate which stage contribute to the highest CO_2 emission..

2.3.3 End-of Pipe Solution for CO_2 Management

CCS is one of the potential solutions for controlling CO_2 emissions. It involves capturing CO_2 emissions from industrial plants and securely storage in reservoirs to enable the usage of fossil fuels while controlling the CO_2 emitted into the atmosphere. Leung *et al.* (2014) reviewed various technologies and issues related to CO_2 capture, separation, transport, and storage. CO_2 capture technology is heavily dependent on the type of CO_2 generating plant and fuel used. Absorption is the most commonly adopted method in the CO_2 separation process due to its efficiency and lower cost. The CO_2 pipeline system is considered a viable transportation solution for large volumes of CO_2 and the saline aquifer shows much promise as an end-of-pipe solution due to its storage capacity and CCS has been considered in the development of several projects both onshore and offshore (Leung *et al.*, 2014). Huaman and Jun (2014) therefore have reviewed the barriers, strategies for accelerating, and the stages of energy-related CO_2 emissions in CCS technology deployment. Their study summarised that suitable planning, visualising, and optimisation of CCS technology capability resulted in a very useful tool for end-of-pipe CO_2 emission management.

2.3.3.1 CO_2 Capture and Storage Planning

PA methodology was used to estimate CO_2 Capture and Storage (CCS) retrofit as well as compensatory renewable power in the South Korean electricity generation sector (Ilyas *et al.*, 2012). The CCS planning tool known as Carbon Storage Composite Curves (CSCC) and Carbon Storage Cascade Analysis (CSCA) was further developed by Ooi *et al.* (2013) to plan the storage of CO_2 captured from power plants and then channel them into geological reservoirs. Allocation of carbon sources and sinks was determined to address the time-dependent planning problem pertaining to CO_2 storage availability. Diamante *et al.* (2014) considered a graphical CCS planning method for source-sink matching of CO_2 sources (e.g., power plants, oil refineries, and cement plants) with sinks (i.e., geological storage sites). They further expanded upon this with an improved Pinch-Analysis-based methodology for targeting CO_2 capture and storage (CCS) systems with multiple time periods and predefined geographical regions (Diamante *et al.*, 2014). Sahu *et al.* (2014) developed an algebraic technique to target the minimum CO_2 to be removed via CCS from existing power plants. The method also considered additional CO_2 emitted due to the parasitic energy loss from the CCS system. By using this approach, CO_2 removal using CCS can be designed to satisfy the emission limits for any country.

A number of works in capturing and recycling CO_2 for the production of value-added products have resulted in promising key technologies for significant emission reduction (Kravanja *et al.*, 2015). CO_2 emissions conversion into valuable products such as chemicals and fuels is also related to CO_2 utilisation alternatives, but chemicals and fuels offer limited storage periods because of their short lifespan (Cuéllar-Franca and Azapagic, 2015). In other words, the CO_2 is usually released from used chemicals and fuels into the atmosphere long before the benefits of the capture can be realised.

2.3.3.2 CO_2 Utilisation

The maturing of CO_2 utilisation technologies has given rise to the emergence of various methodologies for CO_2 capture, utilisation, and storage, or CCUS. CO_2 utilisation technology can be divided into three categories i.e. geological utilisation, chemical and biological utilisation. In oil and gas industry, CO_2 is used as an injected agent that is known as the CO_2-Enchanced Oil Recovery (EOR) agent to remove the oil trapped in rocks so that the oil extraction yield can be increased (Cuéllar-Franca and Azapagic, 2015). The technology was first tested on a large scale in the 1970s in the Permian Basin of West Texas and South-Eastern New Mexico (Melzer, 2012). Li *et al.* (2015) reported that EOR has became the first priority for China's Coal Chemical Industry.

In the food and beverages industry, CO_2 is used as a carbonating agent, preservative, packaging gas, and as a solvent for the flavour extraction and decaffeination process. CO_2 is also required in the pharmaceutical industry as an intermediate agent in drug synthesis and as a respiratory stimulant. Applications in the food industry and pharmaceutical utilisation however are restricted to the sources that produce CO_2 waste streams of high purity. Currently, there are 13 large-scale CCUS integrated projects in China, which are in the early stages including identification (six projects), evaluation (three projects), and definition (four projects). Throughout these projects, China is working towards developing CCUS for commercial use (Li *et al.*, 2016a) to mitigate CO_2 emissions in the country. Planning for the systematic management of CCUS technology (Li *et al.*, 2015) play an important role in mitigating climate change. An optimal integrated CCUS is a potential strategy to utilise captured CO_2 or CO_2 stored in secure reservoirs (Li *et al.*, 2016a) or geological sites, in which fossil fuels (the major contributor to CO_2 emissions) can still be used because the CO_2 emitted into the atmosphere is in control. However, the CCUS implementation are still in the early stage of development (Li *et al.*, 2015).

CO_2 mineralisation as a means of utilisation could act as a bridge between CO_2 emissions storage and utilisation. Mineral carbonation comprises a chemical reaction between a metal oxide such as magnesium or calcium and CO_2 to form carbonates, which are stable and capable of storing CO_2 for long periods (decades to centuries) (Geerlings and Zevenhoven, 2013). However, this method is a high-cost investment that incurs a high energy penalty for large-scale applications. For example, the mineral carbonation life cycle in European power generation has resulted in 15–64% of greenhouse gas (GHG) emission reductions, but has also increased the cost of electricity about 90–370% on a per kWh (electricity) (Giannoulakis *et al.*, 2014) basis. The statistics for CO_2 utilisation by various sectors in the United States is shown in Figure 2.12.

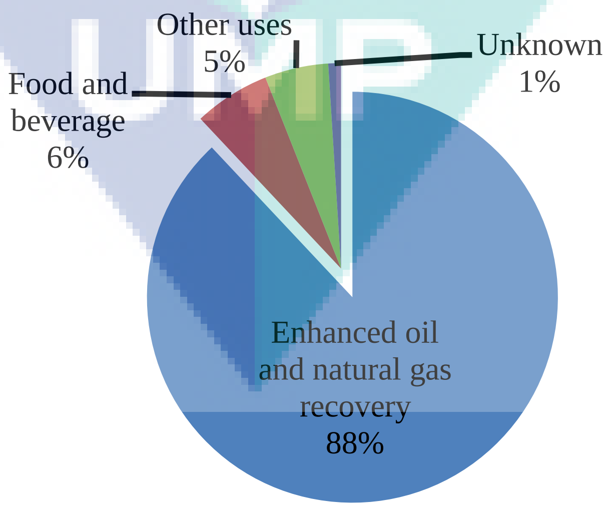


Figure 2.12: CO_2 utilisation by sectors

Most of the established CO_2 emission management involves reducing energy-consuming services (Bandyopadhyay, 2015). Among the potential strategies for CO_2 management are increasing the efficiency of energy conversion or utilisation, fuel switching, enhanced potential CO_2 demands, utilising renewable energy sources, and enhanced CO_2 sequestration either via forestation, ocean fertilisation, or direct artificial CO_2 sequestration (i.e. injection into the ocean and geological formations) (Ghorbani et al., 2014).

2.3.3.3 Waste Management for CO_2 Reduction

Ho *et al.* (2015) introduced a Waste Management Pinch Analysis (WAMPA) method using a graphical approach to identify waste management options based on a specified landfill reduction target and GHG emission target. The tool was designed based on the CEPA approach to identify suitable waste management strategies, which include waste–to-energy, recycling, reduce, and reuse (3R) to minimise GHG emissions.

The solid waste management case study was applied and resulted in reduction of GHG and landfill emission through graphical representation (Ho *et al.*, 2017). The work is seen as a new extension for the application of using PA approach.

2.4 PI-based on PA CO_2 reduction management

In general, previous studies of the graphical and numerical methods of PI have been published into three main categories which are supply side energy planning, demand side management and end-of-pipe emission management. The first category is especially useful in assisting policy-planners to make the right decision on energy mix, while the second and third categories are useful for energy managers in mitigating the impact of CO_2 emissions. Table 2.2 summarises the publications in each category with the description of focus area from the year 2007 until 2016.

Table 2.2: Summary table for the publications in CO_2 emission reduction

Main Categories	References	Description
Supply chain CO_2 Management	Hsu et al. (2013)	A model of carbon management to evaluate the criteria of green supply chain supplier
	Foo et al. (2013)	A mathematical model for regional energy supply chain to plan allocation and capacity of biomass utilisation
	Foo (2015)	An automated targeting model for aggregate planning in production and energy supply chain
	Chaturvedi and Bandyopadhyay (2015)	Aggregate production planning of production as well as aggregate planning of input material supply.
	Li et al. (2016b)	An approach to synthesize the biomass supply chain network
	Tan and Foo (2007)	A graphical procedure (CEPA) for energy allocation with CO_2 emission limits
	Crilly and Zhelev (2008)	CEPA for electricity generation sector
	Perry et al. (2008)	Locally Integrated Energy System (LIES) for energy source mix using Total Site targeting
	Lee et al. (2009)	Extended CEPA using the revised energy planning Composite Curves and segregated planning
	Tan et al. (2009)	PA for CCS planning in power generation sector

Table 2.2 (continue): Summary table for the publications in CO_2 emission reduction

Main Categories	References	Description
Supply chain CO_2 Management	Lam et al. (2010)	Regional Energy Clustering (REC) for regional energy targeting and supply chain synthesis
	Crilly and Zhelev (2010)	Improved CEPA for renewable energy
	Jia et al. (2010)	Regional CO_2 emission pinch analysis
	Atkins et al. (2010)	CEPA for macro-level regional or sector emissions planning
	Harkin et al. (2010)	Combination of PA and mathematical programming for energy penalty in CCS
	Wong et al. (2011)	Agricultural planning for CO_2 emission limit
	Priya and Bandyopadhyay (2013)	Trade-off and limiting Composite Curves for CO_2 emission targeting in power plant mix
	Al-Mayyahi et al. (2013)	Graphical targeting CO_2 emissions associated with utility systems and energy resources networks.
	Walmsley et al. (2014)	CEPA and Energy Return on Energy Investment (EROI) analysis for renewable generation with CCS
	Walmsley et al. (2015)	Improve CEPA for transportation system in New Zealand
	Bandyopadhyay and Desai (2016)	Allocate different energy sources to different demands of a region

Table 2.2 (continue): Summary table for the publications in CO_2 emission reduction

Main Categories	**References**	**Description**
Supply chain CO_2 Management	Li et al. (2016b)	Targeting renewable energy for regional-electricity planning
Demand Side Management	Tjan et al. (2010)	PA for company-level visualisation and decomposition of carbon footprint
	Ng (2010)	Integrated biorefineries for biomass conversion
	Lawal et al. (2012)	Graphical approach for cost-effective CO_2 emission in buildings
	Munir et al. (2012)	Waste-to-resource approach using PA for holistic minimum CO_2 target
	Manan et al. (2014)	PA algebraic approach for CO_2 emission management
	Gharaie et al. (2015)	Retrofit strategy for CO_2 reduction options in the process industries
End-of-Pipe Management	Ilyas et al. (2012)	CCS retrofit and compensatory renewable power demand
	Ooi et al. (2013)	PA targeting for CCS planning problem of corresponding reservoir
	Diamante et al. (2013)	PA for the synthesis of industrial resource conservation networks (RCNs)

Table 2.2 (continue): Summary table for the publications in CO_2 emission reduction

Main Categories	References	Description
End-of-Pipe Management	Diamante et al. (2014)	Unified pinch for CCS with multiple time periods and regions
	Sahu et al. (2014)	PA algebraic targeting technique for grid-wide CCS retrofits
	Ho et al. (2015)	Waste Management Pinch Analysis (WAMPA) for CO_2 emission reduction

2.5 Research Gap

PI-based on PA methodology for CO_2 emission management is an important research area that concerned on numerous environmental issues. There are several key issues are yet to be further addressed.

Energy-efficient design processes, a mix of renewables energy, and hybrid power system are available approaches to reduce reliance on fossil fuel as well as mitigate CO_2 emissions. Besides, many strategies such as waste conversion and energy saving process also can contribute to CO_2 emission reduction in the different phases of a product supply chain. Therefore, there is a need to develop a systematic screening system that can prioritised the highest emission phase of product supply chain for CO_2 emission reduction options hence select the most relevant cost-effective strategies to be applied at particular phase. In addition, there is still room for systematic planning, that considers the interaction and priority of various possible emission reduction strategies using a combination of heuristic and CO_2 management hierarchy.

The PA-based methodology for CO_2 Capture and Utilisation (CCU) was recently introduced and more research into the development of CCUS (CO_2 Captured, Utilisation and Storage) tool are currently in progress. However, most of the studies focussed on CO_2 source-sink matching for optimal planning and the integration tool using PI-based on PA methodology in CCUS is still lacking. It is therefore, crucial to design and develop a future CO_2 utilisation and storage network, as well as the policies and mechanisms, to maximise CO_2 utilised and minimise CO_2 stored as end-of-pipe solution for CO_2 emission. It is an advantage to develop a system that can efficiently plan CO_2 emission sources and simultaneously manage the CO_2 demand, so as to reduce CO_2 emission.

All of the abovementioned research gaps, a methodology for (i) CO_2 emission planning and management throughout the product supply chain and (ii) CO_2 Total Site utilisation and storage are developed to overcome the limitations.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter briefly outlined an overall procedures developed to achieve the aim for this research study. The section begins with an illustrated flow chart to give an overview of overall methodology followed by a brief descriptions for each developed tools. Detailed development for each tool will be described in the subsequent Chapter 4, 5 and 6.

Figure 3.1 illustrates an overall research flow which comprises of three stages to be completed in order to achieve the research objectives. The stages are; (i) state of the art review in CO_2 emission reduction management, (ii) methodology development, and (iii) method validation through case study analysis. Under the second stage of methodology development, three new tools are developed for CO_2 emission management and further validated using illustrated case studies.

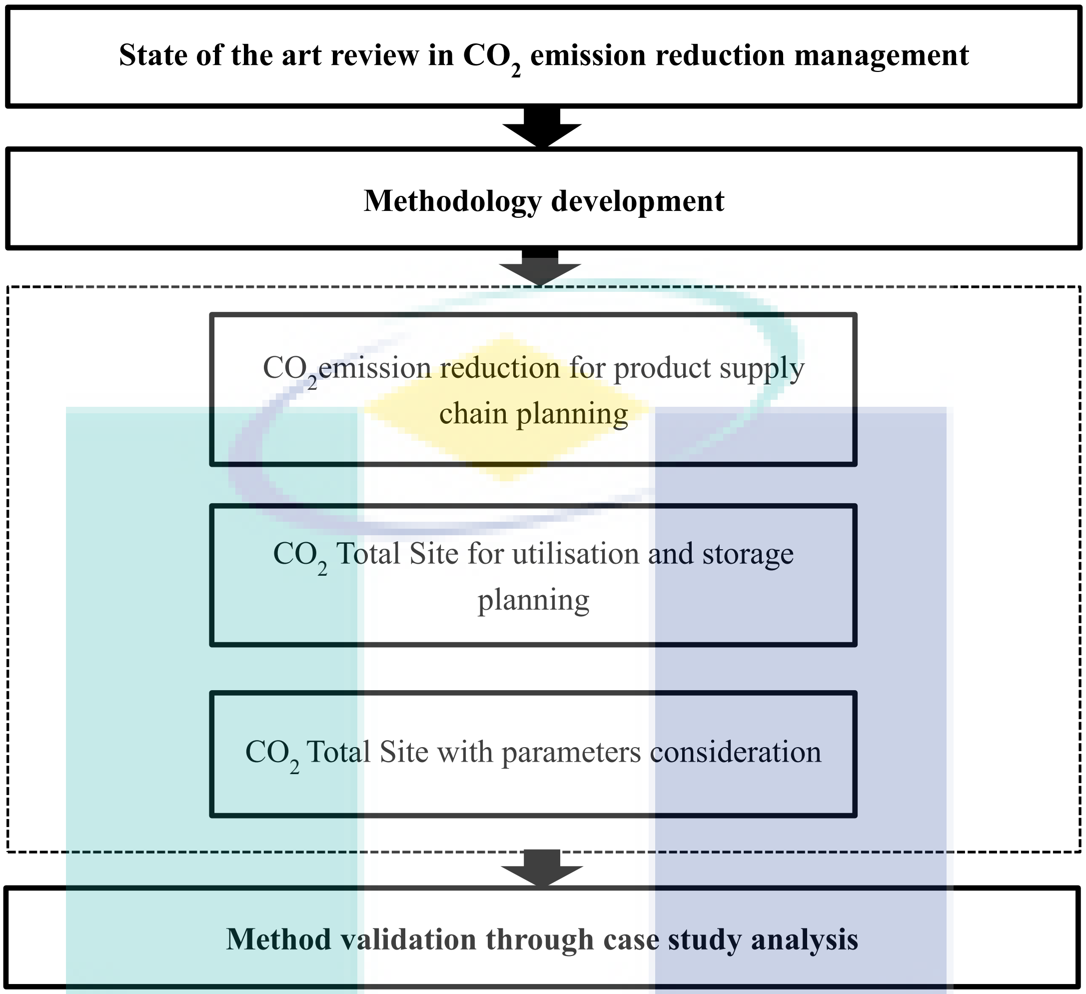


Figure 3.1: Process flow of the research

3.2 Problem Background

In order to achieve environmental sustainability, it is a challenge to develop appropriate methods or tools to manage the evolving field of supply chain. Despite that, the closed loop concepts have provided a holistic view for green supply chain management. The PI methodology also has proven remarkable track record pertaining to environmental sustainability research, especially for emission reduction. Strategies including fuel switching, waste to energy conversion, product reuse or recycling could contribute to CO_2 emission reduction, however this may not be economically feasible to be applied to all processes or phases in the supply chain. Phases are classified as stages involved throughout the supply chain e.g., material acquisition phase, processing phase, manufacturing phase, product distributor phase and many more. Each product may involve different stages of supply chain. Therefore, an appropriate approach is proposed to prioritise reduction strategies to the phases in supply chain that contributes to the highest CO_2 emission. Selection of suitable and effective technologies of strategies is important to improve the profitability and sustainability for an industry. A tool to systematically plan and prioritise strategies with consideration of investment cost using a PI-based on PA graphical approach is developed in this study.

3.3 Methodology Development

PI-based on PA for CO_2 management is an extension of existing PA tools for CO_2 emission reduction. The focal point of PA concept in CO_2 emission reduction is to meet the desired or targeted emissions limit by allowing the allocation of energy resources, chemical process changes or cleaner production options. In this study, the CO_2 management methodology will emphasis on product supply chain and Total Site CO_2 utilisation and storage.

Figure 3.2 illustrates an overall methodology development framework for this research study. The procedure starts with CO_2 emission reduction for product supply chain planning which will be described in detail in Chapter 4. For this step, graphical approach is implemented align with a combination of CO_2 management hierarchy and extended Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) for cost-effective CO_2 reduction planning of a product supply chain. Insight graphs are constructed to evaluate the CO_2 emission at each phase, identify CO_2 emission hotspot phase, screening the viable CO_2 reduction strategies and analyse the most suitable and cost-effective strategies of SHARPS. After selected strategies have been established, the data of remaining CO_2 emission will be brought forward to the next Chapter 5 to be used as a potential of CO_2 sources for Total Site planning.

The CO_2 emission reduction planning is further continued for the development of CO_2 Total Site utilisation and storage management in Chapter 5. Numerical method of CO_2 Utilisation Storage-Problem Table Algirithm (CUS-PTA) is proposed for this methodology. The key target for this method is to maximise the recovery of CO_2 for future utilisation while minimising CO_2 to be sent to storage. A centralised header is introduced to integrate the CO_2 emission from industries and/or plants for optimal CO_2 utilisation before being permanently stored.

The CO_2 Total Site planning is further developed in Chapter 6 with consideration of purification and pressure drop in CO_2 transportation via pipeline. This method is introduced to improve the system design of Total Site CO_2 integration. Detailed development of each methodology is presented in the respective chapters.

The PI-based on PA methodology offers systematic and optimal CO_2 emission reduction strategy for CO_2 management. The CO_2 emission can be reduced while providing a systematic CO_2 management including the strategy to demonstrate low CO_2 emission planning of a product, cost-effective screening for CO_2 reduction strategies, Total Site planning for CO_2 supplies and demands, maximum CO_2 utilisation, minimum CO_2 storage as well as improved Total Site CO_2 transportation. The above-mentioned strategies are vital to improve the CO_2 emission reduction planning.

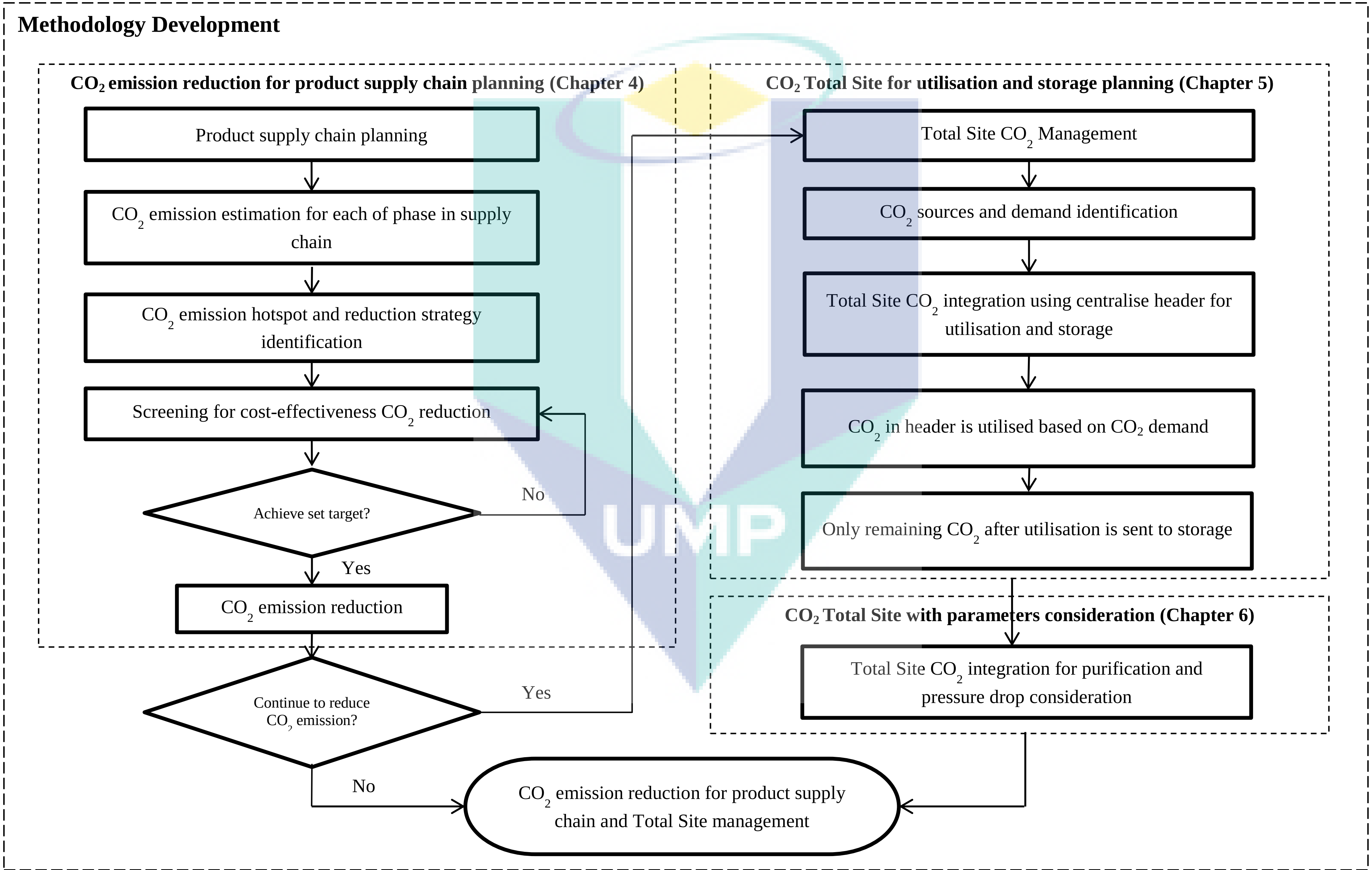


Figure 3.2: Framework of the study

3.4 Data Collection

Data collection starts with a baseline study of a specific product supply chain that need CO_2 emission reduction. In this study, a product of palm cooking oil is selected which need CO_2 emission reduction throughout its supply chain. A product development will undergo several phases throughout its supply chain. The phases need to be identified at first, in order to initiate the CO_2 emission reduction planning from beginning of raw material acquisition or extraction, product transformation until transportation of finished product to end user. Energy generated or consumed at each processing phase will emit CO_2 emission. Thermal and electricity are example of energy forms that are being consumed or generated in various industrial processes. For palm cooking oil, the phases of its supply chain from cradle to gate including (i) palm plantation, (ii) palm oil mill, (iii) palm oil refinery, and (iv) transportation. Any processing data activity that contribute to the CO_2 emission need to be extracted carefully. The information on amount of energy resources whether it is being generated or consumed as well as the quality are extracted from literature or other resources. The data will be used to demonstrate the developed methodology. Appropriate data on CO_2 emissions will be calculated based on the type of energy resources used.

Few general guidelines on data extraction for CO_2 emission reduction are as follows;

(i) For palm plantation phase, at first, amount of production basis need to be determined. From this amount, next is to extract energy or materials used/produced in the palm plantation site. For example, a production basis of 100t/y of palm cooking oil is assumed. For this much of product amount, appropriate data on energy or resources used to produce this amount will be extracted such as machinery used in plantation. To run the plantation machinery, diesel in unit (L/y) is consumed thus this will emit certain amount of CO_2 emission. Therefore, CO_2 emission in unit (tCO_2/y) is calculated based on the total of diesel consumption. Such data can be extracted from related literature.

(ii) For other phases of palm oil mill and palm oil refinery, energy and material used/produced in these phases need to be extracted such as fuel and electricity utilisation. Resources such as diesel fuel (t/y) and grid electricity (MW) are extracted from related literature. Note that additional data on emission factor for diesel in unit (tCO_2/t) and for Malaysia grid in unit (tCO_2/MW) are also need to be extracted in order to calculate the CO_2 emission in unit (tCO_2/y).

(iii) For transportation phase, any transport used to transfer the material or product within the inter-phase is taken into account. The fuel consumption is based on the product or material weight (t/y) to be transported over certain range of distance (km). The CO_2 emission factor in unit (tCO_2/tproduct-km) is extracted from related literature to calculate CO_2 emission (tCO_2/y).

(i) Data extraction of CO_2 sources and demands for case study analysis are also extracted from related literature whenever needed. Other quality measures related to CO_2 emission calculation such as CO_2 flow rate (t/y), CO_2 purity (%), or header purity (%) are extracted from related literature or assumption is made whenever needed.

3.5 Data Analysis

For data analysis, the developed methods will be validated and analysed via various case studies to establish the desired results concerning minimisation of CO_2 emission. The data analysis will be discussed in details in the following chapter.

CHAPTER 4

CO_2 EMISSION REDUCTION FOR PRODUCT SUPPLY CHAIN

4.1 Introduction

A product supply chain is defined as a system that involves a few of product development phases from the beginning of raw materials processing into a finished product that is delivered to the end-user that involve raw material acquisition or extraction, product transformation, and transportation. A graphical tool for CO_2 emission reduction of a product supply chain was developed. This tool is a combination of CO_2 management hierarchy and extended Systematic Hierarchical Approach for Resilient Process Screening (SHAPRS) (Wan Alwi and Manan, 2006). SHAPRS is developed for cost-screening tool for the design and retrofit of minimum water network. It has been further extended for planning of CO_2 reduction throughout supply chain to remain the competitive and profitability in product development but the main concern is to focus on the reduction of environmental emissions. It has been used to screen various CO_2 reduction options that would give the highest savings within the payback period or investment criteria.

