CARBON CAPTURING STORAGE AND UTILIZATION AT BUILDING LEVEL: A FEASIBILITY STUDY BASED ON LIFE CYCLE THINKING

by

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The following individuals certify that they have read, and recommend to the College of Graduate Studies for acceptance, the dissertation entitled:

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Abstract

Anthropogenic greenhouse gas (GHG) emissions from fossil fuel combustion in energy generation are one of the main causes of climate change. It is important to mitigate climate change as it leads to extreme weather and climate events. Buildings are responsible for 40% of the energy consumption in the world. The majority of energy consumed in buildings is for heating in colder regions. Natural gas is a commonly used fuel for building heating despite the GHGs directly emitted during the operation of natural gas building heating systems. Although energy demand can be reduced with energy retrofits, it is impossible to completely eliminate the requirement of thermal energy from the current technologies. Adopting carbon capturing, storage, and utilization technologies at building level can be a solution for reducing the GHG emissions from natural gas building heating systems. However, feasibility assessment, research, and development of this technology are lacking in the current knowledge base. The main goal of this research is to investigate the feasibility of implementing carbon capturing, storage, and utilisation technologies in existing natural gas-based building heating systems. The study developed a life cycle thinking based comparative performance assessment framework to assess the life cycle environmental and economic performance of building-level carbon capturing technologies and compare them to alternative GHG emission mitigation methods used for building heating systems. A fuzzy logic based, multi-attribute decision making approach was used in the comparative performance assessment framework to consider both environmental and economic impacts simultaneously, while handling the uncertainties. The outcomes of the research will contribute to the development of building-level carbon capturing technologies and provide confidence to stakeholders to invest in them. In addition, the knowledge is useful for policy makers and governments in making decisions on climate change mitigation initiatives, while supporting the climate action targets of the Canadian government and global agreements.

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Lay Summary

The study involves reducing Greenhouse gas (GHG) emissions from the building sector. The main goal is to study the possibility of capturing Carbon Dioxide from natural gas building heating systems using building-level carbon capturing technologies. The study developed a performance assessment framework to help decision making on implementing building-level carbon capturing technologies. This study evaluates environmental and economic impacts throughout the life cycle of building-level carbon capturing technologies using the developed performance assessment framework. In addition, the life cycle performance of building-level carbon capturing technologies was compared against commonly used building GHG mitigation technologies under different stakeholder perceptions. The knowledge gained in this research will help innovators to develop GHG emission mitigation technologies, and the research outcomes will act as a research base for building-level carbon capturing technologies.

Preface

I, Don Rukmal Liyanage, developed the research concepts presented in this thesis, and conducted the relevant analyses. Based on the study and the comprehensive literature review that I conducted, I developed the concepts of life cycle thinking based comparative performance assessment of building-level carbon capturing technologies. I was also involved with experimentation on commercial building-level carbon capturing technology to evaluate the technical performance, which was used as input data for one of the case studies conducted in this study. I compiled the literature review conducted in Chapter 3 as a journal article and it is under review by the supervisor. I also submitted a conference article from the operational performance characteristic assessment conducted in Chapter 4 and it was accepted for conference presentation. An additional journal article, based on the contents of Chapter 5 and Chapter 6, is currently being prepared. The research was conducted under the supervision of Dr. Kasun Hewage. Dr. Rehan Sadiq, who is a supervisory committee member, assisted me in developing the research concepts and reviewed and provided recommendations for all the manuscripts.

Conference Articles:

1. **Liyanage, D. R**., Hewage, K., & Karunathilake, H. (2020). Feasibility study of integrating carbon capturing and utilization at building-level natural gas heating systems. In 2nd International Conference on New Horizons in Green Civil Engineering (pp. 1–5).

Submitted journal articles

1. **Liyanage, D. R**., Karunathilake, H., Chhipi-Shrestha, GK., Hewage, K., Sadiq, R. (2020). Prospects of implementing carbon-capturing systems for building-level heating systems – Literature based technical, economic, and environmental feasibility assessment. Submitted to *Renewable and Sustainable Energy Reviews* (Elsevier) in August 2020.

Articles under preparation

2. **Liyanage, D. R**., Karunathilake, H., Chhipi-Shrestha, GK., Hewage, K., Sadiq, R. Feasibility of implementing carbon-capturing systems for building-level heating systems – Life cycle thinking approach. Expected to be submitted to Journal of Cleaner production (Elsevier) in September 2020.

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List of Abbreviations

Acronyms

AB	Alberta
AFUE	Annual Fuel Utilization Efficiency
AHP	Analytic Hierarchy Process
AP	Acidification potential
BC	British Columbia
CCS	Carbon capturing and storage
CCSU	Carbon capturing, storage, and utilization
COP	Coefficient of performance
DHW	Domestic hot water
EOR	Enhanced oil recovery
FETP	Freshwater eco toxicity potential
FGD	Flue gas desulphurization
GHG	Greenhouse gases
GWP	Global warming potential
HTP	Human toxicity potential
IECM	Integrated environmental control module
IGCC	Integrated gasification combined cycle power plants
ISO	The International Organization for Standardization
LCA	Life cycle assessment
LCC	Life cycle costing
LCE	Levelized cost of electricity
MADM	Multi attribute decision making
MB	Manitoba
MCDM	Multi-criteria decision making
MEP	Marine eutrophication potential
METP	Marine eco toxicity potential
NB	New Brunswick

NG	Natural gas
NGCC	Natural gas combined cycle
NS	Nova Scotia
ON	Ontario
PMFP	Particulate matter formation potential
POFP	Photochemical oxidant formation potential
PSA	Pressure swing adsorption
QC	Quebec
SCPC	Super critical pulverized carbon
SK	Saskatchewan
TETP	Terrestrial eco toxicity potential
TOPSIS	Technique of order preference similarity to the ideal solution
TRACI	Tool for reduction and assessment of chemicals and other environmental impacts
TSA	Temperature swing adsorption
US	United States
VPSA	Vacuum pressure swing adsorption
WSM	Weighted sum method

Abbreviations and units

CTU	Comparative Toxicity Unit
CAD	Canadian Dollars
USD	United States Dollars
kg	Kilogram
kg CO2 eq	Kilograms of equivalent Carbon Dioxide
kg CFC11 eq	Kilograms of equivalent Trichlorofluoromethane
kg NOx eq	Kilograms of equivalent Oxides of Nitrogen
kg PM2.5 eq	Kilograms of equivalent particulate matter with a diameter of less than 2.5 µm
kg SO2 eq	Kilograms of equivalent Sulphur Dioxide

kg N eq	Kilograms of equivalent Nitrogen
m^3	Cubic Meter
kJ/kg	Kilo Jules per Kg of water

Chemical Formulas

CH4	Methane
CO_2	Carbon Dioxide
K_2CO_3	Potassium Carbonate
KOH	Potassium Hydroxide
MDEA	Methyl Diethanolamine
MEA	Mono Ethanol Amine
N	Nitrogen
Na_2CO_3	Sodium carbonate
$NaHCO_3$	Sodium Bicarbonate
NaOH	Sodium Hydroxide
NH_3	Ammonia
NO_x	Nitrogen Oxides
O_2	Oxygen
SO_2	Sulphur Dioxide

Acknowledgements

I wish to express my deepest gratitude to my supervisor, Dr. Kasun Hewage, for his continuous support and guidance from the time I started until the end of my MASc. I'm forever grateful for the opportunity he gave me by choosing me as a research student at UBC-Okanagan campus, which is a prestigious university in the world. His patience and faith in me throughout my MASc program and especially on the research project gave me the confidence to excel in the work I'm doing. He has inspired me to challenge my own limits in which I could become a stronger academic and professional. I am always indebted to him for his persistent help, motivation, and inspiration throughout my MASc program.

I wish to show my gratitude to Dr. Rehan Sadiq, for his supervision, encouragement, and mentorship throughout my MASc program. His expertise knowledge always inspired me and his advice helped me in making my research better. My gratitude goes to him for making time to discuss my research amid his busy schedules. I would like to acknowledge Dr. Joshua Brinkerhoff for the advice for my research activities as one of my supervisory committee members. Moreover, I would like to acknowledge the School of Engineering administrative staff, including Ms. Shannon Hohl, Ms. Stephanie Oslund, and Ms. Brittany Parr for their continuous support during the past few years.

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I would like to recognize the great assistance provided by the research team at Life Cycle Management laboratory. I would like to offer my special thanks to Dr. Hirushie Karunathilake and Mr.Tharindu Prabatha for giving me both professional and personal support and guidance throughout the years. I really appreciate the support from Dr. Rajeev Ruparathna who gave me the guidance to successfully start my graduate studies. Moreover, my thanks go to Dr. Piyaruwan Perera, Ms. Ravihari Kottearachchi and Mr. Tharaka Wanniarachchi, Dr. Gyan Kumar Chippi-

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I would like to acknowledge the support and gratitude from my parents, by brother, my family and my parents-in-law, who always believed in me. They always support me in every endeavor I undertook. Lastly, I would like to appreciate Mrs. Harshani Sumanasekara, my wife, for her love, patience, understanding, and tremendous support.

Dedication

Dedicated to my beloved family, friends, and teachers,

Who loved me, protected me,

and made me who I am…

Chapter 1: Introduction

1.1 Background

The world is experiencing extreme weather and climate events such as increase in warm temperatures and decrease in colder temperatures [1]. These events are linked to human activities such as energy generation using fossil fuel combustion, which releases greenhouse gases (GHG) such as CO_2. Cumulative CO_2 emissions will be the main cause that increase the global mean surface temperature in the late 21st century[1]. Therefore, countries such as Canada are implementing various measures to reduce the GHG emissions from all possible sectors to limit climate change [2].

The building sector is considered to be one of the largest energy consumers in the world [3]. It was reported that the building energy consumption of the world will increase by 50% from 2018 to 2050 [4]. Therefore, considering the emissions of buildings is important when reducing GHG emissions. Among the energy consuming activities in buildings, space and water heating contribute to the majority of the GHG emissions of buildings in colder climates [5][6]. For example, space and water heating contribute 82% of the total operational GHG emissions from residential buildings and 70% of the total GHG emissions in commercial buildings [6] in Canada [5]. There are several measures taken to reduce the operational GHG emissions of existing buildings: demand reduction using building retrofitting, integrating renewable energy as the energy source, and using carbon capturing.

Building energy retrofits are more commonly used to reduce the energy consumption of buildings compared to the other building GHG emissions reduction methods [7]. Building energy retrofits are characterized as minor retrofits, such as adding insulation; major retrofits, such as updating inefficient heating systems; and deep retrofits, such as replacing the roof and changing the heating system to renewable technologies [7]. Although there are renewable technologies such as solar thermal heating technologies and biomass systems, these technologies have considerable limitations. Passive solar thermal heating systems are known to have lower improvement in building heating in winter seasons and the intermittent behaviour of energy generation [8]. Therefore, solar thermal systems are used for applications such as pre-heating air, and water heating that have considerably lower energy requirements compared to space heating systems.

Technologies such as ground-source heat pumps are also considered renewable energy sources [9][10]. Although heat pumps consume less electricity in operation, the GHG emission reduction potential depends on the electricity generation energy sources. When electricity is generated using fossil fuel energy sources, the GHG emissions are higher than in natural gas systems. For all of the above reasons, alternative strategies to reducing GHG emissions associated with natural gas based heating systems need to be investigated, as it is unlikely these applications will be fully supported by zero-emission energy sources in the near future. At present, due to the economic and technical challenges associated with carbon source removal, developing carbon sinks that can absorb carbon dioxide (CO_2) emitted by natural gas (NG) based systems has a significant potential for reducing associated emissions.

In addition to developing renewable energy sources, carbon-capturing is becoming an emerging GHG emission reduction alternative for mitigating emissions associated with fossil fuels. This approach is commercially used in inherent CO_2 separation applications such as natural gas processing and chemical production, which produce high-density CO_2 [11]. In addition, it is used by the fossil fuel power generation sector. In addition to reducing the carbon footprint, carbon capturing helps the economy by generating the required CO_2 for emerging carbon utilization technologies. In particular, technologies such as CO_2-derived fuels and CO_2-cured concrete and aggregates are known to have significant potential in the future to replace conventional fuels and materials [12]. Therefore, rather than considering CO_2 as a waste, these technologies will increase the demand for CO_2 in the future.

Recently, the prospect of downsizing existing carbon-capturing strategies to reduce GHG emissions from buildings has been brought into the discussion. The potential of emission reduction without compromising building energy economics is the main motivation behind this strategy. Capitalizing on this idea, some pilot-scale carbon-capturing devices have been developed for use in natural gas building heating systems [13].

However, technically matured carbon capturing technologies that are used in fossil fuel power generation plants suffer from increasing energy consumption and other emissions that may be produced during the carbon capturing process, which can create adverse environmental impacts [14][15]. Furthermore, the carbon capturing process requires raw materials that may have environmental impacts during the extracting and production processes. For example, one of the recently started building-level carbon capturing systems consume 2.5 kg of potassium hydroxide for every 1 kg of captured CO_2 based on the stoichiometry of the chemical reaction. In contrast, it produces potassium carbonate, which can replace commercial products and significantly reduce conventional production [16].

Reducing the GHG emissions of fossil fuel combustion while also generating revenue from the by-products may make this technology more attractive to the building sector. However, the lack of feasibility assessment and research and development activities will be the key challenges for commercialization and market penetration of building-level carbon capturing systems. Successful implementation of the building-level carbon capturing technology requires a comprehensive assessment of the environmental and economic performance by considering all the facts mentioned above. Furthermore, the performance assessment of building-level carbon capturing must be supported by a life cycle thinking-based approach in order to understand the holistic image of environmental and economic impacts.

1.2 Research gap

The research considered in this study was originated based on the above-mentioned background and pressures. Although studies were conducted on implementing carbon capture, storage, and utilization (CCSU) in the power generation sector, the comprehensive literature review indicated that studies on integrating CCSU for building-level heating systems was overlooked. The application of the CCSU to building-level heating systems is substantially different for the power generation sector due to factors such as the physical scale of the energy source, funding capabilities, seasonal variations of the heating load, and the availability of transportation infrastructure. Therefore, the feasibility of implementing CCSU at building-level requires more specific knowledge that is not available in the current body of knowledge. The major research gaps identified in the literature review are explained below.

The feasibility of adapting existing carbon capturing technologies used in fossil fuel power plants into building heating systems

The carbon capturing technologies that are used in the fossil fuel power generation sector can be classified as post-combustion, pre-combustion, and oxy fuel combustion. The technical feasibility of carbon capturing technologies depends on the optimum operational conditions, such as CO_2

composition, and operational parameters, such as operational flexibility. The operation of building heating systems may have differences compared to power plants, such as variation of energy load due to seasonal variations. It is important to identify these differences and suitable carbon capturing technologies that can co-function with building-level heating systems based on the operational conditions and parameters.

Lack of knowledge on the supply chain and operations of practical implementation of building-level carbon capturing

Many of the studies assumed captured CO_2 is transported through pipelines, which requires significant infrastructure development if it is deployed in building scale. Road transportation is more suitable for transporting CO_2 in building scale, according to the literature review. There is a lack of studies considering this situation. Road transportation is an intermittent transportation method and it require temporary storage, which may be a constraint in the building-level application due to limited space in buildings. Furthermore, building heating systems generate heat, which has seasonal variations [17] unlike power generation plants. Estimation of operational characteristics such as actual yield of CO_2, energy consumption, and production of by-products when carbon capturing systems are implemented on building heating systems in different climatic regions must be evaluated based on facts such as seasonal variation of energy load and funding availability.

Lack of life cycle thinking in carbon capture implementation decisions at building-level

Life cycle assessment (LCA) and life cycle costing (LCC) provide a holistic view of the environmental and economic impacts of a process or product system [18]. While the literature review revealed that LCA and LCC studies have been conducted in the power generation sector [19], the life cycle environmental and economic impacts can be considerably different at the building scale due to the differences of the building heating systems and power generation sector as explained above. In particular, important economic parameters such as the investment cost of implementing CCSU can be greatly affected by the reduced scale of building heating systems compared to the power generation sector. Therefore, considering environmental and economic impacts together with life cycle thinking is much needed knowledge when assessing the applicability of building-level CCSU systems. In addition, developing life cycle impacts and a cost database can be useful to decision makers and other stakeholders.

Lack of holistic decision support frameworks for building-level CCSU integration

The economic and environmental impacts are conflicting objectives when making decisions on sustainability [20]. Therefore, it is important to consider both environmental and economic impacts simultaneously for holistic sustainability decision making. Holistic decision support frameworks were developed to assess sustainability for different applications, such as building retrofitting and energy system integration, and carbon capturing in the power generation sector. However, these decision support frameworks are not applicable for building-level CCSU integration due to the different process activities and economic criteria. In addition, the building-level CCSU technology is in its early adoption stages, which may have higher uncertainty in the decision making process. Therefore, developing a holistic decision support frameworks for building-level CCSU integration that consists of uncertainty handling is much needed.

The following specific research questions were formed considering the above research gaps in the existing body of knowledge:

i) What are the technically feasible carbon capturing technologies that can co-function with building-level heating systems?
ii) How can the operational characteristics of carbon capturing technologies be assessed when implemented on building heating systems?
iii) What are the life cycle environmental and economic impacts of CCSU in building scale?
iv) How can the applicability of the CCSU in building scale be assessed based on environmental and economic performance?

1.3 Research motivation

The percentage of buildings that use natural gas for heating is about 25% around the world [21]. The operation of the natural gas heating systems releases GHG emissions. Although many of the studies focused on reducing energy demand by retrofitting the building envelope and using efficient energy sources, energy must still be supplied for heating buildings [21]. There are other energy sources that are known to have a lower carbon footprint, which can be used for building heating applications [5]. Replacing natural gas combustion heating systems with electricity systems can be a solution to reduce GHG emissions, if the regions depend on cleaner energy sources to produce electricity [22]. Although electricity cost per unit of energy is much higher than natural gas, there are energy systems, such as air-source and ground source-heat pumps, that consume significantly less electricity than converting electricity directly into heat. However, these technologies are not environmentally friendly when the electricity grid is powered by fossil fuel energy sources. Renewable energy sources such as solar thermal energy are not commonly used with space heating systems in colder climates due to limitations of solar energy in the winter season [8].

The motivation of the research originates from the need for low carbon energy sources for building heating systems due to the limitations of currently available energy sources to mitigate GHG emissions. The carbon capturing technologies used in the fossil fuel power generation sector can be a solution to reduce the GHG emissions of building heating systems. In addition, CO_2 based industries such as CO_2 based fossil fuel are emerging. Developing local CO_2 sources may increase the development of those technologies while reducing the GHG emissions in buildings.

Understanding the full potential of implementing carbon capturing at building-level requires an integrated approach to assess the environmental and economic performance compared to other alternatives that are already available. It provides confidence to the stakeholders to invest in and develop the technologies. In addition, the knowledge is useful for policy makers to make decisions on these technologies as well as policies that are considered to reduce the carbon footprint. In particular, emerging carbon utilization technologies have the potential to replace currently available products with CO_2 derived products [12] that may require incentives and governmental policy level support for successful implementation. The research outcomes also support the climate action targets of government and global agreements. This research attempts to develop the necessary knowledge to fulfill the above requirements.

1.4 Research objectives

This study aims to investigate the feasibility of implementing carbon capturing, storage, and utilization technologies in existing natural gas based building heating systems. The specific objectives of the research are as follows.

1. Identify the commonly available carbon capturing, storage, and utilization technologies that can co-function with existing natural gas based building heating systems based on the technical parameters

2. Investigate and quantify the regional operational performance characteristics of building-level carbon capturing technologies
3. Investigate and quantify the life cycle environmental impacts and life cycle cost of the identified building-level carbon capturing, storage, and utilization technologies
4. Develop a decision support framework to evaluate the regional applicability of building-level carbon capturing by considering life cycle environmental impacts and life cycle costs and related uncertainties.

1.4.1 Research outcomes and deliverables

Through this research, a method is developed to investigate the operational characteristics of building-level carbon capturing systems. In addition, a life cycle assessment model and a life cycle costing model, which provide comprehensive life cycle environmental impacts, and a cost database for building-level carbon capturing systems that helps technology developers to identify the process improvements and feasible technologies for successful implementation of carbon capturing in building scale, were developed. This model will help to investigate the regional applicability of carbon capturing technologies that can be integrated with building-level heating systems, compared to the available building heating energy sources in a region. The deliverables of this research act as a life cycle thinking based feasibility assessment strategy for implementing carbon capturing storage and utilization technologies in building-level heating systems.

The findings of the research will also act as an initial base for the researchers and innovators who are working on developing cleaner energy sources and carbon economy. In addition, the outcomes of the study help to develop regional government policies by providing policy recommendations for carbon capturing implementation, such as deciding to promote green technology development initiatives, incentivizing stakeholders such as technology developers and building owners. Furthermore, the study outcomes aid building-level stakeholders in making decisions on climate action initiatives, while helping to achieve GHG emission mitigation targets.

1.4.2 Meta language

The specific terms used to describe the above research objective are explained below.

Carbon capturing storage and utilization: The carbon capturing technologies capture CO_2 from flue gas in fossil fuel combustion sources. The captured CO_2 must be disposed of or used up to prevent release to the atmosphere. Carbon storage technologies are used to store CO_2 permanently in geological or offshore CO_2 containment. Carbon utilization technologies are used to utilize CO_2 into a product or use it directly in a different process. For example, the production process of urea uses CO_2 as a chemical feedstock.

Technical parameters: The compatibility of carbon separation technologies is dependant on technical parameters such as operational conditions (e.g. flue gas pressure, CO_2 concentration) and operational parameters (e.g. turndown, operational flexibility).

Operational characteristics: The operational characteristics of carbon capturing technologies include annual carbon capture rate, energy consumption, and net operational GHG emission reduction. In addition, they also include annual generation of by-products, when carbon capturing technologies convert captured CO_2 into by-products.

Life cycle thinking: Life cycle thinking is used to include the economic and environmental impacts of a product or a process considering all stages of its life cycle. The life of a product or a process includes raw material extraction, construction, operation, and end-of-life treatments. This approach was used to assess the life cycle environmental impact of integrating carbon capturing on building-level heating systems from raw material extraction, construction phase, and operational phase that includes transporting CO_2 or by-products from the building. The life cycle economic impacts were assessed by considering operational cost, including initial investment cost, operational cost, and revenue generated by selling the CO_2 and by-products.

Building-level carbon capturing: Building-level carbon capturing refers to the process of capturing CO_2 from the flue gas of fossil fuel combustion building heating systems.

1.5 Thesis organisation

The thesis consists of 7 chapters. The chapters focus on the literature review, methodology, findings, and the conclusions.

Chapter 1: Chapter 1 provides the overall introduction to the background of the study, research gaps, research motivation, research objectives including the deliverables, and the thesis organization.

Chapter 2: Chapter 2 provides information on the overall methodology and research phases, followed by the study to achieve the research objectives.

Chapter 3: Chapter 3 provides the literature review of the study. The literature review includes an overview of the carbon capturing, storage, and utilization (CCSU) technologies, possibilities of adopting the CCSU technology to the building-level, and sustainable implementation of carbon capturing in building scale.

Chapters 4, 5, and 6 present the details of achieving the overall goal of the study by fulfilling the objectives. The chapters elaborate on the methods used to achieve specific objectives, research findings, and deliverables.

Chapter 4: Chapter 4 presents a method developed to estimate the operational characteristics of building-level carbon capturing systems. The method was demonstrated by considering a case study of implementing different carbon capturing technologies in natural gas residential space heating systems in different climatic regions in Canada. The case study consists of a commercial building-level carbon capturing technology and a carbon capturing technology that is used in fossil fuel power generation plants. Although the required performance data on the carbon capturing technology used in fossil fuel power generation plants is available in the literature, the performance data of the commercial building scale carbon capturing technology was not available. Therefore, an experimental study was conducted on the commercial carbon capturing system and the results were also presented in this chapter.

