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

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To my beloved husband, Muhammad Faizal
Umairah, Umaiza,Uzayr
Ibu, Bapak, Mak, Abah and family members

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In the name of Allah, the Most Gracious and the Most Merciful

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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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LIST OF ABBREVIATIONS

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).

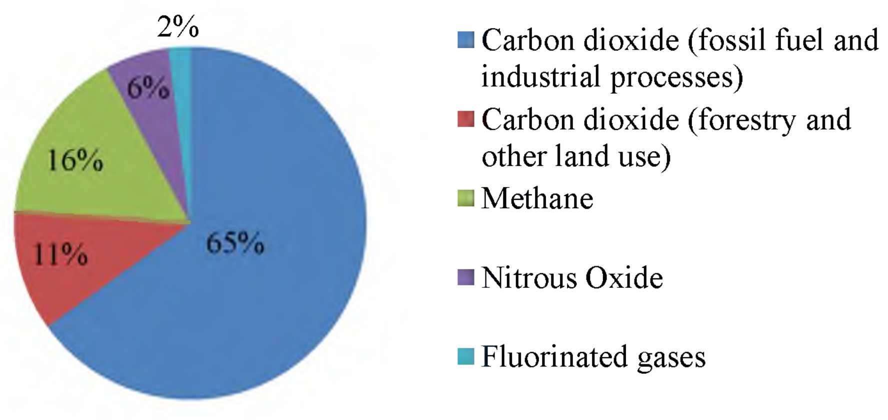

Figure 1.1: Global GHG emission according to gas type (IPCC, 2014)

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.

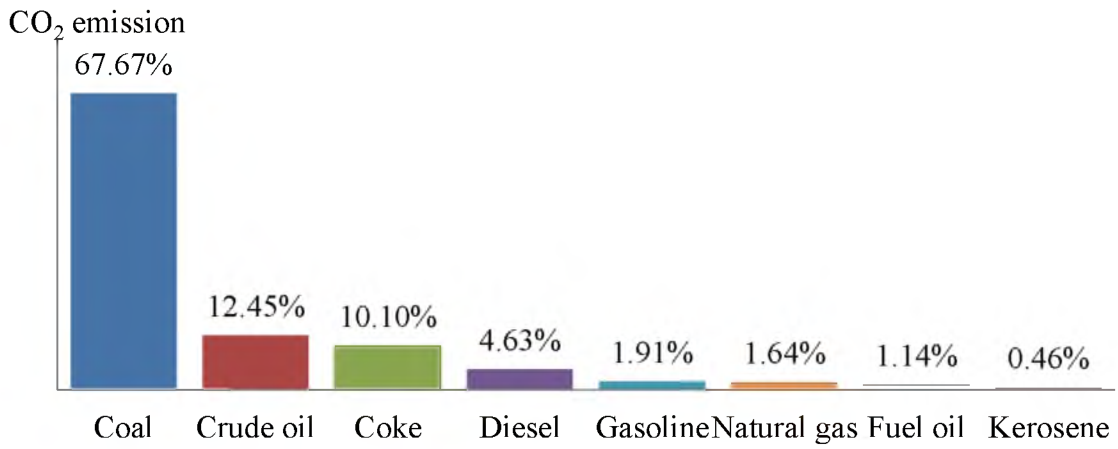

Figure 1.2: Proportion of CO_2 emission from energy sources (2014)

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.

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