4.2 Problem background

CO_2 is emitted throughout product's supply chain activities, i.e., during material acquisition, product manufacturing, transportation and disposal. Strategies including fuel switching, waste to energy, product reuse, energy-efficient motor or CO_2 sequestration can contribute to CO_2 emission minimisation in the different phases of supply chain. Applying CO_2 emission reduction strategies in all supply chain activities will be extremely in high CO_2 emission reduction but may cost in a very high investment and unacceptable payback period. This could prevent inhibit industries to produce a product with low or zero emissions. Selection of suitable and effective technologies for emission reduction is important to improve its profitability and sustainability for an industry. Therefore, applying systematic CO_2 reduction strategies using PI-based on PA graphical approach to hotspot emission of a product supply chain will be more efficient to be implemented and has not considered yet in the related studies. It also could encourage the involved industries in product development to actualise their exertion in CO_2 emission minimisation.

4.3 Methodology

The tool is performed in seven steps. The first step involves the specification of product type, supply chain's phases and basis of production amount. The CO_2 emission is then calculated at each of the phases and a product diagram is constructed to identify which phase that contribute the highest CO_2 emission. Then, this is followed by identification of potential CO_2 emission reduction strategies and investment using CO_2 management hierarchy as a guide for selection. A plot of investment versus CO_2 reduction is developed and constructed to measure the optimal CO_2 emission reduction from the implementation of potential emission reduction strategies.

Next is the cost-screening for the implemented strategies using SHARPS to meet cost-effective emission reduction within desired investment limit or payback period. After the strategies are selected, the product supply chain is redrawn to summarise the final result of CO_2 emission reduction. Following to this step, if the diagram still map the next highest contributor of CO_2 emission, the procedure need to be repeated from step 4 until step 7. If none, the procedure end at this point. This work implements a targeting technique to maximise CO_2 emission reduction, as well as applying the emission hierarchy management from the view of economic perspectives. The objective of this work is to establish the maximum CO_2 emission reduction align with the cost-effective strategy throughout the product supply chain. Figure 4.1 represents the step-by-step procedures for the CO_2 emission reduction management throughout a product supply chain.

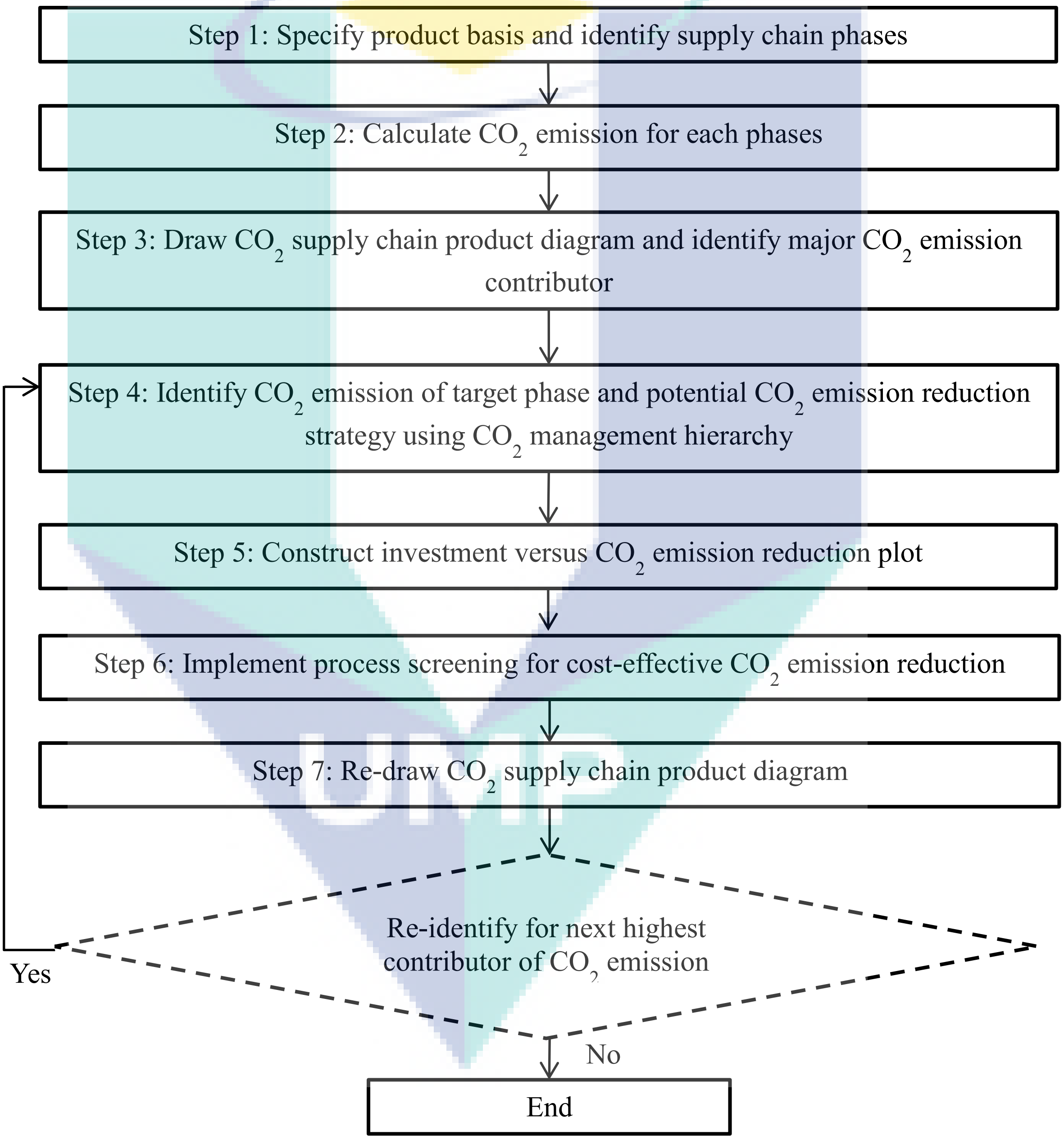


Figure 4.1: CO_2 emission reduction of a product supply chain

4.3.1 STEP 1: Specify Product Basis and Identify Supply Chain Phases

Any product development will emit certain amount of CO_2 emission throughout its supply chain phases. For this step, first is to set the specific product basis in order to calculate the CO_2 emission and next is to identify the product's supply chain phases. Phases of the supply chain are the processes flow involved from beginning until to end use of the product. Note that any specified product may have different phases (*i*,…, *i*+*n*) of its supply chain. Then select a basis value of the production e.g., raw material (ton) per product (ton).

4.3.2 STEP 2: Calculate CO_2 Emission for Each Phases

Each phase contributes different amount of CO_2 emissions. CO_2 emissions generated from possible sources are calculated using Equation (4.1), as adapted from Kaewmai *et al.* (2012). In this work, the emission emitted is calculated based on the energy sources used for each of the phases and cumulative (cum) CO_2 emission is the total CO_2 emission of supply chain, see Equation (4.2).

$$ES_{CO_2,\, i} = (x \times EF)_i \tag{4.1}$$

$$Cum\ ES_{CO_2} = \Sigma (x \times EF)_i \tag{4.2}$$

where;

x is the consumption amount (e.g., thermal, kg fuel or electricity usage, kWh) and EF is the emission factor of energy sources (CO_2 per unit).

4.3.3 STEP 3: Draw CO_2 Supply Chain Product Diagram and Identify Highest CO_2 Emission Contributor

After CO_2 emission for each phase was evaluated, next is to construct a plot of CO_2 supply chain product diagram. The diagram plot cumulative CO_2 emission from starting point of early phase until end of phase. CO_2 emission produced throughout the phases of the supply chain can be observed from the diagram. The highest bar in the diagram indicates the highest emission that is emitted by the respective phase. Once the respective phase been identified, there is a need for product planner or product owner to put an effort or work on strategies to reduce the CO_2 emission emitted in the respective phase. Alternatively, they could also identify any changes that need to be employed so as to reduce the CO_2 emission.

4.3.4 STEP 4: Identify Potential CO_2 Emission Reduction Strategy using CO_2 Management Hierarchy

Among the potential strategies to reduce CO_2 emission is via the CO_2 management hierarchy that consists of three levels including conservation, source switching, and sequestration levels which are arranged in order of increasing priority (Lawal *et al.*, 2012). The hierarchy is illustrated as in Figure 4.2. Three levels of hierarchy are considered which are Level 1 is the implementation of energy conservation measure, Level 2 concentrates on source switching to renewable energy (e.g., biomass, solar, wind), and Level 3 involves performing sequestration for CO_2 removal from the atmosphere and depositing it in natural "carbon sinks" such as trees, ocean-water, or geological reservoirs. Consideration of each level would provide a friendly-environmental design guidelines for prioritising options in CO_2 reduction management.

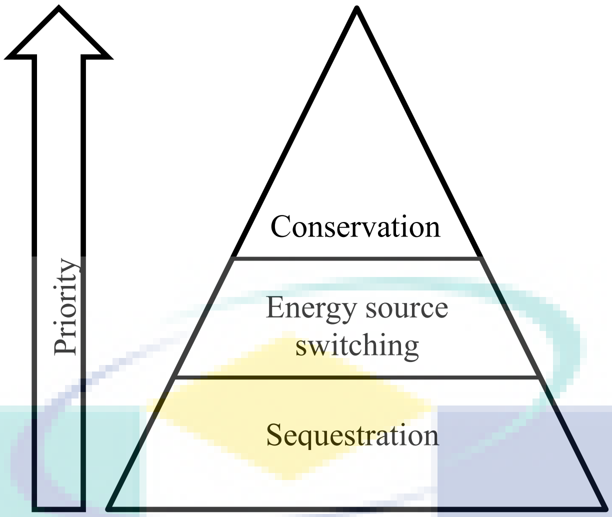


Figure 4.2: CO_2 management hierarchy

The example of energy conservation measure (Level 1) includes better housekeeping, switching to more energy-efficient equipment, and improving equipment efficiency. Conservation opportunities may not require any cost, or may require between a low to high cost of investment. Source switching (Level 2) involves switching to a cleaner energy source e.g., use of renewable energy, or fuel switching while sequestration (Level 3) involves the removal of CO_2 from the atmosphere e.g., deposition of the CO_2 into "CO_2 sinks" such as reservoir storage. After identified the potential CO_2 emission reduction strategies according to the CO_2 management hierarchy, each of the strategy must be compiled with estimated investment requirement and the percentage of CO_2 emission reduction (R). The R value represents an individual contribution of CO_2 emission reduction for each of the strategy ($R^{strategy}$) that can be obtained by using Equation (4.3).

$$R^{strategy}{}_j = [S^{implement}{}_{ij} / Q^{base\ case}{}_i] \times 100\% \quad (4.3)$$

where;

$Q^{base\ case}$ is CO_2 emission before reduction and $S^{implement}$ is CO_2 emission reduction when a strategy is implemented. The $Q^{base\ case}$ and $S^{implement}$ are estimated using Equation (4.1). After $R^{strategy}$ is calculated, the value of CO_2 emission reduction ($CO_2{}^R$) of a strategy can be determined using Equation (4.3). Meanwhile for an individual investment for each of the strategy ($INV^{strategy}$) is estimated using Equation (4.4).

$$CO_2{}^R{}_{j+n} = R^{strategy}{}_j \times [\sum ES_{CO2i} - CO_2{}^R{}_j] \tag{4.4}$$

where;

$\sum ES_{CO2i}$ is a total CO_2 emission of a phase from a product supply chain.

$$INV^{strategy}{}_j = CC_j \times E_j \tag{4.5}$$

where;

CC is the estimated capital cost (USD/unit) and E is the utilised amount to ensure that the strategy proposed would result in CO_2 emission reduction.

4.3.5 STEP 5: Construct Investment versus CO_2 Emission Reduction (ICO_2R) Plot

After determining selected potential of CO_2 reduction strategies that could be applied to the phase, the cumulative investment (*Cum INV*) and cumulative CO_2 emission reduction ($Cum\ CO_2{}^R$) are calculated using Equation (4.6) and Equation (4.7) in order to construct the investment versus CO_2 emission reduction (ICO_2R) plot. The objective of this plot is to visualise the correlation between the investment and the result of emission reduction. It is also to estimate the payback period of selected strategies that need to be implemented.

$$Cum\ INV^{strategy} = INV^{strategy}{}_n + INV^{strategy}{}_{n+1} \tag{4.6}$$

$$Cum\ CO_2{}^R = CO_2{}^R{}_n + CO_2{}^R{}_{n+1} \tag{4.7}$$

For strategy selection, note that the $R^{strategy}$ value is a guide to select the best strategy to be implemented based on CO_2 emission management hierarchy priority and heuristic guidelines. Following are three heuristics that need to be considered before construct the ICO_2R plot.

Heuristic 1: If there are several strategies which can be implemented in parallel, then select the strategy with no cost, followed by a low to high investment cost.

Heuristic 2: If there is more than one possible strategy options for the same appliance, and if only one strategy can be selected, the option which gives the highest CO_2 reduction is chosen regardless of the investment cost.

Heuristic 3: If there are strategies that give the same amount of CO_2 reduction, the lowest investment option should be chosen.

A generic plot of ICO_2R is shown as in Figure 4.3 and m represents the gradient of the plot, which can be calculated using Equation (4.8). The value of m is important as it gives the correlation between investment (y-axis) and CO_2 reduction (x-axis). As the value of m is increasing, the plot will become more steeper hence give lower emission reduction and vice versa. Therefore it is not worth to implement the strategy with highest value of m.

$$m_{n+1} = \frac{INV^{strategy}{}_{n+1} - INV^{strategy}{}_{n}}{CO_2{}^{R}{}_{n+1} - CO_2{}^{R}{}_{n}} \qquad (4.8)$$

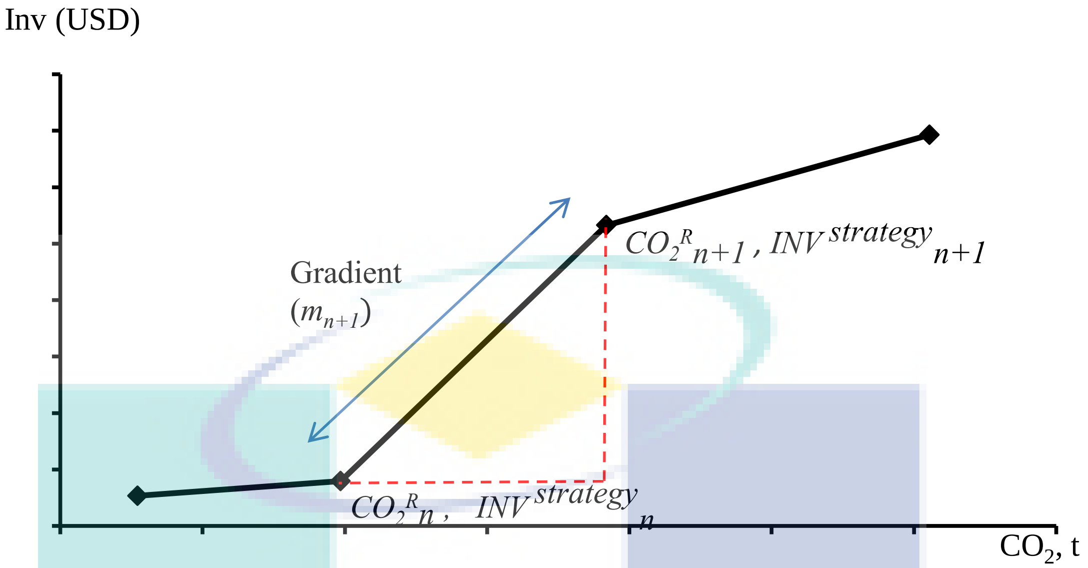


Figure 4.3: Generic plot of ICO_2R

From the plot, the estimation gradient (*m*) of the graph represents the investment cost (refer to capital cost) per annual CO_2 emission reduction. Then, total payback period (*TPP*) in year (*y*) is identified using Equation (4.9). *TPP* is the total payback period for all CO_2 reduction strategies that have been implemented in the phase.

$$TPP = \sum [m_j \times \frac{EF}{CS}] \tag{4.9}$$

where;

where *m* is the slope for each strategy, *EF* is the emission factor of the energy source, and *CS* is price per unit for energy saving or recovery of strategy implemented..

However, if the *TPP* of implemented strategies resulted in an uneconomically viable investment or payback period, following step is required to screen the most cost-effective CO_2 reduction strategies. Otherwise, if the selected strategies are beneficial to the economy, it can be proceed further for CO_2 reduction.

4.3.6 STEP 6: Implement SHARPS to Select Cost-Effective Strategy

The Systematic Hierarchical Approach for Process Screening (SHARPS) was introduced by Wan Alwi and Manan (2006) and the tool was employed to screen the best alternative for cost-effective strategy. The $TPP^{initial}$ is calculated for all potential strategies based on the CO_2 management hierarchy. This value before implementation of SHARPS is compared with TPP^{set}, which is the desired *TPP* that has been set by the plant owner, planner or designer. If $TPP^{initial}$ is equal or lower than TPP^{set}, the strategies can be implemented as it is considered to be economically feasible. However, if $TPP^{initial}$ is higher than TPP^{set}, then SHARPS technique is implemented to achieve the TTP^{after}. SHARPS consists of two strategies as follows:

SHARPS Strategy 1 is based on intensification, which involves reducing the length of the steepest gradient by implementing only part of any option until the new TPP^{after} and INV^{after} are equal or lower to TPP^{set} and INV^{set}.

SHARPS Strategy 2 is based on substitution. The option that causes the steepest gradient is replaced with another option that gives the next highest CO_2 reduction but with a lesser investment cost.

All potential CO_2 emission reduction options must be systematically screened using SHARPS technique, so as to achieve the highest CO_2 emission reduction within a desired *TPP* (TPP^{set}) as specified by the plant owner. This screening technique is applied until the TPP^{set} is achieved.

4.3.7 STEP 7: Re-Draw CO_2 Supply Chain Product Diagram

The CO_2 supply chain product diagram is redrawn with improved CO_2 emission management and then the diagram is used to determine the overall CO_2 emission of the product supply chain. The next contribution phase is determined and this technique will be applied to achieve zero or near to zero CO_2 emission target. In the following section, a few case studies will be demonstrated to validate the developed methodology of CO_2 emission reduction for the product supply chain.

4.4 Case Study 1

A product of palm cooking oil is used as a case study to demonstrate the use of the proposed methodology to reduce CO_2 emission throughout its supply chain. This case study involves gate to gate system boundary, which is emission data is collected from the plantation until palm cooking oil distributor. The emission data is based on CO_2 emission and does not include other GHG emissions for this study.

4.4.1 Palm Oil Product Supply Chain

In general, palm oil is used as cooking oil because of its ability to maintain its properties under high temperature. The palm cooking oil product supply chain is illustrated based on identified system boundaries by the Malaysia palm oil industry supply network as shown in Figure 4.4 and can be divided into four tiers: (1) plantations; (2) mills; (3) refineries; and (4) manufacturers of different palm-based products and also transportations (Choong and McKay, 2014) as shown in Figure 4.4.

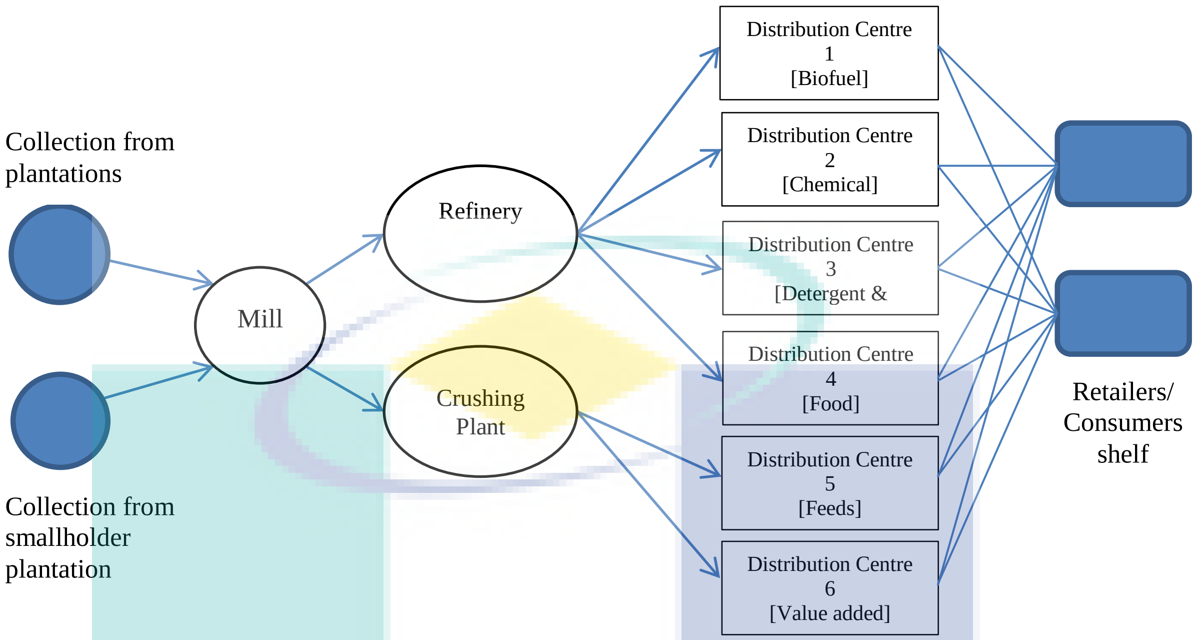


Figure 4.4: The Malaysia palm oil industry supply network (Choong and McKay, 2014)

Palm oil industry is primarily divided into two main processes, which are upstream and downstream process. The upstream process plantation operation involves nursery, seedling preparation, and palm oil mill processing. Meanwhile, the downstream process produces palm oil for food or non-food products. Fresh fruit bunch (FFB) of palm are extracted from the plantation and sent to palm oil mill industry for crude palm oil (CPO) production. CPO is sent to refinery process and distributed for food or non-food production. These products are then ready for consumer. Note that products that are being transported from one location to another required transportation. Therefore, transportation need to be taken in account.

4.4.2 STEP 1: Specify Product Basis and Identify Supply Chain Phases

An assumption of 100 t per y palm cooking oil is being made as the product basis for this analysis. The boundary of limitation for palm cooking oil supply chain is specified from plantation to product distribution centre and has been divided into six phases in sequence: (1) palm plantation, (2) transportation plantation to mill, (3) palm oil mill, (4) transportation mill to refinery, (5) palm oil refinery and (6) transportation to cooking oil distributor centre in a linear path assumption. Figure 4.5 shows the boundary of palm cooking oil supply chain phases. Therefore, several assumptions of palm oil production scenario based on Stichnothe and Schuchardt (2011) are used in this study, which are:

1. Production of 1 t palm cooking oil requires 6.6 t FFB and 1.32 t CPO.
2. 1 t CPO requires 5 t of FFB and FFB yield are assumed to be 20 t/ha, which equals 4 t/ha of CPO.
3. 1 ha of land represents 140 palm trees and 1 palm tree represents 140 kg FFB.
4. All infrastructure and capital goods are excluded.
5. The steam demand is 400 kg per t of FFB and boiler efficiency is approximate 72 %.
6. Total electricity demand for palm oil mill is 81 MJ per t of FBB.
7. Fibres and shells are used as fuel and provide heat and electricity through combined heat and power (CHP) of the palm oil mill.
8. The palm oil residues are considered as burden free apart from transport emissions.
9. The composting plant is located close to the palm oil mill, where electricity is produced on-site from biomass (fibers and shells); can supply 97.6% of the electricity consumption; whereas, only 2.4% comes from the grid.
10. Compost is returned to the palm oil plantation and utilised according to the fertiliser demand.
11. No land use change occurs.
12. Toxicity effect of pesticide application is not considered.
14. Byproducts from oil refining processes are not considered.
13. Only CO_2 emission has been evaluated.
14. Emission from fertilizer is neglected.

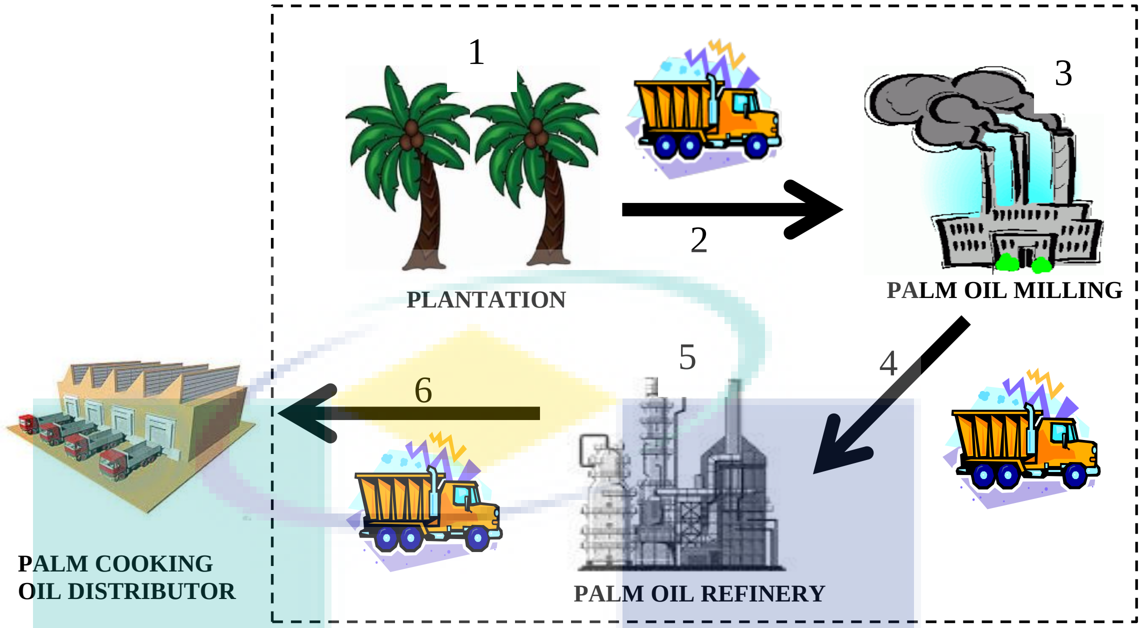


Figure 4.5: Boundary system for palm cooking oil product supply chain

4.4.3 STEP 2: Calculate CO_2 Emission for Each Phases

CO_2 emission for each phase was calculated on the basis of 100 t per y production of palm cooking oil. CO_2 emissions generated from each source of energy are calculated using Equation 4.1, as adapted from Kaewmai *et al.* (2012).

a. Plantation

CO_2 and N_2O emissions are the main contributors which contributing 55% and 45% accordingly due to the fertilizers and diesel used for plantation machinery (Stichnothe and Schuchardt, 2011). However, site preparation, fertilizer and pesticides are excluded and Table 4.1 shows calculated CO_2 emission using Equation 4.1. For 100 t per y palm cooking oil production, 20.04 t per y CO_2 were emitted throughout palm plantation phase.

Table 4.1: CO_2 emission in palm plantation

Production		**FFB, t**	**Diesel consumption, L/y**	**CO_2 emission, tCO_2/y**	
100 t/y palm cooking oil	Machinery use in plantation	1	11	0.03	(Stichnothe and Schuchardt, 2011)
		660	7260	20.04	Calculated

b. Palm Oil Mill

This is the extraction process to produce CPO which consists of sterilization, fruit separation, digestion, oil extraction and oil purification processes. At this phase, FFB was identified as raw material and the CPO was considered as the main product. Myriad amount of water and energy are required to convert FFB into CPO and at this phase, abundant amount of by-products such as palm oil mill effluent (POME), empty fruit bunch, palm kernel shell and mesocarp fiber in palm oil mills are being produced.

In most conventional palm oil mills in Malaysia, most of the fibers generated are used internally as a solid fuel fed to the boiler for steam and electricity generation while POME has been treated using ponding system (most common due to its low capital requirement) and the number of ponds will be dependent on the capacity of the palm oil mill (Chin *et al.*, 2013). The input-output diagram flow rates of the palm oil mill normalized to the rate of t FFB is illustrated in Figure 4.6 and Table 4.2 indicates the energy and material that is being used and produced in the palm oil mill for 100 t per y palm cooking oil. Based on the data provided, the CO_2 emission can be calculated.