Chapter 5: Chapter 5 presents the life cycle environmental and cost model developed to estimate the environmental and economic performance of building-level carbon capturing systems. The life cycle environmental impacts and cost database were developed by considering the case study presented in Chapter 4.

Chapter 6: Chapter 6 presents the life cycle thinking based comparative feasibility assessment framework developed to assess the feasibility of implementing carbon capturing on building heating systems. The feasibility assessment framework was demonstrated using the life cycle environmental impacts and life cycle cost of carbon capturing systems considered in the case study in Chapter 4. In addition, the life cycle assessment and life cycle costing were extended by considering commonly used building heating systems in Canada.

Chapter 7: Chapter 7 presents the conclusions derived from the study, recommendations, originality of the study, and the future research.

Figure 1-1 shows the connection between the chapters and the research objectives that are achieved in each chapter. In addition, the main activities, research outcomes, and deliverables under the relevant chapters are indicated.

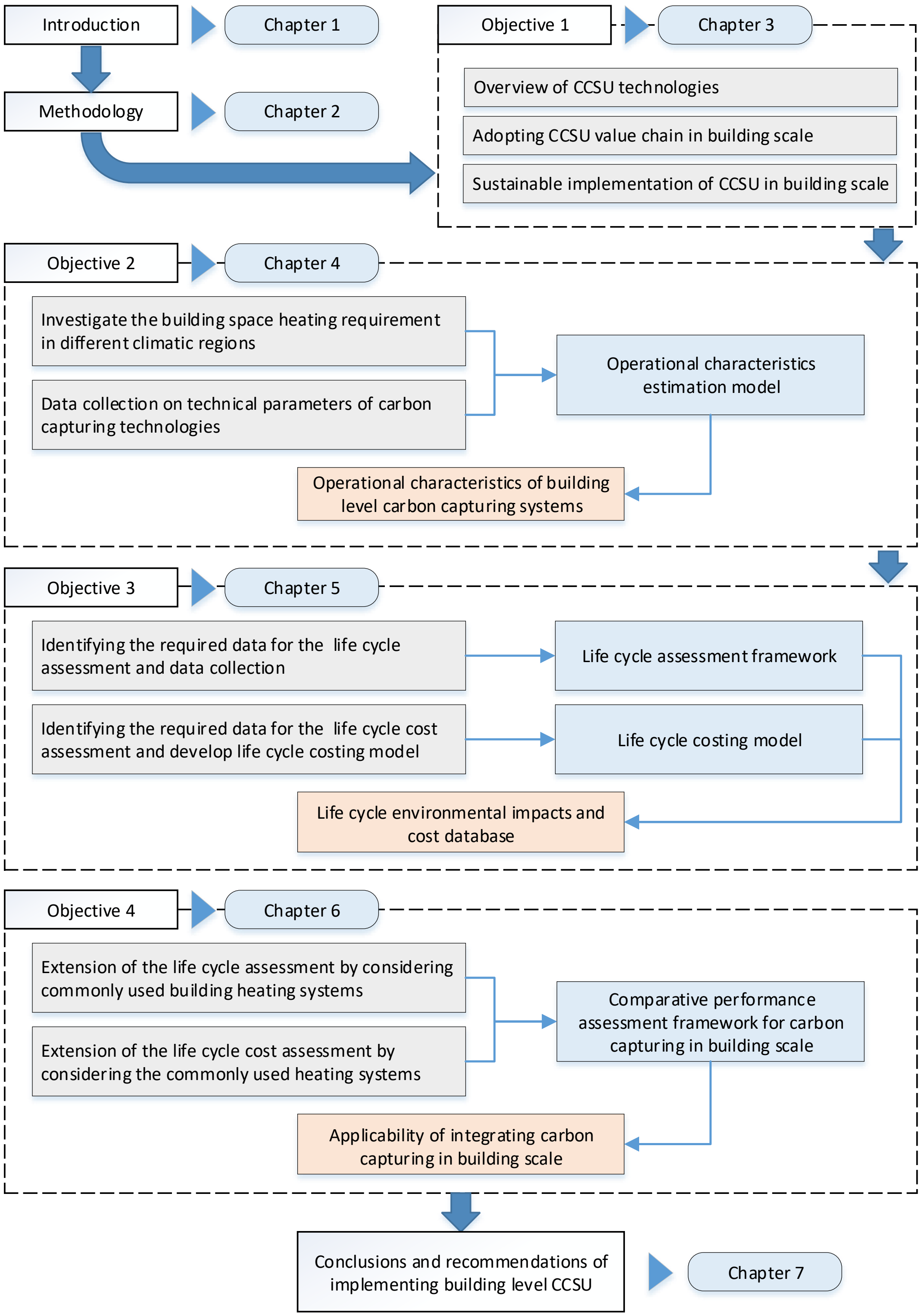

Figure 1-1: Integration of objectives and thesis organization

Chapter 2: Methodology

The focus of the research is to assess the feasibility of implementing carbon capturing, storage, and utilization (CCSU) technologies on building-level heating systems. The study focused on developing a life cycle thinking based comparative performance assessment framework to assess the regional applicability and environmental and economic performance of CCSU in building scale. A case study was also conducted, which includes integrating CCSU with residential natural gas building heating systems in different climatic regions in Canada. This chapter summarizes the overall methodology followed in the study, while more detailed explanations of the specific methods used in different phases are shown in the relevant chapters.

The Figure 2-1 elaborates on the connection between the research phases and phases of methodology to the relevant objectives. Phase 1 consists of conducting a literature review on CCSU technologies and investigating the operational characteristics of building-level carbon capturing technologies, which fulfill Objective 1 and Objective 2. Phase 2 of the research consists of conducting a life cycle assessment and life cycle costing that accomplish Objective 3. Phase 3 consists of developing a life cycle thinking based comparative performance assessment framework that completes Objective 4.

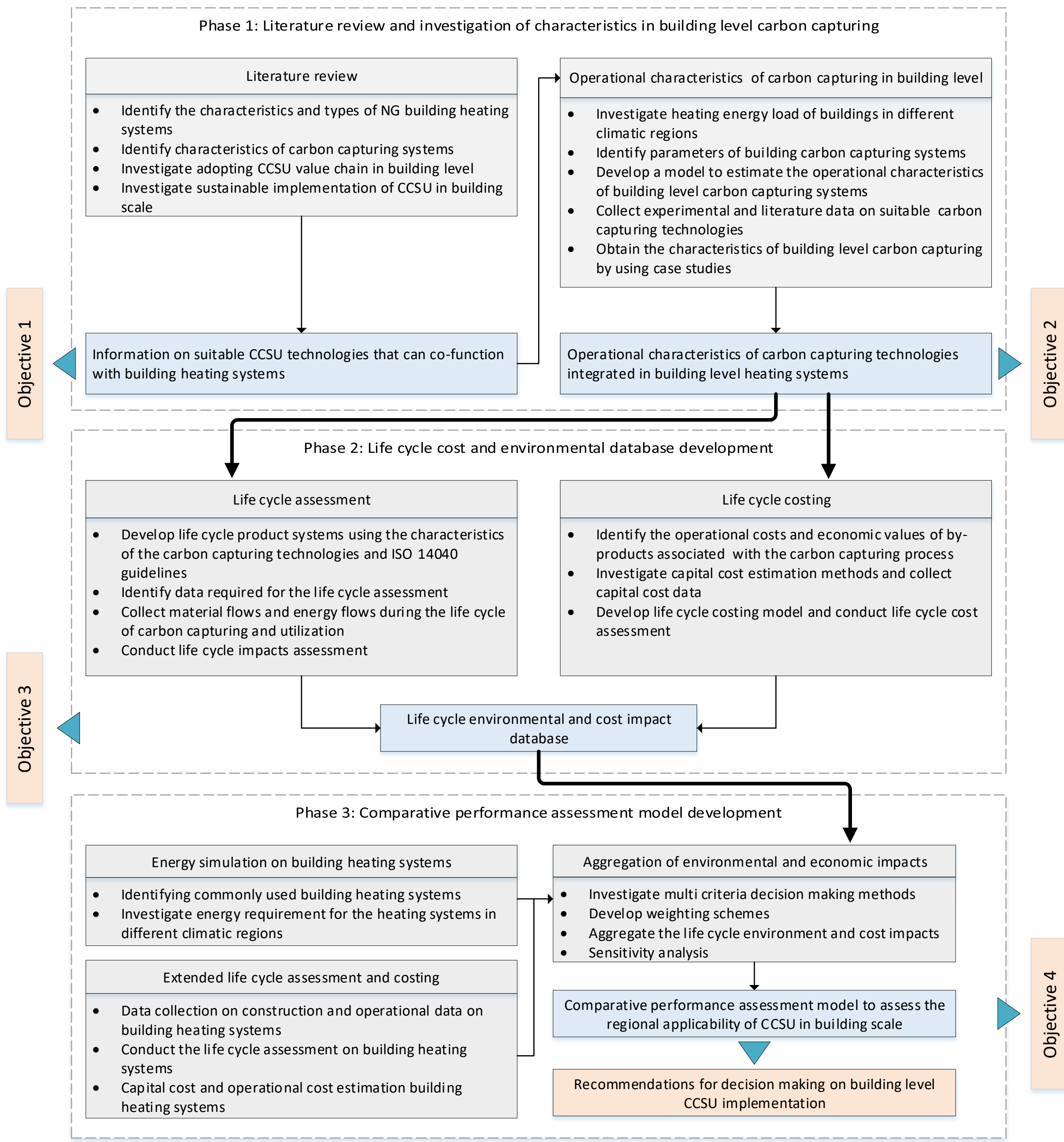

Figure 2-1: Methodology flow

2.1 Phase 1: Literature review and investigation of characteristics of building-level carbon capturing

An extensive literature review was conducted to investigate the potential of reducing the GHG emissions of natural gas building heating systems by implementing carbon capturing, storage, and utilization (CCSU) technologies. The study reviewed published articles of CCSU technologies used in fossil fuel power generation and discussed the possibility of adopting all the stages of the carbon capturing process in the building context. Searching subject-specific databases such as "Compendex Engineering Village" and "ScienceDirect" for keywords was done to collect the literature. The literature review prioritised journal articles published after 2005 from high impact factor journals (with impact factor above 2.5). Apart from that, publications made prior to 2005 were researched in cases where more recent information was unavailable. Furthermore, government reports, conference proceedings, relevant websites, and other reports related to carbon capturing and building heating were also considered.

2.1.1 Investigation of characteristics of building-level carbon capturing

This section involves defining a method to evaluate the operational characteristics of building-level carbon capturing technologies. The operational characteristics considered in this study were carbon dioxide capture rate, energy consumption, and by-product generation of a carbon capturing technology. The defined method used building energy simulation to determine the monthly energy load of buildings, and the capacity of the building heating systems. Published data on thermal and electric energy consumption of carbon capturing technologies were collected to evaluate energy consumption. Carbon capturing efficiency (CO_2 recovery rate) was used to evaluate the maximum CO_2 capture rate. A case study was conducted to demonstrate the operational characteristic estimation method. Data was collected from published literature and experimentation on building-level carbon capturing facilities to determine the technical parameters. The methodology is described in detail in Chapter 4, section 5.2.

2.2 Phase 2: Life cycle environmental impacts and cost database development

Although the carbon capturing process reduces the greenhouse gases emitted during natural gas combustion, there are other processes associated with the carbon capturing process that may cause adverse environmental impacts, including increase of GHG emissions. Therefore, it is important to assess the carbon capturing process considering the holistic picture. Life cycle assessment (LCA) is a standardized procedure for assessing the environmental impacts of a product system or a process. The principles of LCA are given in the ISO 14040 guidelines [23]. The complete life cycle of a product or a system comprises raw material extraction and energy consumption for the production, operational phase, and demolition and final disposal of the product.

Life cycle cost analysis is an economic method used to evaluate the cost of a project, which includes owning, operating, maintaining, and disposing of the project [24]. The life cycle cost method indicates the long-term cost effectiveness of a project rather than focusing on capital cost investment or operational cost of the project. The following sections describe the methodology used in this study to conduct the life cycle assessment and life cycle costing.

2.2.1 Life cycle assessment

The life cycle assessment procedure consists of major phases that are shown in Figure 2-2 and described below.

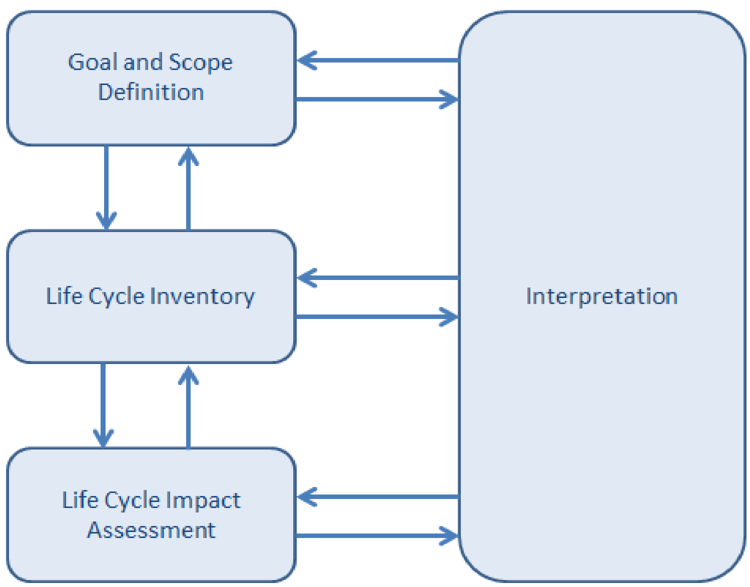

Figure 2-2: LCA stages (ISO 14040, 2006)

- **Goal and Scope Definition:** Defining the objectives of the study and parameters that guide how the study is conducted, including functional unit, system boundary, life cycle inventory, and impact categories.

- **Inventory Analysis:** Determining the inflows to the system that identify resource consumption and energy use, and system outflows including emissions to air, water, and soil within the system boundary per functional unit.

- **Impact Assessment:** Categorizing the life cycle inventory analysis results in terms of their significance and potential environmental impacts, such as ozone layer depletion potential or global warming potential. The outcome of the calculation is a numeric indicator result typically stated on an equivalence basis.

- **Interpretation:** Evaluating the impact assessment results and drawing conclusions and recommendations, considering the defined goal and scope.

The study developed an LCA model according to the guidelines of ISO 14040 [23]. The LCA assessment was a cradle-to-gate assessment that considered construction of the carbon capturing systems and the heating system, raw material and fuel extraction for the operation of the system, transportation of raw material, emissions during the carbon capturing process, and transportation of CO_2 or by-products. SimaPro (Version 8) software was used to model the product system, and the Ecoinvent 3.1 life cycle database was used to develop the life cycle inventory.

The main function of the heating system combined with the carbon capturing system is heat generation for the building. However, the carbon capturing process produces CO_2 or a by-product that may have an economic value. Therefore, the life cycle assessment of the heating system combined with the carbon capturing system must be considered as a multi-functional system. Since the study conducted a comparative performance assessment to evaluate the regional applicability of the building-level carbon capturing systems, it is necessary to partition the total environmental impacts between the functions.

ISO 14044 allows using system expansion, physical allocation, and economic allocation when the product system has multiple functions. The system expansion method is used to expand the system boundary of the product system by including the additional functions related to the co-products generated by the system. In physical allocation, the inputs and outputs of the products system are partitioned according to the physical relationships of the functions such as mass or energy. The economic allocation is used to partition the inputs and outputs of the product system between the functions based on the proportion of the economic values of the products.

ISO 14044 emphasizes the use of the system expansion method whenever possible to avoid any allocations [25]. However, system expansion was not considered in this study as the LCA model must be able to compare carbon capturing systems that produce different by-products. ISO 14044 [25] allows for the use of allocation based on physical quantity of the functions, but since the main functions of the carbon capturing system have different types of physical quantities (energy and mass), it is not possible to use physical allocation in this case. Therefore, the economic allocation method was used in this study to allocate the environmental impacts of the combined process into heat generation. The economic allocation was also recommended in several studies to evaluate the life cycle impacts of carbon capturing and utilization process [26][27].

The study considered the case study used in the previous sections to demonstrate the life cycle assessment model. Data from previous literature was used along with the performance characteristics obtained from Phase 1 to develop the life cycle inventory.

2.2.2 Life cycle costing

The study developed a life cycle costing model to assess the economic impacts of integrating carbon capturing process into the building-level. The model was derived using the general formula for the LCC present-value model and the LCC formula used in building energy and water conservation projects presented in the life-cycle costing manual for the US federal energy management program [24].

The relevant costs of the building heating systems integrated with carbon capturing technologies are investment cost of the carbon capturing system and the operational cost including energy, transportation cost, maintenance cost, and raw material cost. The revenue generated by selling CO_2 or by-products was considered as a positive cash flow. The study continued the case study considered in Phase 1 to demonstrate the life cycle cost model. The operational cost was estimated using the performance characteristics obtained from Phase 1 and the data collected from published literature, and by consulting the manufacturers of commercial building-level carbon capturing systems. The maintenance cost of the carbon capturing process was considered as a fixed percentage of the investment cost when data was not available [28] [29]. In addition, the capital cost was estimated using the order of magnitude method that is widely used in estimating early-stage capital costs in the chemical engineering industry when data is not available [30]. More details of the LCC cost model can be found in Chapter 5, Section 5.2.2.

2.3 Phase 3: Comparative performance assessment framework development

This phase involved defining the life cycle thinking-based comparative performance assessment model to compare the environmental and economic performance of building heating systems integrated with carbon capturing technologies against the alternative GHG emission reduction technologies used in building heating systems. Due to the conflicting nature of the reduction of global warming against most of the non-GHG impact categories and economic impacts, it is essential to aggregate the life cycle impacts and costs simultaneously. In addition, it is important to incorporate uncertainty handling methods, including the uncertainty of the decision maker's perspective. Considering all these factors, the study considered the fuzzy Multi-Attribute Decision Making method (MADM) to aggregate environmental and economic impacts. The detailed methodology is described in Chapter 6, Section 6.2.

The methodology followed in Phases 1, 2, and 3 represents the life cycle thinking based building-level carbon capturing comparative performance assessment framework, which is depicted in Figure 2-3.

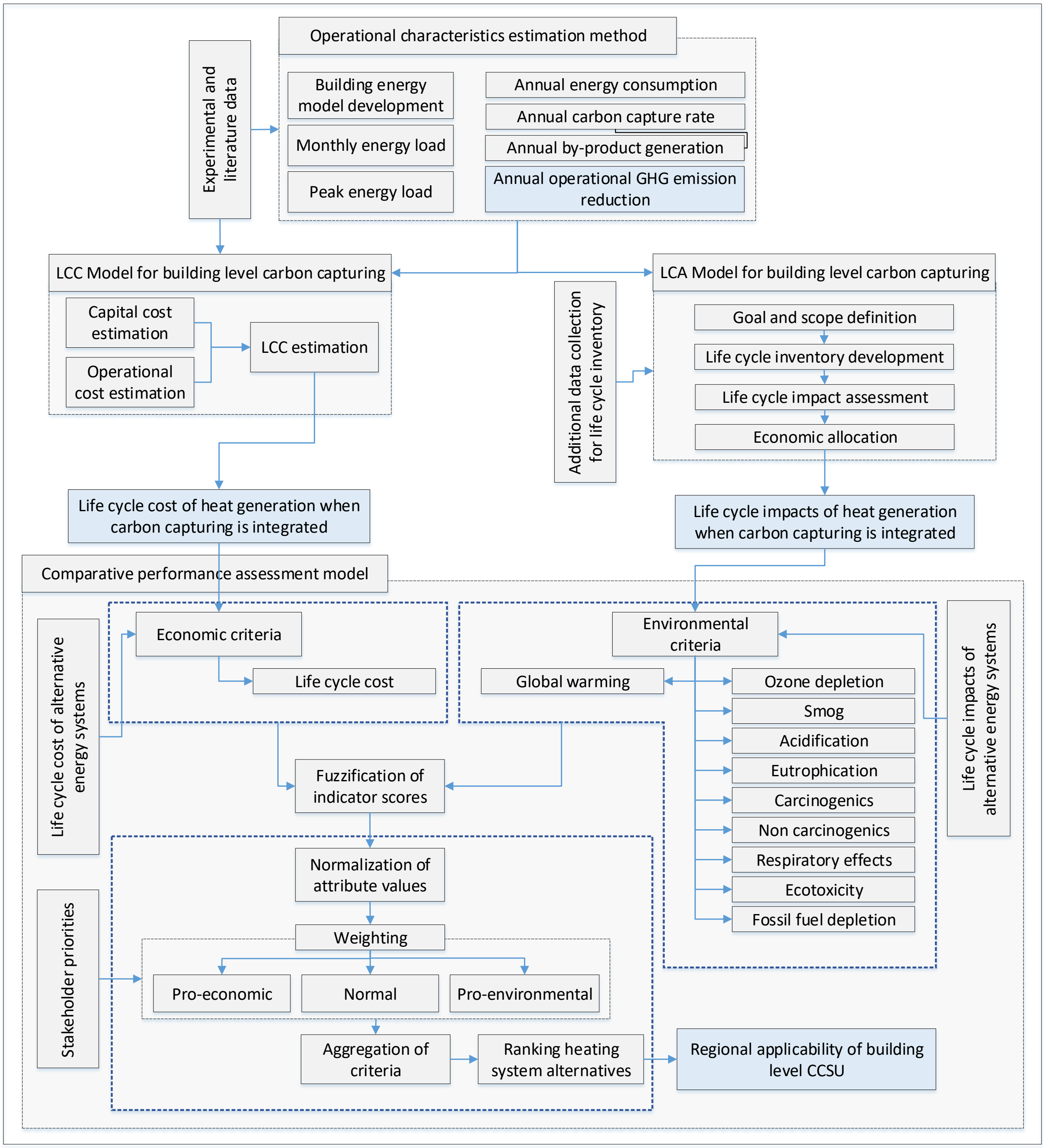

Figure 2-3: Life cycle thinking based building-level carbon capturing comparative performance assessment framework

Chapter 3: Literature Review

The literature review was conducted to identify the carbon capturing, storage, and utilisation (CCSU) technologies that can co-function with building-level heating systems based on technical capabilities and operational conditions. In addition, previous studies related to sustainable implementation of CCSU technologies were reviewed to understand the factors and requirements to assess the sustainability of implementing building-level CCSU. The subsequent sections depict the outcomes of the literature review.

3.1 Overview of carbon capturing, storage, and utilisation (CCSU) technologies

According to the International Energy Agency, 30 million tons of CO_2 are captured annually by carbon capturing facilities. Out of this, 90% of the carbon is captured from industries such as oil and gas production, which produce high density CO_2 streams [31]. Technologies for capturing high density CO_2 have been widely deployed and have reached technological maturity. However, most of the stationary combustion sources produce low concentration CO_2, and technologies used for capturing CO_2 from these sources are in the deployment stage.

The carbon capturing technologies used for stationary combustion energy sources can be classified as post-combustion, pre-combustion, and oxy-fuel combustion [32]. This classification is according to the combustion process and gas extraction point. Post-combustion carbon capturing technology is used to capture CO_2 from flue gas after combustion is completed [33]. It can be used to capture CO_2 from fossil fuel power generation plants [34] [35] [11], process heaters, and combined heat and power plants used in chemical production facilities. This technology is identified as the most practical carbon capturing technology, as it can be implemented as a retrofit to the existing stationary combustion sources without considerably changing the infrastructure or combustion method [32][36][37]. Post-combustion carbon capture is considered to be the most matured carbon capturing technology in the power generation sector, which is in the early stages of deployment [38].

Pre-combustion technology is used to capture CO_2 from fuel before the combustion process is started [32]. The pre-combustion capture process is generally used in fuel gasification processes, where coal [32], biomass [39], or natural gas [35] is used as the main fuel. It is in the early stages of deployment and commercializing projects [38]. In oxy-fuel combustion, the fuel reacts with pure oxygen (O_2) diluted with recirculated flue gas. Oxygen is separated from the air using the cryogenic separation method [40]. The combustion products of oxy-fuel combustion are CO_2 and water vapour. The CO_2 is separated by condensing water vapour [41]. However, large scale oxy-fuel carbon capture facilities have not been established due to the high energy requirement for O_2 separation [32][42].