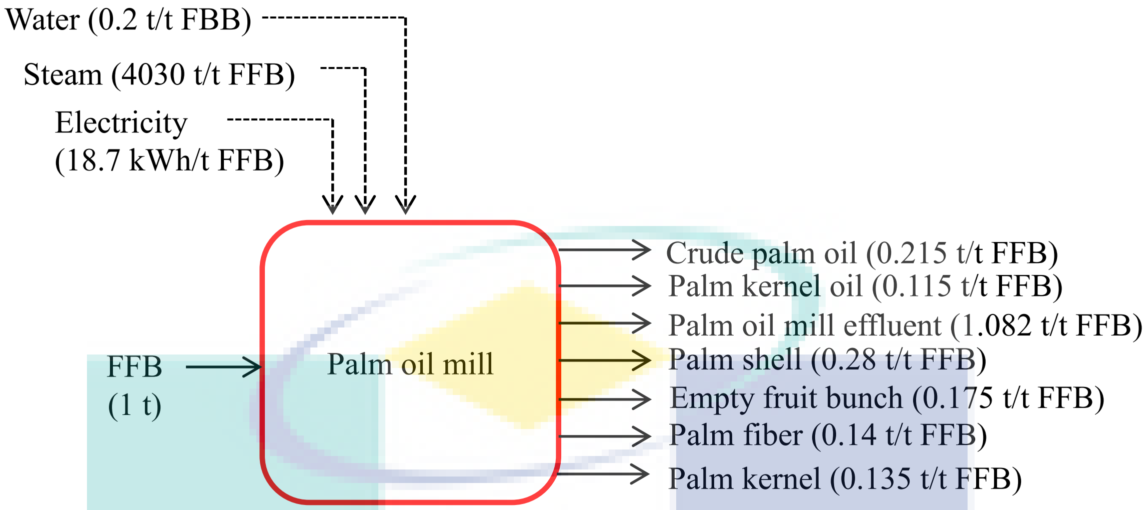


Figure 4.6: In and out diagram for palm oil mill (Kasivisvanathan *et al.*, 2012)

Table 4.2: Energy and materials used in palm oil mill

Energy and materials used/produce in palm oil milling	**Unit per t FFB**		**For per 660 t FFB (100 t/y palm cooking oil production)**		
	Value	**Unit**	**Value**	**Unit**	
Diesel consumption	38.96	L	25.71×10^3	L	(Stichnothe and Schuchardt, 2011)
Electricity consumption	18.7	kWh	12 342	kWh	(Patthanaissaranukool *et al.*, 2013)
Electricity generation from fiber	18.3	kWh	12 078	kWh	
Crude palm oil	0.215	t CPO	141.9	t CPO	(Muhammad *et al.*, 2015)
Palm kernel oil	0.115	t PKO	75.9	t PKO	
Palm shell	0.28	t shell	184.8	t shell	
Empty fruit bunch	0.175	t EFB	115.5	t EFB	
Palm kernel	0.135	t PK	89.1	t PK	
Palm fiber	0.14	t PPF	92.4	t PPF	
Palm oil mill effluent	1.082	t POME	714.12	t POME	

For the 100 t per y palm cooking oil production, Equation (4.1) was used and resulted 248.95 t per y of CO_2 emission throughout this phase as shown in Table 4.3.

Table 4.3: CO_2 emission in palm oil mill

Energy and materials used/produce in palm oil milling	**Unit per 100 t/y palm cooking oil**		**CO_2 emission factor , tCO_2 /unit**	**CO_2 emission, tCO_2/y**
	Value	**Unit**		
Diesel consumption	25.71 $\times 10^3$	L	0.00276 t CO_2 / L	70.96
Electricity consumption	12.34 $x10^3$	kWh	0.00075 t CO_2/kWh	9.26
Palm shell	184.8	t shell	0.55 t CO_2 / t	101.64
Empty fruit bunch	115.5	t EFB	0.51 t CO_2 / t	58.905
Palm kernel	89.1	t PK	0.43 t CO_2 / t	38.313
Palm fiber	92.4	t PPF	0.54 t CO_2 / t	49.896
Total				**328.973**

The CO_2 emission factor of palm shell, EFB, palm kernel and fiber are adapted from Klaarenbeeksingel (2009), diesel consumption from Kaewmai *et al.* (2012) and electricity consumption from Matthew *et al.* (2011).

c. Palm Oil Refinery

Palm oil refinery is necessary for removal of impurities that are obtained in CPO. This process is done through a series of refining process without destroying the beneficial components such as vitamins and antioxidants. CPO can be refined either using physical or chemical refining process to produce refined, bleached and deodorized palm oil (RBDPO) or neutralized, bleached and deodorized palm oil (NBDPO). However, more than 95% of the CPO in Malaysia is refined through preferred physical route, as it reduces the loss of triglycerides, minimizes chemical usage and water consumption, and enables recovery of high quality free fatty acids (FFA), hence leads to considerable reduction of environmental impact (Haslenda and Jamaludin, 2011). Thermal equipments and electrical appliances are the major energy use in the vegetable oil refining process which corresponded to 95.23 % thermal, 4.65 % electrical and 0.12 % other (workers' energy) of the net energy input (Sulaiman *et al.*, 2012). Table 4.4 lists the CO_2 emission of thermal equipements and electrical appliances for 100 t per y of palm cooking oil production using Equation (4.1), with the assumption of diesel fuel being utilised for steam generation and electricity being supplied from the grid.Figure 4.7 shows the overall in-out process diagram for palm oil refinery.

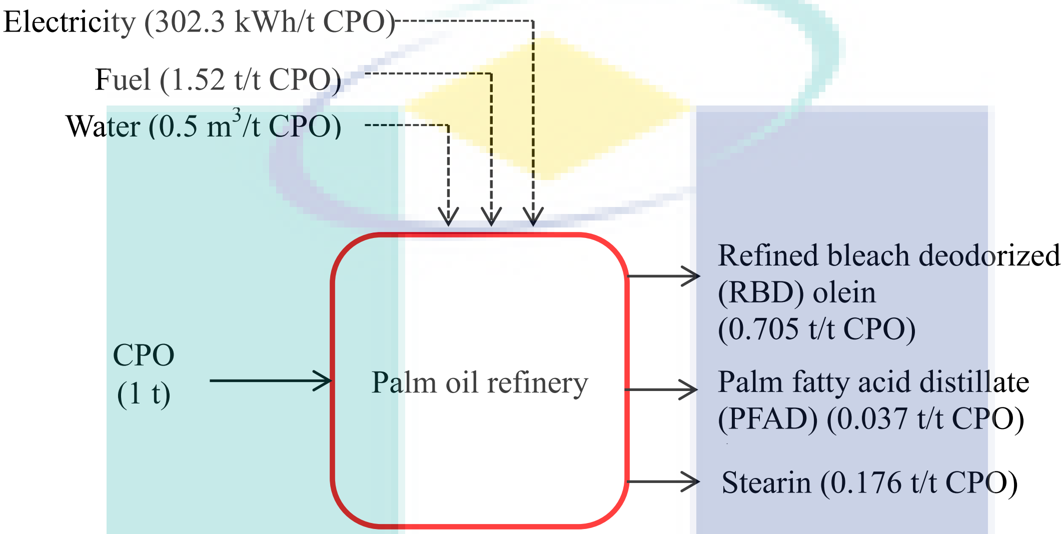


Figure 4.7: In and out diagram for palm oil refinery (Haslenda and Jamaludin, 2011)

Table 4.4: Energy utilisation in palm oil refinery

Type	**Equipment**	**Diesel fuel for energy utilisation, t/y** (Sulaiman *et al.*, 2012)	**Emission factor for diesel, tCO_2/ t** (NRE, 2014)	**Emission, tCO_2/y**
Thermal (steam)	Bleacher	63.67	3.186	202.85
	Deodorizer	151.93	3.186	484.05
	Total	**215.60**	-	**686.90**
Electrical		**Grid electricity utilisation, MW** (Sulaiman *et al.*, 2012)	**Emission factor for Malaysia grid electricity, tCO_2/MW** (NRE, 2014)	**Emission, tCO_2/y**
	Pump	38.14	0.741	28.26
	Motor	4.75	0.741	3.52
	Total	**42.89**	**-**	**31.78**
Total for thermal and electrical emission				**718.68**

d. Transportation

Transportationto transfer material or product to each of the phases has a significant contribution towards CO_2 emission. The area of palm cooking oil supply chain is estimated within 200 km radius using a medium and heavy duty truck. Table 4.5 shows the CO_2 emission result in transportation using modified Equation (4.1). For transportation, the consumption amount of fuel use (x) is depends on product or material weight to be transported and distance.

Table 4.5: CO_2 emission for transportation inter-phase supply chain

No phase (supply chain)	**Transportation inter-phase**	**Product (t/y)**	**Distance (km)**	**CO_2 emission factor , (tCO_2 / t product-km)** (US EPA, 2011)	**CO_2 emission, (tCO_2/y)**
2	Plantation to palm oil mill	660	30	0.000184	3.64
4	Mill to palm oil refinery	132	100		2.43
6	Refinery to product distributor centre	100	200		3.68

Below is the summarised table (Table 4.6) of CO_2 emission for each phases of palm cooking oil product supply chain and total CO_2 emission through palm cooking oil production. The total CO_2 emission throughout the supply chain is the cumulative of each phases of CO_2 emission, which resulted 1077.44 tCO_2 per y.

Table 4.6: Summary of CO_2 emission at each of palm cooking oil supply chain phases

Phase	**CO_2 emission (tCO_2/y)**
1. Plantation	20.04
2. Transportation (Plantation to palm oil mill)	3.64
3. Palm oil mill	328.97
4. Transportation (Mill to palm oil refinery)	2.43
5. Palm oil refinery	718.68
6 Transportation (Refinery to product distributor centre)	3.68
Total	**1077.44**

4.4.4 STEP 3: Draw CO_2 Supply Chain Product Diagram and Identify Highest CO_2 Emission Contributor

Based on the CO_2 emission calculation of each phases in palm cooking oil supply chain, the CO_2 emission supply chain diagram of 100 t per y palm cooking oil production was constructed as in Figure 4.8. The diagram shows the pattern of CO_2 emission throughout the palm cooking oil supply chain. Product planner or product design can focus direct on the highest emission phase as well as put an effort to do significant changes to reduce CO_2 emission.

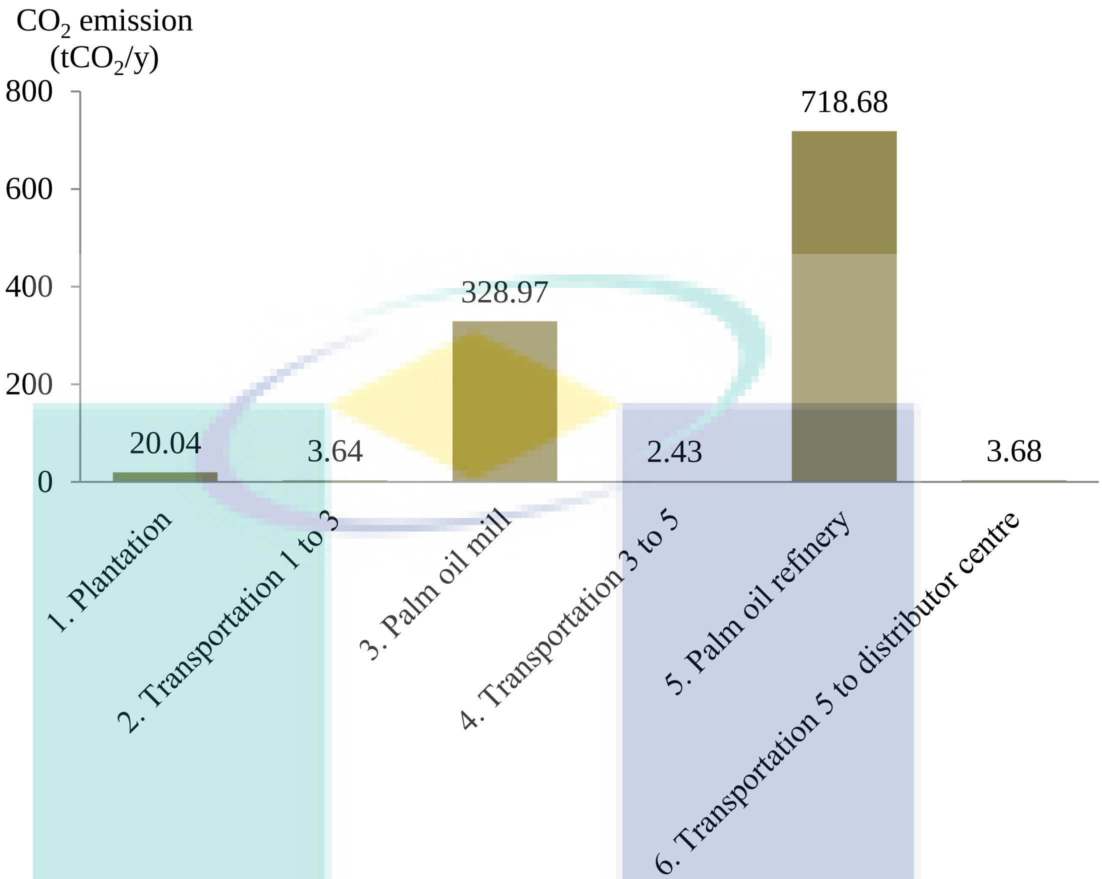


Figure 4.8: CO_2 emission palm cooking oil supply chain diagram

From Figure 4.8 it can be observed that the two phases that have the highest CO_2 emission are the palm oil refinery (phase 5) followed by palm oil mill (phase 3). Palm oil refinery, which contributed the highest CO_2 emission (718.68 tCO2/y), is thus further investigated followed by palm oil mill (if required for emission reduction).

4.4.5 STEP 4: Identify Potential CO_2 Emission Reduction Strategy using CO_2 Management Hierarchy

Several potential options or technologies that are available to reduce CO_2 emission in palm oil refinery (phase 5) have been listed according to the CO_2 management hierarchy. As 100 t of palm cooking oil production is used as a basis (see Table 4.4 for details), it requires 2.66 x 10^6 t per y of steam (with the assumption of 1 t diesel could produced 12 340 t steam) and 42.89 MW per y of electricity power. These resources are accounted as contributors to the CO_2 emission in palm oil refinery. Fuel to steam conversion is measured in this case for CO_2 reduction strategies screening that used steam as indicator. Any conversion for related fuel to steam production is referring to Table 4.7.

Table 4.7: Fuel factor for steam production

Fuel	Conversion steam production		Reference
Diesel	1 t	12,340 t steam	
Biomass (kernel shell, palm fiber, empty fruit bunch)	1 t	3,590 t steam	Prasit and Maneechot (2014)
Biogas	1 t	100 t steam	(Chiodo *et al.*, 2017)

The strategies are listed according to the CMH levels of conservation, source switching, and sequestration levels that are arranged in order of increasing priority. Strategies that can be implemented in parallel are represented by numbers e.g., T1 and T2 while for strategy that can only be implemented one at a time is represented by alphabets after the numbers e.g., a, b, c; T3a or T3b. Table 4.8 shows the list of CO_2 reduction strategy options for palm oil refinery. Two categories have been divided upon energy sources of the plant. The potential strategies are chosen based on the CMH level and the individual contribution of CO_2 emission reduction for each strategy ($R^{strategy}$) is estimated by using Equation (4.2). Note that the value obtained in Table 4.8 is obtained using Equation (4.1) to (4.3) and details explained in Section 4.3.4. There are several options or technologies available to reduce CO_2 emission in the palm oil refinery plant. Process heat recovery e.g. insulating the steam pipe, changing to energy-efficient motor, utilising waste and changing to renewable sources are examples of measures to reduce energy utilisation and generation. For example, the maximised heat recovery and thermal efficiency had resulted in reduction of heating and cooling loads in palm oil processing (Wan Alwi et al. 2009).

Table 4.8: Emission reduction strategies based on CO_2 management hierarchy

Fuel utilisation								
Level	**Option (T)**	**Assumption of saving/ reduction percentage**		**Recovery/ Saving Amount, E_i**		**$S^{implement}$ tCO_2**	**$Q^{base\ case}$ tCO_2**	**$R^{strategy}$**
Conservation	T1. Waste heat recovery	8% steam recovery	Wan Alwi *et al.* (2009)	2.13×10^5 t steam recovery	17.26 t diesel	54.99	718.68	7.7%
Conservation	T2. Steam pipe insulation	5% steam recovery	Wan Alwi *et al.* (2009)	1.33×10^5 t steam recovery	10.78 t diesel	34.34	718.68	4.8%
Source switching	T3a. Biomass (direct combustion)	-	-	740.95 t biomass	-	363.07	718.68	50.5%
	T3b. Biomass (thermal conversion)	-	-	740.95 t biomass	-	363.07	718.68	50.5%
Source switching	T4. Biogas	-	-	2,660 t biogas	-	106.4	718.68	14.8%
Sequestration	T5. CO_2 capture	45% emission capture	Rubin *et al.* (2015)	323.41 tCO_2 capture	-	323.41	718.68	45%
Sequestration	T6. Plant trees	2% emission reduction	Kongsager *et al.* (2012)	2000 tree	-	14.37	718.68	2%
Electricity utilisation								
Level	**Option**	**Assumption of saving/ reduction percentage**		**Recovery/ Saving Amount, E_i**		**$S^{implement}$ tCO_2**	**$Q^{base\ case}$ tCO_2**	**$R^{strategy}$**
Conservation	T7. Use energy efficient motor	45% energy saving	US DOE (2014)	19.3 MW	-	14.30	718.68	2%
Conservation	T8. Heat pump	60 % energy saving	Popa *et al.* (2016)	25.73 MW	-	19.07	718.68	2.7%
Source switching	T9. Install commercial solar cell	75 % energy saving	Fu *et al.* (2017)	32.17 MW	-	23.84	718.68	3.3%

4.4.6 STEP 5: Construct Investment versus CO_2 Emission Reduction Plot (ICO_2R)

The main objective of ICO_2R plot is to estimate the payback period of strategies that have been implemented. Furthermore, the plot can visualise the estimated investment of applied CO_2 reduction strategies. In order to obtain the plot, each of the investment for each strategy is required. In this case, the investment of the CO_2 reduction strategy is based on the capital cost and has been listed as in Table 4.9 and the investment of each strategy is calculated using Equation (4.4).

Table 4.9: Investment for each of reduction CO_2 strategy

Fuel				
CO_2 Reduction Strategy	**Steam recovery/ Utilised Amount, E_i**	**Capital cost (CC) USD/unit**	**INV (USD)**	**References**
T1. Waste heat recovery	2.13×10^5 t steam recovery	0.3/ t steam recovery	63,900.00	Wan Alwi *et al.* (2009)
T2. Steam pipe insulation	1.33×10^5 t steam recovery	0.25/t steam recovery	33,250.00	Wan Alwi *et al.* (2009)
T3a.*Biomass (direct combustion)	740.95 t biomass	120/t biomass	88,914.00	Kasivisvanathan *et al.* (2012)
T3b.*Biomass (thermal conversion)	740.95 t biomass	180/t biomass	133,371.00	Kasivisvanathan *et al.* (2012)
T4. Biogas	2,660 t biogas	28.8/t biogas	766,080.00	Kasivisvanathan *et al.* (2012)
T5. CO_2 capture	323.41 tCO_2 capture	3075/t CO_2 capture	994,485.75	Rubin *et al.* (2015)
T6. Plant trees	2000 trees	12/ tree	24,000.00	Kongsager *et al.* (2012)
Electricity				
CO_2 Reduction Strategy	**Unit required**	**Capital cost (CC) USD/unit**	**INV (USD)**	**References**
T7. Use energy efficient motor	4 unit motors	1304 /motor	5,220.00	US DOE (2014)
T8. Heat pump	2 unit pumps	45 303 /pump	90,620.00	Popa *et al.* (2016)
T9. Install commercial solar cell	-	1150 /saving MW	32,060.00	Fu *et al.* (2017)

Potential CO_2 emission reduction strategies from fuel and electricity will be arranged accordingly to CMH guideline as to provide environmentally friendly in CO_2 management. First level or conservation level would be prioritised followed by source switching and sequestration as described in Section 4.3.4. Then used three heuristics guideline in order to select the applicable strategies. Furthermore, in order to construct the ICO_2R plot, *Cum INV* and *Cum* CO_2^R are required using Equation (4.6) and (4.7) which the value CO_2^R is calculated using Equation (4.3). Table 4.10 summarised the selection of strategies and significant parameters before constructing the ICO_2R plot.

Table 4.10: Investment and CO_2 reduction for selected strategiefor palm oil refinery

Level	Option (T)	INV (USD)	Cum INV (USD)	CO_2^R	Cum CO_2^R
Conservation	T1. Waste heat recovery	63,900.00	63,900.00	54.990	54.990
Conservation	T2. Steam pipe insulation	33,250.00	97,150.00	31.712	86.702
Conservation	T7. Use energy efficient motor	5,220.00	102,370.00	319.269	405.971
Conservation	T8. Heat pump	90,620.00	192,990.00	46.296	452.268
Source switching	T3a. Biomass (direct combustion)	88,914.00	281,904.00	134.589	586.856
Source switching	T4. Biogas	766,080.00	1,047,984.00	19.516	606.373
Source switching	T9. Install commercial solar cell	32,060.00	1,080,044.00	2.246	608.618
Sequestration	T5. CO_2 capture	994,485.75	2,074,529.75	49.528	658.147
Sequestration	T6. Plant trees	24,000.00	2,098,529.75	1.210	659.357

Figure 4.9 shows the plotted graph of ICO_2R that lists all the potential strategies from the data of Table 4.10. The cummulative of $INV^{strategy}$ for potential strategies is USD 2,098,529.75 and the maximum CO_2 reduction is 659.357 CO_2 t/y. Furthermore, each of the gradient is calculated using Equation (4.9) and summarised as in Table 4.11.

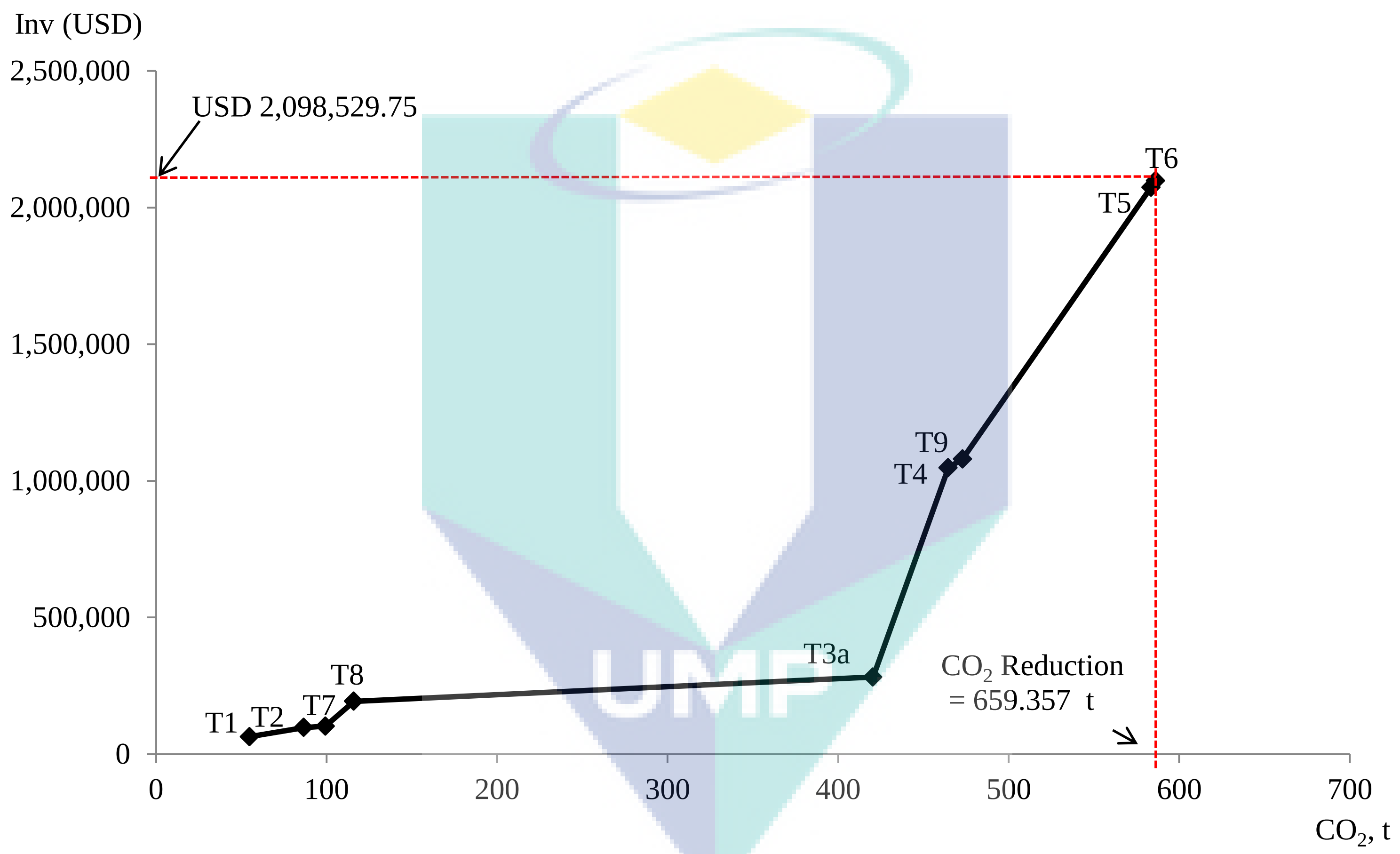


Figure 4.9: ICO_2R plot for potential CO_2 reduction strategies

The example for gradient calculation is demonstrated for T1 and T2 point. At T1 gradient or precisely m_{T1}, the origin point is assumed to be at (0,0) axis in order to calculate the gradient. This value, however is an assumption as it was the starting point of the plot. These calculation are then applied to determine the value of each strategy gradient and are summarised in Table 4.11.

The example of m_{T1} estimation using Equation (4.8):

$$m_{T1} = \frac{INV^{strategy}{}_{T1} - INV^{strategy}{}_{T0}}{CO_2{}^{R}{}_{T1} - CO_2{}^{R}{}_{T0}}$$

$$m_{T1} = \frac{63{,}900.00 - 0}{54.990 - 0}$$

$$m_{T1} = 1162.03$$

The example of m_{T2} estimation using Equation (4.8):

$$m_{T2} = \frac{INV^{strategy}{}_{T2} - INV^{strategy}{}_{T1}}{CO_2{}^{R}{}_{T2} - CO_2{}^{R}{}_{T1}}$$

$$m_{T2} = \frac{97{,}150.00 - 63{,}900.00}{86.702 - 54.990}$$

$$m_{T2} = 1048.48$$

Table 4.11: Gradient of each point in ICO_2R plot

Strategies	Gradient (m_i)
T1. Waste heat recovery	1,162.03
T2. Steam pipe insulation	1,048.48
T7. Use energy efficient motor	16.35
T8. Heat pump	10,732.98
T3a. Biomass (direct combustion)	578.45
T4. Biogas	34,369.78
T9. Install commercial solar cell	7,574.32
T5. CO_2 capture	17,817.57
T6. Plant trees	17,591.01

Next is the calculation for TPP of the plot using Equation (4.9) using the data from Table 4.12. Table 4.13 shows the results of TPP with the capital investment for each of the selected strategies.

Table 4.12: Price and emission factor for energy source

Source of energy	Price per unit energy (USD/unit)	Reference	EF kg CO_2 /kg
Diesel	0.57/kg	(Saari *et al.*, 2016)	3.186
Biogas	0.5/m^3	(Lambert, 2017)	0.4
Palm shell	0.057/kg	(Kasivisvanathan *et al.*, 2012)	0.0055
Empty fruit bunch	0.006/kg	(Andiappan *et al.*, 2015)	0.0051
Palm kernel	0.05/kg		0.0043
Palm fiber	0.022/kg		0.0054
Electricity industrial (Grid)	0.09/kWh		0.75/kWh

Table 4.13: Investment of strategies and payback period

Strategy	$INV^{strategy}$ (Capital Cost, USD)	TPP
T1. Waste heat recovery	63,900.00	1.00
T2. Steam pipe insulation	33,250.00	1.08
T7. Use energy efficient motor	5,220.00	1.13
T8. Heat pump	90,620.00	1.14
T3a. Biomass (direct combustion)	88,914.00	1.19
T4. Biogas	766,080.00	2.41
T9. Install commercial solar cell	32,060.00	2.84
T5. CO_2 capture	994,485.75	2.93
T6. Plant trees	24,000.00	5.32
Total	2,098,529.75	19.04

The initial TPP obtained from the plot to achieve maximum CO_2 emission reduction may result uneconomically viable investment or payback period. In this case study of illustrated palm oil refinery, the TPP is 19.04 y, requiring an investment of USD 2,098,529.75 (see Figure 4.7) which is uneconomically viable. This is not practical or cost-effective to be implemented in the plant and this will eventually discourage other industries from implementing the CO_2 reduction strategies. Therefore, screening techniques are pivotal in selecting suitable strategies to be applied that need to be within the desired investment or payback period.

4.4.7 STEP 6: Implement SHARPS to Select Cost-Effective Strategy

In this section, SHARPS techniques are used to screen the strategies to achieve the desired TPP and investment which are known as TPP^{set} and INV^{set}. The TPP ($TPP^{initial}$) and INV ($INV^{initial}$) from the ICO_2R plot before SHARPS strategy implementation are compared with TPP^{set} and INV^{set}. The TPP^{set} for this study is specified as below 4 y ($TPP^{set} \leq 4$ y) with an investment limit of USD 300,000 ($INV^{set} \leq$ USD 300,000). The steepest positive gradient in the ICO_2R plot gives the highest investment per unit of CO_2 reductions and represents the most costly scheme. SHARPS strategies such intensification or substitution can be implemented to the steepest gradient to reduce the investment at possible highest CO_2 emission reduction.

Figure 4.10 shows several strategies that have been eliminated. The strategy of T4, T9, T5 and T6 that are above the target value of investment have been removed. The remain strategies therefore are being claculated for TPP as the TPP^{set} is set ≤ 3 years. Although the remained strategies are below the target value, the TPP however is higher than the TPP^{set} which is 9.16 y. In order to achieve the target limit, T8 which is the highest gradient among the strategies has been eliminated and T1 which is the second steepest is being intensified and the result is shown in Table 4.14 and the new plot is on the Figure 4.11.

Table 4.14: TPP after strategy screening 2

Strategy	$INV^{strategy}$ (Capital Cost, USD)	TPP (y)
T1. Waste heat recovery	38,340.00	0.60
T2. Steam pipe insulation	33,250.00	1.08
T7. Use energy efficient motor	5,220.00	1.13
T3a. Biomass (direct combustion)	88,914.00	1.16
	165,724.00	3.97

Strategies for T1 (intensified at 60%), T2, T7 and T3a accumulated USD 165, 724.00 of the investment cost and total reduction of CO_2 emission is 428.27 t/y which resulted TPP^{after} 3.97 y.

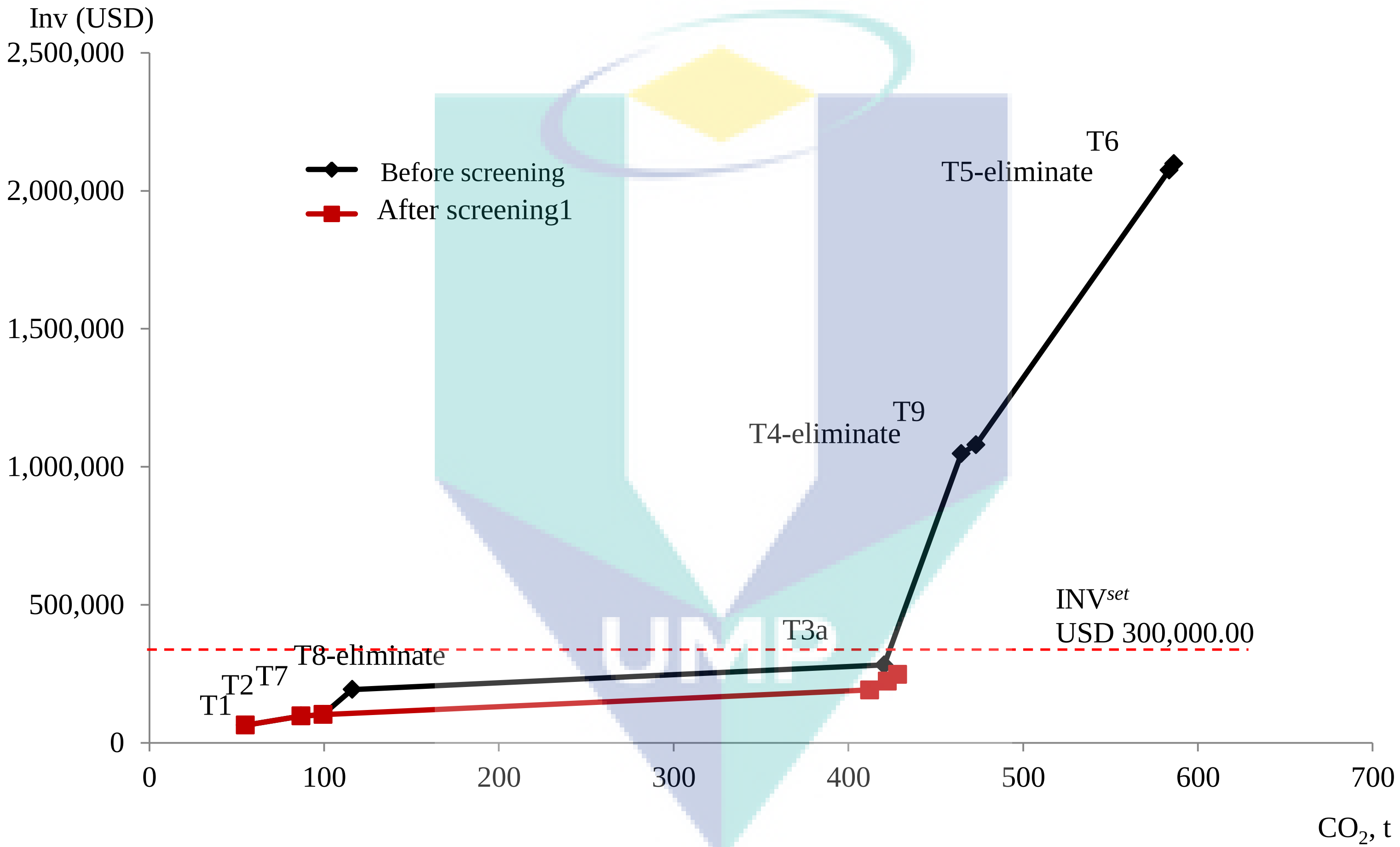


Figure 4.10: The ICO_2R plot screening 1

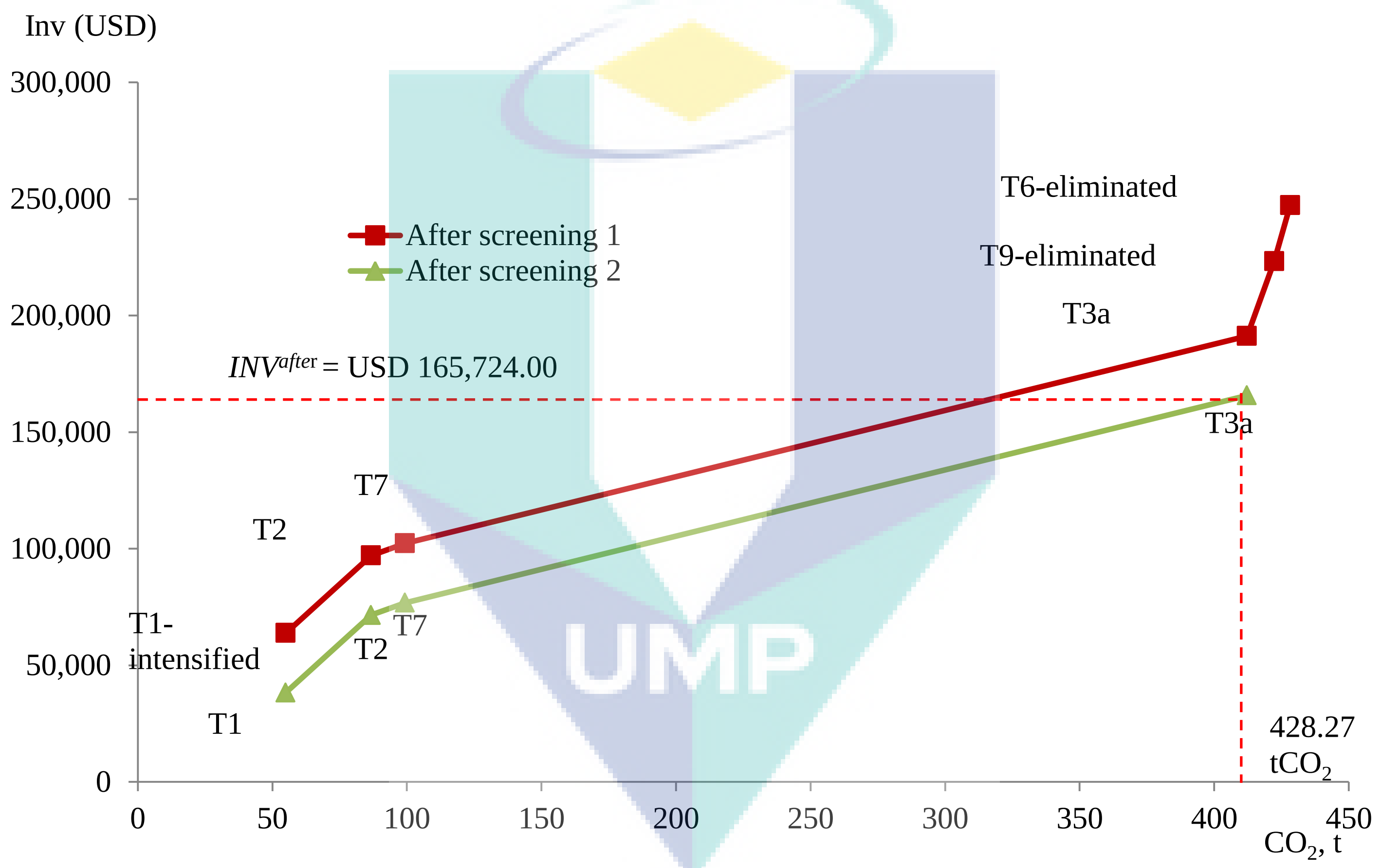


Figure 4.11: The ICO_2R plot screening 2

57% CO_2 reduction of palm oil refinery sector has been achieved within the INV^{set} and TPP^{set}. After applying the strategy, INV^{after} is USD 165,724.00 and TPP^{after} is 3.97 y. For example, T1 or waste heat recovery could be extracted from source such as diesel generator (as the boundary) and this heat can be used for electricity production to be used in the particular plant. It could reduce the dependency on fossil fuel used for electricity generation and simultaneously would reducing CO_2 emission. By implementing strategies T1, T2, T7 and T3a, 428.27 t of CO_2 emission have been reduced from initial value of 718.68 t CO_2 for the palm oil refinery plant. The new CO_2 emission value is recorded 309.03 t/y.

4.4.8 STEP 7: Re-Draw CO_2 Supply Chain Product Diagram

The CO_2 supply chain product diagram is redrawn and CO_2 reduction in palm oil refinery phase is shown in Figure 4.12. Several strategies such waste heat recovery, steam pipe insulation, use of energy efficient motors, and biomass combustion in palm oil refinery plant could result in a major reduction in CO_2 emission. This screening technique is potential to design a plant with suitable emission reduction strategies within a set target of investment and payback period.

Even though CO_2 emission in palm oil refinery is still high but due to limited investment or payback period (usually has been set by the plant owner), the optimal CO_2 reduction could be reduced up to 57% of the total CO_2 emission in palm oil cooking supply chain. Further work is continued to apply CO_2 emission reduction strategy for the second highest CO_2 emission contributor in palm cooking oil supply chain which is palm oil mill phase. Figure 4.12 shows the improved CO_2 supply chain diagram for palm cooking oil product.

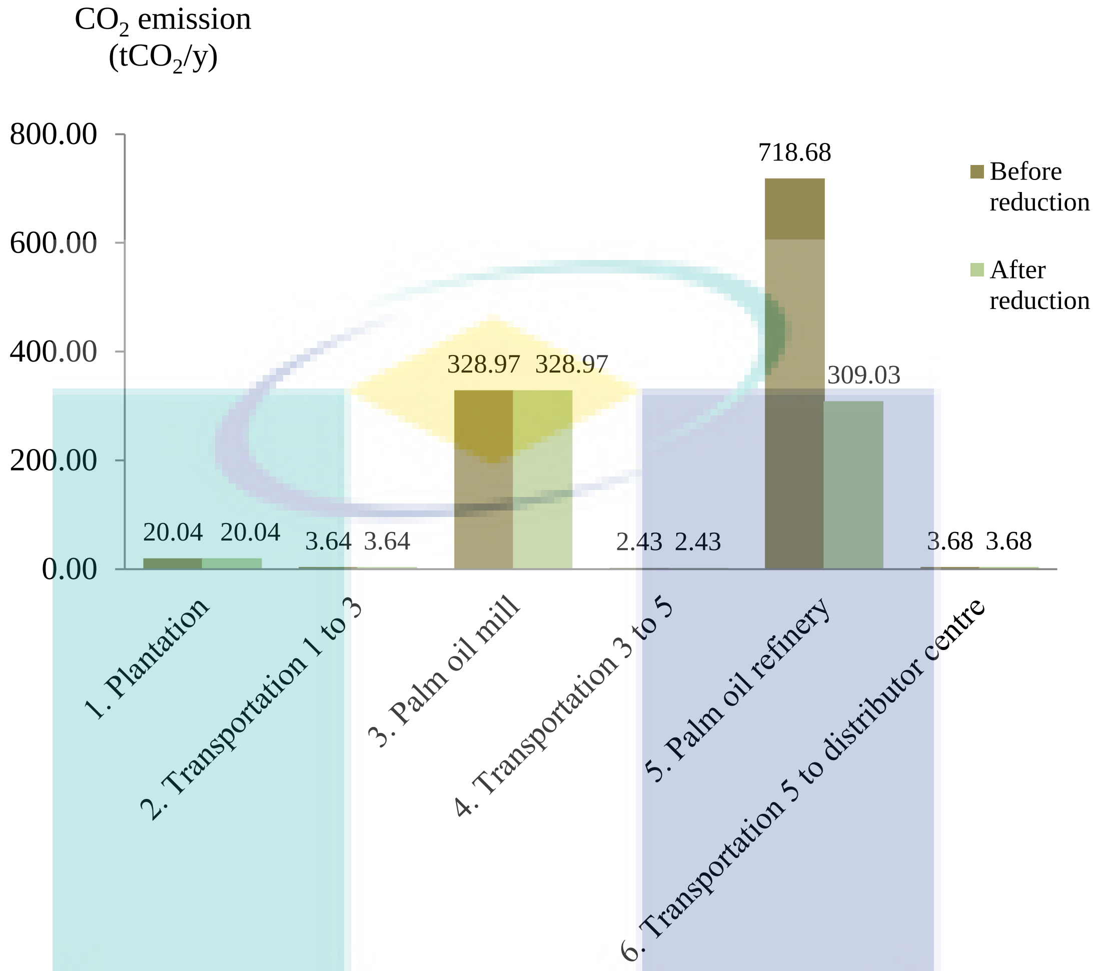


Figure 4.12: The improved CO_2 reduction in palm oil refinery phase

A total of 667.80 t/y CO_2 emissions are emitted throughout the five phases in palm cooking oil supply chain. It can be seen that phase 3 recorded as the new highest CO_2 emission and is identified as the next potential CO_2 emission phase to be reduced in order to achieve lower CO_2 emission or near to zero emission for palm cooking oil production.

4.5 Case Study 2

CO_2 emission planning is demonstrated to the new highest contributor in the palm cooking oil product supply chain which is palm oil mill (phase 3). The emission data is tabulated based on the CO_2 emission and does not includes other GHG emissions for this study.

4.5.1 Palm Oil Mill

Palm oil mill phase has contributed 328.973t/y of CO_2 emission throughout the 100 t/y of palm cooking oil production. Specific emission contributor is stated as in Table 4.2 (Section 4.3.3).

4.5.2 STEP 4: Identify Potential CO_2 Emission Reduction Strategy using CO_2 Management Hierarchy

Several potential options or technologies that are available to reduce CO_2 emission in palm oil mill have been listed according to the CO_2 management hierarchy as shown in Table 4.15. Note that the value obtained in Table 4.15 is calculated by using Equation (4.1) until (4.3) as further explained in Section 4.2.4. The $R^{strategy}$ is used as the indicator and the value is calculated using Equation (4.2).

Table 4.15: Emission reduction strategies based on CO_2 management hierarchy in palm oil mill

Fuel utilisation							
Level	**Option (T)**	**Assumption of saving/ reduction percentage**	**Recovery/ Saving/ Utilised Amount, E_i**		**$S^{implement}$ tCO_2**	**$Q^{base\ case}$ tCO_2**	**$R^{strategy}$**
Conservation	T1. Waste heat recovery	8% steam recovery	2.13×10^5 t steam recovery	17.26 t diesel	54.99	328.97	16.72%
Conservation	T2. Steam pipe insulation	5% steam recovery	1.33 x 105 t steam recovery	10.78 t diesel	34.34	328.97	10.44%
Source switching	T3a. Pyrolysis	-	481.8 t biomass	-	244.75	328.97	74.40%
	T3b. Gasification	-	481.8 t biomass	-	244.75	328.97	74.40%
Sequestration	T4. CO_2 capture	45% emission capture	148.04 CO_2 captured	-	148.04	328.97	45.00%
Sequestration	T5. Plant trees	2% emission reduction	2000 trees	-	14.37	328.97	4.37%
Electricity utilisation							
Level	**Option**	**Assumption of saving/ reduction percentage**	**Recovery/ Saving/ Utilised Amount, E_i**		**$S^{implement}$ tCO_2**	**$Q^{base\ case}$ tCO_2**	**$R^{strategy}$**
Conservation	T6. Use energy efficient motor	45% energy saving	5.55 MW	-	4.16	328.97	1.27%
Conservation	T7. Heat pump	60 % energy saving	3.33 MW	-	5.55	328.97	1.69%
Source switching	T8. Gas turbine (biomethane)	82% energy saving	10.12 MW	-	7.59	328.97	2.31%
Source switching	T9. Install commercial solar cell	75 % energy saving	9.26 MW	-	6.94	328.97	2.11%

4.5.3 STEP 5: Construct Investment versus CO_2 Emission Reduction Plot (ICO_2R)

Each investment for each strategy is required to plot the ICO_2R. The investment of the CO_2 reduction strategy is based on the capital cost as listed in Table 4.16. and the value are calculated by using Equation (4.4) for strategy investment. Table 4.17 shows the cumulative investment and CO_2 reduction of the strategies after rearranged all potential strategies according to CMH and heuristics guideline in order to construct ICO_2R plot.

Table 4.16: Potential CO_2 reduction strategy for palm oil mill

CO_2 Reduction Strategy	**Steam recovery/ Utilised Amount, E**	**Capital cost (CC) USD/unit**	**INV (USD)**	**References**
T1. Waste heat recovery	2.13 x 10^5 t steam recovery	0.3/ t steam recovery	63,900.00	Wan Alwi *et al.* (2009)
T2. Steam pipe insulation	1.33 x 10^5 t steam recovery	0.25/t steam recovery	33,250.00	Wan Alwi *et al.* (2009)
T3a. Pyrolysis	481.8 t biomass	303/t biomass	145,985.40	Kasivisvanathan *et al.* (2012)
T4b. Gasification	481.8 t biomass	190/t biomass	91,542.00	Kasivisvanathan *et al.* (2012)
T5. CO_2 capture	145.53 tCO_2 capture	3075/t CO_2 capture	447504.75	Rubin *et al.* (2015)
T6. Plant trees	2000 trees	12/ tree	24,000.00	Kongsager *et al.* (2012)
	Unit required	**Capital cost (CC) USD/unit**	**INV (USD)**	
T7. Use energy efficient motor	2 unit motors	1304 /motor	2,608.00	US DOE (2014)
T8. Heat pump	2 unit pumps	45 303 /pump	90,606.00	Popa *et al.* (2016)
T9. Gas turbine (biomethane)	2 unit (500kW)	179,647	359,294.00	Andiappan *et al.* (2015)
T10. Install commercial solar cell	-	1150 /saving MW	10,649.00	Fu *et al.* (2017)

Table 4.17: Investment and CO_2 reduction of the strategy

Level	Option (T)	INV (USD)	Cum INV (USD)	CO_2^R	Cum CO_2^R
Conservation	T1. Waste heat recovery	63,900.00	63,900.00	54.990	54.990
Conservation	T2. Steam pipe insulation	33,250.00	97,150.00	28.604	83.594
Conservation	T6. Use energy efficient motor	2,608.00	99,758.00	3.106	86.701
Conservation	T7. Heat pump	90,606.00	190,364.00	4.090	90.790
Source switching	T3b. Gasification	91,542.00	281,906.00	177.207	267.997
Source switching	T8. Gas turbine (biomethane)	359,294.00	641,200.00	1.407	269.404
Source switching	T9. Install commercial solar cell	10,643.25	651,843.25	1.257	270.661
Sequestration	T4. CO_2 capture	455,216.39	1,107,059.64	26.241	296.901
Sequestration	T5. Plant trees	24,000.00	1,131,059.64	1.401	298.302

The total of $INV^{strategy}$ for potential strategies is USD 1,131,059.64 and the maximum CO_2 reduction is 298.302 CO_2 t/y. Figure 4.14 shows the plotted graph of ICO_2R that lists potential strategies for palm oil mill. In the plot, the INV^{set} has been outlined to visualise selected strategies with an investment limit. For example, the INV^{set} is limited to USD 150,000.00 or below and is specified as equal or below 2 y ($TPP^{set} \leq 2$ y).

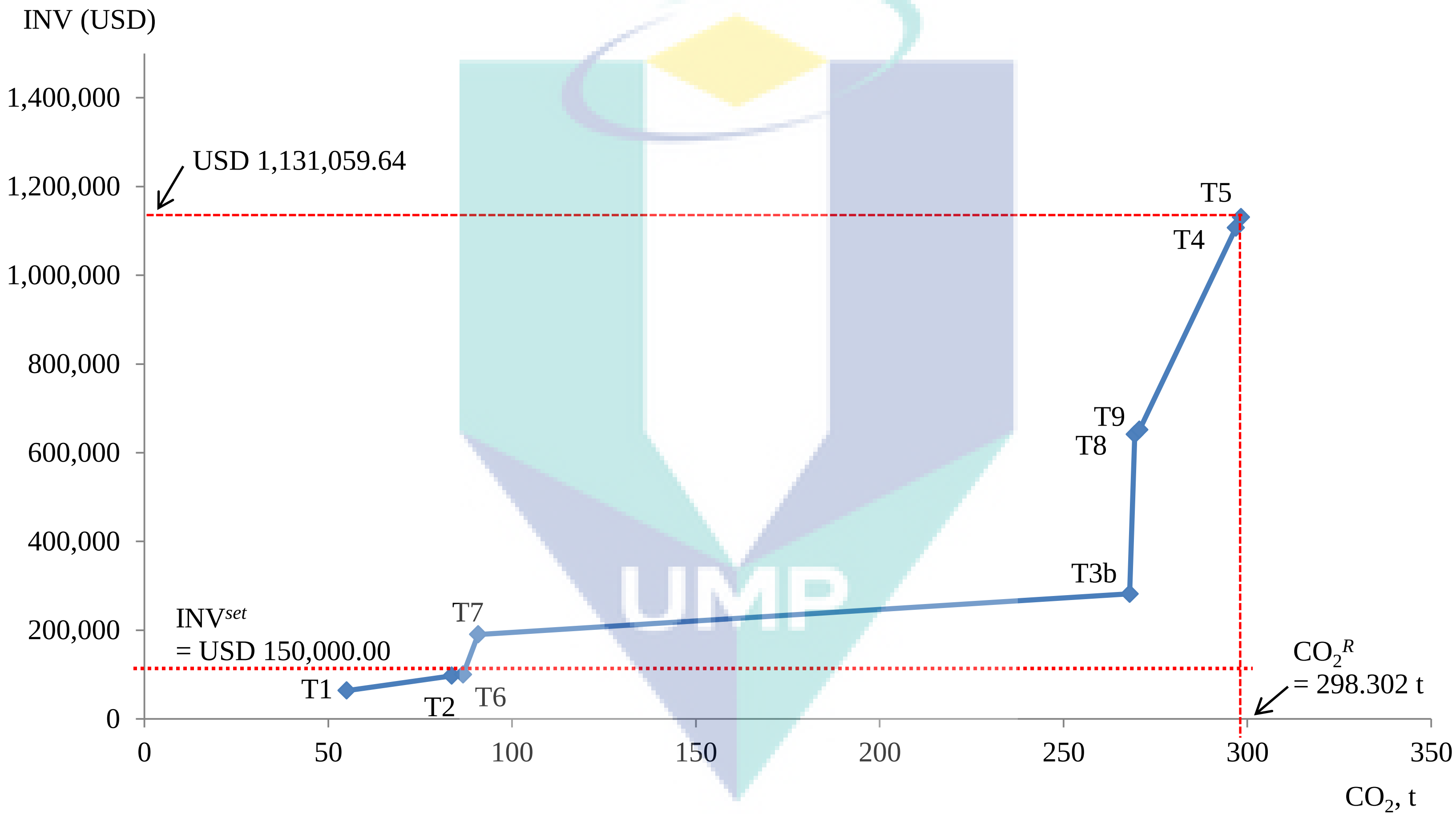


Figure 4.13: ICO_2R plot for CO_2 reduction potential strategies in palm oil mill

4.5.4 STEP 6: Implement SHARPS to Select Cost-Effective Strategy

In order to have optimal CO_2 reduction within the investment and payback period target, SHARPS techniques are further implemented by mapping the plot of gradients. Each gradient for each strategy is calculated using Equation (4.8) and is summarised as in Table 4.18. Details of calculation are explained in Section 4.3.6. Strategies that have high gradient will be eliminated or intensified (follows the rules of SHARPS).

Table 4.18: Gradient of each point in ICO_2R plot (case study 2)

Strategies	**Gradient (m_i)**
T1. Waste heat recovery	1,162.02
T2. Steam pipe insulation	1,162.42
T6. Use energy efficient motor	839.54
T7. Heat pump	22,155.73
T3b. Gasification	516.58
T8. Gas turbine (biomethane)	255,424.22
T9. Install commercial solar cell	8,467.89
T4. CO_2 capture	17,347.83
T5. Plant trees	17,131.36

Even though the strategies are below the investment limit but the TPP value obtained is above the TPP^{set} ($TPP \leq 2$ y) as shown in Table 4.19. TPP is evaluated by using Equation (4.9) for selected CO_2 reduction strategies.

Table 4.19: TPP after strategies screening 1 (case study 2)

Strategy	**INV^{strategy} (Capital Cost, USD)**	**TPP (y)**
T1. Waste heat recovery	31,950.00	0.50
T2. Steam pipe insulation	16,625.00	0.60
T6. Use energy efficient motor	2,608.00	1.34
T3b. Gasification	91,542.00	1.36
	142,725.00	3.80

Figure 4.15 shows the plot of ICO_2R after further used of SHARPS strategies such substitution or elimination and intensification to achieve the desired TPP. The graphical plot gives the final result TPP^{after2} of 2 y within an investment of USD 120,687.00. This was achieved by eliminating the steepest positive gradient, which is T8 (the most costly option) followed by elimination of T7 (next steepest gradient), T4, T9, T5 and intensified T1 and T2 to give a significant payback period. After applying the screening techniques, several CO_2 reduction strategies were identified to achieve the targeted payback period of equal or below 2 y with an investment limit below USD 150,000.00. The resulting set of strategies include T1 (waste heat recovery), T2 (installation of steam pipeline insulation) and T3b (biomass gasification). The implemented SHARPS strategies resulted an overall CO_2 reduction of 81% (266.15 t CO_2), by combining 3 selected strategies and applying them to the system.