Post-combustion and pre-combustion technologies require carbon separation methods to separate CO_2 from gas. Absorption, adsorption, and membrane separation are well known methods to separate CO_2. In contrast, the oxy-fuel method does not require any specific CO_2 separation method as the combustion products are only CO_2 and water vapour. The water vapour can be removed by condensation of the combustion products [43]. The captured CO_2 has to be stored or utilized in order to stop CO_2 being released to the atmosphere. In addition, it has to be compressed and liquefied after the capturing process, depending on the CO_2 transportation, storage and utilisation method [44].

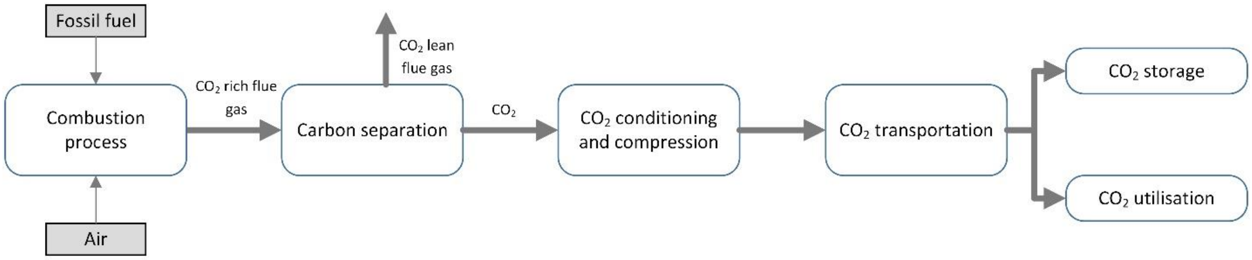

Figure 3-1: Post-combustion carbon capturing process

3.1.1 Carbon separation methods

The major modes of separation currently in practice are absorption, adsorption, chemical looping, membrane separation, hydrate-based separation, and cryogenic distillation. In the absorption process, CO_2 from the flue gas is absorbed by a liquid solution called absorbent [45]. Chemical absorption and physical absorption are the main processes [42][45]. In chemical absorption, CO_2 reacts with the chemical solvent and forms an intermediate compound [46]. In physical absorption, the CO_2 bonds with the solvent using Van der Waals forces in a liquid solution without any reaction [47]. Generally, bonds formed between CO_2 and the solvent in chemical absorption are stronger than in physical absorption. Therefore, CO_2 absorption efficiency in chemical absorption is higher than in physical absorption. Chemical absorption is more suitable for capturing CO_2 from flue gas that has low pressure and low CO_2 concentration [46]. Chemical absorption is used in post-combustion technology, while the physical absorption method is used in pre-combustion technology [42].

In the adsorption method, the substances (adsorbate) adhere to a solid surface (adsorbent). The adhered substances can be removed later by changing the temperature or pressure. The adsorption process can be categorized as physi-sorption and chemi-sorption. Adsorption and desorption processes are performed by 3 main methods: pressure swing adsorption, vacuum swing adsorption, and temperature swing absorption. Apart from that, electric swing adsorption and pressure and temperature hybrid processes are also used for the adsorption process, which are considered advanced technologies [48]. Furthermore, the adsorption method can be used for post-combustion capture [41].

Membrane separation is a novel technology compared to the other separation methods discussed above. This carbon separation method is considered to be a flexible method, as it can be used in post- and pre-combustion technologies [49]. In membrane technologies, a majority of the energy is consumed by developing the required pressure difference across the membranes [50]. This technology is very economical when high purity CO_2 is not required. Post-combustion technology requires membranes with high selectivity, as the CO_2 concentration of the flue gas is very low [49]. High selectivity membranes consume more energy and are significantly more expensive compared to low selectivity membranes. Therefore, it is a challenge to implement membrane systems commercially in post-combustion carbon capturing systems [51], meaning membrane separation methods can still be implemented only in labs. Figure 3-2 shows the classification of carbon capture technologies.

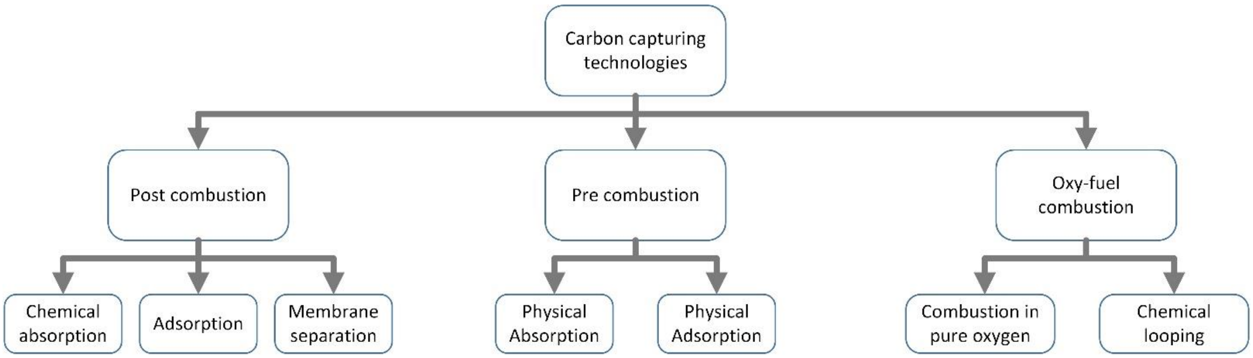

Figure 3-2: Classification of carbon capturing technologies

3.1.2 CO_2 transportation

The captured CO_2 should be transported from the carbon sources to specific storage locations. In the United States (US), several million tons of CO_2 is transported annually for enhanced oil recovery. The transportation methods should be capable of transporting CO_2 efficiently with minimal leakage. More importantly, transportation methods should be economically viable [52]. CO_2 can be transported using pipelines, tanker trucks, ships, and railroads [53]. Pipeline systems are the most efficient and viable method to transport CO_2 on a large scale. Tanker trucks are used to transport CO_2 for short distances. In addition, transporting CO_2 using tanker trucks and railroads is overlooked in the literature.

Pipeline transportation can be used for both on-shore and off-shore CO_2 transportation [54]. However, pipelines are not tested in offshore CO_2 transportation [55]. Fixed or towed pipes are considered the most commercially viable method to transport CO_2 to the ocean. Recompression stations are used to increase the pressure head (compensate the pressure head). Pipeline transportation facilities consist of a CO_2 conditioning facility that conducts CO_2 compression and further separation from water vapour and other gases. Generally, CO_2 is compressed to 100-150 bar to transport CO_2 through pipelines [54]. In some cases, CO_2 is compressed to liquid so that it can be pumped. This method reduces the energy requirement for transporting CO_2 through pipelines [54].

Waterborne transport is another method to transport CO_2 over very large distances [56]. Ships and other modes of watercraft can be used to transport CO_2 under conditions where pipelines are not feasible. The CO_2 should be in liquid form to reduce the volume to transport using ships [57]. In contrast to CO_2 transport using pipelines, ship transportation is considered as a discrete type of transportation method [57]. Therefore, ship transportation requires buffer storage or temporary storage [58] [59]. The CO_2 is transferred from temporary storage to the ships in loading facilities. Ship transport can be used to transport CO_2 from the loading facilities to an offshore or onshore storage facility. Furthermore, there are studies being conducted to inject CO_2 directly to the ocean using ships [59].

3.1.3 Carbon storage

Captured CO_2 can be stored in geological storage or offshore storage and can be converted to mineral carbonates [41]. Depleted oil or natural gas reservoirs [60] and saline aquifers are considered as geological CO_2 storage. Furthermore, unmineable coal beds are also considered as geological CO_2 storages. Generally the CO_2 is injected into geological formations at depths higher than 800 m [41]. Geological storage should consist of a porous rock and cap rock to store CO_2. The porous rock acts as the storage medium where CO_2 is stored. The cap rock is used to prevent CO_2 from leaking out of the storage. The CO_2 is trapped in storage by physical trapping, dissolution in salt water, and being absorbed into coal or organic-rich shale, replacing methane (CH_4) and other gases. The dissolved CO_2 can react with rocks and minerals and be stored permanently. The CO_2 can be stored as compressed gas, liquid CO_2, or in a supercritical phase, which depends on the condition of the storage [41]. Furthermore, storing CO_2 in geological formations has become a promising option due to the expertise of the oil and gas industry with geological formations [41].

The ocean can be considered as a natural carbon sink that currently absorbs 7 $GtCO_2$ per year [56]. Apart from that, CO_2 can be intentionally injected into the sea in the ocean storage method [61]. CO_2 can be injected into the water column of the ocean or to the sea floor. It is possible to inject CO_2 to the sea as gas, liquid, solid, and hydrates, and this depends on the technology of injection. The CO_2 is dissolved in the ocean regardless of the form it has when injected. To release CO_2 as gas, it has to be injected at a depth less than 500 m. When CO_2 is released below 500 m and above 2500 m, it is released as liquid and moves upward (towards the surface of the water) while dissolving. If the release depth is higher than 2500 m, the CO_2 is released as liquid and moves down (towards the ocean floor). The CO_2 can be dissolved completely before it goes to the ocean surface or remain as a CO_2 lake at the ocean floor until it is completely dissolved. Deep ocean storage is still in the research phase and there are no pilot scale projects going on [56].

3.1.4 CO_2 utilization

There are various methods to utilise CO_2 in the industry. Carbon capturing can be used as a chemical feedstock in industries such as synthesizing methanol and other types of polymers [62]. Furthermore, it can be used directly as a carbonating agent, preservative, and a solvent in the food and beverage industry [41][63]. Moreover, CO_2 is used as a working fluid in refrigeration cycles [64]. In addition, CO_2 is used in many industries such as steel manufacturing, power generation, metal working and welding, and pneumatics[63].

Enhanced oil recovery (EOR) is also considered as a fuel production method that has an increasing demand for CO_2 [41]. In the EOR process, CO_2 is injected with other chemicals into the underground oil reservoir so that the oil trapped in the rocks is removed [65]. This method is capable of extracting between 30%-60% of the trapped oil [41]. Most of the CO_2 comes out with the oil, and the oil needs to be treated before use. However, some of the CO_2 can be released into the atmosphere during this treatment process [41].

In addition, there are other industrial uses that have been introduced recently. Mineral carbonation is considered as a storage method in a few studies [66][41][67], while others consider it a utilisation method [41][63]. In this process, CO_2 is reacted with minerals such as wollastonite and serpentine and forms mineral carbonates [66]. Therefore, CO_2 can be permanently stored in a chemical. On the other hand, this method has a higher capacity than all the fossil reserves in the world as the magnesium and calcium-rich minerals can be easily mined [67]. However, this method requires an input energy, thus contributing to additional GHG emissions indirectly.

Bonaventura, et al. (2017) described a novel method to capture CO_2. This process produces sodium bicarbonate ($NaHCO_3$) as a by-product during the carbon capturing process [36]. The process uses Trona, a low cost mineral used to produce sodium carbonate (Na_2CO_3), as the chemical solvent. The process can be controlled so that only a fraction of the CO_2 is utilised. The other fraction can be stored or utilised in another method. It is also possible to use ammonia (NH_3) to capture CO_2 while producing ammonium salts [68]. In this process, ammonium salts has to be separated from the solvent using filtration or sedimentation. Separated ammonium can be used in the agriculture industry as a fertilizer ingredient [69]. Utilizing CO_2 as part of another product may avoid the energy consumption and GHG emissions of producing that product. A summary of carbon storage and utilisation is shown in Figure 3-3.

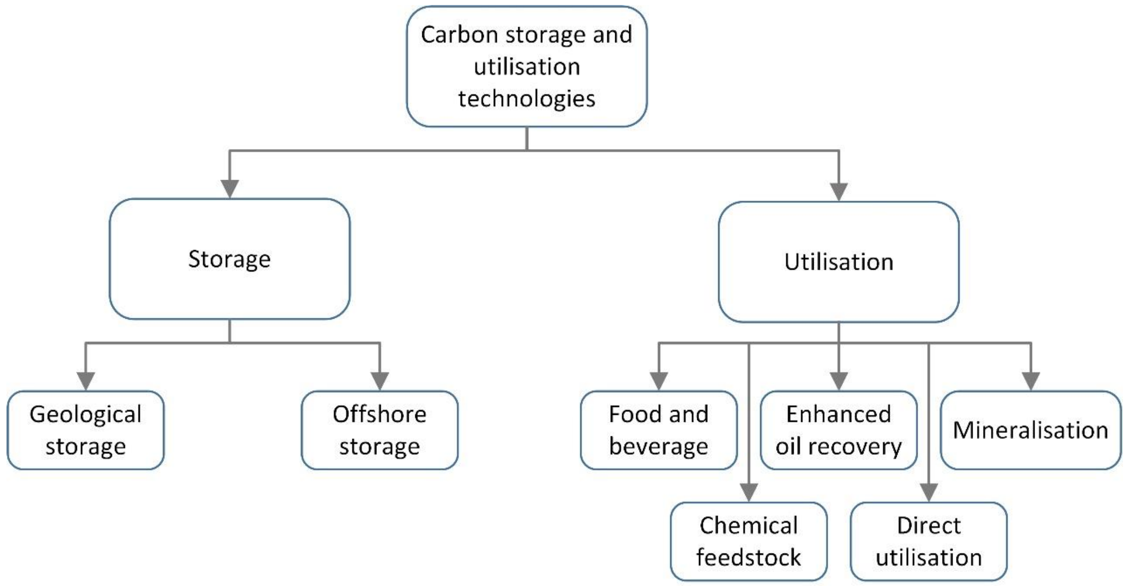

Figure 3-3: Classification of carbon storage and utilisation methods

3.2 Adopting the CCSU value chain for building scale

The CCSU value chain consists of the carbon-capturing process, CO_2 transportation, and CO_2 storage or utilization process. All the processes in the CCSU value must be able to be adopted successfully to use carbon capturing technology in building scale. Among the three carbon capturing technologies, pre-combustion capture technology cannot be used with natural gas building heating furnaces as there is no intermediate CO_2 generation during the combustion process. Oxy-fuel combustion needs an added oxygen supply and different combustion system, and therefore is not considered in this study. Only post-combustion technology is considered to investigate the potential of adopting CCSU value chain for the building scale.

3.2.1 Operational conditions and CO_2 output of carbon separation technologies

Chemical absorption, adsorption, and membrane separation are the separation technologies used in post-combustion carbon capture technology as explained in section 3.1.1. Flue gas properties including temperature, pressure, and CO_2 concentration can be considered as important parameters when selecting suitable carbon separation technologies [70]. Table 3-1 shows the operational conditions of the above-mentioned carbon separating technologies. In addition, Table 3-1 shows the optimum CO_2 composition and CO_2 purity after the separation process in chemical absorption, adsorption, and membrane separation methods [71].

Table 3-1: Operating conditions and outputs of carbon separation technologies [45][71][72][73][74]

Carbon separation method	*Operating temperature*	*CO_2 composition*	*CO_2 purity*	*CO_2 capture %*
Chemical absorption using Methyl Ethanolamine (MEA)	45 - 50 °C	>5%	>95%	80-95%
Chemical absorption using Econamine	80 – 120 °C	>5%	>95%	80-95%
Chemical absorption using 2n Methyl Diethanolamine (MDEA)	35 – 40 °C	>5%	>95%	80-95%
Chemical adsorption PSR	50°C	>10%	75-90%	80-95%
Physical adsorption PSA	50 – 100 °C	>10%	75-90%	80-95%
Membrane separation	-	>15%	80-95%	60-80%

The CO_2 composition of flue gas from natural gas combustion systems varies from 7% to 10% [59]. Therefore, chemical absorption technology must be able to be used with building heating systems without modifications to the boiler system. In fact, membrane separation and adsorption processes cannot be used with natural gas building heating systems directly, as the optimum CO_2 composition is higher than the flue gas composition of flue gas in natural gas heating systems [49]. However, recent studies indicate that the CO_2 composition of flue gas can be increased by recirculating flue gas through the combustion system [59]. This procedure is used in natural gas combined cycle (NGCC) combustion systems as the CO_2 composition of flue gas is 3%-4%. The same procedure can be used in building heating systems with some modification to the combustion process.

The temperature of flue gas of building heating systems decreases as the efficiency of the heating system increases. Annual Fuel Utilization Efficiency (AFUE) is used to categorize building heating systems based on their efficiency. A standard-efficiency building has the lowest AFUE, which is 78%-80%, and the flue gas temperature is approximately 232°C [75]. Mid-efficiency furnaces are widely used in buildings and the efficiency can reach 83% with a flue gas temperature of 149°C [75]. Therefore, flue gas must be cooled in both standard and mid-efficiency furnaces. In fact, high efficiency condensing heating systems emit flue gas at a much lower temperature, which is approximately 50°C [75]. It indicates that high-efficiency furnaces can be used without cooling systems in most of the carbon separation technologies shown in Table 3-1.

3.2.2 Energy consumption of the carbon separation process

The carbon capturing process requires energy for its operation. Chemical absorption technology requires thermal energy for regeneration of the solvent. In addition, electricity is required for operation of auxiliary equipment such as pumps and compressors. Table 3-2 shows the energy consumption of the chemical absorption method with different types of solvents.

Table 3-2: Energy consumption of chemical absoprtion technology [14] [76] [77] [78][79]

Separation process	*Desorption energy*	*Auxiliary energy*
Commercial level solvents		
Chemical absorption with MEA	3.53 GJ_{th} /tCO_2	0.0432 GJ_{th} /tCO_2
Chemical absorption Econmaine FG+	3.18 GJ_{th}/ tCO_2	Data not available
Chemical absorption KS-1	3.08 GJ_{th}/ tCO_2	Data not available
Chemical absorption KS-2	3.0 GJ_{th}/ tCO_2	Data not available
Chemical absorption CANSOLV	2.33 GJ_{th}/ tCO_2	Data not available
Chemical absorption H3	2.8 GJ_{th}/ tCO_2	Data not available
Chemical absorption with UNO MK3	2.24 GJ_{th} /tCO_2	0.0612 GJ_{th} /tCO_2

In the chemical absorption method, the required energy has to be supplied as heat using steam. The temperature of the steam should be in the range of 100°C to 140°C [80]. Generally, the steam is extracted from steam turbines in power plants that are integrated with carbon capturing systems. Therefore, there is a possibility of using thermal energy from standard-efficiency furnaces as the temperature of flue gas is 232°C. In addition, using the thermal energy from low-efficiency furnaces can reduce the flue gas temperature. Since the carbon capture process requires lower temperature gas, extracting thermal energy from flue gas may reduce the cooling load. In fact, medium- and high-efficiency furnaces have to be modified to extract thermal energy as the flue gas temperature is low. However, it might reduce the heat generation of the furnace. As a solution, the required thermal energy can be supplied using electric heaters. Studies have been conducted on integrating solar energy systems for carbon capturing systems to reduce the regeneration energy requirement from the power plant [80][81]. The same procedure can be applied to building-level heating systems integrated with carbon capturing systems to minimize fuel consumption. Furthermore, chemical absorption technology requires energy to operate compressors, pumps, condensers, and re-boilers that are the auxiliary components of the carbon capturing systems.

Table 3-3 shows the energy consumption of adsorption and membrane separation technologies. Adsorption and membrane separation methods do not need thermal energy for operation. Instead, these technologies require electricity for compression, generating vacuum, and to run auxiliary components. In fact, post-combustion technology requires membranes with high selectivity, as the CO_2 concentration of the flue gas is very low [49]. The membrane technologies that are suitable for post-combustion are considered to be costly and also consume more energy. The Table 3-3 shows the Membrane separation technology has higher variation of energy consumption. The membrane separation technology consume relatively low energy when the CO_2 concentration is high. However, it consume significant amount of energy when used to capture CO_2 from low concentration flue gas mixtures. Therefore, it is a challenge to implement membrane systems commercially in post-combustion carbon capturing systems [51] and they are not commonly used commercially in natural gas carbon power plants due to the lower CO_2 concentration in flue gas.

Table 3-3: Energy consumption of adsorption and membrane separation technologies [76] [77]

Separation process	***Energy requirement***
VPSA	2.140 GJ_E/tCO_2
PSA	2.3 – 2.8 GJ_E/tCO_2
TSA	6.12 – 6.46 GJ_E/tCO_2
Membrane separation POL-POL	0.5 - 6 GJ_E/tCO_2

3.2.3 Operational parameters of carbon separation technologies

Brunetti et al. investigated major operational parameters that affect the efficiency of carbon capturing systems [79]. The authors mentioned that operational flexibility, turndown, and reliability are important parameters when designing carbon capturing systems. The definitions of the above operational parameters are shown below.

- Operational flexibility: The ability of the system to operate in variable gas compositions [71]
- Turndown: The ability of the system to operate under gas flow rates that are less than the design flow rates [71]
- Reliability: The ability to operate continuously without unscheduled shutdown [71]
- Adaptability: The time required for adapting the carbon capturing system for the changes of the inflow properties [71]

Brunetti et al. shows that membrane systems are highly flexible when the CO_2 concentration is higher than 20% [79]. The flexibility of membrane systems decreases dramatically when the CO_2 concentration is less than 20% and as a result of the composition changes, the CO_2 recovery rate and the purity of CO_2 are reduced. The adsorption method is also considered a highly flexible carbon capturing technology. Absorption systems are considered moderately flexible compared to membrane systems. In addition, absorptions systems require changes in the liquid flow rate when composition of gas is changed [82]. The liquid flow rate is limited by the size of the systems and thus limit the flexibility of the absorption system. It indicates that the absorption systems must be oversized when systems are subjected to higher variations of gas composition.

Most power generation plants are operated with a steady combustion rate. In contrast, the thermal energy load of a building changes considerably with time, and as a result, the fossil fuel combustion rate and the CO_2 flow rate are changed. Carbon capturing systems must therefore be able to maintain performance with variations of gas flow rates, so the turndown capability of carbon capturing systems is important when used in a building context. Brunetti et al. shows that membrane systems can maintain the purity of the CO_2 stream even in 10% of the design flow [79]. As a result, membrane systems are identified as higher turndown capable systems. Absorption technology can maintain its CO_2 recovery and CO_2 purity in the downstream in 30 to 100% of its design flow. Although chemical absorption technology can maintain the purity even when the flow is less than 30% of its design flow, the CO_2 recovery can be reduced considerably. Adsorption technology can also deliver CO_2 recovery and CO_2 purity down to 30% of its design flow [71][83].

Although operational flexibility and turndown measures the resilience of the carbon capturing systems for variations of flow and composition, it is important to investigate how much time is needed for system adaptation. Buildings heating systems in particular are subjected to frequent load changes. Membrane separation systems can adapt to such variations instantaneously, while absorption and adsorption technologies can adapt within 5-15 minutes [71].

The building environment has fewer technical experts than the industrial environment where carbon capturing systems are currently installed. Therefore, carbon capturing systems must be more reliable. The membrane separation is known as extremely reliable as it has fewer control components [79]. The absorption method is considered to be moderately reliable [71] [79]. More specifically, the equipment used to reduce degradation of chemicals can cause unscheduled shutdowns and require maintenance frequently. The adsorption method is also moderately reliable [71] compared to membrane separation. The summary of adopting carbon separation technologies is shown in 3-4.

Table 3-4: Summery of adopting the carbon separation technologies at building-level

	Chemical absorption	***Adsorption***	***Membrane separation***	***Suitability of the carbon capturing system***
Operational conditions				
Operating temperature	Gas cooling is required for standard and medium efficiency furnaces Gas cooling is not required for high efficiency furnaces	Gas cooling is required for standard and medium efficiency furnaces Gas cooling is not required for high efficiency furnaces	Gas cooling is required for standard and medium efficiency furnaces Gas cooling is not required for high efficiency furnaces	Absorption, adsorption, and membrane separation have the same suitability

	Chemical absorption	**Adsorption**	**Membrane separation**	**Suitability of the carbon capturing system**
CO_2 composition	*Exhaust gas recirculation is not needed Best option	Exhaust gas recirculation is needed Moderate option	Exhaust gas recirculation is needed	Absorption method is more suitable
Carbon capture performance				
CO_2 purity	*Captured CO_2 can be used with any utilization method and storage method	Captured CO_2 can be used with few utilization methods and storage method	Captured CO_2 can be used with few utilization methods and storage method	Absorption method is more suitable
CO_2 capture rate	*Has higher CO_2 recovery	Has moderate CO_2 recovery	Has low CO_2 recovery	Absorption method is more suitable
Energy requirement	*Thermal energy is required – The furnace can be modified or can be use electrical heating Medium energy requirement	Only electricity is needed. High energy requirement	Only electricity is needed. High energy requirement as the CO_2 concentration is low	Absorption method is more suitable
Operational parameters				
Operational flexibility	Medium flexibility	*High flexibility	Low flexibility (For $CO_2 < 20\%$)	Adsorption method is more suitable
Turndown	Can maintain CO_2 recovery and purity down to 30% Can maintain CO_2 purity below 30%	Can maintain CO_2 recovery and purity down to 30%	*Can maintain CO_2 recovery and purity down to 10%	Membrane separation method is more suitable

	Chemical absorption	Adsorption	Membrane separation	Suitability of the carbon capturing system
Reliability	Medium reliability	Medium reliability	*High reliability	Membrane separation is more suitable
Adaptability	Within 5-15 min	Within 5-15 min	*Instantaneous	Membrane separation is more suitable

The membrane separation technology shows higher performance over operational flexibility, turndown, adaptability, and reliability compared to other technologies. However, membrane separation requires a higher percentage of CO_2 in the inflow (over 20%), which is considerably higher than the flue gas composition (less than 10%) of natural gas building heating systems. Although flue gas recirculation is a possible solution [84][85], it may need considerable modifications to existing heating systems, which requires further research.

Adsorption technology has lower performance compared to all the above factors. In fact, it performs well in operational flexibility compared to absorption technology, although absorption technology requires less energy. The absorption method is much better than membranes in the market in terms of recovery and purity [79] (increase in selectivity becomes a challenge in membranes). However, adsorption technology may also require flue gas recirculation since it operates in a higher CO_2 percentage (Over 10%). The absorption technology has moderate performance over all the factors, while operating in very low CO_2 concentrations (>5%). The absorption technology may be more applicable for natural gas furnaces as it does not require any modifications to the building heating system.

3.2.4 Transportation of CO_2 and by-products in building scale

CO_2 utilisation and storage can be considered as one critical phase of building-level carbon capturing that defines the economic viability. In order to store CO_2 in geological storage, it is necessary to transport CO_2 across very long distances, especially in places such as Canada where geological carbon storage areas are widely dispersed. Pipeline transportation is the only commercially available method to transport CO_2 for long distances [86]. However, carbon transportation by pipeline from individual buildings would be infeasible as a considerable capital investment is required to develop such infrastructure. Middleton & Bielicki (2009) show that the pipeline transportation cost would be extremely high for low CO_2 flow rates [87]. Moreover, CO_2 needs to be highly compressed and conditioned for transportation, which increases the cost considerably for small scale applications. Therefore, CO_2 transport using pipelines and storage in geological storage would not be economically viable for small scale applications such as building heating systems.

Road transportation is considered less attractive in large scale CO_2 transportation applications. Road transportation costs twice as much as pipeline transportation in large scale carbon capture and storage projects [88]. However, tanker trucks are used to transport CO_2 from CO_2 distribution terminals to customers for carbon utilization purposes [88]. Generally, CO_2 should be in liquid form to be transported by tanker trucks to maximize transportation capacity. Therefore, compression and refrigeration systems must be integrated on carbon capturing systems. In addition, intermediate storage systems must be implemented in buildings to store CO_2. When CO_2 is converted in a by-product during the carbon capturing process [36] [68], the by-products must be transported instead of CO_2 gas. That reduces the space requirement as well as the energy requirement for CO_2 compression and liquefaction. However, this process requires frequent loading and unloading of chemicals. As a result, public acceptance of utilising carbon during separation would be questionable.

An average residential building in Canada that uses natural gas (NG) for heating emits approximately 6 tons of CO_2 per year [89]. Furthermore, the majority of the emissions are in the winter season and may exceed 1 ton of CO_2 per month in an average residential house. The carbon capture percentage is therefore mostly limited by the material handling and transporting capacity despite the higher CO_2 capture efficiency of modern carbon capturing technologies, and the viability of building-level carbon capturing systems depends on efficient transporting methods for CO_2 and by-products.

3.2.5 Technical drivers and barriers

The study revealed that chemical absorption technology is more suitable for operation at building-level heating systems, based on the flue gas properties without substantial changes to the combustion system. However, the chemical absorption method requires 5-15 minutes to adapt to changes in flue gas rates. In addition, it has moderate reliability. Therefore, chemical absorption technology may require substantial work on improving the control mechanisms and reliability to integrate with building-level heating systems. Membrane separation, which is more favourable in building operation according to most of the criteria, requires flue gas circulation due to the lower CO_2 concentration. Therefore, heating systems may require considerable modifications to be used with membrane separation technologies.

In addition, buildings have limited space compared to power generation plants, meaning space limitations are a main barrier for buildings. Chemical absorption in particular requires tall columns that may not be able to be installed in a building [90], while membrane separation may require a large area [91]. Sound generation due to the operation of pumps, compressors, and other equipment in carbon capturing may also raise issues in a building environment. Furthermore, maintaining the carbon capturing systems may require technical expertise, and building maintenance staff have to work with chemicals and degraded products, which may require extensive training.

The transportation of captured CO_2 or by-products is identified as one of the main challenges. Although pipeline transportation is commonly used in large scale facilities, using it at the building scale may not be practical due to the necessarily large infrastructure. Road transportation would be the most practical method for building-level operation, although it is a discreet type of transportation. Road transportation requires intermittent storage in buildings, which may require considerable space. In addition, the captured CO_2 must be liquefied for storage and transportation, and that requires a considerable amount of energy.

3.3 Sustainable implementation of carbon capturing, storage, and utilization process at building-level

The study revealed that integrating carbon capturing has potential when considering the technical aspects. However, increased energy demand, emissions during operation, and production of raw material required for the carbon capturing process may cause significant environmental impacts in the life cycle of the carbon capturing process. It also carries a significant economic burden with the increase of energy, material, and transportation cost. In addition, the carbon capturing process may increase the maintenance work in building heating systems, which can reduce the acceptability of implementing carbon capturing by building owners. Therefore, it is necessary to consider the environmental impacts, economic cost and benefits, and social acceptance for the successful adaptation of the carbon capturing value chain at building-level heating systems.

3.3.1 Environmental impacts

The life cycle of carbon capture consists of material acquisition, carbon capture and storage facility construction, carbon capturing phase, CO_2 transportation, and CO_2 storage and utilisation. Each stage consists of various material and energy flows that affect the overall life cycle performance of the carbon capturing strategy. The life cycle assessment (LCA) method is commonly used to assess the performance of the whole process and to observe the holistic impact of a system.

Singh, Strømman, & Hertwich (2011) have conducted a LCA on a natural gas combined cycle power plant with MEA chemical absorption carbon capturing and storage [92]. The study shows that the MEA chemical absorption method can reduce total GHG emissions by 75%. However, results indicate that the overall global warming potential (GWP) is reduced by 64% after accounting for all the life cycle stages of the carbon capturing process. Furthermore, 75% of the GWP is due to direct emissions from the plant in the carbon capture and storage (CCS) scenario. More interestingly, the majority of the remaining GWP is due to emissions in the natural gas production cycle. Although both with CCS and without CCS the emissions related to natural gas production are considered, the increase of emissions in the CCS scenario is due to an increase in fuel consumption. Furthermore, the study shows that CO_2 storage and transportation only account for less than 3% of the GWP. Petrescu et al. conducted a LCA on a pulverized coal power plant with carbon capturing and storage [33] and it shows that the impacts on the GWP by CO_2 storage and transportation are 14%.

There are non-GHG environmental impacts from carbon capturing, although it can reduce the GWP significantly. It has been found that in NGCC power plants, sulphur dioxide (SO_2) is reduced from 3.1 mg/kWh to 0.0005 mg/kWh after integrating a MEA carbon capturing system [93]. However, Korre, Nie, and Durucan (2010) show that carbon capturing using MEA chemical absorption can increase the acidification potential of the overall process by 20% [94] in coal combustion plants. Furthermore, the acidification potential (AP) may increase up to 43% in natural gas power plants. The main reason for the increase of AP is that the carbon capturing process increases emissions such as ammonia (NH_3) and mono ethanol amine (MEA). Furthermore, the increase in fuel production and chemical production also increases the AP. More interestingly, coal power plants have less impact on AP compared to NG power generation plants. That is due to a considerable loss of SO_2 emissions in coal combustion due to the flue gas desulphurization (FGD) used especially for the carbon capturing process [95]. Figure 3-4 shows the change of all the life cycle impacts after implementing MEA based carbon capturing in natural gas power plants. It indicates that carbon capturing increases the toxicity more than 100%. Increase of fuel consumption and direct emissions such as formaldehyde and MEA caused this significant increase [92].

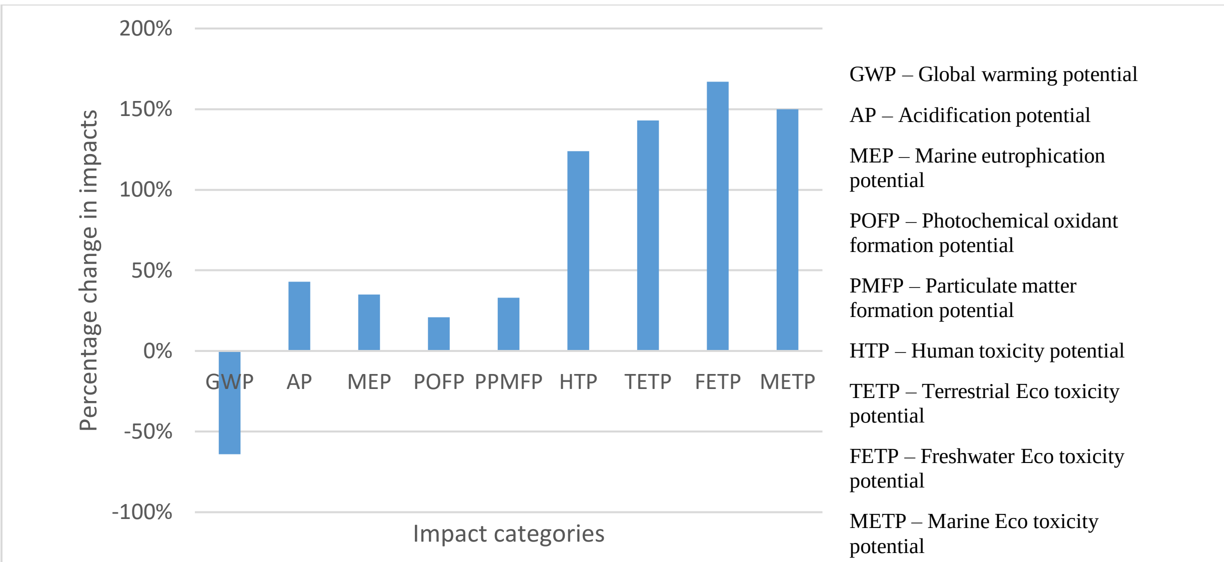

Figure 3-4: Life cycle impact change after implementing carbon capturing in NGCC power plant (The figure was created using the results of [92])

Although storing captured CO_2 in geological or offshore storage can retain CO_2 permanently, utilization of CO_2 may not. Production of CO_2-derived polymers and using CO_2 for yield boosting greenhouses have fewer relative climate benefits, as the majority of CO_2 is released to the atmosphere in a short time [12]. CO_2-derived fuels have medium climate benefits as a result of combustion of fuels releasing CO_2 to the atmosphere [12]. CO_2-cured concrete aggregates and building materials are considered highly beneficial to the atmosphere as they can retain a majority of the CO_2 in the building materials for a long time [12]. Therefore, the fate of the captured CO_2 must be considered when studying the environmental impact of carbon capturing.

3.3.2 Economic cost and benefits

The literature review shows that there is a lack of knowledge on costing about most of the carbon separation technologies. Rubin et al. has conducted a comprehensive review on costing of carbon capturing and storage [96] technologies that are applied for supercritical pulverized coal power plants (SCPC), natural gas combined cycle power plants (NGCC), and integrated gasification combined cycle power plants (IGCC). The study shows NGCC with carbon capture would increase the levelized cost of electricity (LCE) by 26%. The cost of avoided CO_2 can be 58-121 USD/t CO_2 without storage or utilisation. Furthermore, when captured CO_2 is utilised for enhanced oil recovery, the total cost of avoided CO_2 is reduced to 10-112 USD/t CO_2.

The operational cost can be increased significantly by installing carbon capturing systems. The operational cost of using carbon capturing consists of the cost of solvent addition, electricity consumption for auxiliary equipment, and fuel consumption to generate heat for the building and solvent regeneration. Considerable increase of operational energy of the building-level carbon separation and transportation would be a barrier when integrating carbon capturing systems in building heating systems. However, there are other possibilities that can reduce the operational cost of carbon capturing systems. Carbon taxes for fuels can be reduced, as integrating carbon capture reduces the GHG emissions of fuel combustion. Furthermore, there are carbon trading mechanisms such as “cap-and-trade” [97] that are implemented in provinces such as Nova Scotia [98]. Currently, only industries that produce more than 25,000 tons of GHG per year participate in this program. In this method, when GHG emissions are higher than the cap, the participants have to purchase emissions allowances or carbon offsets that are equal to the exceeded emissions. Conversely, if participants produce less emissions than the cap, they can sell their unused allowances. These programs are implemented in the USA for residential and commercial buildings to promote low carbon economy [99]. This method would help residents to sell emission allowances, thus reducing the operational cost of carbon capturing systems even further [99].

The literature shows that separating CO_2 and utilization process always increases the cost of the energy generation process, despite the revenue generated from utilizing CO_2 and the reduction of tax. However, the cost of converting CO_2 into a different product during the carbon capturing process is overlooked in the studies. Furthermore, heating systems may able to provide a continuous supply of CO_2 as feedstock. Therefore, the building-level carbon capturing process may create opportunities for production processes that use CO_2. In addition, converting CO_2 into a valuable product during the capturing process may have the potential to reduce the total operational cost as it does not require processes such as compression, liquefaction, purification, and transportation of CO_2.

Table 3-5 shows the percentage increase of capital cost after integrating the carbon capturing system [96]. It indicates that integrating carbon capturing to NGCC power plants has the highest percentage increase of capital cost. However, the capital cost per unit power required for a NGCC power plant is substantially less than the capital cost per unit power required for SCPC power plants [100]. Therefore, the cost increment percentage does not indicate that installing carbon capturing is more costly for natural gas combined cycle power plants.

Table 3-5: Percentage increase of capital cost of integrating carbon capturing in power plants [96]

Power plant type	***Percentage increase of capital cost***
Supercritical pulverized coal power plant	58%-91%
Natural gas combined cycle power plant	76%-121%
Integrated gasification combined cycle power plant	30%-47%

Table 3-5 shows that the capital cost of a power generation plant can be increased up to 121% after integrating a carbon capturing system. The power generation plant is a complex system that includes various components such as boilers, turbines, heat exchangers, and generators. Therefore, if integrating carbon capturing systems increases the capital cost by 121% in such a complex process, integrating carbon capture in building scale may increase the capital cost substantially. The capital cost of carbon capture is therefore a very important factor that determines the potential of a building-level carbon capturing system compared to its competitors. On the other hand, a carbon capture system can be designed on a smaller scale that only reduces part of the emissions in the building scale. That may reduce the capital cost, although it compromises the GHG emission reduction potential.

Integrating carbon capturing systems may increase small industries and job opportunities in community scale. In particular, emerging CO_2 utilization technologies such as CO_2-cured concrete and CO_2 derived fuels have a large potential to utilize more than 1 Gt of CO_2 per year. It may be more economical to supply the required amount of CO_2 from nearby buildings when considering the significant transportation costs incurred when CO_2 is transported across long distances [96]. In contrast, the cost of captured CO_2 from buildings may be higher than the CO_2 derived from commercial industries, as the scale of the production is low in buildings. Therefore, future studies must be conducted to investigate the economic justification of cost of CO_2 captured from building heating systems by considering the demand and the existing pathways of acquiring CO_2 and by-products in industrial applications.

3.3.3 Environmental and economic sustainability assessment

The above information shows the importance of considering both life cycle economic impacts and environmental impacts when assessing the feasibility of implementing CCSU in building scale. However, it is important to consider both economic and environmental impacts together when assessing performance, as economic and environmental criteria have multiple conflicting objectives in most cases [20]. The above review on the LCA studies shows that there are conflicts even between the environmental impacts (e.g. impacts such as acidification and fossil fuel depletion increase while the global warming potential decreases). Aggregating environmental and economic impacts using the multi-attribute decision making (MADM) method is a widely used method for sustainability studies [101]. It provides a more holistic view of the impacts of the alternative on sustainability.

Multi-criteria decision analysis can be categorized as elementary, unique synthesizing criteria, and outranking methods [102]. Among the elementary MADM methods, dominance, maximin, and maximax methods are considered as non-preference methods [102]. These methods do not require the decision maker's preference. The conjunctive and disjunctive methods were used when the alternatives must be screened out, when the performance scores of alternatives exceed a threshold value of all criteria. The weighted additive and the weighted product method also belong to the elementary methods and do require the decision maker's preference [102]. Among these methods, the weighted sum method is the most commonly used method in decision making for sustainability of energy systems [101] [102].

AHP and TOPSIS methods belong to unique synthesizing criteria. The techniques are widely used in decision making in energy systems [102][20]. AHP has the unique characteristic of a computing inconsistency index that is used to evaluate consistency in the decision-making process. It is also widely applied when considering different levels in decision making criteria [103][104]. The TOPSIS (Technique of Order Preference Similarity to the Ideal Solution) method is used when the decision makers want to avoid risk and simultaneously maximize benefits [105] [106]. ELECTRE and PROMETHEE are considered as outranking methods, while ELECTRE can handle both quantitative and qualitative criteria [107], and PROMETHEE is less complex and is used with scores without normalizing [107].

The multi-criteria analysis approach is frequently used in carbon capture studies. Tang and You used multi criteria analysis approach to study implementing carbon capturing in solid waste incineration plant [108]. Life cycle environmental impacts are considered as indicators of environmental criteria, and economic penalty and profit were considered as economic criteria. Volkart et al. studied the performance of carbon capturing compared to different alternative energy sources by considering economy, environment, society, and security of supply, where life cycle environmental impacts were considered as indicators of environmental criteria[109]. Tang and You studied different carbon capturing technologies that can be used with coal combustion power plants using life cycle environmental impacts as indicators of environmental impacts, while levelized cost of electricity and CO_2 avoidance cost were considered as indicators of economic criteria [105]. These studies used TOPSIS and WSM methods as the multi-criteria decision analysis methods. Most of the studies used different weighting profiles that considered different stakeholder perspectives for estimate weights of the criteria. These studies showed the importance of using a multi-criteria approach on carbon capturing technologies due to the significant changes in the cost and non-GHG environmental impacts, while reducing GHG environmental impacts.

3.3.3.1 Uncertainty handling used in sustainability assessment

Various types of uncertainties occur when evaluating sustainability. The uncertainties can broadly be classified into classes: epistemic and aleatory uncertainties [20]. Epistemic uncertainties are caused due to the lack of knowledge, incomplete information, and ignorance. Aleatory uncertainties are inherent uncertainties and caused by natural variability of the system. Epistemic uncertainties can be further classified as model uncertainty, parameter uncertainty, and scenario uncertainty. Model uncertainties are uncertain model structure and representation of systems (e.g., equations), whereas parameters uncertainties are due to uncertainty in model parameter values resulted by inaccurate data [110] and especially with the qualitative data [20]. Scenario uncertainties are caused by the variations of the scenarios in defining the system, which may change over the time due to external factors [111].

To handle the uncertainties, the studies commonly used probabilistic methods such as Mont Carlo simulations. However, these methods are criticized for their complexity and the requirement for extensive data [110]. Fuzzy set theory is also used to handle the uncertainties of data, with less complexity compared to probabilistic methods.

Fuzzy set theory was used in sustainability assessment studies to handle incompleteness and imprecision of data [110] [112]. Fuzzy set or fuzzy number is a set of real numbers, where each element of the set is mapped to a membership function, which act as the weight of the element. The membership function is a real number that is valued between 0 and 1 [113]. Inspired by fuzzy set theories, MADM methods were developed to use fuzzy numbers instead of crisp numbers. Fuzzy based MADM methods avoid limitations and practical constraints, such as uncertainty of information and availability of data that can be encountered in classic MADM methods. Fuzzy MADM methods are widely used in decision making in sustainability studies [102].

3.3.4 Summary

The main purpose of this chapter is to provide guidance to assess the feasibility of integrating capturing in building heating systems to reduce GHG emissions. A comprehensive literature review was conducted to investigate the potential of integrating carbon capturing, storage, and utilisation in natural gas building heating systems. Adopting the carbon capturing process used in fossil fuel combustion power generation facilities was an area of focus. The carbon capturing process includes CO_2 capturing, transportation, storage, and utilization technologies. The operational conditions required for the optimum operation of CO_2 separation technologies were further investigated. In addition, operational parameters such as operational flexibility, turndown, and reliability of CO_2 separation technologies were reviewed. This helped to identify the suitable carbon separation technologies that can function in the building context. The study also discussed the possible pathways of CO_2 transportation in the building scale. Finally, the study summarized the potential drivers of and barriers to installing carbon capturing in the building scale.

Of the three main carbon capturing technologies, post-combustion technology can be used with NG building heating systems. Therefore, the carbon separation technologies used in post-combustion technologies were considered. The study revealed that membrane separation technology is more favourable for the operation of building heating systems based on operational parameters such as turndown, reliability, and adaptability. However, this membrane separation and adsorption technology requires flue gas recirculation due to the low CO_2 concentration in building heating systems, so it may require significant changes to building heating systems. Chemical absorption and adsorption technologies have moderate performance over operational parameters. The study also indicates that chemical absorption technology can be used directly with building heating systems without modifications to the combustion systems.

Carbon capturing systems would significantly increase the operational cost with currently available technologies. However, the operational cost may be reduced with energy efficient carbon capturing technologies and policy level involvement such as tax reduction and introducing carbon credits. Evidence of the increased capital cost of the carbon capturing process is identified as the one of the main barriers to implementing carbon capturing in the building-level. Although the carbon capturing process reduces GHG emissions, there can be adverse environmental impacts from carbon capturing systems, such as increased human toxicity and acidification potential. The study also revealed that CO_2 transportation in the building scale is challenging and requires further research.

Chapter 4: Operational GHG Emission Reduction with Building-level Carbon Capturing Technologies

This section presents the strategy developed to estimate the operational characteristics of building-level carbon capturing. The operational characteristics considered in this study are annual CO_2 capture rate, annual energy consumption (thermal and electricity), and annual operational GHG emission reduction potential.

4.1 Background

Implementing carbon capturing strategies on building heating systems was recently considered in the industry and there are commercially available systems. The literature review shows that there is a possibility to use post-combustion carbon capturing technologies, such as chemical absorption, that are used in the power generation sector on building-level heating systems. In particular, operational parameters such as CO_2 concentration of flue gas in building heating systems are much more suitable for the chemical absorption method. One of the main challenges of implementing carbon capturing in building scale, however, is to transport the captured CO_2. Most of the carbon capturing applications are large scale and use pipeline transportation. There is evidence in the literature that pipeline transportation is infeasible in smaller scale applications due to significant investment and operational cost increases to transport unit CO_2. Therefore, pipeline transportation may not be suitable in the building scale. Road transportation may be more appropriate for transporting CO_2 in building scale as it is known to be suitable at a smaller scale.