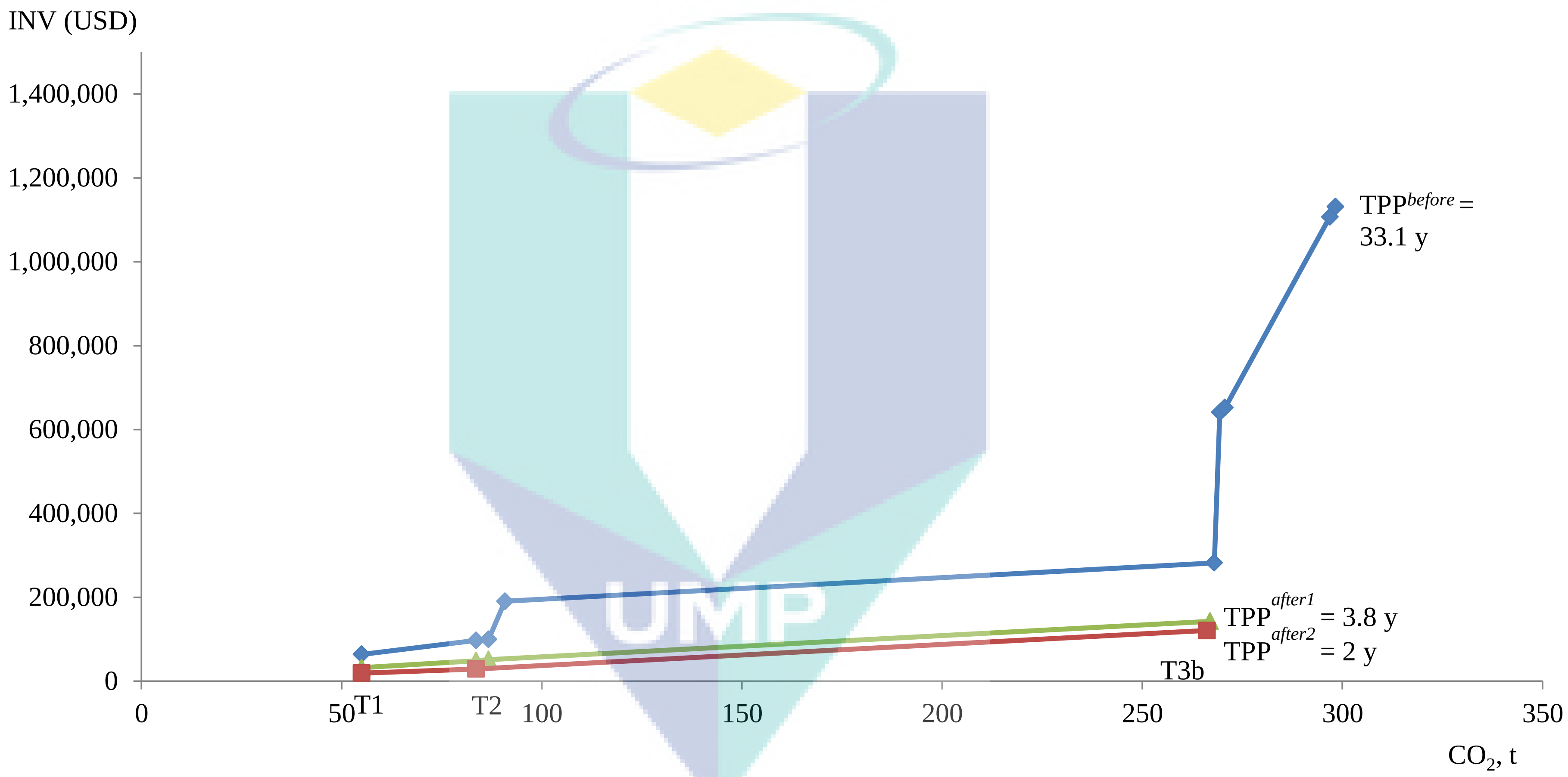


Figure 4.14: The ICO_2R plot for palm oil CO_2 reduction strategy screening

4.5.5 STEP 7: Re-Draw CO_2 Supply Chain Product Diagram

After applying the CO_2 emission reduction strategy with SHARPS screening, CO_2 emission in palm oil mill has been reduced to 62.82 t/y. The CO_2 supply chain product diagram is redrawn as shown in Figure 4.16. The CO_2 emission of 667.80 t/y from total palm cooking oil supply chain has been reduced to 401.65 t/y after implemented the CO_2 strategies at different phases of supply chain. In this case, two phases which are palm oil refinery and palm oil mill have been analysed to implement the selected CO_2 reduction strategies. The result has indicated that a holistic CO_2 emission reduction management throughout the product supply chain has been successfully developed for systematically planning with the cost-effective CO_2 reduction strategies.

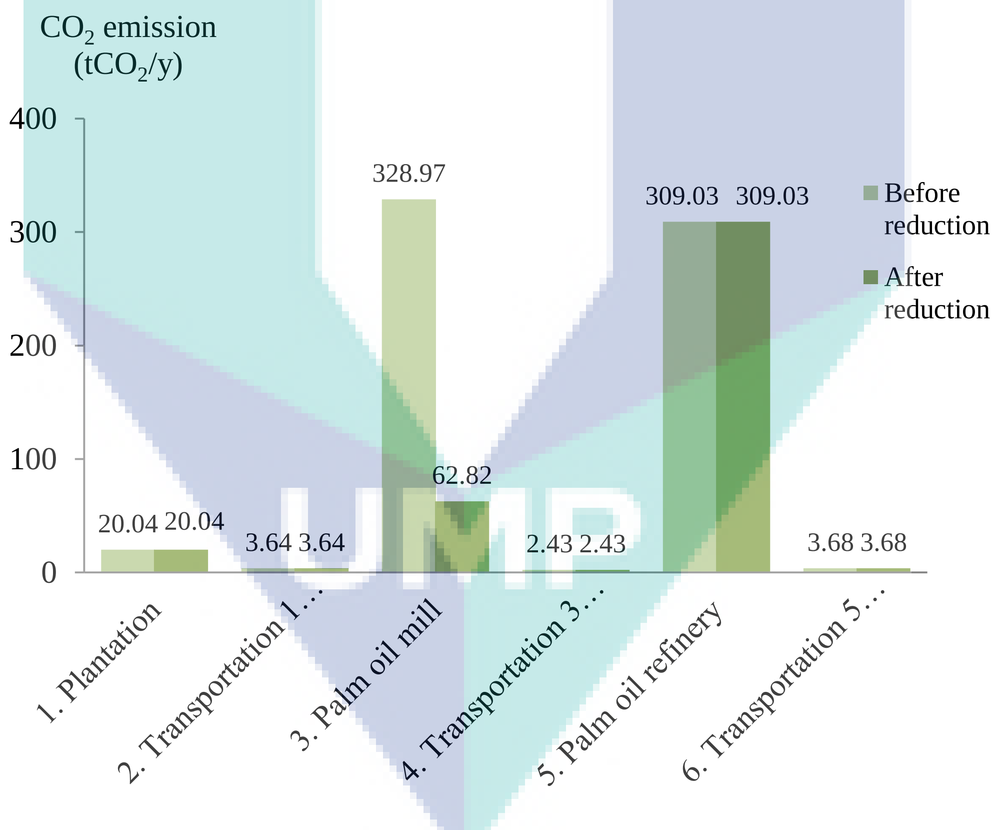


Figure 4.15: The CO_2 reduction in palm oil mill phase

4.6 Conclusion

CO_2 reduction management throughout the product supply chain has been developed successfully. Figure 4.17 shows the overall result of CO_2 emission reduction for two highest emission contribution phases of the palm cooking oil product supply chain.

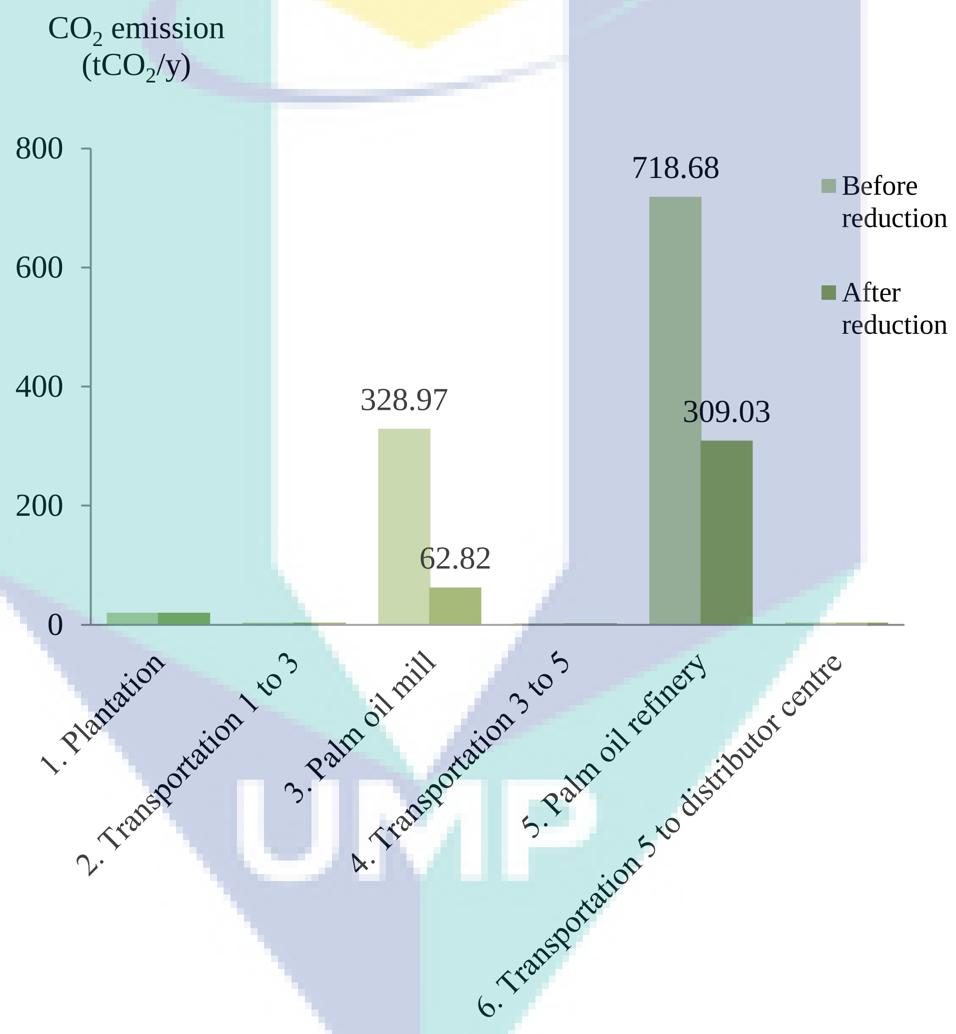


Figure 4.16: CO_2 reduction in palm cooking oil supply chain after implemented CO_2 reduction management

Before implementation of CO_2 reduction strategies, the initial value of total CO_2 emission is 1077.44 t. The value has been reduced to 402 t which are about an overall of 63% reduction. Figure 4.18 illustrates the final result of CO_2 emission supply chain for palm cooking oil production. The remaining CO_2 emission from palm oil refinery and palm oil mill, however could be further reduced later in the next Chapter 5 by using CO_2 Total Site management which is the CO_2 emission end-of-pipe management throughout integrated CO_2 utilisation and storage.

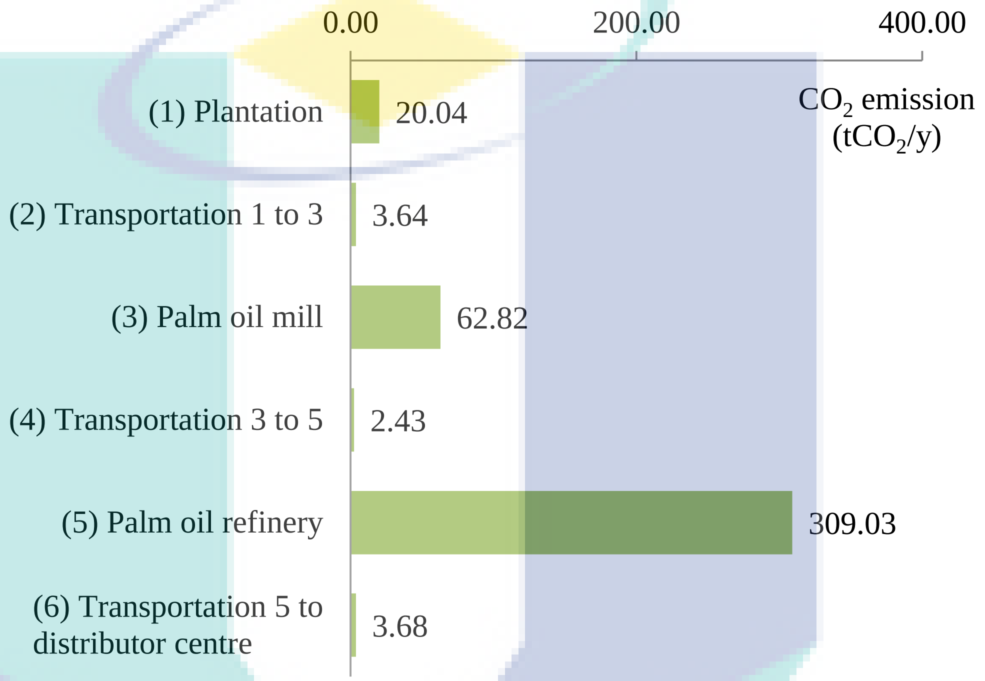


Figure 4.17: Reduced CO_2 emission in palm cooking oil supply chain

To sum up for this chapter, the methodology proposed graphical approaches that provide better insight for users to screen for various CO_2 emissions reduction strategies within the desired investment limits and payback period. The targeted cost-effective CO_2 emission reduction was achieved by implementing the SHARPS strategies align with the CMH for selection of CO_2 reduction strategies. The CO_2 reduction strategies can be prioritised thoroughly based on the CMH levels, that are conservation, source switching, and sequestration, while SHARPS was used to prioritise all the potential strategies for cost-feasibility.

The product planner or plant owner now can manage to plan for low CO_2 emission product, which is also economically feasible. A proper management of CO_2

emission will reduce the dependency on fossil fuels simultaneously reduce the CO_2 emission. Eventually, these also will boost a company's image and competitiveness. The company's effort to minimise the emissions can be promoted via certain means such as product labelling. The opportunities to emphasis on proper CO_2 emission can also increase awareness towards the government, industries, business, and consumers on the importance of environmental conservation and sustainability as these are the key driver in establishing circular economies.

CHAPTER 5

CO_2 EMISSION MANAGEMENT FOR TOTAL SITE PLANNING

5.1 Introduction

The increase in anthropogenic CO_2 emissions from various energy-intensive industries has initiated an urgent need for effective CO_2 emission mitigation strategies by injecting CO_2 into geological storage (CO_2 capture and storage, CCS) or utilisation (CO_2 capture and utilisation, CCU). The CO_2 utilisation by recycling the captured CO_2 or used the CO_2 as raw material however, is much more desirable and consistent align with industrial ecology principles (Meylan *et al.*, 2015). In order to further reduce the CO_2 emission or remaining CO_2 emission (after implemented CO_2 emission management) from industries, Total Site planning for CO_2 management is further developed to optimise holistic CO_2 end-of-pipe management.

A new Total Site concept with CO_2 integration of sources and demands that incorporate with CO_2 purity is analogous to the Total Site Heat Integration concept from Dhole and Linnhoff (1993). Throughout the Total Site, all CO_2 sources and demands are interconnected via a CO_2 pipeline header system directed to CO_2 storage in geological reservoir. As CO_2 utilisation technologies begin to mature, and as more industries which require different purity of CO_2 as their demands or raw materials, it will be convenient if industries can tap CO_2 supply from the CO_2 headers. This would subsequently reduce the amount of CO_2 stored in geological reservoirs.

A few large-scale CCS projects and CO_2 header pipes to channel captured CO_2 from industries into dedicated geological reservoirs have been planned in many countries. For example, the Global CCS Institute (Global CCS Institute, 2014) reported that in China, CO_2 sources from various industries located in potential areas are identified and the captured CO_2 is sent and sequestered in dedicated geological storage via pipeline transport. Therefore, the integration of an existing CCS network with CO_2 utilisation or conversion into value-added products such as solvents, chemicals, and pharmaceuticals (also known as CCUS network), has the potential to generate additional revenue and compensate part of the cost by implementing CO_2 emission reduction strategies (e.g. cost of CO_2 capture technology, transportation, etc.) because of the main challenge of CCUS is the need to transfer CO_2 across distances and cost to integrate the CO_2 sources, sinks, and storage.

The concept of CO_2 Total Site integration proposed in this study differs from the concept of interplant hydrogen integration (Alves and Towler, 2002) from several aspects such the CO_2 sources and demands is cascaded based on the locations of CO_2 sources and demands along the header and is not based on their purity. Remaining CO_2 from palm oil refinery and mill from previous chapter would be supplied as CO_2 sources for CO_2 Total Site. In addition, the newly proposed CO_2 Total Site method also includes the targeting of CO_2 purity at each location of the header, targeting the minimum flow rate of fresh CO_2 supply needed for the demands, and screening for the appropriate CO_2 sources to enable the full utilisation of CCU and the minimum amount of high purity CO_2 to be sent to the CO_2 storage or reservoir.

5.2 Problem Background

The key aspect of this study is to develop a targeting methodology that maximises the recovery of CO_2 for future utilisation and minimises CO_2 to be sent for sequestration through centralised CO_2 headers with excluded cost consideration. It involves the integration of CO_2 capture and CO_2 utilisation across industries and/or plants that are linked via gas headers before the CO_2 sources are permanently stored.

The captured CO_2 will be used as CO_2 sources meanwhile the CO_2 utilisation will be utilised as CO_2 demands. The size of reservoir for CO_2 storage has been neglected in this study. The CO_2 sources are assumed being supplied from the captured flue gas that has been purified on site. Below is the summarised problem statement for the methodology development.

Given a set of CO_2 sources (S_i) and CO_2 demands (D_j) at different purities (P) along the headers, it is desired that a planning methodology to maximise the utilisation of CO_2 sources to satisfy CO_2 demands across Total Site be developed, and that the amount of CO_2 sent to storage be minimised. The methodology consists of one high-purity header that attached to CO_2 storage or reservoir and one low-purity header that accept CO_2 sources at different purity, which can be used to satisfy CO_2 demands. A stream of fresh CO_2 is available for mixing with the CO_2 source headers to satisfy the targeted CO_2 demand purity requirement. The role of general CO_2 Total Site planning is illustrated as in Figure 5.1.

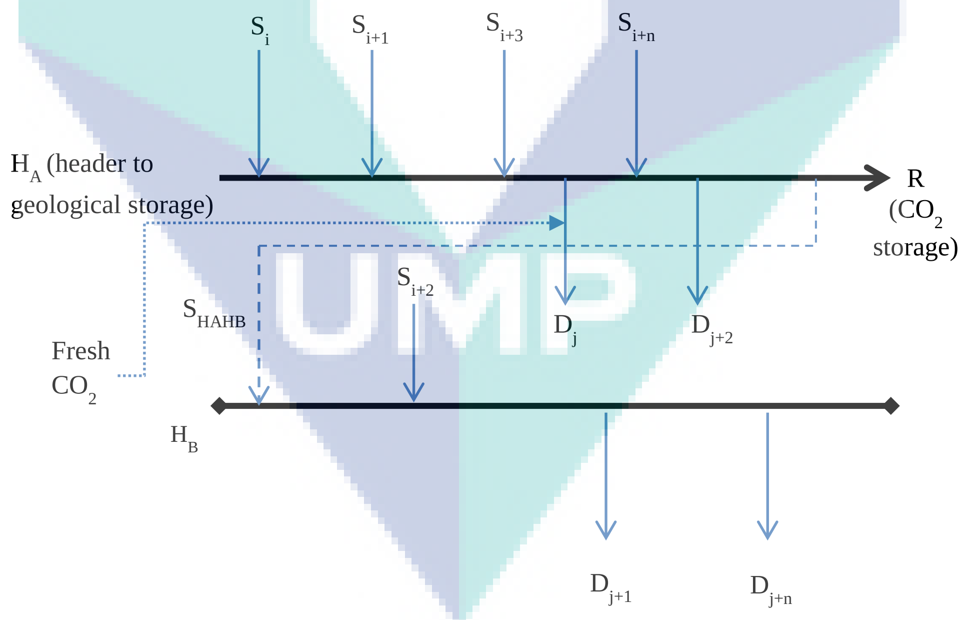


Figure 5.1: Illustration of CO_2 Total Site

H is the header, indicated by Header A (H_A) and Header B (H_B); S_i is the CO_2 emission source supply into the header; S_{HAHB} is the CO_2 emission source from Header A to Header B; and Dj is the CO_2 demand required from the header.

During the development of CO_2 Total Site planning, several issues have been highlighted. The CO_2 purity headers have been created based on the various industrial CO_2 capture technology. Any CO_2 purity supplied into the header could be priced differently based on supplied CO_2 purity and this can be used as a guideline for policy maker. Different CO_2 purity sources and demands should be managed in order to satisfy the industry's requirement and remaining CO_2 can be sent into storage. All of these issues have been addressed and it can be applied for CCUS planners to design future CO_2 headers and develop proper CCUS policies and mechanisms to maximise CO_2 utilised and minimise CO_2 stored. This methodology is developed to achieve optimal CO_2 target for minimisation with a new role of CO_2 Total Site planning.

5.3 Methodology

CO_2 Total Site planning is developed by using CO_2 Utilisation and Storage-Problem Table Algorithm (CUS-PTA). Developing this methodology involved several steps and detailed descriptions will be provided in the next subsections. Figure 5.2 illustrates the overall process flow of CUS-PTA methodology.

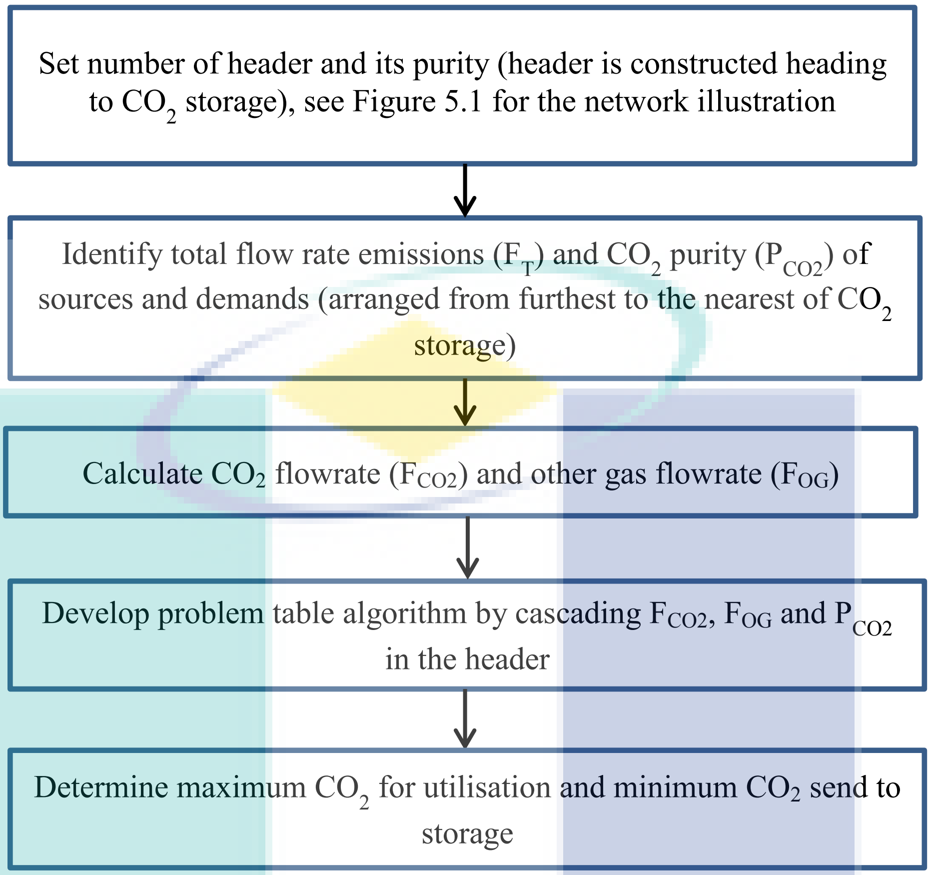


Figure 5.2: Process flow for CUS-PTA methodology

Different scenarios have been demonstrated to satisfy several issues that raised during the development CUS methodology. Scenario 1 is demonstrated if two headers are constructed while Scenario 2 if only a header is constructed in order to connect all the CO_2 sources and demands. Scenario 3 is then further discussed if CO_2 sources less than demands for Header 1 and Scenario 4 is for the CO_2 demands more than sources in Header 2. Following is the step-by-step procedures to develop the CUS methodology.

5.3.1 STEP 1: Specify CUS Header for Allocation of CO_2 Sources and Demands

The number of CUS headers is decided based on the flue gas purity of CO_2 sources and demands in a potential area. The flue gas CO_2 flow rate and purity are determined based on the requirements of the demands. For example, the first header (H1) can be set to only accept flue gas with certain CO_2 purity; a geological storage (the final destination) can accept e.g. 80–100% CO_2 purity. The second header (H2) can be set at a lower purity than H1 to satisfy the other lower purity demands. For example, the header can accept flue gas with between 50% and 79.99% CO_2 purity. Because H1 is designed for reservoir storage as the final destination, the flue gas within H2 must be fully consumed by the last demand at the end of its pipeline. This can be controlled by allowing only a limited amount of sources to be injected into this header.

5.3.2 STEP 2: Identify of CO_2 Sources and Demands

Industries along the header that can capture CO_2 (sources) and industries that can utilise CO_2 (demands) are identified. The gas flow rate (F_T) of the sources and the minimum gas CO_2 purity (P_{CO2}) that can be accepted are obtained. The F_T of flue gas emissions usually can be identified from sources that being supplied into the header. Specifically, the amount of CO_2 (F_{CO2}) within the gas can be calculated using Equation (5.1) and other gases flow rate (F_{OG}) such as N_2, O_2, CO, NO_x, and SO_x can be calculated using Equation (5.2).

$$F_{CO_2} = F_T * (P_{CO_2}/100) \tag{5.1}$$

$$F_{OG} = F_T - F_{CO_2} \tag{5.2}$$

5.3.3 STEP 3: Construct CUS-PTA

The problem table algorithm (PTA) is constructed to determine the amount of CO_2 target based on the CO_2 Total Site concept. Available CO_2 sources and demands that have been identified in a region are arranged, based on their location along the header from furthest to the nearest of CO_2 storage. The source gas flow rates (F_T) and the gas CO_2 purity (P_{CO2}) are obtained from the data. Other industries that can utilise CO_2 (demands) and the minimum P_{CO2} they can accept are also determined. Table 5.1 illustrates the CUS-PTA.

The number of sources (*S*) and demands (*D*) that CO_2 can be injected into or took out for utilisation from header are listed in Column 1. Each source and demand's value of P_{CO2} and F_T is arranged in Column 3 and 4. Based on the P_{CO2}, each of S and D will be arranged accordingly to the header which has been set (see Figure 5.1). In Column 4, the source flow rate value is indicated as a positive value, as it is adding more flue gas to the header, while the demand flow rate is indicated as a negative value, as the flue gas is being extracted from the header. The calculated F_{CO2} and F_{OG} using Equations (5.1) and (5.2) are listed in Column 5 and 6 of CUS-PTA. The next key step is to cascade the sources and demands for the first header (e.g. H1). Sources and demands must match each other and this can be done by performing a F_T and F_{CO2} cascade. At the source locations, F_T and F_{CO2} for H1 are accumulated from the top to the bottom row, starting from zero in Column 7 and 8, using Equations (5.3) and (5.4). The CO_2 purity of H1 (P_{CO2}^{H1}) after accumulating all of the sources can be calculated using Equation (5.5) and is listed in Column 9. After the end of the H1 line, the remaining gas within H1 will be sent to the geological reservoir for long-term storage.

$$Cum\ F_{T\ k,q}^{\ \ H1} = Cum\ F_{T\ k,q-1}^{\ \ H1} + F_{T\ k,q}^{\ \ H1} \quad (5.3)$$

$$Cum\ F_{CO_2 k,q}^{\ \ H1} = Cum\ F_{CO_2 k,q-1}^{\ \ H1} + F_{CO_2 k,q}^{\ \ H1} \quad (5.4)$$

where,

k is set for CO_2 source and q is set for CO_2 demand, F_T is for flue gas flowrate, F_{CO2} is for CO_2 flowrate.

$$P_{k,q}{}^{H1} = \frac{Cum\ F_{CO_2k,q}{}^{H1}}{Cum\ F_{Tk,q}{}^{H1}} \tag{5.5}$$

$Cum\ F_T{}^{H1}$ is the cumulative source and demand of flue gas flow rates at the header, and $Cum\ F_{CO2}{}^{H1}$ is the cumulative amount of CO_2 flow rate, with $P_{CO2}{}^{H1}$ being the purity of the header.

At the demand locations, F_T and F_{CO2} are accumulated from the top to the bottom row with $F_T{}^{H1\text{-}D}$, $F_T{}^{H2\text{-}D}$, $F_{CO2}{}^{H1\text{-}D}$, and $F_{CO2}{}^{H2\text{-}D}$ values are considered, as shown in Equations (5.6) and (5.7). The $F_T{}^{H2\text{-}D}$ and $F_{CO2}{}^{H2\text{-}D}$ calculations that are indicative of H2 will be explained in the next section. These equations are described below.

$$Cum\ F_{CO_2k,q}{}^{H1} = Cum\ F_{CO_2k,q\text{-}1}{}^{H1} + F_{CO_2k,q}{}^{H1\text{-}D} + F_{CO_2k,q}{}^{H2\text{-}D} \tag{5.6}$$

$$Cum\ F_{Tk,q}{}^{H1} = Cum\ F_{Tk,q\text{-}1}{}^{H1} + F_{Tk,q}{}^{H1\text{-}D} + Cum\ F_{Tk,q}{}^{H2\text{-}D} \tag{5.7}$$

$F_T{}^{H\text{-}D}$ is the flue gas flow rate from header to demand and $F_{CO2}{}^{H\text{-}D}$ is the CO_2 flow rate from header to demand. The $F_T{}^{H1\text{-}D}$ and $F_{CO2}{}^{H1\text{-}D}$ values are derived from CO_2 Total Site Utilisation Rule 1 or 2 to satisfy the CO_2 demands. There are two utilisation rule concepts that must be followed prior to execute the CUS-PTA technique.

Table 5.1: Illustrated CUS-PTA construction

1	2	3	4	5	6	7	8	9	10	11	12	…	17	18	…
S/D	Descrip-tion	$P_{CO2}^{S/D}$	F_T^{H1}	F_{CO2}^{H1}	F_{OG}^{H1}	Cum F_T^{H1}	Cum F_{CO2}^{H1}	P_{CO2}^{H1}	$F_{CO2}^{H1\text{-}D}$	$F_T^{H1\text{-}D}$	$F_{CO2}^{FC\text{-}D}$		Cum F_T^{H2}	Cum F_{CO2}^{H2}	
S1	Cement														
S2															
S3	--														
D1	--														
S4															
S5															
D2															
S6															
S7															
D4															

Accumulated flue gas flow rate and CO_2 flow rate from top to bottom in header. The remaining flue gas will be sent to storage

CO_2 supplied from header to satisfy demands

Fresh CO_2 supplied if required for high purity demand then header

Last row of the columns for H2 should give a zero value if not designed not to send to

Examples of identified sources and demands point

a. CO_2 Total Site Utilisation Rule 1

The demand requires a higher CO_2 purity ($P_{CO2q}{}^{D}$) (e.g. 95%) than the accumulated CO_2 purity in H1 ($P_{CO2}{}^{H1}$) (e.g. 87%). To satisfy the requirement, a mixture of pure CO_2 from the centralised CO_2 generator is needed for blending with the header gas. Equations (5.8) and (5.9) are used to determine the amount of $F_{CO2}{}^{H1\text{-}D}$ (Column 10) and $F_T{}^{H1\text{-}D}$ (Column 11) that are required for H1 to supply the demand. Equation (5.10) is used to estimate the flow rate of pure CO_2 ($F_{CO2}{}^{FC\text{-}D}$) needed to satisfy the demand purity for H1 (Column 12).

If $P_{CO2\,q}{}^{D} > P_{CO2}{}^{H1}$

$$P_{CO2}{}^{H1\text{-}D} = F_{OG\,q}{}^{D} * P_{CO2\,q}{}^{H1} / (1 - P_{CO2}{}^{H1}) \tag{5.8}$$

$$F_T{}^{H1\text{-}D} = F_{CO2}{}^{H1\text{-}D} / P_{CO2}{}^{H1} \tag{5.9}$$

$$P_{CO2}{}^{FC\text{-}D} = F_{CO2}{}^{H1\text{-}D} - F_{CO2\,q}{}^{D} \tag{5.10}$$

b. CO_2 Total Site Utilisation Rule 2

The demand requires equal or lower CO_2 purity ($P_{CO\,q}{}^{D}$) (e.g. 85%) than the accumulated CO_2 purity in H1 ($P_{CO2}{}^{H1}$) (e.g. 87%). In this case, F_T from H1 is directly supplied to demand, $F_T{}^{H1\text{-}D}$ (Column 11) as the purity demand requirement is fulfilled, as per Equation (5.11). This assumes that the demand can accept equal or higher purity sources. $F_{CO2}{}^{H1\text{-}D}$ (Column 10) can be calculated using Equation (5.12).

If $P_{CO2\,q}{}^{D} \leq P_{CO2}{}^{H1}$

$$F_T{}^{H1\text{-}D} = F_{T\,q}{}^{D} \tag{5.11}$$

$$F_{CO_2}{}^{H1\text{-}D} = F_T{}^{H1\text{-}D} . P_{CO2}{}^{H1} \tag{5.12}$$

The last row for Column 7 (*Cum* F_T) and Column 8 (*Cum* F_{CO2}) gives the minimum target of F_T and F_{CO2} to be sent to geological storage for the carbon mitigation initiative. The summation of Column 12 gives the total amount of pure CO_2 supplied by the centralised pure CO_2 generator ($F_{CO2}{}^{FC}$) that needs to be blended with H1 to satisfy the high-purity demand as shown in Equation (5.13).

$$F_{CO2}{}^{FC} = \sum_{i=0}^{n} F_{CO2}{}^{FC\text{-}D} \tag{5.13}$$

Next, the same procedures are applied to the other header if required (e.g. H2). Requirements of the sources and demands in H2 are addressed by performing cascading of F_T and F_{CO2} using Equations (5.14) and (5.15). The *Cum* $F_T{}^{H2}$ and *Cum* $F_{CO2}{}^{H2}$ are shown in Columns 13 and 14. The utilisation rules are followed to satisfy CO_2 demands. However, the cleaner flue gas from H1 has more potential to be utilised instead of using pure CO_2 to satisfy higher CO_2 purity demands for Utilisation Rule 1. The amounts of F_T taken from H2 ($F_T{}^{H2\text{-}D}$) and H1 ($F_T{}^{H1\text{-}D}$) to satisfy demand at H2 can be calculated using Equations (5.16) and (5.17). Similar equations can be derived by replacing H1 with H2.

$$Cum\ F_{CO_2 k,q}{}^{H2} = Cum\ F_{CO_2\ k,q\text{-}1}{}^{H2} + F_{CO_2 k,q}{}^{H2} \tag{5.14}$$

$$Cum\ F_{T\ k,q}{}^{H2} = Cum\ F_{T\ k,q\text{-}1}{}^{H2} + F_{T\ k,q}{}^{H2} \tag{5.15}$$

$$F_T{}^{H2\text{-}D} = (F_{Tq}{}^{D} * P_{CO_2}{}^{H1}) - [\frac{F_{Tq}{}^{D} * P_{CO_2}{}^{H1}}{P_{CO_2}{}^{H2} - P_{CO_2}{}^{H1}}] \tag{5.16}$$

$$F_T{}^{H1\text{-}D} = F_{T\,q}{}^{D} - F_T{}^{H2-D} \tag{5.17}$$

As H2 is designed not to be sent to geological storage, the last row of Cum $F_T{}^{H2}$ (Column 13) and *Cum* $F_{CO2}{}^{H2}$ (Column 14) should not yield any excess, where the surplus value of F_T and F_{CO2} should be reduced by part of the sources (preferably the one with lower purity) into H2 until the last row of *Cum* F_T^{H2} and *Cum* F_{CO2}^{H2} gives a zero value, which is also the Pinch Point for this system.

5.4 Case Study 3

Case study 3 is demonstrated for the developed tool and is adapted from the work by Hasan *et al.* (2014) and Munir *et al.* (2012). The CUS–PTA is a numerical approach for planning and managing CO_2 sources and demands by using centralised headers. The identification data of CO_2 sources and demands are listed in Table 5.2 (sources) and Table 5.3 (demands). Eight sources of potential CO_2 captures to be sent to dedicated CO_2 geological storage and four potential points of CO_2 demands for CO_2 utilisation are identified. In addition, distance (*Dt*) of CO_2 sources and demand are identified by the assumption of distance heading to potential CO_2 storage. The remaining CO_2 emission from palm oil refinery and palm oil mill (from previous Chapter 4) are among the potential CO_2 sources that could be injected into centralised headers for further CO_2 reduction management.

Table 5.2: Data for CO_2 sources

Source (S)	Description	P_{CO2}, %	F_T, t/y	F_{CO2}, t/y	F_{OG}, t/y	*Dt*, km
S1	Cement	90	138.8	124.9	13.9	410
S2	Palm oil refinery	70	441.4	309.0	132.4	390
S3	Power (coal based)	85	1174.3	998.2	176.1	360
S4	Power (NG based)	88	101.5	89.3	12.2	290
S5	Palm oil mill	65	96.7	62.9	33.8	270
S6	Petrochemical	80	615.4	492.3	123.1	210
S7	Gas processing	90	36.5	32.8	3.6	190
S8	Iron & steel (corex)	95	27.9	26.5	1.4	150

Table 5.3: Data for CO_2 demands

Demand (D)	Description	P_{CO2}, %	F_T, t/y	F_{CO2}, t/y	F_{OG}, t/y	Dt, km
D1	Beverage plant	99	50.0	49.5	0.5	340
D2	Enhance oil recovery	80	208.3	166.6	41.7	240
D3	Methanol production	50	83.3	41.7	41.7	110
D4	Micro algae production	10	220.0	22.0	198.0	100

5.4.1 Scenario 1

Referring to Table 5.2 and Table 5.3, two headers were set with a purity range between 80–99.99% for Header 1 (H1) and 50–79.99% for Header 2 (H2). Headers are based on the purity data range. Equations (5.1) to (5.5) were used to determine the flow rate and purity of CO_2 sources and demands. The CO_2 sources and demands were arranged accordingly to the distance from furthest to the nearest of storage. Sources of S1, S3, S4, S6, S7, and S8 can supply CO_2 to H1, meanwhile S2 and S5 can supply to H2. The same concept is applicable for the demands. Demands of D1 and D2 can extract CO_2 from H1, meanwhile D3 and D4 can extract from the lower purity range i.e. H2, to satisfy their need. The arrangement of sources and demands along the header are tabulated as in Table 5.4. Positive values indicate CO_2 flow rate being fed into the header and negative values represent CO_2 flow rate being discharged from the header.

Table 5.4: CO_2 sources and demands arrangement and header selection

S/D	Header	Description	P_{CO2}, %	F_T, t/y	F_{CO2}, t/y	F_{OG}, t/y	Dt, km
S1	H1	Cement	90	138.8	124.9	13.9	410
S2	H2	Palm oil refinery	70	441.4	309.0	132.4	390
S3	H1	Power (coal)	85	1,174.3	998.2	176.2	360
D1	H1	Beverage plant	99	-50.0	-49.5	-0.50	340
S4	H1	Power (Natural gas)	88	101.5	89.3	12.2	290
S5	H2	Palm oil mill	65	96.7	62.9	33.8	270
D2	H1	Enhanced oil recovery (EOR)	80	-208.3	-166.6	-41.7	240
S6	H1	Petrochemical	80	615.4	492.3	123.1	210
S7	H1	Gas processing	90	36.5	32.8	3.7	190
S8	H1	Iron & steel	95	27.9	26.5	1.4	150
D3	H2	Methanol production	50	-83.3	-41.7	-41.7	110
D4	H2	Micro algae production	10	-220.0	-22.0	-198.0	100

The location of each source and demand are important in this region for targeting the CO_2 supplied and amount of CO_2 required to be sent to geological storage. As explained in the methodology section, CUS−PTA is performed to optimise CO_2 utilisation and minimise CO_2 storage. The CUS−PTA for Scenario 1 is shown in Table 5.5.

The minimum amount of remaining CO_2 in Column 7 (*Cum* F_T^{H1}) after cascade is 1882.6 t/y, which needs to be sent to geological reservoirs for permanently stored; CO_2 purity in the stream is accumulated at 84%. Table 5.5(continue) shows the CUS–PTA performed for H2. It can be seen that there is excess CO_2 in the last row in Column 17 (*Cum* F_{CO2}^{H2}), 162.3 t/y of CO_2. As H2 does not have access to storage, this value needs to be deducted with any source from H2 (i.e. S2), the source that contains the highest amount of CO_2 in H2. Instead of sending the entire 441.4 t/y of S2 which is the highest in amount of CO_2 source to H2, only 206.6 t/y of S2 is supplied into H2 to ensure that the CO_2 demand requirement is balanced, so that there are no excess CO_2 at the end of header H2. This is also the Pinch Point of the system and note that prior to consider CO_2 Total Site, the CO_2 (e.g. S2 with Cum F_T^{H2}, 234.8 t/y) from header H2, which cannot be stored, will be emitted to the environment.

Prior to satisfy the high-purity demand of CO_2, fresh CO_2 from the centralised pure CO_2 generator is requested. 46.5 t/h of $F_{CO2}^{FC\text{-}D}$ is injected to satisfy the D1 demand and no fresh CO_2 is supplied to H2, as the purity demands in H2 are lower than the supply stream. Note that H1 is capable of supplying CO_2 to H2 whenever it is required (e.g. $F_T^{H1\text{-}H2}$) by following the CO_2 Total Site utilisation rules; if not required, the remaining CO_2 emissions are injected into storage as the final destination. Optimal CUS network for Scenario 1 is illustrated in Figure 5.3.

Table 5.5: CUS-PTA for Scenario 1

1	2	3	4	5	6	7	8	9	10	11	12
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1} t/y	F_{CO2}^{H1} t/y	F_{OG}^{H1} t/y	$Cum\ F_T^{H1}$ t/y	$Cum\ F_{CO2}^{H1}$ t/y	P_{CO2}^{H1}	$F_{CO2}^{H1\text{-}D}$ t/y	$F_T^{H1\text{-}D}$ t/y	$F_{CO2}^{FC\text{-}D}$ t/y
S1	Cement	0.90	138.8	124.9	13.9						
						138.8	124.9	0.90			
S2	Palm oil refinery	0.70									
						138.8	124.9	0.90			
S3	Power (coal)	0.85	1174.3	998.2	176.1						
						1313.1	1123.1	0.86			
D1	Beverage plant	0.99	-50.0	-49.5	-0.5				-3.0	-3.5	46.5
						1309.6	1120.1	0.86			
S4	Power (Natural gas)	0.88	101.5	89.3	12.2						
						1411.1	1209.4	0.86			
S5	Palm oil mill	0.65									
						1411.1	1209.4	0.86			
D2	EOR	0.80	-208.3	-166.6	-41.7				-178.5	-208.3	0
						1202.8	1030.9	0.86			
S6	Petrochemical	0.80	615.4	492.3	123.1						
						1818.2	1523.2	0.84			
S7	Gas processing	0.90	36.5	32.9	3.7						
						1854.7	1556.1	0.84			
S8	Iron & steel	0.95	27.9	26.5	1.4						
						1882.6	1582.6	0.84			
D3	Methanol production	0.50									
						1882.6	1582.6	0.84			
D4	Micro algae production	0.10									
						1882.6	1582.6	0.84			

Table 5.5(continue): CUS-PTA for Scenario 1

			13	14	15	16	17	18	19	20	21
		$P_{CO2}^{S/D}$	F_T^{H2} t/y	F_{CO2}^{H2} t/y	F_{OG}^{H2} t/y	Cum F_T^{H2} t/y	Cum F_{CO2}^{H2} t/y	P_{CO2}^{H2}	$F_{CO2}^{H2\text{-}D}$ t/y	$F_T^{H2\text{-}D}$ t/y	F_{OG}^{H2} t/y
S2	Palm oil refinery	0.70	441.4	309.0	132.4						
						441.4	309.0	0.70			
						441.4	309.0	0.70			
						441.4	309.0	0.70			
						441.4	309.0	0.70			
S5	Palm oil mill	0.65	96.7	62.9	33.8						
						538.1	371.8	0.69			
						538.1	371.8	0.69			
						538.1	371.8	0.69			
						538.1	371.8	0.69			
						538.1	371.8	0.69			
D3	Methanol production	0.50	-83.3	-41.7	-41.7				-57.56	-83.3	-25.7
						454.8	314.3	0.69			
D4	Micro algae production	0.10	-220.0	-22.0	-198.0				-152.02	-220.0	-68.0
						234.8	162.3	0.69			

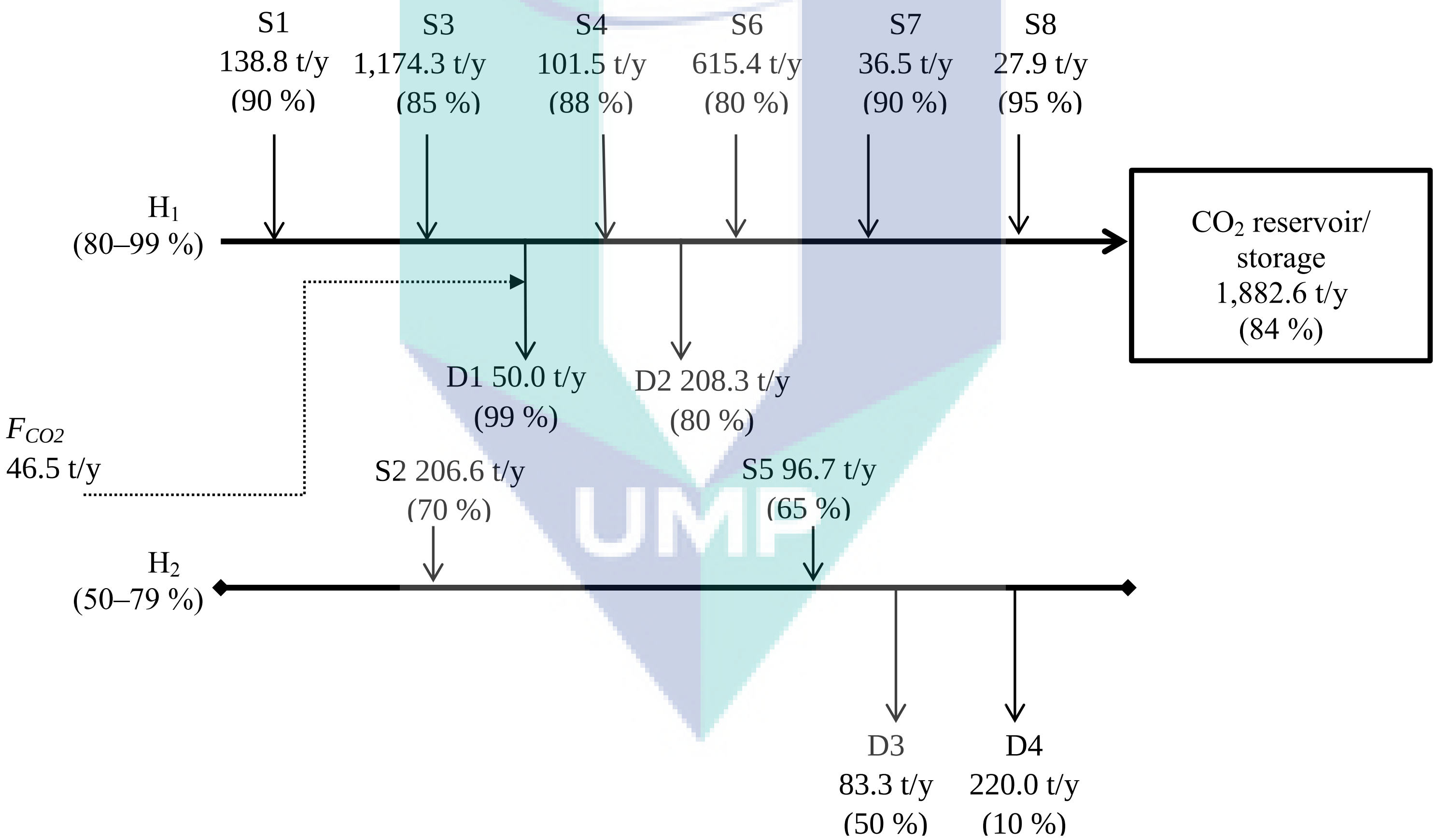


Figure 5.3: Optimal network for CO_2 Total Site Scenario 1

5.4.2 Scenario 2

In this section, CO_2 Total Site is established via the proposed method using a header approach for Scenario 2. There is a total at eight CO_2 sources and four CO_2 demands, as previously stated in Table 5.2 and Table 5.3. All of the sources and demands are integrated to estimate the optimal CUS by using one header. The CUS–PTA is performed according to the steps developed in targeting method for CO_2 Total Site. As the number of header is set to one, equations for H2 are thus neglected. The CUS−PTA for Scenario 2 is shown in Table 5.6.

The minimum amount of remaining $Cum\ F_T^{H1}$ in Column 7 of Table 5.6 after cascade is 2118.2 t/y, which needs to be sent to geological reservoirs for CO_2 storage. 47.3 t/y of $F_{CO2}^{FC\text{-}D}$ is injected to satisfy the D1 demand which is higher than Scenario 1. The remaining CO_2 flow rate in Column 8 ($Cum\ F_{CO2}^{H1}$) of Scenario 2 is also higher than Scenario 1 because all excess CO_2 will be sent to storage. The CO_2 purity in the stream header however is accumulated at 81% purity, which is slightly lower compared to CO_2 purity accumulated in Scenario 1.

There will be no CO_2 being captured since no pinch point is considered, but it still yields the highest amount of CO_2 for storage thus more CO_2 with lower purity to be sent to the storage. If there is an increase of CO_2 sources at various purity, more fresh CO_2 flow rate need to be supplied to balance the accumulated purity in the header as the CO_2 storage reservoir is assumed to accept CO_2 with purity 80% and above. This will not only increase the capital cost for pure CO_2 generation, but the impurity in the flue gases also have significant impacts on the reservoir system of the geological storage area (Pearce *et al.*, 2015). An optimal network for Scenario 2 is illustrated in Figure 5.4.

Table 5.6: CUS-PTA for Scenario 2

1	2	3	4	5	6	7	8	9	10	11	12
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1} t/y	F_{CO2}^{H1} t/y	F_{OG}^{H1} t/y	$Cum\ F_T^{H1}$ t/y	$Cum\ F_{CO2}^{H1}$ t/y	P_{CO2}^{H1}	$F_{CO2}^{H1\text{-}D}$ t/y	$F_T^{H1\text{-}D}$ t/y	$F_{CO2}^{FC\text{-}D}$ t/y
S1	Cement	0.90	138.8	124.9	13.9						
						138.8	124.9	0.90			
S2	Palm oil refinery	0.70	441.4	309.0	132.4						
						580.2	433.9	0.75			
S3	Power (coal)	0.85	1174.3	998.2	176.1						
						1754.5	1432.1	0.82			
D1	Beverage plant	0.99	-50.0	-49.5	-0.5				-2.2	-2.7	47.3
						1751.8	1429.8	0.82			
S4	Power (Natural gas)	0.88	101.5	89.3	12.2						
						1853.3	1519.2	0.82			
S5	Palm oil mill	0.65	96.7	62.9	33.8						
						1950.0	1582.0	0.81			
D2	EOR	0.80	-208.3	-166.6	-41.7				-169.0	-208.3	0.0
						1741.7	1413.0	0.81			
S6	Petrochemical	0.80	615.4	492.3	123.1						
						2357.1	1905.3	0.81			
S7	Gas processing	0.90	36.5	32.9	3.7						
						2393.6	1938.2	0.81			
S8	Iron & steel	0.95	27.9	26.5	1.4						
						2421.5	1964.7	0.81			
D3	Methanol production	0.50	-83.3	-41.7	-41.7				-67.6	-83.3	0.0
						2338.2	1897.1	0.81			
D4	Micro algae production	0.10	-220.0	-22.0	-198.0				-178.5	-220.0	0.0
						2118.2	1718.6	0.81			

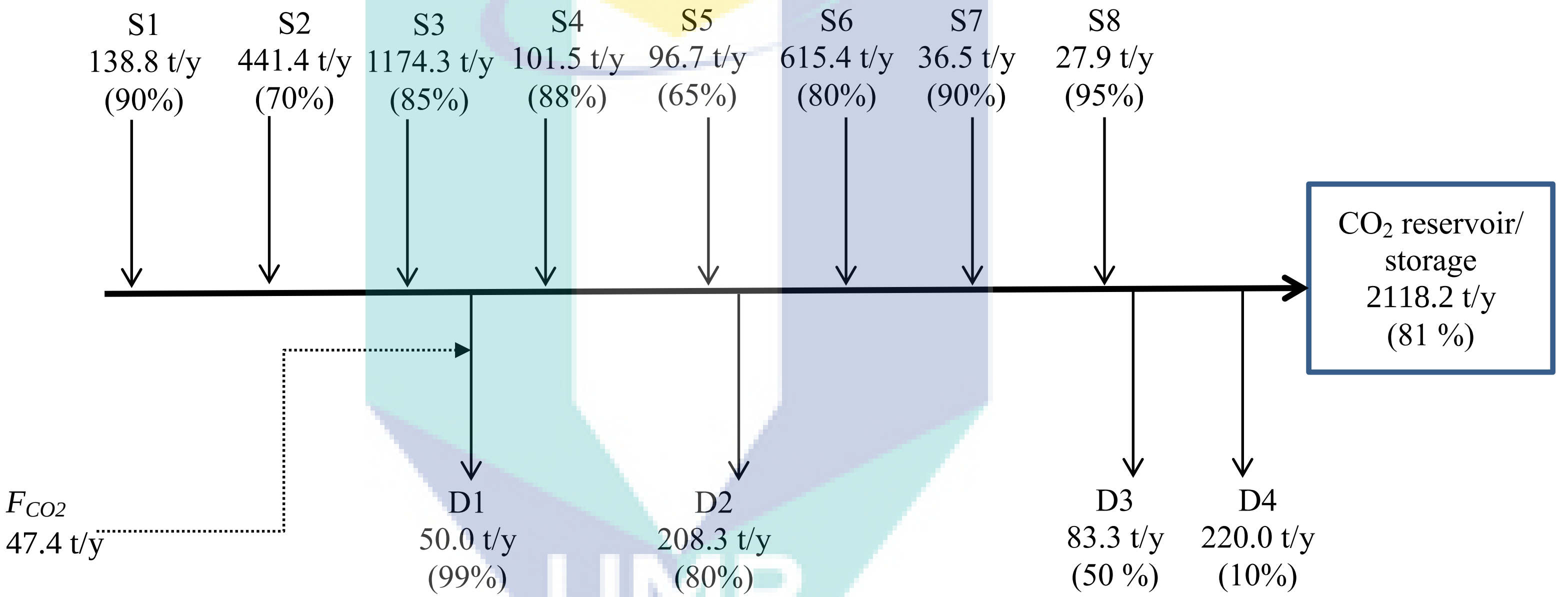


Figure 5.4: Optimal network for CO_2 Total Site Scenario 2

5.4.3 Scenario 3

Scenario 3 is 'what if' situation based on the Scenario 1. Data for Scenario 3 is adapted and modified from the previous Table 5.2 and Table 5.3. The situation is what if the CO_2 sources with high purity is deficit and could not be supplied to satisfy the demand in H1 while CO_2 sources and demands in H2 remained the same. Only S3, S7 and S8 are supplied into H1 and do not have sufficient amount to satisfy the demand for D1 and D2 as shows in Table 5.7 which indicate that the Column 7 has accumulated negative value of F_T^{H1} (-97.2 t/y) at -78 t/y of CO_2 flowrate. However, there are surplus flow rate from H2 that could satisfy the shortage in H1 and simultaneously prevent CO_2 from H2 being emitted to the environment as H2 has no access to CO_2 storage. Therefore, excess flow rate in H2 as tabulated at the last row in Column 16 (234.8 t/y) is potential to be supplied to H1 with the additional of fresh CO_2 to achieve desired purity at H1.