The comprehensive literature review showed that this research area was overlooked, although this method has significant potential to reduce GHG emissions. Although many studies have been considered on the performance of carbon capturing systems in the fossil fuel-based power generation sector, no studies have been conducted on the performance of these technologies at building-level. In addition, there is a lack of knowledge on performance parameters such as CO_2 recovery rate in the commercially available systems. Therefore, evaluating these performance parameters experimentally is necessary.

Since carbon capturing technology has not been studied thoroughly, the first step in introducing the technology would be assessing the feasibility of using carbon capturing technologies for building-level emission reduction. It requires performance characteristics such as annual carbon capturing rate, energy consumption, and by-product generation rate. To address this gap, the study proposes a performance characteristics evaluation strategy. The findings of this section will help researchers to assess the feasibility of building-level carbon capturing systems and develop benchmark performance characteristics.

4.2 Methods and Procedure

The literature review indicated that the carbon capturing process can be categorized as CO_2 separation from the flue gas and conversion of CO_2 into a by-product. It was assumed in this study that the separated CO_2 is transported using the road transportation method, where the captured CO_2 is temporarily stored in liquid form in the building. Therefore, the study considered two carbon capturing strategies based on the carbon capturing methods that are suitable for building operation. The carbon capturing strategy that separates CO_2 from flue gas was called Type 1, while the carbon capturing strategy that converts CO_2 into by-products was called Type 2. According to the literature, the converted by-product can be in solid or liquid form in the Type 2 carbon capturing strategy [36][68]. It is also transported after being temporarily stored in the building. Therefore, the maximum capture rate of CO_2 is restricted by the amount of storage available for the by-products (CO_2 or other chemical). The process flow diagrams of the two types of the carbon capturing processes are shown in Figure 4-1 and Figure 4-2.

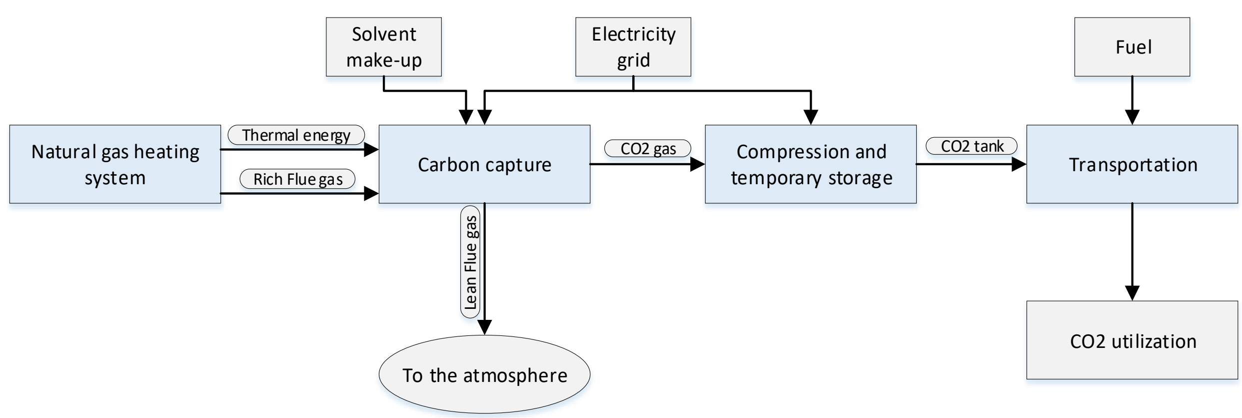

Figure 4-1: The carbon capturing process that separates CO_2 from flue gas (Type 1)

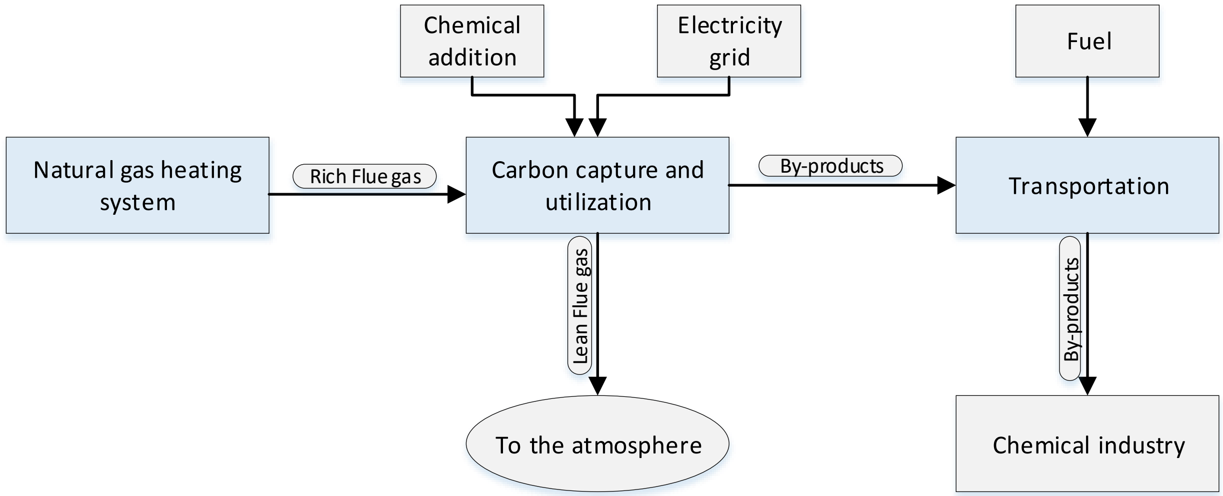

Figure 4-2: The carbon capturing process that converts CO_2 into a by-product (Type 2)

The chemical absorption, membrane separation, and adsorption methods are carbon separation methods that can be used with post-combustion carbon capturing technology. Among them, the chemical absorption method is most suitable for fossil fuel combustion sources that produce low CO_2 concentrations similar to natural gas building heating systems (CO_2 concentration is less than 10%). In addition, the chemical absorption method performs well on low CO_2 concentration combustion products, while providing high purity and high CO_2 recovery rate [79]. Therefore, the chemical absorption method was considered as the carbon separation in Type 1 building-level carbon capturing systems. Although the chemical absorption method uses different types of solvents, the operation of the system is same. Since it must reuse the chemical solvents, the chemical absorption carbon capturing system requires thermal energy for the regeneration process. The study assumed that the carbon capturing process has an auxiliary natural gas boiler that is used for this purpose. It was assumed that the carbon capturing system captures CO_2 from the furnaces and boilers used for building heating and regeneration of the carbon capturing system. In addition, the carbon capturing system requires electricity to operate auxiliary components.

The Type 2 building-level carbon capturing strategy was inspired by commercial level systems that use potassium hydroxide (KOH) and capture CO_2 while producing K_2CO_3. Since these technologies do not need regeneration of the solvents or chemicals, it was assumed that energy was consumed only for auxiliary components such as agitators and pumps. In addition, the literature review showed that commercial building carbon capturing systems are equipped with heat recovery systems used to recover heat flue gas and the reaction of chemicals and CO_2. Therefore, the model is included with heat recovery of the Type 2 system.

4.2.1 Assessment of characteristics of building-level carbon capturing systems

Figure 4-3 shows the model developed to assess the characteristics of carbon capturing systems. The first step of the model is to compare the optimum operating conditions of the carbon capturing system against the flue gas properties. The CO_2 composition of the flue gas must be within the optimum CO_2 concentration required by the carbon capturing system. If the required CO_2 gas concentration is higher than the CO_2 concentration in the flue gas, the heating system must be incorporated with flue gas recirculation. That situation was not considered in this study as the research aim was to assess the feasibility of implementing CCSU in the existing building heating systems.

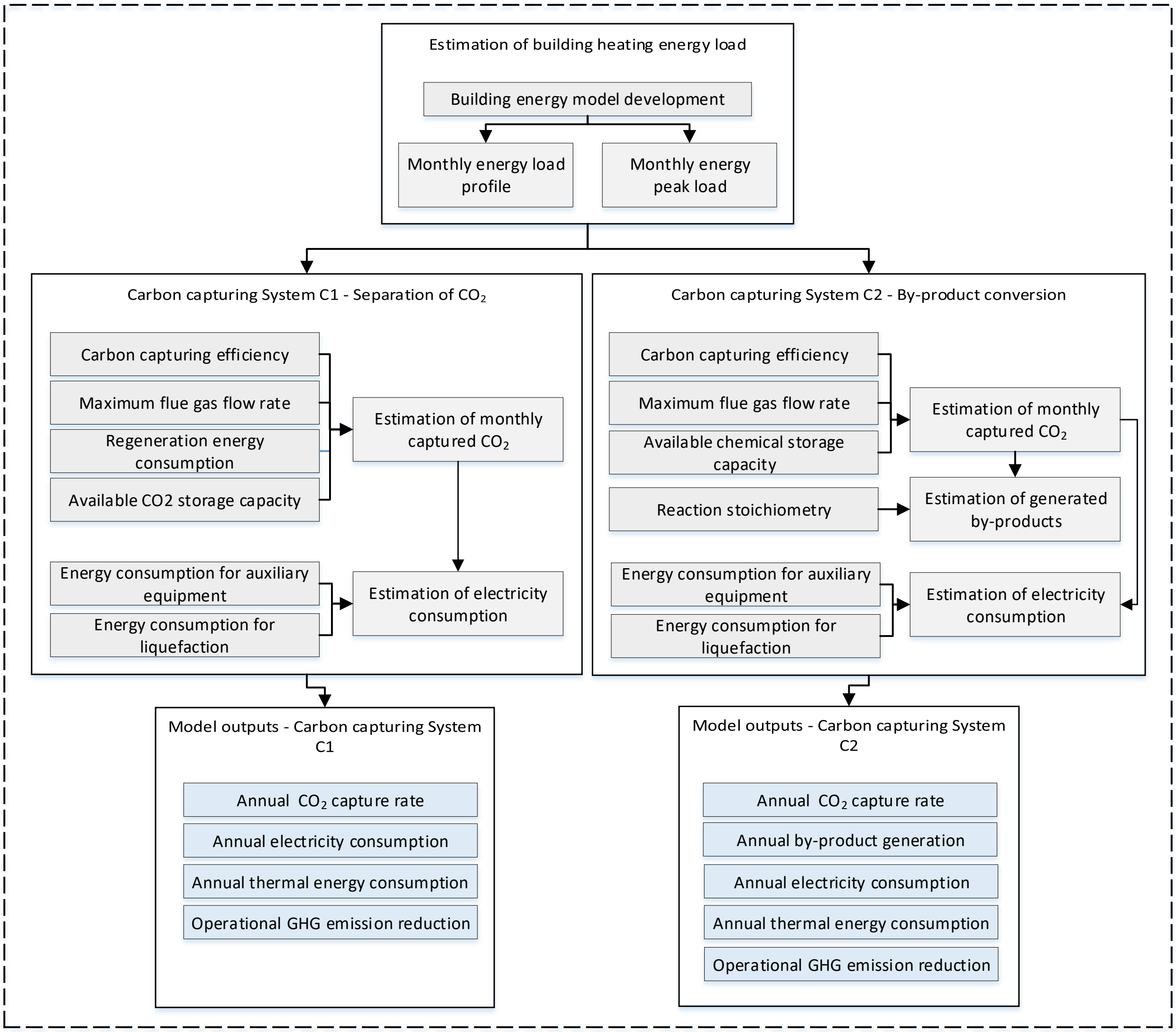

Figure 4-3: Operational characteristics estimation model

The main outputs of the model of the Type 1 building-level carbon capturing systems are the annual CO_2 capture rate, annual electricity consumption, and the annual thermal energy consumption (including energy consumption of the building heating system and the regeneration heating system). The model outputs of the Type 2 are the annual CO_2 capture rate, annual by-product generation, annual thermal energy consumption (excluding thermal energy saved by the heat recovery system), and the annual electricity consumption. The model uses the following procedure to estimate the above characteristics if data on energy consumption and amount of captured CO_2 is not available.

4.2.1.1 Estimation of amount of captured CO_2, and the operational energy

In order to estimate the annual captured CO_2, the monthly energy load profile of the building is required. Therefore, the study used HOT2000 software for the building energy model and obtained the monthly energy load profile. The following sections explain the procedure used to evaluate the annual CO_2 capture rate and other parameters using the energy profile.

CO_2 capture rate: Type 1 building-level carbon capturing system

The chemical absorption carbon capturing system captures CO_2 using a chemical solvent. If the solvent needs to be reused and only CO_2 is separated out of the system, the carbon capturing system requires thermal energy for the solvent regeneration process. In the power generation sector, regeneration energy is supplied by steam extracted from a boiler or turbine. However, if thermal energy is extracted from the building heating system, the capacity of the system is reduced. Therefore, it was assumed a separate boiler is connected to the carbon capturing system that can generate the required thermal energy. It was also assumed that the carbon capturing system captures CO_2 that is leaving the building heating system and the regeneration heating system. Therefore, the total thermal energy requirement is estimated using Equation 4-1, when the system is operating at maximum capacity.

$$E_{total,i} = \frac{E_{0,i}}{1 - EF_{NG} \times \eta_{CO2} \times E_{re}} \quad \text{--------------------- Equation 4-1}$$

Where,

$E_{total,i}$ = Monthly natural gas consumption with carbon capture (MJ/month)

$E_{0,i}$ = Monthly natural gas consumption without carbon capture (MJ/month)

η_{CO2} = Carbon capturing efficiency (90%)

EF_{NG} = Emission factor of Natural gas (kg CO_2/MJ)

E_{re} = Regeneration energy consumption (MJ/kgCO_2)

The maximum amount of captured CO_2 in i^{th} month is calculated using Equation 4-2.

$$CC_{max,i} = E_{total} \times EF_{NG} \times \eta_{CO2} \qquad \text{---------------------} \quad \text{Equation 4-2}$$

Where,

$CC_{max,i}$ = Maximum amount of CO_2 that can be captured in i[th] month (kg CO_2)

Estimation of carbon capture rate when there is limited CO_2 storage capacity

If the captured CO_2 is limited by the CO_2 storage capacity, the actual captured CO_2 is calculated using Equation 4-3 below.

$$CC_i = \begin{cases} S, & CC_{max} < S \\ CC_{max}, & CC_{max} \geq S \end{cases} \qquad \text{---------------------} \quad \text{Equation 4-3}$$

Where,

CC_i = Captured CO_2 in i[th] month (kg CO_2/month)

S = Maximum amount of CO_2 that can be stored

The annual captured CO_2 can be calculated by taking the summation of the captured CO_2 in each month in the year.

CO_2 capture rate: Type 2 building-level carbon capturing system

For carbon capturing systems that do not require regeneration thermal energy, the model assumes the monthly maximum CO_2 capture rate calculated using Equation 4-4 below.

$$CC_{max,i} = E_{o,i} \times EF_{NG} \times \eta_{CO2} \qquad \text{-----------------------} \quad \text{Equation 4-4}$$

In addition, if the carbon capture rate is restricted by by-product storage, Equation 4-5 is used to estimate the monthly carbon capture rate.

$$CC_i = \begin{cases} S, & CC_{max} < S \\ CC_{max}, & CC_{max} \geq S \end{cases} \qquad \text{------------------------} \quad \text{Equation 4-5}$$

Where,

S = The maximum amount of CO_2 equivalent to the by-product storage capacity

Annual natural gas energy consumption

If the carbon capturing rate is not limited by CO_2 storage capacity or CO_2 flow rate, the total natural gas consumption can be found using the equation. However, if there are any of the above restrictions, the model estimates the total natural gas energy consumption of Type 2 building-level carbon capturing system using Equation 4-6 below.

$$NG\ consumption\ (Type\ 1) = \sum_{year}(CC_i \times E_{re} + E_{0,i}) \quad \text{-------- Equation 4-6}$$

Since Type 2 building carbon capturing systems include a heat recovery system, natural gas consumption must be reduced. The heat recovery systems in commercial building carbon capturing systems were designed to preheat the domestic water supply. If the carbon capturing system is connected to a space heating system, the heat transferred to the domestic heat system was attributed to the space heating system, although it is not directly transferred to the space heating system. Equation 4-7 and Equation 4-8 show the natural gas saved by the Type 2 carbon capturing system and the annual natural gas consumption.

$$E_{R,i} = (F_{w,i} \times E_w) / \eta_{thermal} \quad \text{------------------------- Equation 4-7}$$

Where,

$E_{R,i}$ = Recovered natural gas in i^{th} month (MJ/month)

$F_{w,i}$ = Domestic hot water consumption in i^{th} month (l/month)

E_w = Heat recovery rate of the building carbon capturing system (MJ/l)

$\eta_{thermal}$ = Thermal efficiency of the domestic hot water system

Thus, the annual thermal energy consumption of the Type 2 building carbon capturing system is given by Equation 4-8.

$$NG\ consumption\ (Type\ 2) = \sum_{year}(E_{0,i} - E_{R,i}) \quad \text{-------- Equation 4-8}$$

Annual electricity energy consumption

The electricity and auxiliary energy, including compression and liquefaction of CO_2, can also be found as energy per unit mass of captured CO_2. Therefore, the annual electric energy can be calculated by multiplying the amount of captured CO_2 and the energy consumption per unit captured CO_2 [23], [114].

Annual by-product generation: Type 2 building-level carbon capturing system

The annual by-product generation was estimated using the stoichiometric ratio of the chemical reaction occurring in the carbon capturing system.

4.2.2 Case-specific methods and analysis

In Canada, where building-level emissions are primarily due to heating applications, forced air furnace and electric baseboard heaters are commonly used as primary heating systems. Forced air furnaces are used by 55% of buildings while 26% use electric baseboard heaters. Moreover, heating stove, boilers, and heat pumps are also used for heating and 56% of the buildings' heating requirement is fulfilled by natural gas in Canada. In addition, 15% of energy for boilers and furnaces is produced by burning oil, wood, coal, and distillates [115]. Generally, boilers and furnaces are classified into three categories according to their efficiency: *low-efficiency*, *mid-efficiency* and *high efficien*cy heating systems [116] [117]. The efficiency and use of these types of boilers and furnaces are shown in Table 4-1.

Table 4-1: Boiler/furnace classification

Boiler/Furnace type	**Efficiency (%)**	**Percentage use (%)**
Low efficiency (Natural draft boilers/furnaces)	78%	1%
Medium efficiency (forced draft or induced draft boilers/furnaces)	80%-83%	37%
High efficiency (condense boilers/furnaces)	90%	62%

Since the majority of natural gas space heating systems consist of high efficiency furnaces, the study considered implementing carbon capturing systems in residential space heating systems that consist of high efficiency furnaces. In order to demonstrate the model described above, two carbon capturing systems are considered. A chemical absorption system that uses MEA as the solvent was considered as one of the systems and it is widely used in fossil fuel generation plants. Although there was no evidence found that this method is used in the building scale, the study used it as the optimum operating conditions of the system as it is compatible with the heating systems used in buildings, according to the literature review. Since carbon capturing systems separate CO_2 from flue gas, the study considered it a Type 1 system. This system was called "System C1". The other system considered in this study was a commercial building-level carbon capturing system that converts CO_2 into K_2CO_3 using KOH. It is a Type 2 carbon capturing system and it is called "System C2" in the study. In addition, the commercial carbon capturing system considered in this study has a heat recovery system, which extracts the heat from flue gas and the reaction. More details of the systems are shown below.

4.2.2.1 System C1: The MEA carbon capturing process

The literature review showed that the chemical absorption technology is more suitable for operation in building scale natural gas heating systems. **Figure 4-4** shows the process diagram of the Mono Ethanol Amine (MEA) based carbon capturing system. The carbon capturing process is described as follows. The carbon capture system consists of 2 columns: absorber and stripper. The flue gas produced by the combustion source goes to the absorber, where CO_2 and the MEA solution come in contact and react. The treated gas with low CO_2 concentration exits the system. The CO_2-rich MEA solution then goes to the stripper, where the MEA solution is regenerated by removing CO_2. The rich MEA solution has to be heated to remove CO_2. Steam is used to deliver thermal energy. The reboiler is used to produce steam. The steam and CO_2 mixture leave from the top of the stripper. The steam is condensed by the condenser and transferred to the stripper. CO_2 is then removed from the condenser. The lean MEA goes to the absorber through the cross heat exchanger, which transfers heat to the rich MEA solution [46].

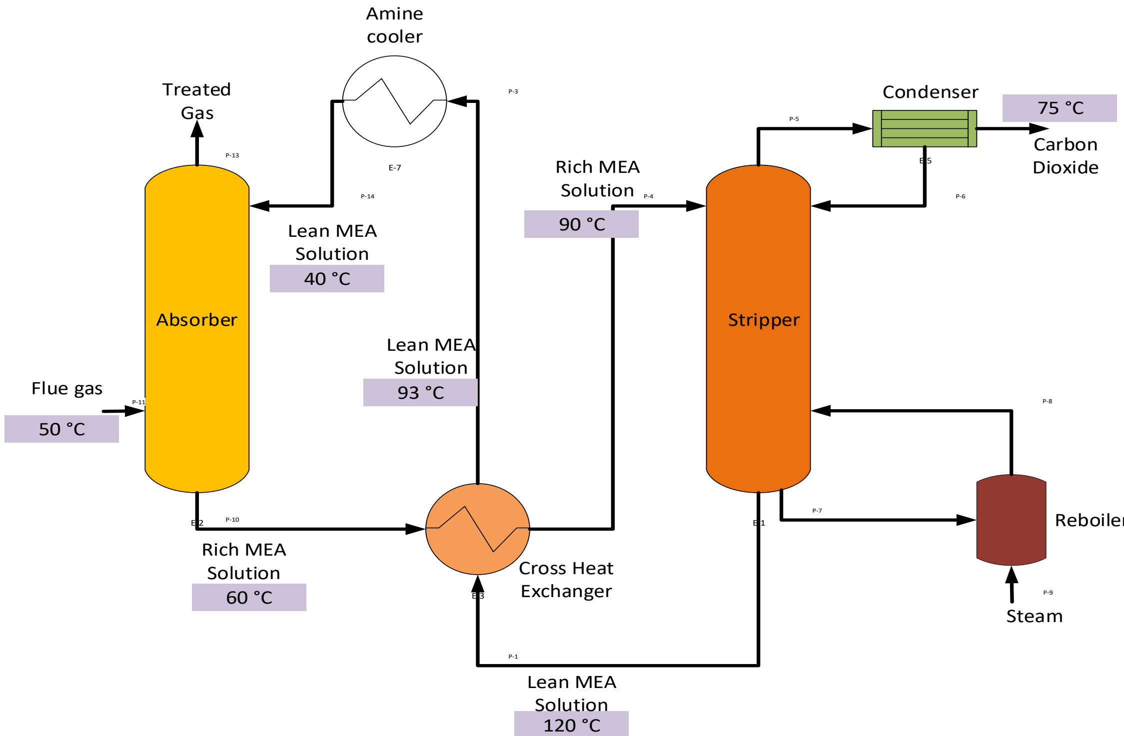

Figure 4-4 Process diagram of the MEA based carbon capturing system

4.2.2.2 System C2: KOH-based carbon capturing

The schematic diagram of System C2 is shown in Figure 4-5. System C2 operates as follows. The reactant chemical (KOH) is loaded in the reaction chamber. The CO_2 rich flue gas flows through the inlet duct and enters the reaction chamber. The CO_2 of the flue gas reacts with KOH in the reaction chamber and forms K_2CO_3, the by-product. From the reaction chamber, the CO_2 lean flue gas flows to the outlet duct of the chamber. The chemical reaction is shown in Equation 4-9. In addition, water is circulated through the heat exchanger. The heat exchanger is used to transfer thermal energy from the flue gas to the water, when lean flue gas passes through the heat exchanger.

$$2KOH(s) + CO_2(g) \rightarrow K_2CO_3(s) + H_2O(l) \quad \text{--------------} \quad \text{Equation 4-9}$$

The chemicals must be agitated using an agitator while KOH is converted into K_2CO_3. This agitator operates for 1 to 2 minutes at 15-minute intervals. The time interval and the operating time of the agitator are programmable. The agitator is rotated by a three-phase motor that is connected to a gear box. The water pump circulates the water through the heat exchanger to the water storage. The carbon capturing system is not directly connected to the boiler outlet; instead the flue gas is diverted to a separate duct as shown in the Figure 4-5: Schematic diagram of KOH-based building-level carbon capturing system. The blower is used to draw gas from the flue gas mainstream to the flue gas intake duct.