Table 5.7: CUS-PTA for CO_2 demand more than sources in H1

1	2	3	4	5	6	7	8	9	10	11	12
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1} t/y	F_{CO2}^{H1} t/y	F_{OG}^{H1} t/y	$Cum\ F_T^{H1}$ t/y	$Cum\ F_{CO2}^{H1}$ t/y	P_{CO2}^{H1}	$F_{CO2}^{H1\text{-}D}$ t/y	$F_T^{H1\text{-}D}$ t/y	$F_{CO2}^{FC\text{-}D}$ t/y
						0.0	0.0	-			
S2	Palm oil refinery	0.70									
						0.0	0.0	-			
S3	Power (coal)	0.85	50.0	42.5	7.5						
						50.0	42.5	0.85			
D1	Beverage plant	0.99	-50.0	-49.5	-0.5				-2.8	-3.3	46.7
						46.7	39.7	0.85			
S5	Palm oil mill	0.65									
						46.7	39.7	0.85			
D2	EOR	0.80	-208.3	-166.6	-41.7				-177.1	-208.3	-
						-161.6	-137.4	0.85			
S7	Gas processing	0.90	36.5	32.9	3.7						
						-125.1	-104.5	0.84			
S8	Iron & steel	0.95	27.9	26.5	1.4						
						-97.2	-78.0	0.80			
D3	Methanol production	0.50									
						-97.2	-78.0	0.80			
D4	Micro algae production	0.10									
						-97.2	-78.0	0.80			

Table 5.7(continue): CUS-PTA for CO_2 demand more than sources in H1

		13	14	15	16	17	18	19	20
S/D	Description	F_T^{H2} t/y	F_{CO2}^{H2} t/y	F_{OG}^{H2} t/y	Cum F_T^{H2} t/y	Cum F_{CO2}^{H2} t/y	P_{CO2}^{H2}	F_{CO2}^{H2-D} t/y	F_T^{H2-D} t/y
S2	Palm oil refinery	441.4	309.0	132.4					
					441.4	309.0	0.70		
S3	Power (coal)								
					441.4	309.0	0.70		
D1	Beverage plant								
					441.4	309.0	0.70		
S5	Palm oil mill	96.7	62.9	33.8					
					538.1	371.8	0.69		
D2	EOR								
					538.1	371.8	0.69		
S7	Gas processing								
					538.1	371.8	0.69		
S8	Iron & steel								
					538.1	371.8	0.69		
D3	Methanol production	-83.3	-41.7	-41.7				-57.56	-83.3
					454.8	314.3	0.69		
D4	Micro algae production	-220.0	-22.0	-198.0				-152.02	-220.0
					234.8	162.3	0.69		

Table 5.8 shows final result of CUS−PTA for Scenario 3. All remaining sources from H2 are supplied to satisfy demands in H1. As H1 required higher purity (P ≥ 80%), an additonal fresh CO_2 is needed to achieve the desired purity header. In this case, purity header H1 is set at minimum desired purity at 80 %. Equation (5.18) is used to identify the additional fresh CO_2 needed to be blended with H2 source ($F_{CO2}^{FC\text{-}H1}$). Therefore, the first row of $Cum\ F_{CO2}^{H1}$ is the total amount of $F_{CO2}^{FC\text{-}H1}$ and F_{CO2}^{H2} as shown in Equation (5.19).

$$F_{CO2}^{FC\text{-}H1} = (Cum\ F_T^{H2} * 0.8) - (Cum\ F_T^{H2} * P_{CO2}^{H2}) \quad (5.18)$$

$$Cum\ F_{CO2}^{H1} = F_{CO2}^{FC\text{-}H1} + Cum\ F_{CO2}^{H2} \quad (5.19)$$

By referring to the first row in Table 5.8, $Cum\ F_T^{H2}$ (234.8 t/y) was supplied to satisfy the demands for H1 and $Cum\ F_{CO2}^{H1}$ has become 187.8 t/y with increased purity of 80 %. The remaining F_T^{H1} (138.3 t/y) in the last row of Column 7 is then sent to CO_2 storage. Excess of F_T from H2 supply to H1 could prevent CO_2 surplus in H2 from being emitted to the environment as all of the remaining F_T^{H2} are sent to H1 which have access to storage. The optimal network of Scenario 3 is shown in Figure 5.5.

Table 5.8: Final CUS-PTA for Scenario 3

1	2	3	4	5	6	7	8	9	10	11	12
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1}	F_{CO2}^{H1}	F_{OG}^{H1}	$Cum\ F_T^{H1}$	$Cum\ F_{CO2}^{H1}$	P_{CO2}^{H1}	$F_{CO2}^{H1\text{-}D}$	$F_T^{H1\text{-}D}$	$F_{CO2}^{FC\text{-}D}$
			t/y	t/y	t/y	t/y	t/y		t/y	t/y	t/y
						234.8	187.8	0.80			
S2	Palm oil refinery	0.70									
						234.8	187.8	0.80			
S3	Power (coal)	0.85	50.0	42.5	7.5						
						284.8	230.3	0.81			
D1	Beverage plant	0.99	-50.0	-49.5	-0.5				-2.1	-2.6	47.4
						282.2	228.2	0.81			
S5	Palm oil mill	0.65									
						282.2	228.2	0.81			
D2	EOR	0.80	-208.3	-166.6	-41.7				-168.5	-208.3	-
						73.9	59.8	0.81			
S7	Gas processing	0.90	36.5	32.9	3.7						
						110.4	92.6	0.84			
S8	Iron & steel	0.95	27.9	26.5	1.4						
						138.3	119.1	0.86			
D3	Methanol production	0.50									
						138.3	119.1	0.86			
D4	Micro algae production	0.10									
						138.3	119.1	0.86			

Table 5.8(continue): Final CUS-PTA for Scenario 3

13	14	15	16	17	18	19	20	21	22	23
F_T^{H2} t/y	F_{CO2}^{H2} t/y	F_{OG}^{H2} t/y	$Cum\ F_T^{H2}$ t/y	$Cum\ F_{CO2}^{H2}$ t/y	P_{CO2}^{H2}	$F_{CO2}^{H2\text{-}D}$ t/y	$F_T^{H2\text{-}D}$ t/y	$F_{CO2}^{FC\text{-}H1}$ t/y	$F_T^{H2\text{-}H1}$ t/y	$F_{CO2}^{FC\text{-}H1} + F_{CO2}^{H2}$ t/y
								25.59	234.8	187.85
441.4	309.0	132.4								
			441.4	309.0	0.70					
			441.4	309.0	0.70					
			441.4	309.0	0.70					
96.7	62.9	33.8								
			538.1	371.8	0.69					
			538.1	371.8	0.69					
			538.1	371.8	0.69					
			538.1	371.8	0.69					
-83.3	-41.7	-41.7				-57.56	-83.3			
			454.8	314.3	0.69					
-220.0	-22.0	-198.0				-152.02	-220.0			
			234.8	162.3	0.69					

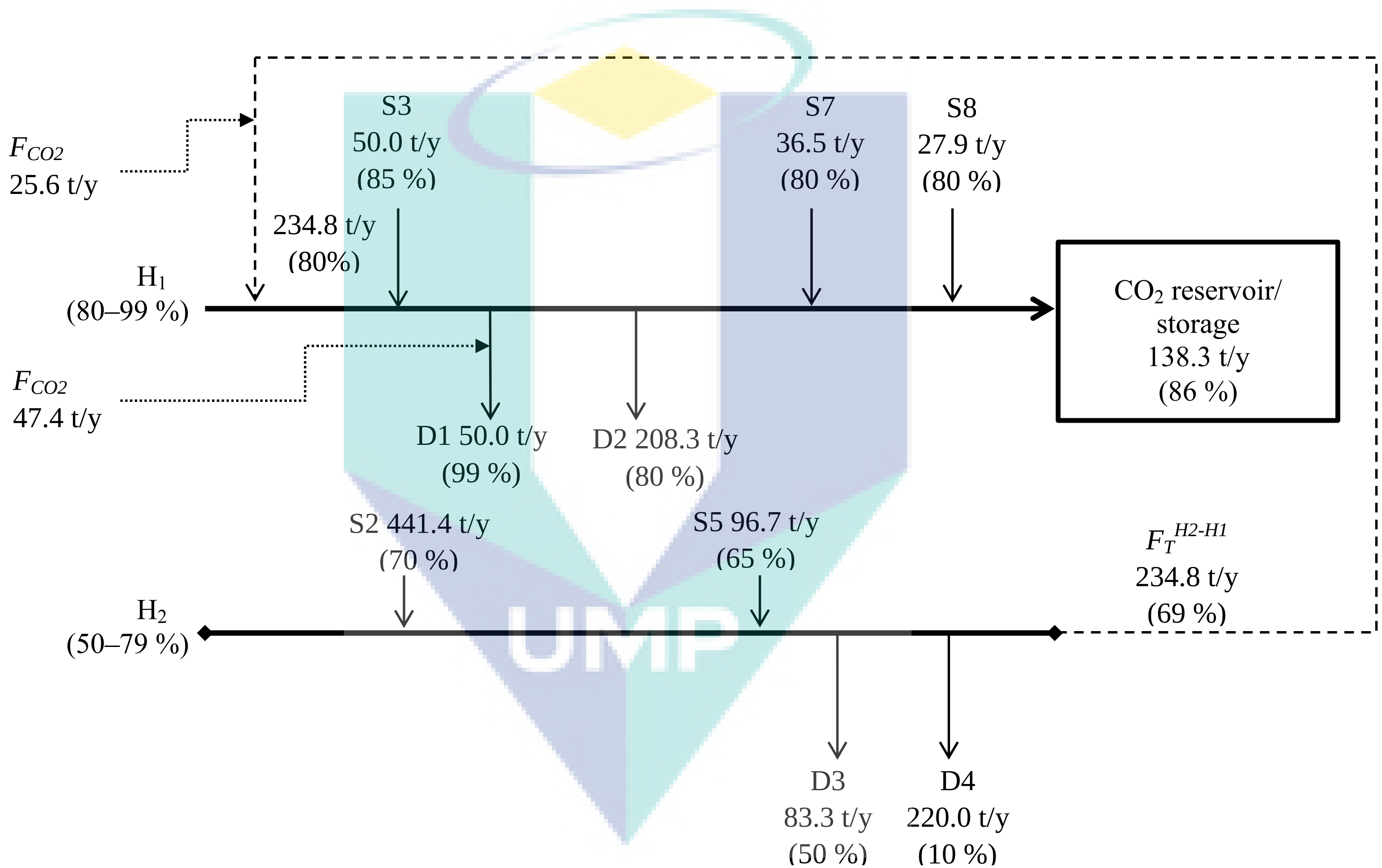


Figure 5.5: Optimal network for CO_2 Total Site Scenario 3

5.4.4 Scenario 4

Data of CO_2 sources (Table 5.2) and CO_2 demands (Table 5.3) are modified for scenario 4 for the condition 'what if' the CO_2 demands are more than CO_2 sources in H2. Note that only data in H2 are modified while H1 remained the same as previous in Scenario 1. Table 5.9 tabulates data for scenario 4. By referring to the last row of Column 16, the negative value of $Cum\ F_T^{H2}$ (-65.2 t/y) indicates that the amount of CO_2 sources in H2 is insufficient to satisfy the demands header. However, the insufficient amount could be supplied from F_T^{H1} as it has surplus amount of CO_2 which is supposed to be sent to the storage.

Table 5.10 shows final CUS-PTA to satisfy the demand in H2. The purity of H2 has been set to have a lower purity compared to H1. CO_2 with high purity from H1 cannot be sent to H2. Therefore, in order to satisfy the H2 demand, any higher purity of F_T^{H1} are neglected as H2 demands only accept supply with equal or lower purity respectively. In the last row of Column 7, F_T^{H1} has decreased to 1817.4 t/y after 65.2 t/y is transferred to H2 as indicated in Column 22 ($F_T^{H1\text{-}H2}$). Not only the H2 demand has been satisfied, the amount of CO_2 to be sent to storage also been reduced as the CO_2 been used for utilisation. The purity of H2 also has been increased to 71 % (P_{CO2}^{H2}) as shown in Column 18. No excess amount is generated in H2 (see $Cum\ F_T^{H2}$ in Column 16) which indicates there will be no CO_2 emitted to the environment. The optimal network for Scenario 4 is shown in Figure 5.6.

Table 5.9: CUS-PTA for CO_2 demand more than sources in H2

1	2	3	4	5	6	13	14	15	16	17	18	19	20	21
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1} t/y	F_{CO2}^{H1} t/y	F_{OG}^{H1} t/y	F_T^{H2} t/y	F_{CO2}^{H2} t/y	F_{OG}^{H2} t/y	$Cum\ F_T^{H2}$ t/y	$Cum\ F_{CO2}^{H2}$ t/y	P_{CO2}^{H2}	F_{CO2}^{H2-D} t/y	F_T^{H2-D} t/y	F_{OG}^{H2} t/y
S1	Cement	0.90	138.8	124.9	13.9									
									0.0	0.0	-			
S2	Palm oil refinery	0.70				441.4	309.0	132.4						
									441.4	309.0	0.70			
S3	Power (coal)	0.85	1174.3	998.2	176.1									
									441.4	309.0	0.70			
D1	Beverage plant	0.99	-50.0	-49.5	-0.5									
									441.4	309.0	0.70			
S4	Power (Natural gas)	0.88	101.5	89.3	12.2									
									441.4	309.0	0.70			
S5	Palm oil mill	0.65				96.7	62.9	33.8						
									538.1	371.8	0.69			
D2	EOR	0.80	-208.3	-166.6	-41.7									
									538.1	371.8	0.69			
S6	Petrochemical	0.80	615.4	492.3	123.1									
									538.1	371.8	0.69			
S7	Gas processing	0.90	36.5	32.9	3.7									
									538.1	371.8	0.69			
S8	Iron & steel	0.95	27.9	26.5	1.4									
									538.1	371.8	0.69			
D3	Methanol production	0.50				-233.3	-116.7	-116.7				-161.21	-233.3	-72.1
									304.8	210.6	0.69			
D4	Micro algae production	0.10				-370.0	-37.0	-333.0				-255.68	-370.0	-114.3
									-65.2	-45.0	0.69			

Table 5.10: Final CUS-PTA for Scenario 4

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1} t/y	F_{CO2}^{H1} t/y	F_{OG}^{H1} t/y	$Cum\ F_T^{H1}$ t/y	$Cum\ F_{CO2}^{H1}$ t/y	P_{CO2}^{H1}	$F_{CO2}^{H1\text{-}D}$ t/y	$F_T^{H1\text{-}D}$ t/y	$F_{CO2}^{FC\text{-}D}$ t/y	F_T^{H2} t/y	F_{CO2}^{H2} t/y	F_{OG}^{H2} t/y
S1	Cement	0.90	138.8	124.9	13.9									
						138.8	124.9	0.90						
S2	Palm oil refinery	0.70										441.4	309.0	132.4
						138.8	124.9	0.90						
S3	Power (coal)	0.85	1174.3	998.2	176.1									
						1313.1	1123.1	0.86						
D1	Beverage plant	0.99	-50.0	-49.5	-0.5				-3.0	-3.5	46.5			
						1309.6	1120.1	0.86						
S4	Power (Natural gas)	0.88	101.5	89.3	12.2									
						1411.1	1209.4	0.86						
S5	Palm oil mill	0.65										96.7	62.9	33.8
						1411.1	1209.4	0.86						
D2	EOR	0.80	-208.3	-166.6	-41.7				-178.5	-208.3	-			
						1202.8	1030.9	0.86						
S6	Petrochemical	0.80	615.4	492.3	123.1									
						1818.2	1523.2	0.84						
S7	Gas processing	0.90	36.5	32.9	3.7									
						1854.7	1556.1	0.84						
S8	Iron & steel	0.95	27.9	26.5	1.4									
						1882.6	1582.6	0.84						
D3	Methanol production	0.50										-233.3	-116.7	-116.7
						1882.6	1582.6	0.84						
D4	Micro algae	0.10										-370.0	-37.0	-333.0
						1882.6	1582.6	0.84						
						1817.4	1527.8	0.84						

Table 5.10(continue): Final CUS-PTA for Scenario 4

		16	17	18	19	20	21	22	23
		Cum F_T^{H2} *t/y*	*Cum* F_{CO2}^{H2} *t/y*	P_{CO2}^{H2}	$F_{CO2}^{H2\text{-}D}$ *t/y*	$F_T^{H2\text{-}D}$ *t/y*	F_{OG}^{H2} *t/y*	$F_T^{H1\text{-}H2}$ *t/y*	$F_{CO2}^{H1\text{-}H2}$ *t/y*
		65.2	54.8	0.84					
S2	Palm oil refinery								
		506.6	363.8	0.72					
		506.6	363.8	0.72					
		506.6	363.8	0.72					
		506.6	363.8	0.72					
S5	Palm oil mill								
		603.3	426.6	0.71					
		603.3	426.6	0.71					
		603.3	426.6	0.71					
		603.3	426.6	0.71					
		603.3	426.6	0.71					
D3	Methanol production				-164.99	-233.3	-68.3		
		370.0	261.7	0.71					
D4	Micro algae				-261.66	-370.0	-108.3	65.2	54.81
		0.0	0.0	-					

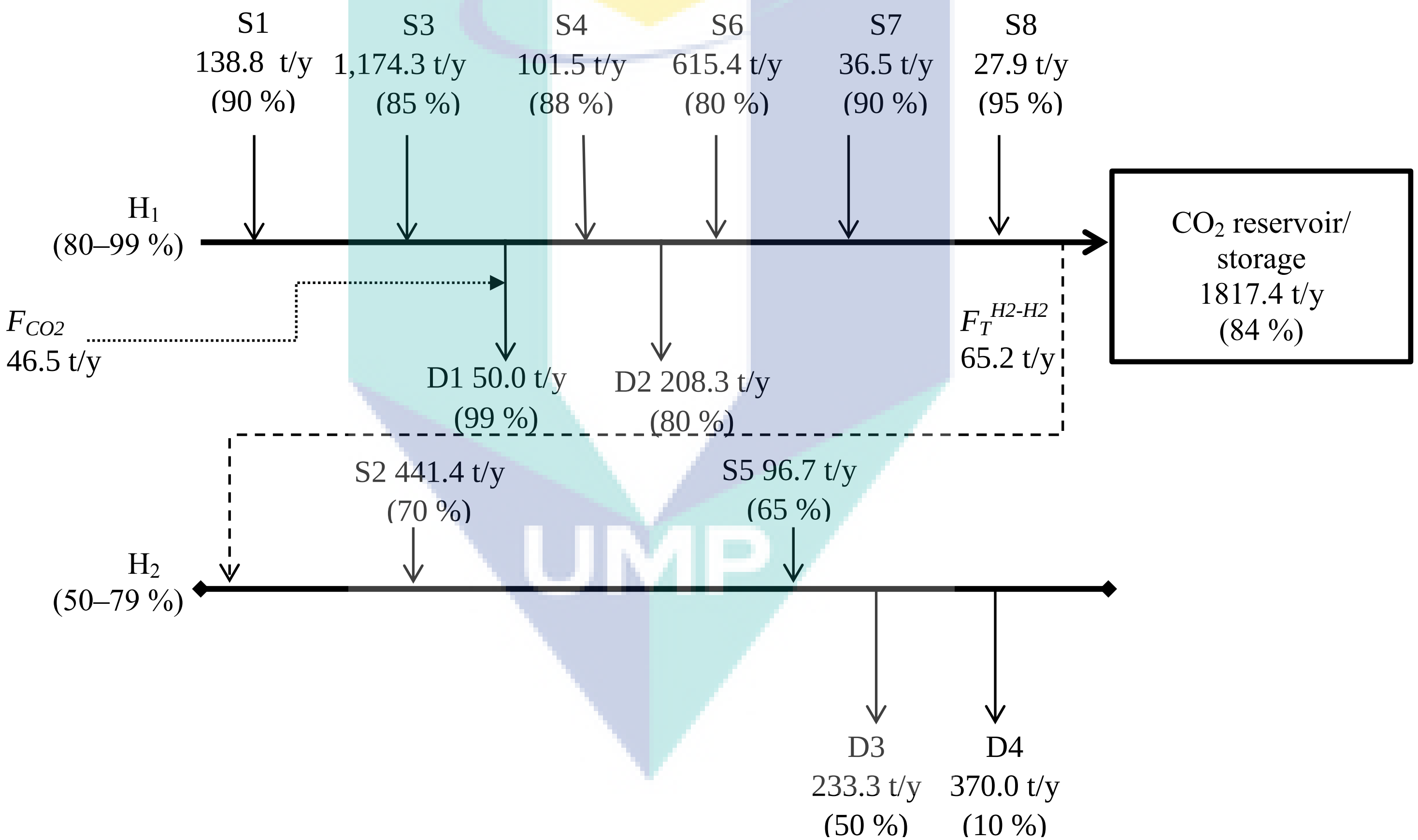


Figure 5.6: Optimal network for CO_2 Total Site Scenario 4

5.5 Conclusion

In this chapter, a targeting approach for CO_2 utilisation and storage with integrated CUS network was developed. This method was applied to a hypothetical Case study 3 to determine the potential of maximum CO_2 exchange using multiple and single CO_2 headers of different purity, with a centralised pure CO_2 generator.

Based on previous Chapter 4 for CO_2 emission of product supply chain management, the remaining CO_2 emission obtained from palm oil refinery and palm oil mill are taken into account in this chapter as potential of CO_2 sources that could be supplied into the developed CUS network. A total of four scenarios were established to illustrate the case study.

For Scenario 1, multiple headers are assumed to be used throughout the CUS network management. As a result, the CO_2 emission for both abovementioned plants (palm oil refinery and palm oil mill) have been reduced about 56% reduction and the other 44 % is expected to be emitted to the environment.

As for Scenario 2, only single header is assumed to be used in the network and the remaining CO_2 emissions in CUS network are sent to CO_2 storage.This scenario shows that zero emission can be achieved. However, by using only single header would result low CO_2 purity accumulated in the respective header hence this will increase the overall capital cost for fresh CO_2 generation. This is because as the CO_2 purity is low, more additional fresh CO_2 with high purity need to be supplied to meet the desired purity limit for storage. Furthermore, it will create uncertain storage conditions and lead to difficulty in controlling the CO_2 purity from various emission sources.

As for Scenario 3 and Scenario 4, these are ‘what if’ situations created based on Scenario 1. For Scenario 3, the situation shows that if the high purity CO_2 sources of H1 is deficit and is not sufficient to satisfy the demand in H1, the surplus from H2 can satisfy the shortage in H1. Since CO_2 surplus from H2 is low purity, additional fresh high purity CO_2 can be added up to meet the desired purity header. Hence no excess CO_2 will be emitted to the environment. But this will charge additional capital cost for CO_2 generation. For Scenario 4, the situations shows that if low purity CO_2 sources in H2 is not sufficient to satisfy the demands, the surplus from H1 can satisfy the shortage in H2. Since CO_2 surplus from H1 is high purity, the purity of H2 will be increased. Besides, no excess CO_2 will be generated in H2 hence reduced the amount of CO_2 to be sent to the storage as well as no CO_2 emitted to the environment.

This new technique enables plant owner or designer to plan and manage CO_2 emission efficiently in a more sustainable manner. The targeting technique also enables planner to conduct further analysis and feasibility studies systematically to match potential CO_2 sources and demands in a CUS integrated system. For optimal CUS network, detailed assessments and considerations of layout and pipelines condition, availability of CO_2 sources, as well as CO_2 demands and storage locations are crucial to be considered. Therefore, an extended CUS network is further developed and demonstrated in the following Chapter 6 with consideration of compressor component to overcome the pressure drop along the pipeline and additional CO_2 purifier to satisfy higher purity demands.

CHAPTER 6

CO_2 TOTAL SITE PLANNING WITH CONSIDERATION OF PURIFICATION AND PRESSURE DROP

6.1 Introduction

The methodology for CO_2 Total Site planning is further developed in this chapter considering important parameters of CO_2 transfer to maximise the CO_2 exchange before sending the excess CO_2 to the storage. Equipment such as compressor is needed to ensure that process transfer of CO_2 in the pipeline functions normally, as unanticipated pressure drop may resulted in leakage (Noothout *et al.*, 2013). Purification is a process to upgrade the concentration to satisfy high purity CO_2 demand and has been widely used in the hydrogen network (Wang *et al.*, 2016) to reduce production load. This is optional instead of using fresh CO_2 to satisfy high purity CO_2 demand. For CO_2 capture technology, CO_2 will be removed from the flue gas at first and will undergo regeneration before further compressed for storage or utilisation. CO_2 in the flue gas is absorbed by the lean solvent in the CO_2 absorption process while most of the absorbed CO_2 are regenerated from the rich solvent in the CO_2 regeneration process (Zhang and Guo, 2014).

Dense phase or supercritical condition of CO_2 is the most efficient state for CO_2 to be transported via pipeline and it is required to maintain the pressure in the pipeline above the critical point of CO_2 (Wetenhall *et al.*, 2014). In the Gas Processors Suppliers Association (GPSA) Engineering Data book (GPSA, 1998), the critical point of CO_2 occurs at pressure 7.38 MPa and temperature 31.4 °C and generally, the most practiced operating pressure is between 7.4 and 21 MPa to ensure CO_2 single-phase flow in the pipeline (Dakota Gasification Company, 2016). The critical point properties of CO_2 are at 31 °C and 7.37 MPa and the density of CO_2 at this point is assumed 467.69 kg/m3 (Fenghour *et al.*, 1998).

In this chapter, in order to enhance the integrated system of CO_2 Total Site, the CUS−PTA with consideration of purification process to purify CO_2 and pressure drop during the CO_2 transportation in header were introduced.

6.2 Problem Background

Referring to CO_2 Total Site network (in Chapter 5), the first point of the header which is the furthest location from storage is assumed to be operated at 21 MPa in order to transfer CO_2 along the pipeline. CO_2 flow rate exchange (flow in or out) that occurred throughout the header will affected the process of CO_2 transfers. Therefore, pressure drop during CO_2 transportation in the pipeline system has been included to identify the implication of pressure drop in the CO_2 Total Site design. Consideration of such important parameters for the transportation of CO_2 via pipeline shows that this methodology implements practical scenario. In addition, in the previous Chapter 5, purification process is not considered in the CO_2 Total Site network but in this chapter, further process of purification to upgrade the purity level of CO_2 supply from the header will be investigated.

6.3 Methodology

Four steps for the methodology contruction are explained in the following sub-sections. Figure 6.1 gives the overall process flow of the methodology. The first two steps of the methodology are similar as constructed in previous chapter. Hence, the details explanation for CO_2 sources and demands identification, and CUS−PTA methodology performance could be refer in Section 5.3.2 and 5.3.3. Single phase or supercritical CO_2 is assumed in the pipeline transportation system and single header was applied in CO_2 Total Site.

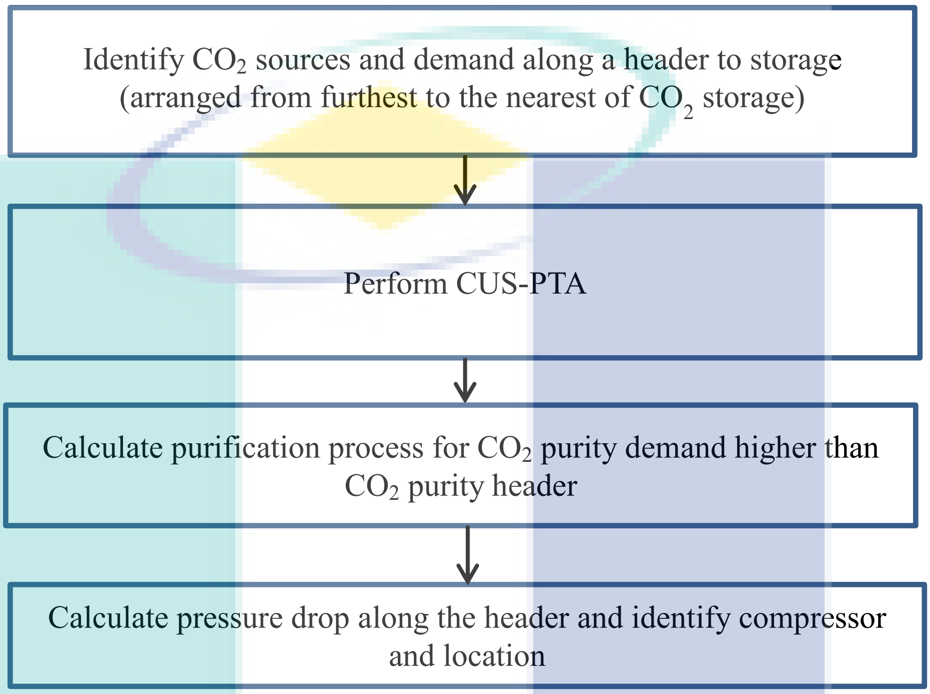


Figure 6.1: Process flow of CO_2 Total Site planning with parameters consideration

6.3.1 STEP 1: Identify CO_2 Sources and Demands

Industries which can capture CO_2 (Sources) and utilise CO_2 (Demands) were identified. The corresponding data of total flue gas flow rate (F_T), CO_2 flow rate (F_{CO2}), CO_2 purity of flue gas (P_{CO2}), and other gases (F_{OG}) were evaluated using Equation (5.1) until Equation (5.5) as stated in previous Section 5.3. Next, the distance from each point of source or demand along the header to the storage was then estimated.

6.3.2 STEP 2: Perform CUS-PTA

The identified CO_2 sources and demands are arranged based on their location along the header. Positive flow rate value represents sources while negative value represents demands. The next step is to accumulate F_T and F_{CO2} by cascading them downwards while the cumulative P_{CO2} is indicated by dividing the cumulative F_{CO2} with cumulative F_T. To match the CO_2 sources and demand, the F_T header would be supplied directly to the demands if the required demand purity is lower or equal to the header purity. However, if the demand requires higher purity than the header purity, a purification process is proposed to satisfy this demand.

6.3.3 STEP 3: Calculate Purification Process

For a demand that requires a higher purity than the CO_2 purity in the header, purification is considered so that to be able to utilise CO_2 extracted from the header to the demand site. The purification process generates two outputs (Zhang et al., 2011)—one of which has a higher purity as the product, F_{Di} and the other one being the by-product or tail gas (F^G), as shown is Figure 6.2. Note that the gas flow rate from the header, $F_T{}^H$, that supplies to demand is known as the feed ($FP_{in}{}^{H\text{-}D}$) of the system. The recovery efficiency (R^{ER}) can be calculated if the flow rate and purity of the product (FP^D P^D), flow rate and purity of the feed ($FP_{in}{}^{H\text{-}D}$, $P_{in}{}^{H\text{-}i}$) are determined.

Figure 6.2: Block diagram for purification process

The cumulative flow rate from the header to satisfy D1, $F_{in}^{H\text{-}D}$ is calculated using Equation (6.1). Equation (6.2) is used to calculate the tail gas flow rate (F^G) of the process and Equation (6.3) can be used to determine the purity of the tail gas of the system. Note that P represents purity and R^{ER} is the recovery efficiency of the purification process.

$$FP_{in}^{H\text{-}D} = \frac{F_T^{\ D} \times P_{CO2}^{\ D}}{R_{ER} \times (P_{CO2}^{\ H})} \tag{6.1}$$

$$F^G = FP_{in}^{H\text{-}D} - F^D \tag{6.2}$$

$$FP_{in}^{H\text{-}D} * P^{H\text{-}D} = F^D P^D + F^G P^G \tag{6.3}$$

For a demand that requires equal or lower purity (P_{CO2}) than CO_2 purity (P^H) in the header, $FP_{in}^{H\text{-}Di}$ is directly supplied per demand required without purifier installation as stated in the TSCI purity rule concept in previous Section 5.3.3. Equation (6.4) and Equation (6.5) represent the direct supply of flow rate from header to demand.

$$FP_{in}^{H\text{-}D} = F^D \tag{6.4}$$

$$FP_{in}^{H\text{-}D} \times P^{H\text{-}D} = F^D P^D \tag{6.5}$$

6.3.4 STEP 4: Calculate Pressure Drop and Identify Compressor

Pressure drop due to friction along the CO_2 pipeline transportation is calculated as pressure, which must be taken into consideration to ensure that CO_2 transportation functions normally. Equation (6.6) outlines the pressure drop estimation (Fox and McDonald, 1992), where f is the friction factor (0.0165), m is mass flow rate (kg/s), ρ is the fluid density (kg/m^3), L is pipe length (km), and D is the pipe diameter (m). For turbulent pipe flow that typifies the fluid flow in a plant, f would depend on the Reynolds number and relative roughness Ɛ/D, which is the ratio of the mean height of roughness of the pipe to the pipe diameter. The value follows the Colebrook equation i.e. Equation (6.7) and has been simplified into a Moody chart that presents the Darcy friction factor for circular pipe flow (Cengel and Cimbala, 2006).

$$\Delta P_d = f \frac{m^2}{\rho} \frac{L}{D^5} \frac{8{,}000}{\Pi^2} \tag{6.6}$$

$$\frac{1}{\sqrt{f}} = -1.8 \log \left[\frac{6.9}{Re} + \left(\frac{\mathcal{E}/D}{3.7} \right)^{1.11} \right] \tag{6.7}$$

For the estimation of the pressure drop in this study, a roughness value, Ɛ of 0.0457 mm, was used as the recommended value for commercial steel pipelines (Wetenhall et al., 2014) and the diameter of the pipe was assumed to be 27-in (Noothout et al., 2013). Note that L (km) is the distance between each of the source or demand points.

6.4 Case Study 4

Currently, there are about 6,500 km of total CO_2 pipelines worldwide, in which most of them are linked to EOR operations associated with or under development for CO_2 storage (Noothout *et al.*, 2013). The CO_2 transportation has become more important and optimal condition is required for operation. As to implement in CO_2 Total Site, purification process and pressure drop of CO_2 transportation via pipeline are further analysed. A length of 410 km is assumed for CO_2 header from the starting point of CO_2 source or demand until to the storage.

6.4.1 STEP 1: Identify CO_2 Sources and Demands

Data of CO_2 sources and demands from previous Section 5.3 are used in this study. Previously developed methodology has targeted CO_2 purity at each point of the header for optimal CO_2 utilisation, requiring minimum fresh CO_2 supply and remains CO_2 to be sent to storage. Distance is identified from the point of source or demand to the point of storage throughout the header. The CO_2 sources and demand are rearranged from the furthest up to nearest from the point of permanent CO_2 storage. Figure 6.3 illustrates the network of CO_2 sources, demand and storage by a header system and estimated distances at each point of sources and demands.

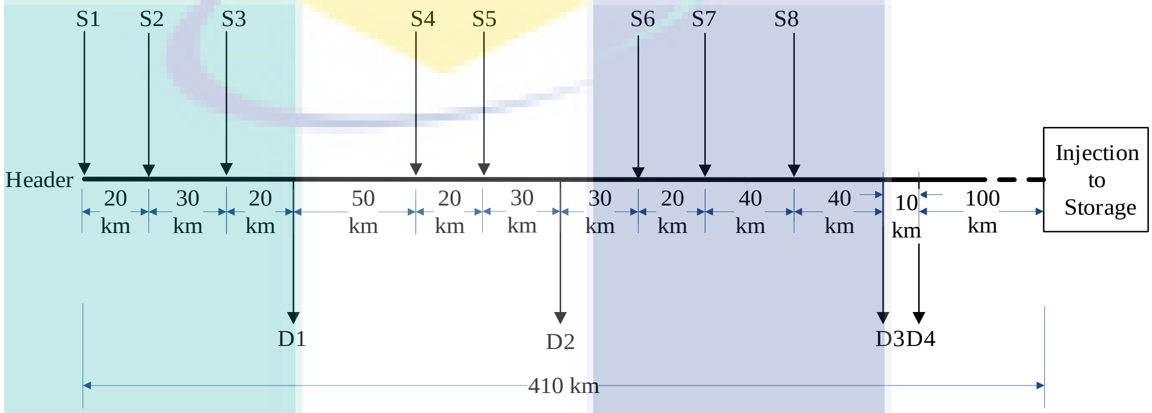


Figure 6.3: Location of CO_2 sources and demand from furthers to nearest head to storage

The CO_2 sources and demand are rearranged according to the location along the header. S1 is the furthest point of the pipeline header and follows by the nearest points towards the storage.

6.4.2 STEP 2: Perform CUS-PTA

The CO_2 sources and demands are matched by targeting the maximum CO_2 utilisation before the remaining captured CO_2 is sent to storage. The CUS-PTA is explained in the previous chapter (Chapter 5). For this chapter, if the demand requires higher purity than the header purity, a purification process is proposed to satisfy this demand.

6.4.3 STEP 3: Calculate Purification Process

A purification process is required when the purity of demand is higher than the supply purity. The flow rate from the header is calculated using Equation (6.1) to satisfy F_{D1} (demand of D1) that required 99% of CO_2 purity which is higher than the purity header (82%). Table 6.1 shows the CUS–PTA which required purification process due to satisfy the demand.

Table 6.1: Purity demand higher than purity header in CUS-PTA for CO_2 Total Site

1	2	3	4	5	6	7	8	9
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1}	F_{CO2}^{H1}	F_{OG}^{H1}	Cum F_T^{H1}	Cum F_{CO2}^{H1}	P_{CO2}^{H1}
S1	Cement	0.90	138.8	124.9	13.9			
						138.8	124.9	0.90
S2	Palm oil refinery	0.70	441.4	309.0	132.4		0.0	
						580.2	433.9	0.75
S3	Power (coal)	0.85	1174.3	998.2	176.1		0.0	
						1754.5	1432.1	0.82
D1	Beverage plant	0.99	-50.0	-49.5	-0.5			
S4	Power (Natural gas)	0.88	101.5	89.3	12.2			

By using Equation (6.1), 67.4 t/y of $F_{in}^{H\text{-}D1}$ (Column 10) is identified for the purification process inlet to satisfy 50 t/y demand of 99% purity. Note that the recovery efficiency (R^{ER}) of the purification process is assumed 0.9. The tail gas is supplied back (F^G) 17.4 t/y into the header with a purity (P^G) of 32 % using Equation (6.2) and (6.3). Purification is the process to increase the purity of flow rate that would generate two outputs (Zhang *et al.*, 2011). In this case, as the purification is satisfied to supply the demand, the other output (tail gas) would return into the header back as remaining CO_2 source and would prevented tail gas from emitted to atmosphere. Diagram for purifier installaltion is illustrated as Figure 6.4.

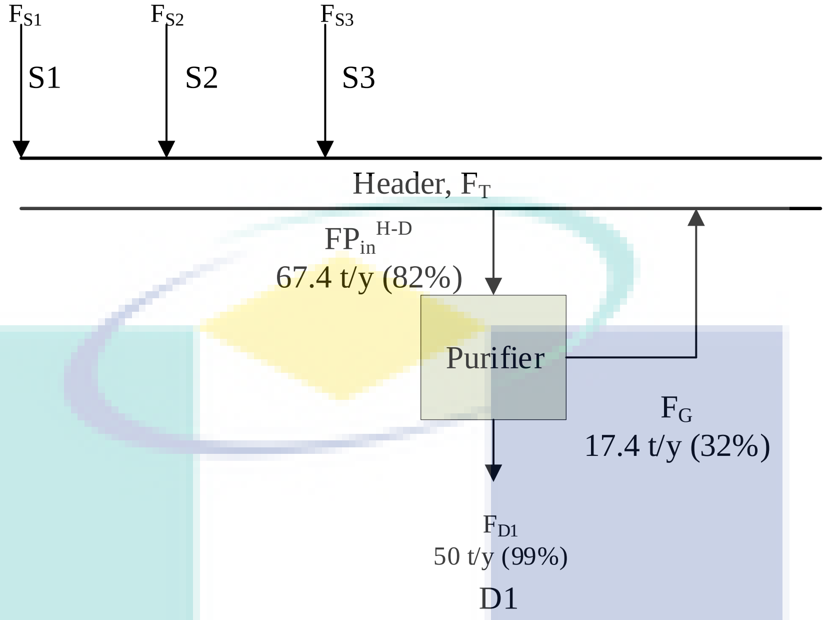


Figure 6.4: Mass balance of the purification process

For a demand that requires equal or lower purity (P_{CO2}) than CO_2 purity (P_H) in the header, FP_{in}^{H-D} is directly supplied per demand required without installation of purifier. Table 6.2 gives the result of CUS−PTA considering the purification process for higher purity demand.

Table 6.2: CUS−PTA with purification

1	2	3	4	5	6	7	8	9	10	11	12
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1} t/y	F_{CO2}^{H1} t/y	F_{OG}^{H1} t/y	$Cum\ F_T^{H1}$ t/y	$Cum\ F_{CO2}^{H1}$ t/y	P_{CO2}^{H1}	$FP_{in}^{H\text{-}D}$ t/y	F^G t/y	P^G
S1	Cement	0.90	138.8	124.9	13.9						
						138.8	124.9	0.90			
S2	Palm oil refinery	0.70	441.4	309.0	132.4						
						580.2	433.9	0.75			
S3	Power (coal)	0.85	1174.3	998.2	176.1						
						1754.5	1432.1	0.82			
D1	Beverage plant	0.99	-50.0	-49.5	-0.5				-67.4	-17.4	0.32
						1704.5	1396.7	0.82			
S4	Power (Natural gas)	0.88	101.5	89.3	12.2						
						1806.0	1486.1	0.82			
S5	Palm oil mill	0.65	96.7	62.9	33.8						
						1902.7	1548.9	0.81			
D2	EOR	0.80	-208.3	-166.6	-41.7				-208.3		
						1694.4	1379.4	0.81			
S6	Petrochemical	0.80	615.4	492.3	123.1						
						2309.8	1871.7	0.81			
S7	Gas processing	0.90	36.5	32.9	3.7						
						2346.3	1904.5	0.81			
S8	Iron & steel	0.95	27.9	26.5	1.4						
						2374.2	1931.0	0.81			
D3	Methanol production	0.50	-83.3	-41.7	-41.7				-83.3		
						2290.9	1863.3	0.81			
D4	Micro algae production	0.10	-220.0	-22.0	-198.0				-220.0		
						2070.9	1684.3	0.81			

6.4.4 STEP 4: Calculate Pressure Drop and Identify Compressor

The CUS-PTA with purifier installation and estimation of the pressure drop is given in Table 6.3. The last row in *Cum* F_T (Column 7) and *Cum* F_{CO2} (Column 8) gives the minimum target to be sent to CO_2 storage for permanently stored. There are no changes in the flue gas flow rate as CUS with purification network. This extended CUS-PTA involved the calculation of pressure drop using Equation (6.6), accumulated total pressure drop at 21.73 MPa, as shown in the last row of Column 15 (*Cum* ΔPd). Distance or pipeline length between each point of CO_2 sources/demands and fluctuated flue gas flow rate in the header are the main factors of pressure drop in CUS network.

Table 6.3: CUS-PTA with purification and pressure drop

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
S/D	Description	$P_{CO2}^{S/D}$	F_T^{H1} t/y	F_{CO2}^{H1} t/y	F_{OG}^{H1} t/y	Cum F_T^{H1} t/y	Cum F_{CO2}^{H1} t/y	P_{CO2}^{H1}	$FP_{in}^{H\text{-}D}$ t/y	F^G t/y	P^G	L km	ΔPd MPa	Cum ΔPd MPa
S1	Cement	0.90	138.8	124.9	13.9							20	0.005	
						138.8	124.9	0.90						0.01
S2	Palm oil refinery	0.70	441.4	309.0	132.4							30	0.133	
						580.2	433.9	0.75						0.14
S3	Power (coal)	0.85	1174.3	998.2	176.1							20	0.809	
						1754.5	1432.1	0.82						0.95
D1	Beverage plant	0.99	-50.0	-49.5	-0.5				-67.4	-17.4	0.32	50	2.140	
						1704.5	1396.7	0.82						3.09
S4	Power (Natural gas)	0.88	101.5	89.3	12.2							20	0.955	
						1806.0	1486.1	0.82						4.04
S5	Palm oil mill	0.65	96.7	62.9	33.8							30	1.581	
						1902.7	1548.9	0.81						5.62
D2	EOR	0.80	-208.3	-166.6	-41.7				-208.3			30	1.269	
						1694.4	1379.4	0.81						6.89
S6	Petrochemical	0.80	615.4	492.3	123.1							20	1.526	
						2309.8	1871.7	0.81						8.42
S7	Gas processing	0.90	36.5	32.9	3.7							40	3.146	
						2346.3	1904.5	0.81						11.56
S8	Iron & steel	0.95	27.9	26.5	1.4							40	3.218	
						2374.2	1931.0	0.81						14.78
D3	Methanol production	0.50	-83.3	-41.7	-41.7				-83.3			10	0.751	
						2290.9	1863.3	0.81						15.53
D4	Micro algae production	0.10	-220.0	-22.0	-198.0				-220.0			100	6.194	
						2070.9	1684.3	0.81						21.73

Pressure drop in pipeline must be considered in CUS network as it might abrupt changes in CO_2 compressibility (Witkowski *et al.*, 2014). Two points of compression are considered throughout the CUS network at which each of the compression points is assumed to make up 11 MPa of pressure to overcome 21.73 MPa of pressure losses along the header. Wong (2013) indicated that installation of booster station is required at every 100 km to 150 km that based on 8.5 kWh/t of energy consumption required for 1 MPa CO_2 compression. Therefore two units of compressors at 0.0935 MW capacity of each are required to manage CO_2 transfer along single CUS header. As for estimation, two headers of CUS Total Site would double the required number of compressors that consequently increases the capital cost of CUS network. Figure 6.5 illustrated the CUS design network with installation of purifier and compressors to transport CO_2 along the header.

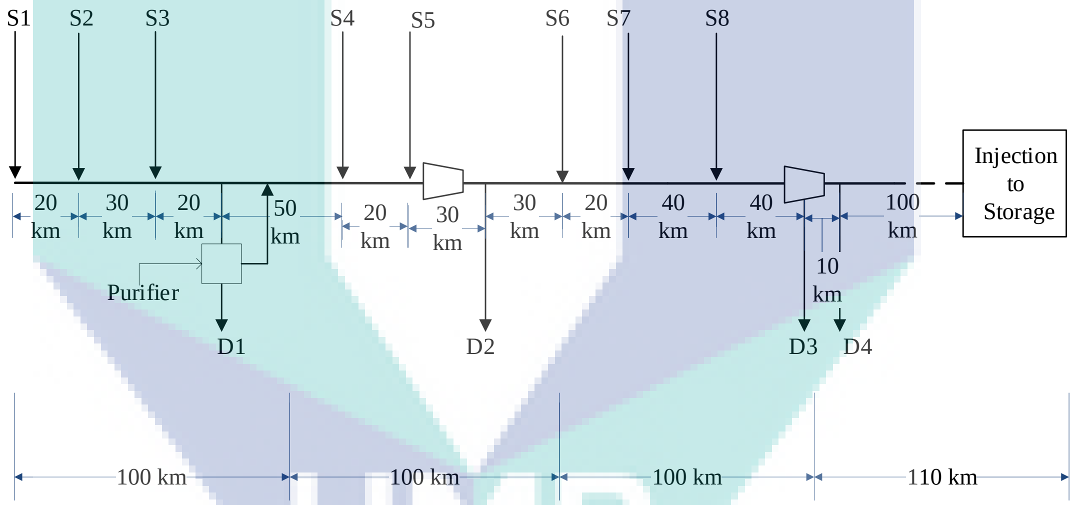


Figure 6.5: CUS design network with purifier and installation of compressor

6.5 Conclusion

CO_2 Total Site has potential to integrate major CO_2 emitter supplies into a centralised system, enabling its supply to any potential demands along the header. This chapter proposed improved methodology for further development of the CUS planning for this study. A unit of purification was identified to satisfy the demand which has higher CO_2 purity than the header instead of utilise pure CO_2. It would be convenient to control the CO_2 from the header simultaneously maximised the CO_2 utilisation. The more CO_2 is being utilised, the more CO_2 could be reduced or sent to the storage as indicates in Table 6.4. CUS network with purification has resulted lower $Cum\ F_T$ that need to be sent to storage which align with the main objective of this study that aims to reduce CO_2 emission.

Table 6.4: Comparison CO_2 Total Site with/without purification

	Without Purification	With Purification
Flue gas from header	2.7 *t/y*	67.4 *t/y*
Fresh CO_2 supply	47.3 *t/y*	-
Total flue gas sent to storage (CO_2 purity)	2118.2 *t/y* (81%)	2070.9 *t/y* (81%)

Total pressure drop (ΔPd) of CUS network in this study was determined to be 21.73 MPa over 410 km of pipeline length. Significant number of compressor could be estimated by referring to the pressure drop calculation. A single header of CUS network would require two compressors while two headers at the same distance might require four compressors in order to maintain the CO_2 phase during transfer processes. However, the installation of compressors might give penalty on CO_2 generation with the additional energy requirement but this issue is not covered in this study. The improved CO_2 Total Site methodology with consideration of the purification process and compression is seen as a realistic assessment for CUS design development.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 Summary

Development of PI methodologies for CO_2 emission reduction planning and management has been a vital research area to mitigate CO_2 footprint and concern on environmental issue. This work presents the PI-based on PA methodology for CO_2 management of product supply chain and Total Site utilisation and storage. These developed methodologies provided clear insights and good target estimation for problems dealing with resource planning and conservation.

(1) A holistic framework for CO_2 emission reduction planning and management throughout the product supply chain and CO_2 Total Site was developed. This methodology is essential in providing more realistic CO_2 emission planning starting from supply chain planning where the highest emission contribution or emission hotspot phase in the supply chain was identified to plan for further emission reduction options. The developed methodology implemented graphical approach that provides quantitative insights for screening various of CO_2 reduction options prioritising the highest contribution of CO_2 emissions. After implementation of CO_2 management on the product supply chain, the remaining emissions was futher reduced considering CUS for Total Site. The aim is to integrate CO_2 sources and demand for CO_2 to be fully utilised before being sent to the storage as CO_2 emission end-of-pipe solution.

(2) A new systematic methodology was developed to screen for CO_2 emission reduction strategies, which including consideration of emission emitted from fuel and electricity usage. This methodology was designed to prioritise various CO_2 emissions reduction strategies based on carbon management hierarchy and screened for cost-effective strategy using SHARPS technique to achieve the desired investment and payback period target. The developed visualisation tool provides clear insights for users as well as helps to perform systematic selection for various CO_2 emission reduction strategies. Selected strategies that gives result within the targeted investment and payback period are potential to contribute positive impact for sustainable economy and environment.

(3) A targeting methodology for Total Site CO_2 utilisation and storage was developed. A new concept of CO_2 integration was introduced which maximises the CO_2 utilisation before it is sent to CO_2 sequestration or storage using a centralised header. CUS−PTA was successfully developed to optimise the CO_2 exchange between CO_2 sources and demands before excess CO_2 is sent to the storage as a means of emission mitigation. The developed methodology is seen as an effective end-of-pipe management to cater the issue of CO_2 emission.

(4) The CUS−PTA was developed by incorporating important parameters such purification and pressure drop for CO_2 transfer using pipeline. Installation of purifier would result high CO_2 utilisation and simultaneously reduced fresh CO_2 requirement. On top of that, a method to determine the number of compressor (considering pressure drop) has also been proposed. The methodology enables planner to conduct further analysis study for integrated pipeline system of CO_2 utilisation and storage.

7.2 Recommendations

The recommendation for future research of PI-based on PA CO_2 management are described as below:

(1) Emission throughout product supply chain from cradle to grave is crucial as to plan the reduction strategies comprehensively with consideration of other GHG e.g., methane, nitrous oxide, flourinated gases using PI-based on PA approaches. By including consideration of other gas emissions throughout the product supply chain, it will yield more virtual on environmental impacts.

(2) Even though graphical approach for product supply chain CO_2 management could provide better understanding, there is also a need to develop using PI-based mathematical programming to cater for more cases or complex problem such as complex route transportation or uncertainty production.

(3) Most of the works on PI-based on PA methodologies are focused on energy planning and industrial applications. Recent works are moving towards the reduction of CO_2 emission via waste management that consequently can be extended to consider other important footprints such as nitrogen footprint (NF), phosphorus footprint (PF), land footprint (LF), and biodiversity footprint (BF).

(4) Research to develop systematic and integrated CO_2 capture, utilisation, and storage tools for strategic CO_2 mitigation planning is currently in progress. Present PI-based on PA methodologies on emission planning and management mostly focus on CCS planning. Therefore, the integrated CUS planning approach still has room for further development, so that other constraints such as multiple-period CO_2 sources and demands and batch CO_2 emission production or transportation are considered as well.

(5) The CUS network design could be further analysed for energy and economic feasibility to develop sustainable CO_2 emission planning and management.

Furthermore, it can also include the CO_2 reservoir size or geological storage-life capacity for an optimal CUS network.

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APPENDIX A

List of journals:

Manan, Z. A., **Mohd Nawi**, W. N. R., Wan Alwi, S. R. and Klemeš, J. J. (2017). Advances in Process Integration Research for CO_2 Emission Reduction – A Review Journal of Cleaner Production *167, 1-13* Impact factor: 5.715 (Q1)

Mohd Nawi, W. N. R., Wan Alwi, S. R., Manan, Z. A., & Klemeš, J. J. (2016). Pinch Analysis targeting for CO_2 Total Site planning. Clean Technologies and Environmental Policy (CTEP) *18:2227-2240*. Impact factor: 1.934 (Q2)

Mohd Nawi, W. N. R., Wan Alwi, S. R., Manan, Z.A., Klemeš, J. J. (2016). A Systematic Technique for Cost-Effective CO_2 Emission Reduction in Process Plants. Clean Technologies and Environmental Policy (CTEP) *18:1769-1777* Impact factor: 1.934 (Q2)

Mohd Nawi, W. N. R.; Wan Alwi, S. R.; Manan, Z. A. and Klemeš, J. J. (2016). Regional and Total Site CO_2 Integration Considering Purification and Pressure Drop. Chemical Engineering Transactions *52, 1171-1177* (Scopus cited)

Mohd Nawi, W. N. R.; Wan Alwi, S. R.; Manan, Z. A. and Klemeš, J. J. (2015). A New Algebraic Pinch Analysis Tool for Optimising CO_2 Capture, Utilisation and Storage. Chemical Engineering Transaction *45, 265-270* Impact factor: 0.82 (Scopus cited)

Mohd Nawi, W. N. R.; Wan Alwi, S. R.; Manan, Z. A. and Klemeš, J. J. (2014). A Graphical Approach for the Planning and Design of a Low Carbon Product. Chemical Engineering Transaction *39, 205-210* Impact factor: 1.01 (Scopus cited)

List of conferences:

19th Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES 2016). 27-31 August 2016, Prague, Czech Republic. *Regional and Total Site CO_2 Integration Considering Purification and Pressure* Drop (Keynote presentation)

10th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2015). 27 Sept – 2 Oct 2015, Dubrovnik, Croatia.). *A Systematic Technique for CO_2 Emission Reduction in Process Plants* (Keynote presentation)

18th Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES 2015). 23-27 August 2015, Kuching, Sarawak, Malaysia. *Pinch Analysis Tool for Optimising CO_2 Capture, Utilisation and Storage* (Oral presentation)

1st International Conference of Low Carbon Asia in conjunction with The 4th Annual Meeting of Low Carbon Asia Research Network (ICLCA) 2015 Double Tree by Hilton Hotel, Johor Bahru. *A concept of Total Site-Carbon Integration for CO_2 capture, utilisation and storage* (Poster presentation)

17th Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES 2014). 23-27 August 2014, Prague, Czech Republic. *Planning and Design of a Low Carbon Product* (Keynote presentation).
International Conference on Oil Palm and the Environment in Malaysian Agro Exposition Park Serdang (MAEPS). 24-25 Oct 2013, Selangor. Carbon management in palm oil industry (Poster presentation).