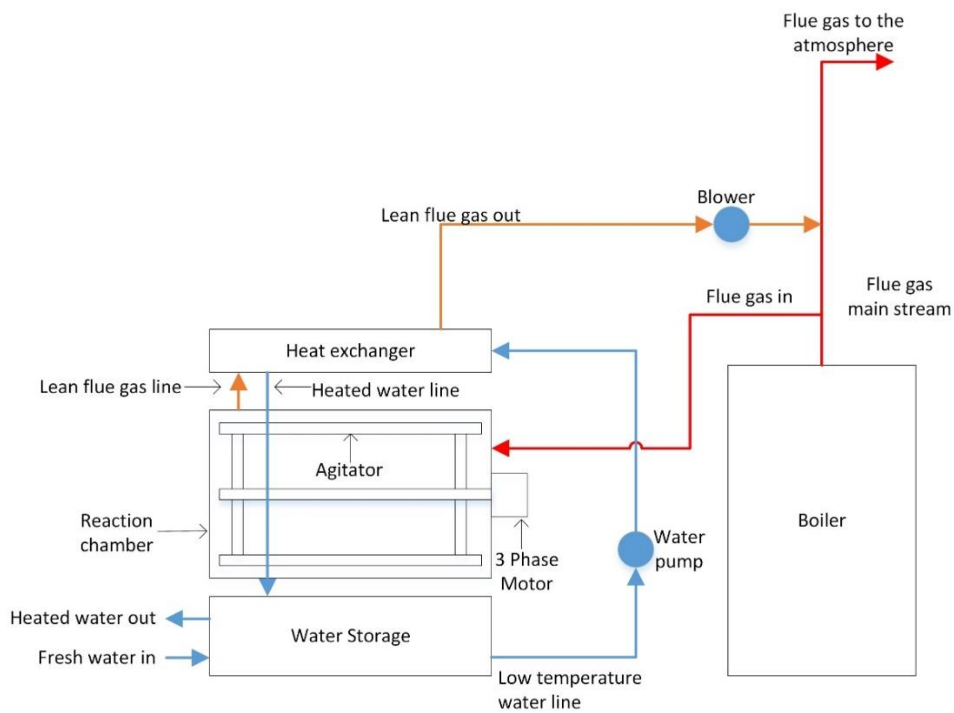

Figure 4-5: Schematic diagram of KOH-based building-level carbon capturing system

4.2.2.3 Scenario development

To evaluate the performance of System C1 and C2, the study developed 7 Scenarios as shown in Table 4-2. It was considered that System C1 has 4 different maximum CO_2 storage scenarios. The maximum required storage was calculated using the characteristic estimation model including the maximum monthly energy load. The study did not consider different storage sizes of System C2 as it is a commercial system and comes in only one size. The maximum CO_2 flow rates were estimated in the "Experimental study" section. However, the study considered two different scenarios of System C2, namely, Scenario C2.1 and Scenario C2.2. Scenario C2.1 represents only the carbon capturing function, while Scenario C2.2 represents the carbon capturing function with heat recovery. The saved natural gas was attributed to the building heating system.

Table 4-2: Description of the scenarios

Scenarios	***Building heating system type***
Scenario 0	Residential space heating system that is equipped with a natural gas condense furnace.
Scenario C1.1	Residential space heating system that is equipped with a natural gas condense furnace and carbon capturing system C1 (90% carbon capturing efficiency) that has 25% of the maximum carbon capture capacity.
Scenario C1.2	Residential space heating system that is equipped with a natural gas condense furnace and carbon capturing system C1 (90% carbon capturing efficiency) that has 50% of the maximum carbon capture capacity.
Scenario C1.3	Residential space heating system that is equipped with a natural gas condense furnace and carbon capturing system C1 (90% carbon capturing efficiency) that has 75% of the maximum carbon capture capacity.
Scenario C1.4	Residential space heating system that is equipped with a natural gas condense furnace and carbon capturing system C1 (90% carbon capturing efficiency) that has the maximum carbon capture capacity.
Scenario C2.1	Residential space heating system that is equipped with a natural gas condense furnace and carbon capturing system C2 (without heat recovery) that has experiment-based observed carbon capture efficiency and maximum KOH capacity of 200 kg.
Scenario C2.2	Residential space heating system that is equipped with a natural gas condense furnace and carbon capturing system C2 (with heat recovery) that has experiment-based observed carbon capture efficiency and maximum KOH capacity of 200 kg.

4.2.2.4 Building energy simulation

The study used HOT 2000 v11.7b23 building energy simulation software for residential building energy modeling. The HOT 2000 software is widely used for building energy simulation on single-family detached residential houses. The study considered an approximately 2000 ft^2 single-family detached residential house located in each of the eight provinces: Ontario (ON), Quebec (QC), British Columbia (BC), Alberta (AB), Manitoba (MB), Saskatchewan (SK), Nova Scotia (NS), and New Brunswick (NB). Since these provinces have more than 90% of the population in Canada, they were the only ones considered in this study. Furthermore, the buildings were considered to be located in cities with the highest population in the selected provinces. In addition, the selected cities cover the majority of the climatic zones in Canada. Details of the developed building model are shown in Table 4-3 below. Table 4-4 shows the heating degree days and the climatic regions of the selected cities obtained from the HOT 2000 energy modeling software.

Table 4-3: Building model information

Information	*Value*
Above grade heated flow area	1430 m^2
Below grade heated flow area	620 m^2
Number of doors on the main floor	2
Number of windows on the main floor	7
Number of doors on the second floor	0
Number of windows on the second floor	4
Number of occupants	2 adults and 2 children

Table 4-4: Heating degree days and climatic regions of the selected cities

Province	*City*	*Heating degree days*	*Climatic region*
Ontario	Toronto	3520	Zone 5

Province	City	Heating degree days	Climatic region
Quebec	Montreal	4200	Zone 6
British Columbia	Vancouver	2825	Zone 4
Alberta	Calgary	5000	Zone 7A
Manitoba	Winnipeg	5670	Zone 7A
Saskatchewan	Saskatoon	5700	Zone 7A
Nova Scotia	Halifax	4000	Zone 6
New Brunswick	Moncton	4680	Zone 6

The energy model of the residential house was developed in HOT2000 building energy simulation software by considering the minimum requirements given in the 2015 national building energy code. The overall thermal transmittance of walls, roofs, floors, doors, and fenestration were determined by building energy code 2015 [118] as shown in Table 4-5. It was assumed that the space heating system is a natural gas condensed furnace with 90% of steady state efficiency.

Table 4-5: Overall thermal transmittance values of building components [118]

Building component	***Overall thermal transmittance W/(m^2.K)***			
	Zone 4	Zone 5	Zone 6	Zone 7A
Above-ground opaque building assembly				
Walls	0.315	0.278	0.247	0.210
Roofs	0.227	0.183	0.183	0.162
Floors	0.227	0.183	0.183	0.162
Assembly in contact with the ground				
Walls	0.568	0.379	0.284	0.284
Roofs	0.568	0.379	0.284	0.284
Floors	0.757	0.757	0.757	0.757

Building component	Overall thermal transmittance W/(m².K)	Building component	Overall thermal transmittance W/(m².K)	Building component
Other components				
Doors	2.2	2.2	2.2	2.2
All fenestration	2.4	2.2	2.2	2.2

The space heating system is considered a condensing furnace that has EFF of 90%. The water heating system also a natural gas boiler with 0.67 efficiency.

4.2.2.5 Experimental study

System C2 was connected to a 250,000 BTU domestic hot water (DHW) boiler in an office building located in Calgary, AB. The boiler is non-modulating, which generates heat at maximum power when it is operating. Figure 4-6 shows an instrumentation setup developed to estimate the technical performance of the carbon capturing system. The Table B-1, Table B-2, and Table B-3 in the Appendix show the description of the data points. The instrumentation setup consisted of Pitot tubes, CO_2 sensors, and temperature sensors at the flue gas inlet and outlet of the carbon capturing system. They were used to measure the inlet and outlet CO_2 mass flow rates. In addition, temperature sensors and a water flow sensor were installed at the inlet and outlet of the water supply to measure the heat recovery rate. The calibration process was explained in the Appendix C . The calculation procedure is shown below.

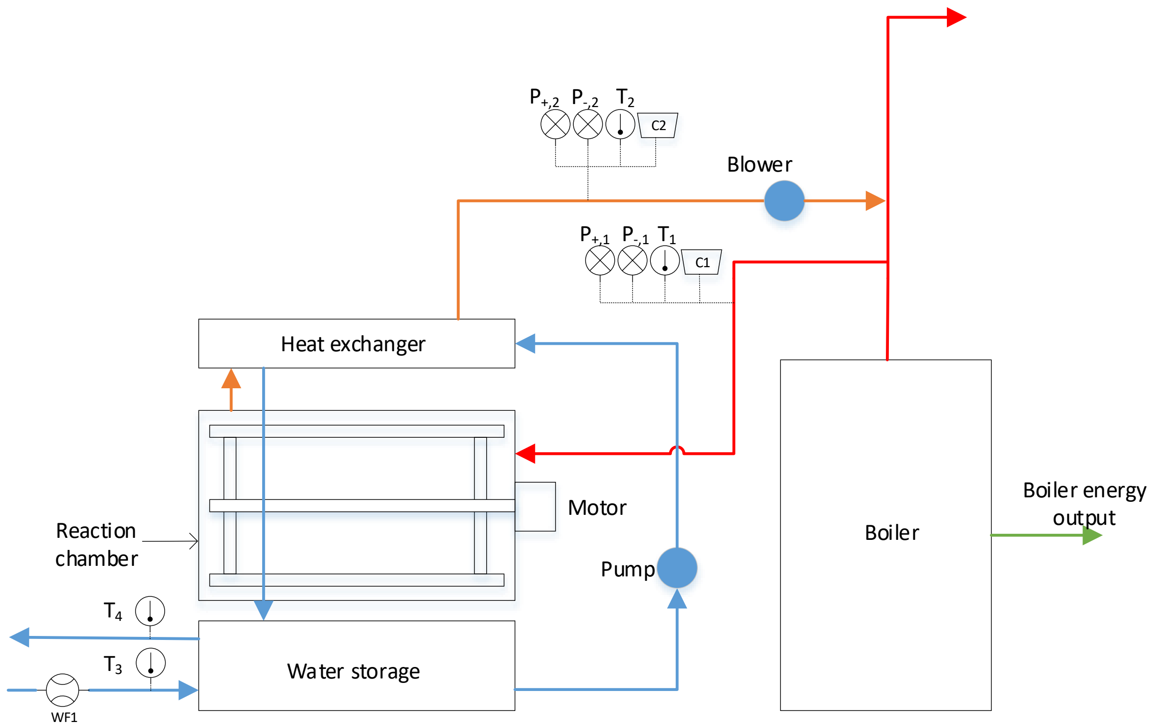

Figure 4-6: Instrumentation setup of technical performance evaluation

The flue gas flow rate was calculated using Equation 4-10, Equation 4-11, and Equation 4-12. Ideal gas equations are used to evaluate the gas properties.

$$\rho = \frac{P_{-} \times M_{air}}{R(T + 273)} \qquad \text{--------------------- Equation 4-10}$$

$$U_{mean} = \sqrt{\frac{2(P_{+} - P_{-})}{\rho}} \qquad \text{--------------------- Equation 4-11}$$

$$\dot{m_{CO2}} = M_{CO2} \times \frac{P\_UAC \dot{\times} 10^{-6}}{R(273 + T)} \qquad \text{--------------------- Equation 4-12}$$

Where,

M_{air} is the molar mass of air (kg/mol).

ρ is the density of the gas flow (kg/m^3).

R is the universal gas constant (J.mol^{-1}.K^{-1}).

P_+ is the pressure from the total port of the Pitot tube (Pa).

P_- is the pressure from the static port of the Pitot tube (Pa).

T is the temperature of the fluid (°C).

The inlet and outlet CO_2 flow rates were measured and recorded continuously at constant time intervals. Then, cumulative inlet and outlet CO_2 mass was evaluated using numerical integration (Trapezoidal method) method on a daily basis. The average carbon capture efficiency was calculated using Equation 5. Note that the carbon capture efficiency calculated using Equation 4-13 only indicates the reduction of CO_2 of the flue gas that diverted through the carbon capturing system.

$$\eta_{CO2} = \frac{\sum_{i=1}^{n} M_{in,i} - \sum_{i=1}^{n} M_{out,i}}{\sum_{i=1}^{n} M_{in,i}} \qquad \text{--------------------- Equation 4-13}$$

Where,

η_{CO2} is the carbon capture efficiency.

i is the day on which the CO_2 mass is measured.

n is the number of days to complete the carbon capture cycle.

$M_{in,i}$ is the total inlet CO_2 mass on i^{th} day (kg).

$M_{out,i}$ is the total outlet CO_2 mass on i^{th} day (kg).

In addition to the above technical parameters, the study also measured the ratio of flue gas diverted from the main flue gas line of the boiler. The ratio helps determine the maximum amount of flue gas that can be used to capture CO_2. The study did not use any mechanism to measure the flue gas flow rate of the boiler outlet. Instead, the study considered the time between when the temperature starts to increase and when it starts to decrease as the time interval when the boiler operates. It is assumed that the boiler operates at maximum power during this time. Emission factor data are used to estimate the CO_2 mass output.

The heat recovery rate was calculated using Equation 4-14.

$$Q_{heat} = \rho_{water} \times \dot{V_w} \times S_{water} \times (T_{out} - T_{in}) \quad \text{------------- Equation 4-14}$$

Where,

Q_{heat} is the heat recovery rate (kW).

P_{water} is the density of water (kg/m^3).

$\dot{V_w}$ is the water volume flow rate (m^3/s).

S_{water} is the specific heat capacity of water (kJ/kg/s).

T_{out} is the outlet water temperature (°C).

T_{in} is the inlet water temperature (°C).

Similar to the previous step, the heat recovery rate and water flow rates were recorded continuously at constant time intervals. Then, cumulative recovered heat and the amount of water that flowed through the system were evaluated using the numerical integration method on a daily basis. The average heat recovery rate (heat recovered per 1 liter of water) was calculated using Equation 4-15 below.

$$\eta_{heat} = \frac{\sum_{i=1}^{n} Q_{in,i}}{\sum_{i=1}^{n} V_{in,i}} \quad \text{--------------------- Equation 4-15}$$

η_{heat} is the heat recovery rate (kJ/l).

$Q_{in,i}$ is the recovered in ith day (kJ).

$V_{in,i}$ is the volume of water that flowed through the system on ith day.

4.2.2.6 Carbon capturing system parameters

The performance parameters of System C1 are shown in Table 4-6. The carbon capturing efficiency and maximum CO_2 flow rate of System C2 are estimated in the experimental study. The performance data of the System C2 is provided in the Section 4.3.1.

Table 4-6: Parameters of carbon capturing system C1

Parameter	***Parameter value***
Carbon capturing efficiency (%)	90
Energy consumption for regeneration ($MJ_{thermal}/kgCO_2$)	3.53
Energy consumption for auxiliary components ($MJ_{Electricity}/kgCO_2$)	0.0434
Energy consumption for compression and liquefaction ($MJ_{Electricity}/kgCO_2$)	0.29

The electricity consumption of System C2 was evaluated using the technical specifications and operating time of the components as shown in Table 4-7. The data for Table 4-7 was obtained from a technical report of the carbon capturing system provided by the manufacturer.

Table 4-7: Specifications of the auxiliary components in carbon capturing system C2

Component	*Manufacturer details*	*Specifications*	*Operating time*
Agitator motor	Manufacturer = Leeson Model ID = 171646	Voltage = 230 V Current = 5 A Power = 1.15 hp Rotational speed = 1760 rpm	1 minute for every 15 minutes
Water circulation pump	Manufacturer = Grundfos Model ID = UP15 - 18BUC7	Voltage = 110 V Current = 0.74 A	Full time
Blower	Manufacturer = Rotom Model ID = R7-RB3	Voltage = 110 V Current = 0.34 A	Full time

The raw material requirement and formation of the by-products can be calculated using the stoichiometry of the chemical reaction, where 2.54 kg of raw material is required per kg of CO_2 captured and 3.13 kg of by-product is generated per kg CO_2 captured during the carbon capture process.

4.2.2.7 GHG emissions of electricity generation in regions.

The study considered 8 provinces located in Canada. They are Ontario, Quebec, British Columbia, Alberta, Manitoba, Saskatchewan, Nova Scotia, and New Brunswick. The GHG emission factors of the electricity generation of the above mentioned regions are shown in Table 4-8 [119].

Table 4-8: GHG emission factors for electricity generation

Province	*GHG emission factor (gCO_2/kWh)*
Ontario	20
Quebec	1.5
British Columbia	9.7
Alberta	800
Manitoba	2.1
Saskatchewan	710
Nova Scotia	720
New Brunswick	330

4.2.2.8 Summary of the assumptions in the case study

The assumptions made for analysis of System C1 are listed below.

- System C1 captures CO_2 in flue gas from both the building heating system and the auxiliary heating system.
- The thermal and electric energy consumption are proportional to the captured CO_2.

The assumptions made for the analysis of System C2 are listed below.

- The carbon capturing system can take all the flue gas when the building heating system operates at maximum capacity.
- The flue gas fan and agitator of System C2 (with or without heat recovery) are operated throughout the month if there is an energy generation requirement.
- The water pump is not operated in System C2 in Scenario C2.1, where heat recovery is not considered.
- The water pump of System C2 operates throughout the year in Scenario C2.2, where heat recovery is considered.

4.3 Results

This section presents the results of the experimental study and the results obtained by using the characteristics estimation model in different scenarios of heating systems that are integrated with carbon capturing systems.

4.3.1 Technical performance evaluation of System C2

The collected data of CO_2 inflow, CO_2 capture rate, and heat transfer rate observed from 2020-07-02 to 2020-03-20 are shown in Table 4-9. The average CO_2 emissions from the furnace were observed as 28.96 kgCO_2/day. It varied from 4-48 kgCO_2/day with a standard deviation of 10.67 kgCO_2/day. The average mass of CO_2 diverted into System C2 was 16.81 kgCO_2/day. It varied from 2.85-28.13 kgCO_2/day, with a standard deviation of 6.17 kgCO_2/day.

Table 4-9: Experimental results

Date	***Carbon capture Efficiency (%)***	***Carbon capture rate (kg/day)***	***Carbon inflow (kg/day)***	***Heat transfer rate (kg/L)***	***CO_2 from exhaust gas (kg/day)***	***Percentage of CO_2 diverted through the carbon capturing system***
2/7/2020	9.76%	0.96	9.82	12.15	18.95	52%
2/8/2020	8.83%	1.70	19.29	26.30	33.31	58%
2/9/2020	9.56%	1.87	19.56	23.04	34.36	57%
2/10/2020	5.58%	1.10	19.72	16.15	33.69	59%
2/11/2020	2.81%	0.58	20.71	31.66	34.43	60%
2/12/2020	0.20%	0.04	18.55	25.70	34.40	54%
2/13/2020	1.46%	0.29	19.73	21.32	34.41	57%
2/14/2020	0.00%	0.00	18.70	25.62	33.52	56%
2/15/2020	1.08%	0.19	18.04	0.46	32.32	56%
2/16/2020	0.62%	0.11	18.09	0.14	31.98	57%
2/17/2020	0.09%	0.02	25.50	2.34	45.95	56%
2/18/2020	13.78%	1.66	12.02	23.83	20.70	58%
2/19/2020	14.13%	3.13	22.15	56.48	38.25	58%
2/20/2020	16.44%	3.64	22.13	48.20	38.83	57%
2/21/2020	18.74%	3.98	21.22	38.79	36.22	59%
2/22/2020	6.26%	0.53	8.47	1.86	14.71	58%
2/24/2020	19.15%	2.77	14.46	36.80	24.16	60%
2/25/2020	19.81%	4.12	20.79	35.59	34.88	60%
2/26/2020	17.60%	3.44	19.54	15.86	32.40	60%
2/27/2020	12.80%	3.60	28.13	60.80	48.46	58%

Date	**Carbon capture Efficiency (%)**	**Carbon capture rate (kg/day)**	**Carbon inflow (kg/day)**	**Heat transfer rate (kg/L)**	**CO_2 from exhaust gas (kg/day)**	**Percentage of CO_2 diverted through the carbon capturing system**
2/28/2020	7.36%	1.37	18.61	15.75	32.00	58%
3/3/2020	13.78%	2.24	16.27	51.48	29.49	55%
3/4/2020	14.62%	1.35	9.20	7.28	16.43	56%
3/7/2020	11.70%	1.52	13.00	0.78	23.40	56%
3/11/2020	21.76%	3.68	16.92	42.26	28.19	60%
3/12/2020	19.22%	1.63	8.47	2.82	13.55	63%
3/13/2020	21.07%	4.66	22.11	40.07	37.44	59%
3/14/2020	15.32%	0.44	2.85	0.81	3.79	75%
3/15/2020	21.79%	4.09	18.75	0.20	31.97	59%
3/16/2020	19.07%	4.17	21.84	15.08	35.14	62%
3/17/2020	18.35%	4.41	24.05	16.07	39.34	61%
3/18/2020	8.58%	1.60	18.65	11.82	32.66	57%
3/19/2020	1.79%	0.08	4.40	7.64	7.65	58%
3/20/2020	2.93%	0.58	19.89	8.99	33.42	59%
3/21/2020	1.10%	0.06	5.23	0.37	8.46	62%
3/22/2020	2.64%	0.22	8.21	0.33	13.70	60%

The percentage of CO_2 mass diverted through System 2 varied from 52-75%, with an average of 60%. The study calculated the maximum CO_2 intake through System C2 by considering the average fraction of CO_2 mass diverted through System 2, and the CO_2 emission rate of the heating system. The maximum CO_2 intake was 2.4 gCO_2/s. It represents the CO_2 emissions from a 44 kW furnace by assuming an emission factor of 0.054 kg/MJ. The carbon capturing efficiency was calculated using the CO_2 that entered System 2. The results show that the average CO_2 capture efficiency is 13% and the maximum carbon capturing efficiency is 21%. The maximum carbon-capturing efficiency was observed when the carbon capturing system was refilled with KOH. It is gradually reduced when KOH is reacted due to the reduction of surface area of reactants exposed to CO_2.

The heat recovered from the flue gas and the chemical reaction was transferred to domestic water in the building. The water flow through System C2 on weekdays was 2-264 L/day. The average water flow was 94 L/day. The heat transfer rate varied from 2-60 kJ/L, with an average of 26 kJ/l. In addition, the water flow rates on weekends were 0.14-23 L/day. The results also indicate that the heat transfer rate is reduced when there is low water usage.

4.3.2 Energy consumption, captured CO_2, and produced by-products

This section describes the results obtained by applying the building-level carbon capturing characteristics estimation model and the building energy simulation. Results of integrating carbon capturing in residential building space heating systems and domestic hot water systems are shown separately.

4.3.2.1 Results of the space heating system scenarios

This section presents the monthly energy consumption profile of the space heating systems, annual thermal energy and electricity consumption of carbon capturing scenarios, and annual reduction of CO_2 from the space heating systems by the carbon capturing scenarios.

Energy simulation results of the space heating system

The energy simulation results show that the design power of the residential space heating system was 13.5kW-27kW. Figure 4-7 shows the monthly energy consumption of the residential space heating system. The results show that natural gas was not consumed in June, July, and August in ON and QC. Similarly, BC, MB, NS, and NB did not require energy for space heating in July and August, while SK did not need thermal energy in July. The house located in AB required space heating energy throughout the year. The maximum energy required was in January in all provinces. MB required the highest annual energy and BC required the lowest.

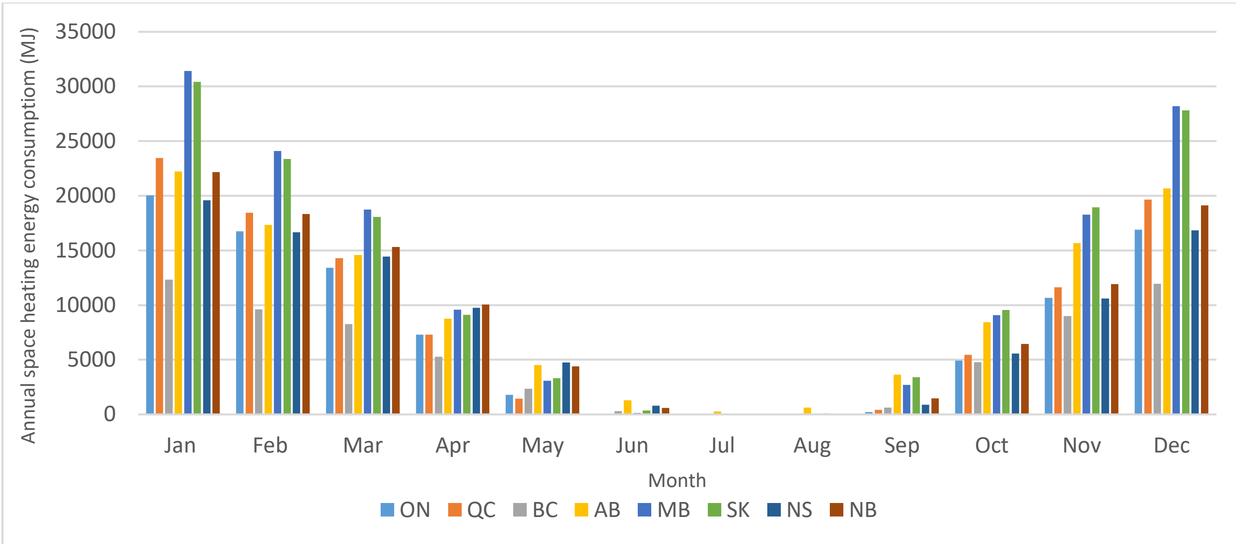

Figure 4-7: Monthly space heating energy consumption

<u>Annual percentage reduction of GHG emissions from energy consumption of space heating systems in different provinces</u>

Table 4-10 shows the amount of captured CO_2 in Scenario C1.1 to Scenario C2, and the generated by-products in Scenario C2.1 and Scenario C2.2.

Table 4-10: Annual captured CO2

Province	*Annual captured CO_2 ($kgCO_2$/ year)*					*By-products generated in Scenario C2.1 and C2.2 (kg/year)*
	Scenario C1.1	**Scenario C1.2**	**Scenario C1.3**	**Scenario C1.4**	**Scenario C2.1 and C2.2**	
ON	2,212	3,848	4,990	5,505	492	1,543
QC	2,543	4,375	5,580	6,106	497	1,559
BC	1,488	2,643	3,491	3,861	444	1,393
AB	2,948	4,973	6,451	7,062	589	1,848

Province	Annual captured CO_2 ($kgCO_2$/ year)					By-products generated in Scenario C2.1 and C2.2 (kg/year)
	Scenario C1.1	Scenario C1.2	Scenario C1.3	Scenario C1.4	Scenario C2.1 and C2.2	
MB	3,640	6,166	7,910	8,691	568	1,781
SK	3,613	6,096	7,856	8,641	577	1,810
NS	2,434	4,229	5,433	5,974	545	1,709
NB	2,706	4,688	5,985	6,570	557	1,746

Figure 4-8 shows the annual percentage reduction of operational GHG emissions (due to the thermal and electricity energy consumption of the integrated system) in Scenario C1.1 to Scenario C1.4 compared to Scenario 0. The maximum allowable CO_2 flow rates were determined by the maximum monthly averaged flow rate of CO_2 produced by the heating systems. However, the rest of the months have lower heat energy generation required for building heating. As a result, Scenario C.1.1 to Scenario C1.3, which have limited allowable CO_2 flow rates, had higher GHG emission reduction percentages when considering total GHG emissions released from natural gas combustion and generation of electricity that was consumed by the carbon capturing system.

The study included GHG emissions of electricity generation that were consumed by the carbon capturing systems, which are included when estimating the energy related to GHG emission. Therefore, the carbon capturing system has higher emission reduction potential when located in provinces that use renewable and nuclear energy, such as ON, BC, and QC, and lower emission reduction potential in provinces that use fossil for electricity generation, such as AB, SK, and NS.

Scenario C1.1 has a reduction of 33% to 37% of GHG emissions related to energy consumption, although the carbon capturing system was reduced to 25% of its maximum capacity. Scenario C1.2 and Scenario C1.3 also had reduction of 56% to 63%, and 73% to 80% of GHG emission reduction, respectively. However, Scenario C1.4, which did not have any limitations on the maximum flow rates, had a reduction of 80% to 88% GHG emissions. The lowest percentage reduction of the GHG emissions were observed in AB and the highest reduction was observed in QC.

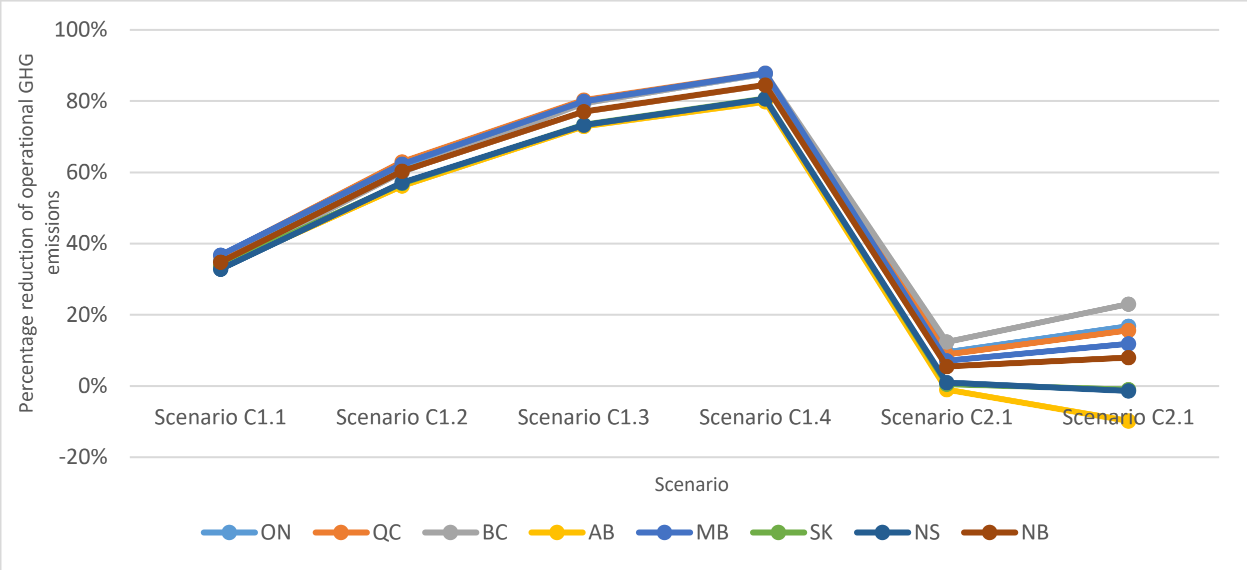

Figure 4-8: Annual percentage reduction of energy consumption related operational GHG emissions compared to Scenario 0

Although carbon capturing System C1 has a net reduction in operational GHG emissions related to energy consumption in all provinces, carbon capturing systems C2.1 and C2.2 showed an increase of GHG emissions in some provinces. Figure 4-8 shows that Scenario C2.1 has a net reduction of 1% to 12% of GHG emissions in provinces except AB, where the highest reduction of GHG emissions was observed in BC and the lowest was shown in NS and SK. AB shows an increase of 1% in GHG emissions compared to Scenario 0. Scenario C.2.2 has better performance compared to Scenario C2.1 in ON, QC, BC, MB, and NB, where the operational GHG emission reduction increased by 8% to 23% compared to Scenario 0. However, the operational GHG emissions in AB, NS, and NS increased by 1% to 10% compared to Scenario 0. This can be caused by the increase of operational electricity consumption in Scenario C2.2 compared to C2.1, which increased the operational GHG emissions significantly in the provinces that depend on fossil fuels.

Annual thermal and electric energy consumption of carbon capturing systems

Figure 4-9 shows the annual thermal energy consumption of the building heating system and carbon capturing Scenario C1.1 to Scenario C1.4. Scenario C1.1 consumed 5.3 to 12.8 GJ/year, which is an 8 to 9% increase of thermal energy compared to space heating systems. Scenario C1.2 consumed 9.3 to 21.7 GJ/year, which is a 14% to 15% increase of thermal energy compared to space heating systems. Scenario C1.3 consumed 12.3 to 27.9 GJ/year, while Scenario C1.4 consumed 13.6 to 30.7 GJ/year. Scenario C1.3 increased natural gas consumption by 19%, while Scenario C1.4 increased natural gas consumption by 21%. The results also show that the maximum energy consumption was in MB and the minimum energy consumption was in BC, which reflects the variation of thermal energy demand of the provinces. In addition, the thermal energy consumption is increased from Scenario C1.1 to Scenario C1.4 due to the increase of regeneration energy consumption that is proportional to captured CO_2.

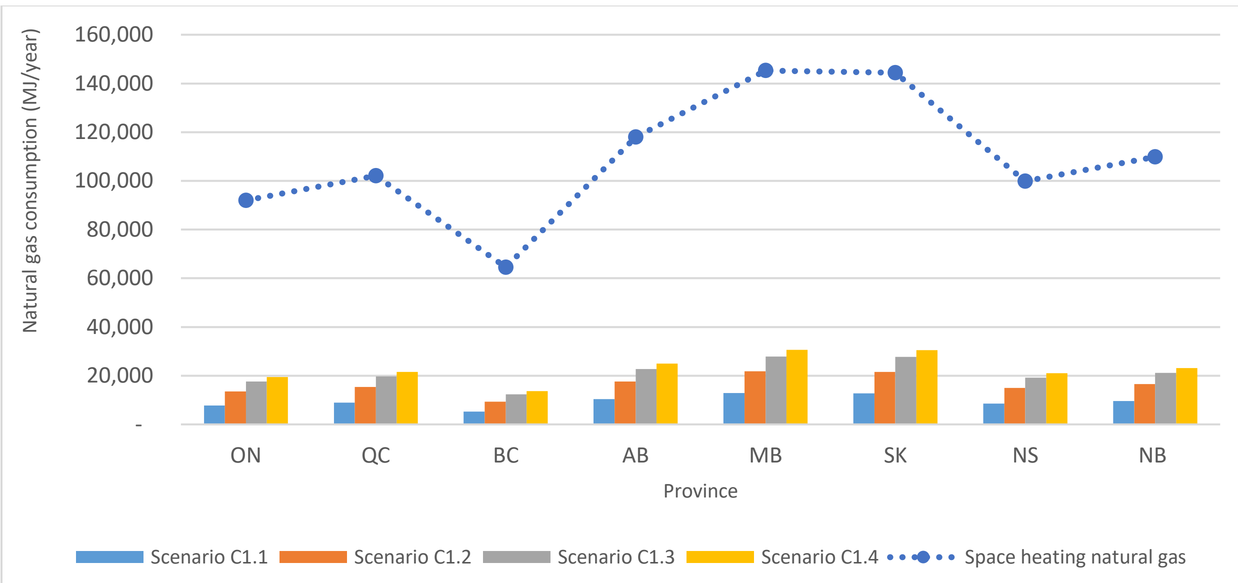

Figure 4-9: Natural gas consumption of the space heating systems and carbon capturing systems

Figure 4-10 shows the annual energy consumption of Scenario C1.1 to Scenario C1.4, Scenario C2, and the annual electricity usage for building appliances and air distribution fans (for the purpose of comparison). The electricity consumption is proportional to the captured amount of CO_2, which is increased from Scenario C1.1 to Scenario C1.4. The electricity consumption of Scenario C1.1 was 495 MJ/year to 1212 MJ/year, which was only an increase of 2% to 4% compared to the annual electricity consumption of buildings before integrating carbon capturing systems. Scenario C1.2 increased electricity consumption by 3% to 7%, while Scenario C1.3 increased it by 4% to 10%. Scenario C1.4 consumed 1286 MJ/year to 2895 MJ/year, which increases electricity consumption by 4% to 10%. The highest percentage increase of building electricity consumption was shown in MB and the lowest percentage increase was shown in BC, as a result of building energy load variations among climatic regions.

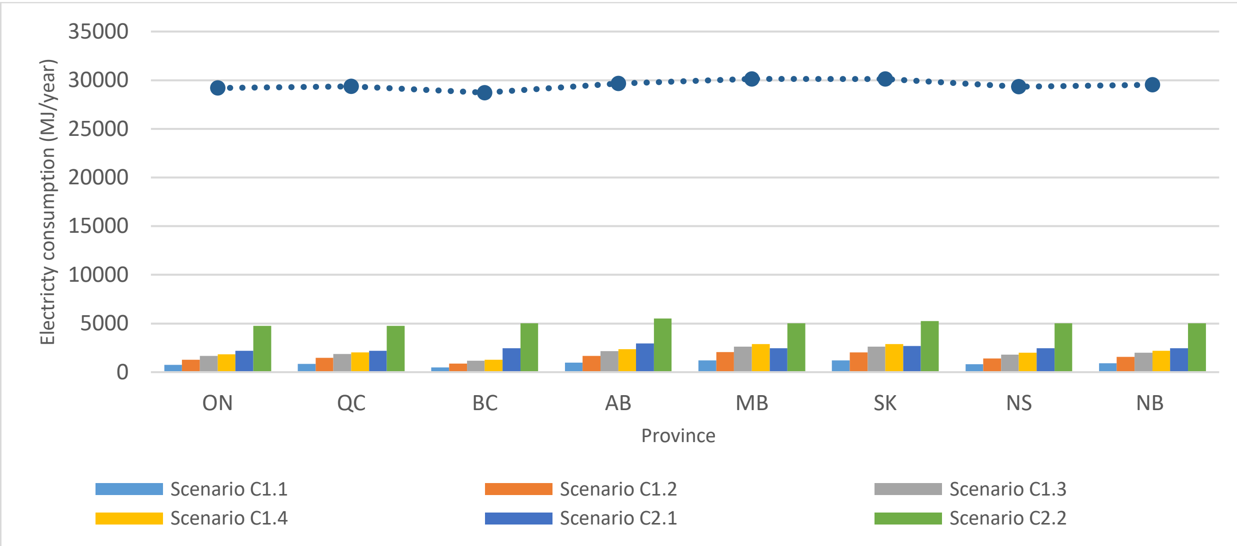

Figure 4-10: Electricity consumption of building appliances and carbon capturing systems

Electricity consumption of Scenario C2.1 was evaluated as 245.2 MJ/month by considering the operation of the agitator and fan of carbon capturing system C2.1 (the operation of the water pump was not considered as this study only focused on the carbon capturing function of System C2.1). The annual electricity consumption of Scenario C2.1 was 2206 MJ/year to 2942 MJ/year, which was an increase of 8% to 10% energy consumption. The electricity consumption of the water pump of Scenario C2.2 was estimated as 214 MJ/month, which is an increase of 87% electricity compared to Scenario C.2.1. As a result, Scenario C.2.2 increases the monthly electricity consumption of the house by 16% to 19%.

4.4 Discussion

The results revealed that the space heating system combined with the MEA-based chemical absorption carbon capturing technology reduced operational energy related GHG emissions (electricity and natural gas) by 80% to 88%, when the carbon capturing system operates at maximum capacity. The variation of GHG emissions among the provinces was caused by different energy sources used for electricity generation in different provinces. The space heating system integrated with the KOH-based commercial building-level carbon capturing system without heat recovery reduced GHG emissions by 6% to 12% in provinces that use primarily renewable and nuclear energy for electricity generation. However, there is a reduction of less than 1% or even an increase of operational GHG emissions when the systems are located in provinces that use fossil fuel to generate electricity. The KOH-based commercial building-level carbon capturing system with heat recovery system performs well in provinces that use primarily renewable and nuclear energy for electricity generation, while reducing the operational GHG emissions by 8% to 23%. However, it increases the operational GHG by 1% to 10% in provinces that depend on fossil fuel for electricity generation.

One of the assumptions made about the KOH-based commercial building-level carbon capturing system without heat recovery was that the fan and agitator operate through the month when there is need for thermal energy (see Section 4.2.2.8 on page 65 for the list of assumptions). In contrast, the electricity consumption of the MEA-based chemical absorption carbon capturing technology was proportional to the amount of captured CO_2. As a result, the electricity consumption per unit mass of captured CO_2 in the KOH-based commercial building-level carbon capturing system was higher than the MEA-based chemical absorption carbon capturing technology when the monthly amount of captured CO_2 was decreased. The effect of GHG emissions due to the electricity consumption of MEA-based chemical absorption carbon capturing technology was not considerable compared to the KOH-based commercial building-level carbon capturing system. The KOH-based commercial building-level carbon capturing system with heat recovery has additional electricity consumption for the water circulation pump that is used for heat recovery. Since the water circulation pump operates throughout the year, electricity consumption increased significantly, emitting higher GHG emissions than it saves during electricity consumption.

The water heating requirement of residential buildings is lower than in commercial and institutional buildings. As a result, the natural gas savings of the KOH-based commercial building-level carbon capturing system with heat recovery must be increased in larger buildings. It may alter the results as the electricity consumption does not change. In addition, the space heating systems generate more energy in peak winter times. In contrast to the space heating system, the water heating systems have a steady energy generation rate throughout the year. Therefore, the KOH-based commercial building-level carbon capturing system with heat recovery may perform better when it is integrated with a water heating system than the space heating system, as it consumes the same amount of energy per month. On the other hand, it was assumed that the auxiliary components in the KOH-based commercial building-level carbon capturing system operate at maximum capacity, although this assumption may be wrong if the components are overdesigned and operate below their maximum capacities. Therefore, the actual energy consumption may be less than the estimation in this study.

Four different capacities were considered in the MEA-based chemical absorption carbon capturing technology. The capacities were defined as a percentage of the maximum amount of CO_2 that can be stored in a month by assuming 90% carbon capturing efficiency. The space heating system generates a substantial amount of energy in months such as January, while the heat generation rate is relatively low in other months. Since the capacities of the carbon capturing systems were based on the month that produces the highest amount of energy, the overall GHG emission reduction percentage is higher than the percentage of the maximum capacity of the MEA-based chemical absorption carbon capturing system. This result is important when designing the carbon capturing systems as the investment cost of the system relates to the capacity (flue gas flow rates) [29].

MEA-based chemical absorption technology was considered in this study as the carbon capturing technology that separate CO_2 during the carbon capturing process. The literature review indicated that the chemical absorption method is more suitable for capturing CO_2 from low concentration combustion products compared to other separation technologies such as adsorption and membrane separation, which are used in post-combustion carbon capturing technologies. Although the MEA-based chemical absorption method is technically matured, there are other types of chemical solvents, such as Econamine and KS-1, which have higher performance than MEA-based chemical solvents. The regeneration energy consumption of these technologies is relatively lower than the regeneration energy consumption in MEA-based carbon capturing technologies. Therefore, these technologies may increase operational GHG emission reduction if incorporated at the building-scale. However, these technologies are not considered in this study due to lack of available data.

The study only considered GHG emissions related to energy consumption of the operational phase of the heating systems and carbon capturing systems. However, there are other phases in the life cycle of the process that release GHG emissions. The results show that the MEA-based chemical absorption carbon capturing technology increased natural gas consumption. GHG emissions are not only released during combustion, but also during the extraction, processing, and transportation processes. In addition, the carbon capturing process consumes raw materials. In particular, the KOH-based commercial building-level carbon capturing system consumed a significant amount of raw material as it does not regenerate the material used to capture CO_2. In addition to the GHG-related environmental impacts, the carbon capturing process may involve non-GHG-related environmental impacts. For example, the MEA-based chemical absorption carbon capturing technology releases ammonia gas during operation, which may create acidification. In contrast, the carbon capturing process also generates by-products that may have economic value, which can replace conventional production of the material. Consequently, the carbon capturing process should receive credit for reducing GHG emissions and other environmental impacts related to the conventional production of by-products that are generated by the carbon capturing process. It emphasizes the need to consider the life cycle of the carbon capturing process when evaluating the effect on GHG emissions and other environmental impacts, instead of relying on operational GHG emissions for the decision making process.

4.5 Summary

This chapter presented a strategy developed to assess the operational performance of building-level carbon capturing. The model consists of initial screening of the carbon capturing technology based on operational conditions of the building heating systems. The operational performance characteristics of the carbon capturing strategies, such as annual electricity and thermal energy consumption, carbon capturing rate, and annual by-product generation rate, were estimated using performance parameters such as carbon capturing efficiency.

The study conducted a case study that considered integrating building-level carbon capturing in 8 provinces in Canada with different climatic regions. The MEA-based chemical absorption method was considered as the carbon capturing strategy that separates CO_2. There was no evidence found that this carbon capturing technology was used in building scale. A KOH-based carbon capturing technology was considered as the carbon capturing strategy that converts CO_2 into a by-product. This technology was developed as a commercial system and consists of a heat recovery system to extract heat from the exothermic reaction and flue gas. The study conducted an experimental study to estimate the performance parameters of the above-mentioned commercial technology due to the lack of data in current literature.

The results show that carbon capturing strategies can reduce GHG emissions significantly in all provinces. Lower net operational GHG emission reduction can be seen in provinces such as AB due to the higher carbon footprint of electricity generation, which indicates that electricity consumption of the carbon capturing systems has a significant impact on performance. The rest of the operational characteristics obtained from this section will be used in Chapter 5 for the life cycle assessment and life cycle costing.

Chapter 5: Life Cycle Environmental and Economic Impacts of Carbon Capturing and Utilization on Building-level Heating Systems

This chapter presents the life cycle assessment and life cycle cost models developed to assess the environmental and economic impacts of building-level carbon capturing systems. The models are demonstrated using the case study explained in Chapter 4.

5.1 Background

The carbon capturing process is involved with many other processes that can increase the environmental impacts significantly. In particular, carbon capturing technologies such as chemical absorption require raw materials for operation, while emitting chemicals such as formaldehyde and MEA to the atmosphere. In addition, carbon capturing systems consume a significant amount of energy (thermal and electric) during the operational phase. Since these processes involve different activities that cause environmental impacts, it is necessary to study the carbon capturing process considering the life cycle of the process, including all the processes that are required.

Life cycle assessment (LCA) is a standardized procedure to evaluate the environmental impacts of a process or a product by considering various phases in the life cycle, from raw material extraction to demolition. The technique is governed by the principles developed in ISO 14040. The LCA procedure is used in many studies related to CCSU and is conducted by following 4 main steps: goal and scope definition, life cycle inventory development, life cycle impact assessment, and interpretation. The life cycle impacts generated from the life cycle assessment study are used in various studies for sustainable decision making.

In addition to that, the carbon capturing process increases the capital and operational cost of energy systems significantly. The operational cost increases due to an increase in energy consumption, raw material consumption, and maintenance cost. Therefore, considering all the cost and revenue generated through the process would provide the economic impacts of the process in a holistic manner. Life cycle costing is a technique that is used to include all aspects of economic flows of a process. It is defined as the sum of all costs incurred by a system or an item during its life span. The LCC methodology is widely used in assessing economic impacts of energy systems and carbon capturing systems.

To investigate the environmental and economic impacts of implementing carbon capturing at the building scale, the study developed LCA and LCC models. The key objective of this section is to present the models using the case study conducted in Chapter 4.

5.2 Methods and Procedure

The study aimed to investigate the life cycle environmental and economic impacts of integrating carbon capturing on residential building space heating systems and water heating systems. In order to include regional variability in the study, buildings are assumed to be located in major cities in eight different provinces: Ottawa in Ontario (ON), Montreal in Quebec (QC), Vancouver in British Columbia (BC), Calgary in Alberta (AB), Winnipeg in Manitoba (MB), Saskatoon in Saskatchewan (SK), Halifax in Nova Scotia (NS), and Moncton in New Brunswick (NB). This section used carbon capturing scenarios and characteristics obtained from the model introduced in Chapter 4. The main characteristics used in this chapter are annual captured CO_2, annual production of by-products, and annual thermal energy and electricity consumption of all scenarios. The overall methodology used in this study is shown in Figure 5-1. The subsequent sections explain the methods and procedure followed in this chapter.

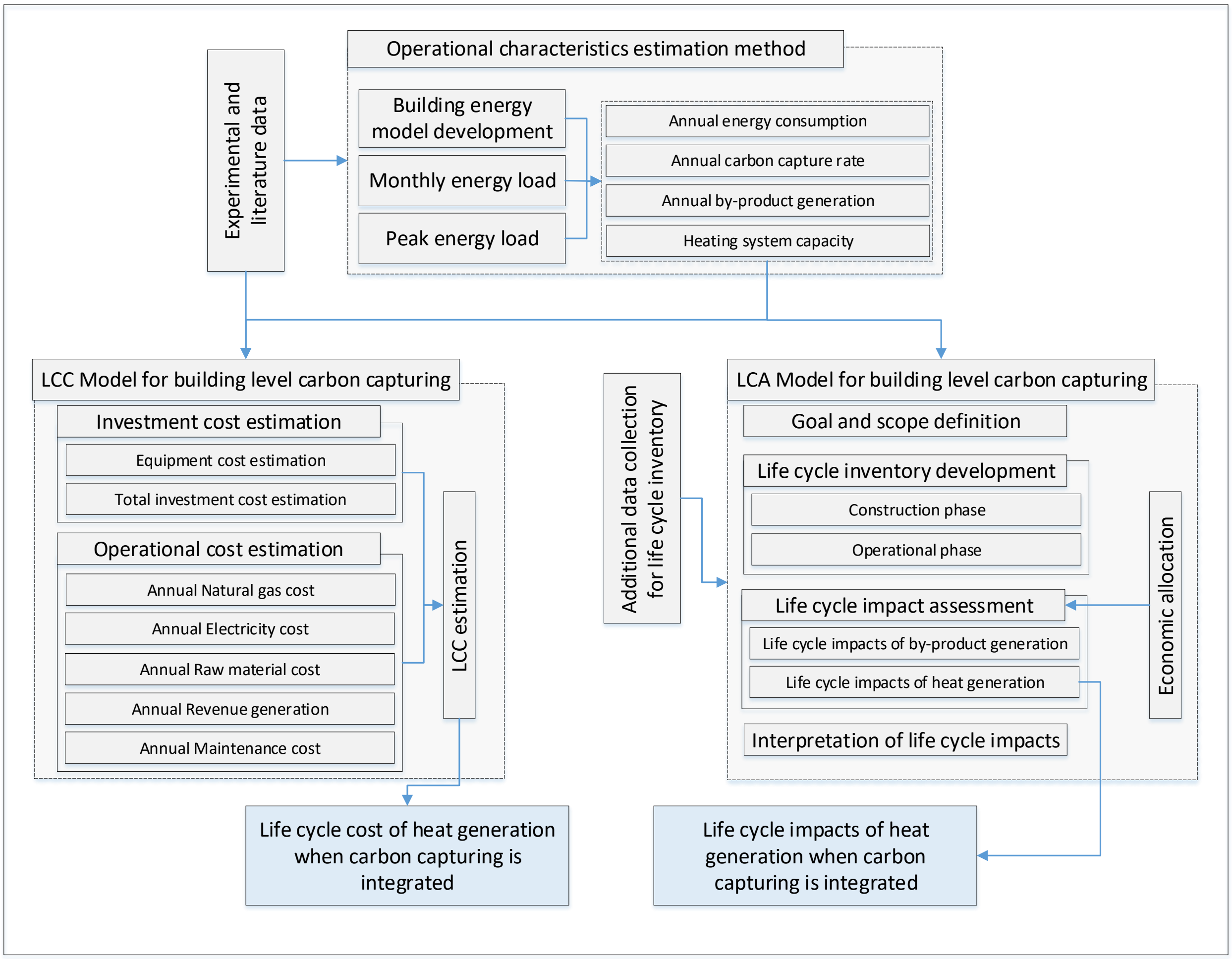

Figure 5-1: Overall methodology for life cycle performance assessment

5.2.1 Life cycle assessment

The life cycle assessment was conducted using the framework provided by ISO 14040 [44]. This study considered cradle-to-gate life cycle of all the heating systems including the carbon capturing systems, which comprises raw material extraction (Cradle), construction of the system, raw material transportation, operational energy consumption and emissions, and transportation of the by-products to a utilization facility (Gate). The following subsections explain those main steps.

5.2.1.1 Goal and scope definition

The goal of the life cycle assessment phase of this study was to evaluate the life cycle environmental impacts of integrating carbon capturing systems at building-level natural gas heating systems. The study considered a residential natural gas space heating system. The functional unit was defined as the annual space heating thermal energy requirement of the relevant building. Since the study considered regional variance, the functional unit was different for each province considered in the study. The functional units of each scenario that were obtained from Chapter 4 are given in Table 5-1 below.

Table 5-1: Annual thermal energy requirement of buildings

Province	***City***	***Annual thermal energy requirement (MJ/ year)***
ON	Ottawa	92029
QC	Montreal	102068
BC	Vancouver	64540
AB	Calgary	118052
MB	Winnipeg	145276
SK	Saskatoon	144444
NS	Halifax	99864
NB	Moncton	109821

The study considered the 7 scenarios shown in Table 5-2 that were also introduced in Chapter 4. Scenario 0 was the base scenario that consists of a conventional natural gas residential building space heating system. Scenario C1.1 to Scenario C1.4 consist of integrating an MEA-based chemical absorption carbon capturing system into the above mentioned natural gas heating system. Scenario C1.4 has the maximum CO_2 storage capacity, while Scenario C1.1, Scenario C1.2, and Scenario C1.3 have storage capacities of 25%, 50%, and 75% of the maximum CO_2 storage capacity, respectively. Scenario C2.1 consists of integrating a KOH-based commercial building-level carbon capturing system without heat recovery system. Scenario C2.2 consists of integrating a KOH-based commercial building-level carbon capturing system with heat recovery system. A summary of the scenarios is shown in Table 5-2.

Table 5-2: Description of the scenarios

Scenarios	***Building heating system type***
Scenario 0	Residential space heating system that is equipped with a natural gas condense furnace.
Scenario C1.1	Residential space heating system that is equipped with a natural gas condense furnace and System C1 (90% carbon capturing efficiency) that has 25% of the maximum carbon capture capacity.
Scenario C1.2	Residential space heating system that is equipped with a natural gas condense furnace and System C1 (90% carbon capturing efficiency) that has 50% of the maximum carbon capture capacity.
Scenario C1.3	Residential space heating system that is equipped with a natural gas condense furnace and System C1 (90% carbon capturing efficiency) that has 75% of the maximum carbon capture capacity.
Scenario C1.4	Residential space heating system that is equipped with a natural gas condense furnace and System C1 (90% carbon capturing efficiency) that has the maximum carbon capture capacity.
Scenario C2.1	Residential space heating system that is equipped with a natural gas condense furnace and System C2 (13% carbon capturing efficiency without heat recovery) that has maximum KOH capacity of 200 kg.
Scenario C2.2	Residential space heating system that is equipped with a natural gas condense furnace and System C2 (13% carbon capturing efficiency with heat recovery) that has maximum KOH capacity of 200 kg.

System boundary

The study considered the manufacturing and operational phases of building heating systems, including carbon capturing systems, which is a cradle-to-gate system boundary. The manufacturing phase comprises raw material extraction, and energy consumption by the manufacturing of the heating systems and carbon capturing systems. The operational phase of the heating system includes the energy necessary for generating the required thermal energy. The operational phase of Scenario C1.1 to C1.4 involves production of chemical solvents, production of natural gas for the regeneration thermal energy requirement, and generating electricity for the auxiliary equipment, compression, and liquefaction of captured CO_2. The operational phase of Scenario C2.1 involves production of KOH that is consumed during operation, reduction (avoidance) of CO_2 by the capturing process, and electricity consumption by the auxiliary equipment. Furthermore, the study considered transportation of the required chemicals, generated CO_2, and by-products. Scenario C2.2 consists of the heat recovery system. Although the recovered heat can only be transferred into the domestic hot water system, the recovered natural gas and emissions were attributed to the heating system that is integrated with the carbon capturing system. Figure 5-2 shows the system boundary used in Scenario C1.1 to Scenario C1.4. Figure 5-3 shows the system boundary of Scenario C2.1, and Figure 5-4 shows the system boundary of Scenario C2.2.

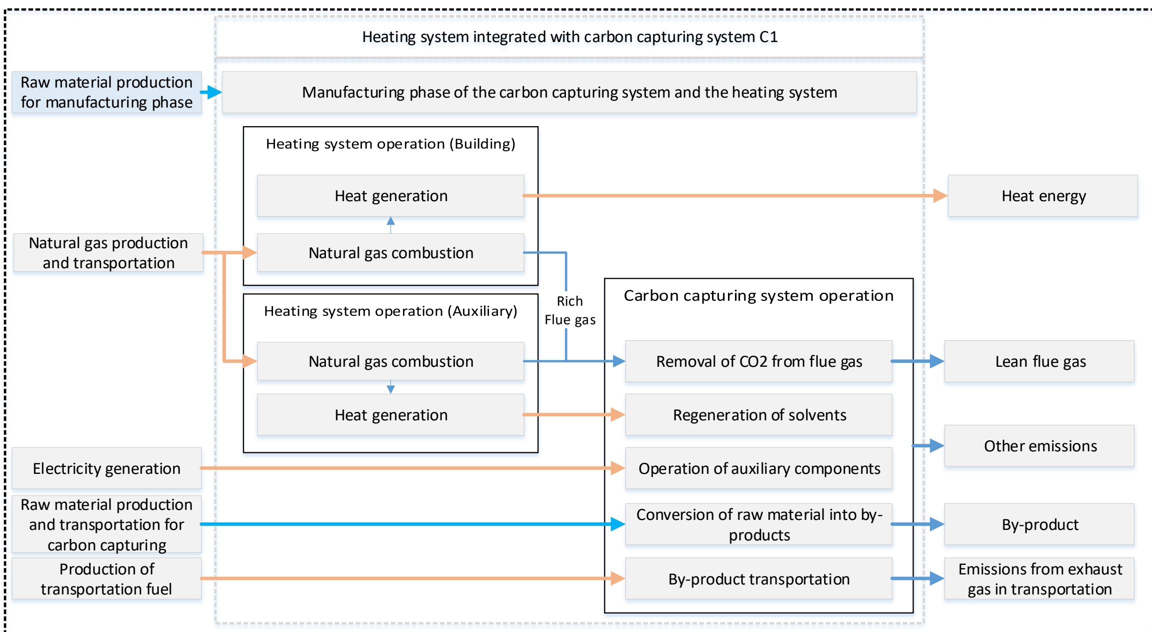

Figure 5-2: The system boundary used in Scenario C1.1 to Scenario C1.4

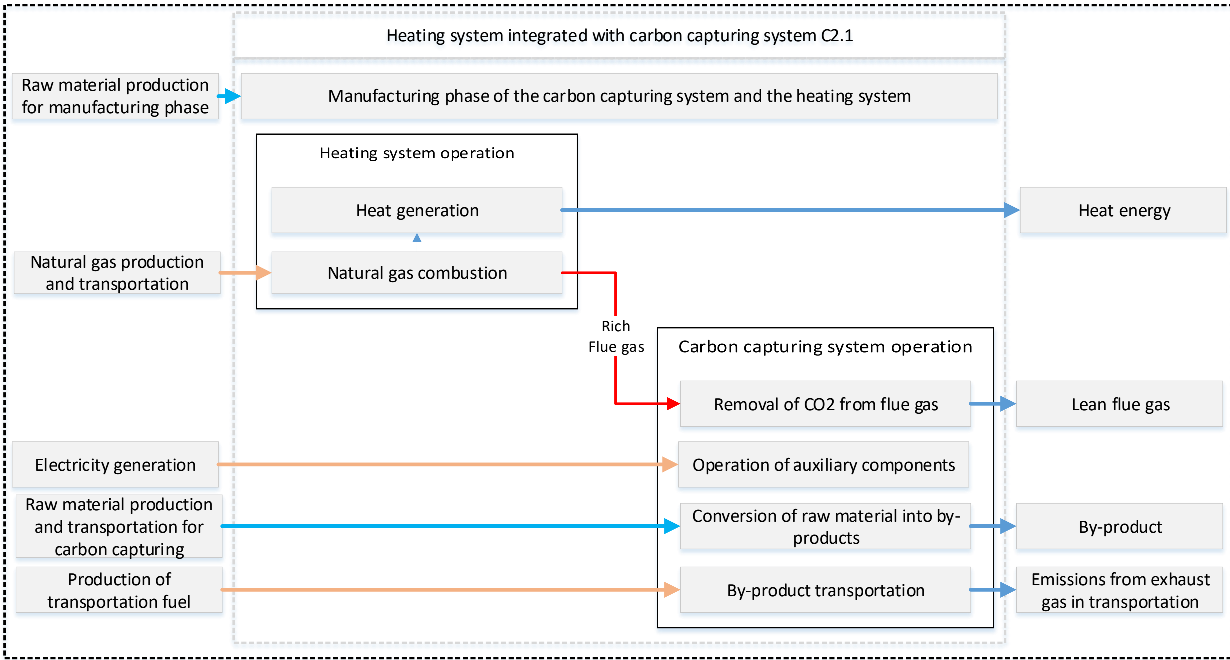

Figure 5-3: The system boundary used in Scenario C2.1

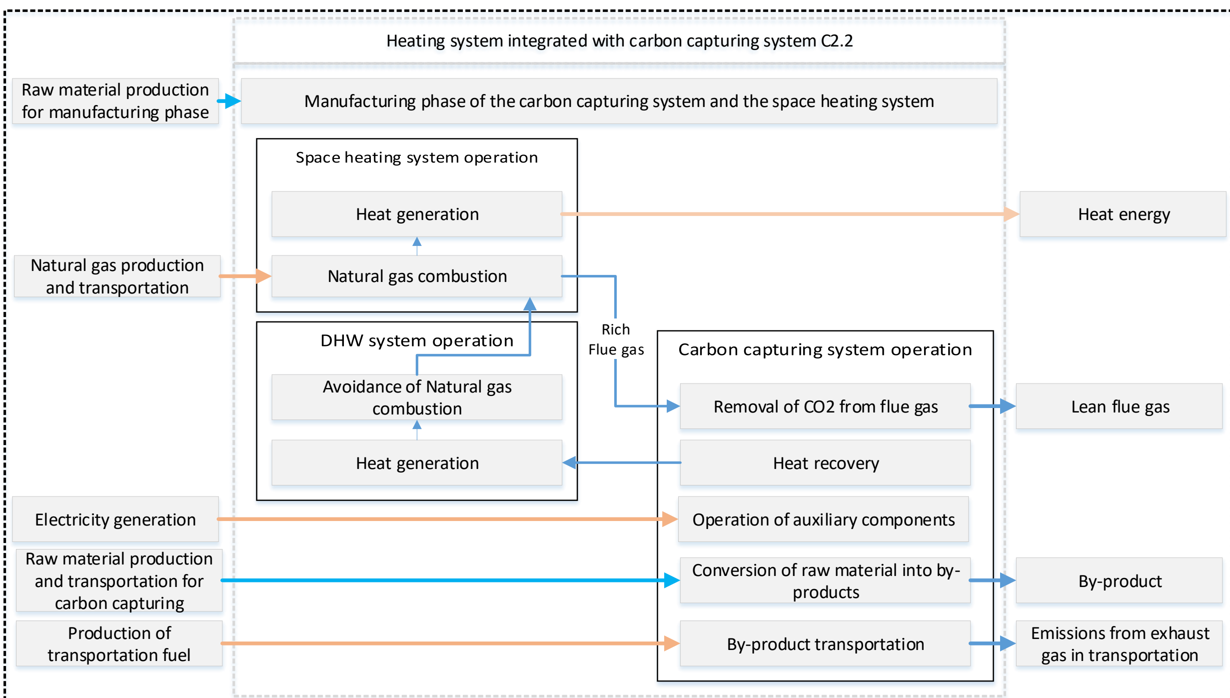

Figure 5-4: The system boundary used in Scenario C2.2

Economic allocation

When the heating system is combined with the carbon capturing system, the combined system generates by-products. The main functions of the combined system are generating heat for building heat and generating by-products. Therefore, the product system must be studied as a multi-functional system. However, the study required the impacts related to heat generation to understand the actual environmental impacts of implementing carbon capturing on the building heat generation process. The CO_2 generated by carbon System C1 and the K_2CO_3 generated by carbon System C2 have commercial value. In addition, the economic value of the heat generation can also be derived from natural gas prices. Therefore, the economic allocation method was used to find the environmental impacts of heat generation in all scenarios that were involved with carbon capturing.

Table 5-3 shows the average natural gas prices. Since the economic value of the heat was considered in this study, the carbon tax was not included when evaluating the economic value of the heat. The economic value of CO_2 was considered as USD 36/ tCO_2, which is the selling price of CO_2 in the Enhanced Oil Recovery industry [96]. The economic value of the K_2CO_3 was given by the manufacturer of carbon capturing system C2 as CAD 1700 per ton of K_2CO_3.

Table 5-3: Energy costs in Canadian provinces [120] [121]

Province	***Average monthly residential Natural gas Cost (CAD – for consumption of 7.37GJ)***			
	Commodity	**Carbon tax**	**Variable**	**Fixed**
Ontario	21	7	34	20
Quebec	24	7	73	33
British Columbia	11	11	38	32
Alberta	14	11	13	32
Manitoba	16	0	34	20

Province	**Average monthly residential Natural gas Cost (CAD – for consumption of 7.37GJ)**			
	Commodity	**Carbon tax**	**Variable**	**Fixed**
Saskatchewan	27	0	18	23
Nova Scotia	69	0	64	22
New Brunswick	66	0	72	18

The environmental impacts were allocated by evaluating the economic partitioning factor using Equation 5-1 below [122].

$$P_i = \frac{n_i . x_i}{\sum_{i=1}^{n} n_i . x_i} \qquad \text{---------------------} \quad \text{Equation 5-1}$$

Where,

P_i = Partitioning factor of the i^{th} co-product

n_i = Quantity of the i^{th} co-product

x_i = Economic value of the products

5.2.1.2 Life cycle inventory development

The life cycle inventory consists of the construction of the carbon capturing systems and heating systems, operational phase of the system, and the transportation of CO_2 and by-products. The operational phase includes energy required for operation of the system, extraction of the raw materials required for operation, and emissions from the product systems. The construction data of the chemical absorption system (Scenario C1.1 to Scenario C2.2) and the heating systems were derived from literature and the Econinvent 3 LCA database. The construction data of System C2 (Scenario C2.1 and Scenario C2.2) was obtained from the manufacturer of commercial systems. The energy requirement of the building heating systems was estimated using building energy modeling. The thermal and electrical energy requirements for operation of the carbon capturing systems were estimated from manufacturer data and literature data. The life cycle inventory of extraction of raw material, emissions, and energy generation was developed using the Ecoinvent 3 LCA database. The subsequent sections describe the development of the life cycle inventory.

Construction phase of the carbon capturing systems

Life cycle inventory for the construction phase of System C1 was based on the literature data on large scale systems. It is assumed that the material quantity is directly proportional to the flue gas flow rate and solvent flow rate as shown in Table 5-4. The reference flows are derived from the IECM software package [29]. The reference flows were used to estimate the capital cost of the carbon capturing technologies. The operational period of the carbon capturing systems and the heating systems was considered as 20 years, which is the life time of heating systems such as heat pumps [123]. Therefore, the manufacturing data accounted for a year in each scenario.

Table 5-4: Life cycle inventory data for the manufacturing phase of the carbon capturing system [35]

Equipment	***Material***	***Amount (kg)***	***Reference flow***	***Reference flow value (kmol/h)***
Absorber	Stainless steel	345422	Flue gas flow rate	113381
Stripper	Stainless steel	174959	MEA flow rate	19400
Amine storage tank	HLPE	5760	MEA flow rate	19400
Amine make-up tank	HLPE	177	MEA flow rate	19400
NaOH storage tank	HLPE	1920	MEA flow rate	19400
Piping and other equipment	Stainless steel	82000	MEA flow rate	19400

The LCI of the System C2 construction phase consists of the material required to manufacture the system. The material requirement was derived from engineering drawings of the commercial building carbon capturing system and is shown in Table 5-5.

Table 5-5: LCI of manufacturing phase of System C2

Component	***Number of components***	***Material***	***Quantity per component (m^2)***	***Total (m^2)***
Front and rear panel	2	10 gauge steel	1.26	2.53
Support rib	2	10 gauge steel	0.68	1.35

Component	Number of components	Material	Quantity per component (m^2)	Total (m^2)
Top panel	1	16 gauge steel	1.48	1.48
Front panel	1	16 gauge steel	1.57	1.57
Reaction chamber	1	16 gauge steel (304)	0.45	0.45
Spar	24	10 gauge steel	0.05	1.12
Side panel	4	16 gauge steel	1.23	4.90
Reaction chamber access	1	10 gauge steel (304)	0.30	0.30

Operational phase of the carbon capturing systems

The life cycle inventory for the operational phase of the carbon capturing system C1 consists of electricity and thermal energy consumption, chemical emissions to the air, chemicals consumed during the operation of the system, transportation of raw material, and transportation of the captured CO_2. The electricity and thermal energy requirements were determined by the characterization estimation model described in Chapter 4. The chemicals and energy consumed during the carbon capturing process of System C1 and the emissions are shown in Table 5-6 below [35].

Table 5-6: Life cycle inventory data for the operational phase of the carbon capturing system [35]

Chemicals consumed during operation of the system	
Chemical	*Amount (kg/tCO_2)*
Activated carbon	0.075
NaOH	0.13
MEA	1.5
Chemical emissions to the air	
Chemical	***Amount (kg/ tCO_2)***

Chemical	*Amount (kg/ tCO_2)*
MEA	0.063
NH_3	0.035
Formaldehyde	0.262×10^{-3}
Acetaldehyde	0.167×10^{-3}
Energy consumption	
Energy component	**Amount ($MJ_{thermal}$/$kgCO_2$ or $MJ_{Electricity}$/$kgCO_2$)**
Energy consumption for the regeneration	3.53
Energy consumption for auxiliary components	0.0434
Energy consumption for Compression and liquefaction	0.29

The study used global default transportation statistical data on basic chemicals in the Ecoinvent 3 library [124][125][126] to estimate the transportation data of the material. These statistics are based on commodity flow surveys from the United States Department of Transportation. The details of the transportation data are shown in Table 5-7. It was assumed that the captured CO_2 is transported to a facility that uses CO_2 as a feedstock. The transportation distance was 50 km and a CO_2 tanker was used to transport the CO_2.

Table 5-7: Global average transportation data (Based on commodity flows in USA – adopted from Ecoinvent LCA library)

Transport medium	*Average shipping distance*	*Share of mass*
Truck	285 km	73%
Rail	426 km	21%
Marine	5337 km	11%

The operational phase of carbon capturing system C2 consists of electricity consumption, chemicals consumed during operation of the system, transportation of raw material, and transportation of generated by-products (K_2CO3). The electricity consumption, chemicals consumed from the carbon capturing system, and the amount of generated by-products were evaluated from the characterization estimation model described in Chapter 4.

The Canadian importers database indicates that KOH is mainly imported from the USA [127]. The main KOH importers in Canada are located in Toronto, Montreal, and Edmonton. Although the information on major importers in Canada is available, the exact locations of the KOH exporters and transportation mediums are not available. Therefore the study used global default transportation statistics data on basic chemicals in the Ecoinvent 3 library [124][125][126], as shown in Table 5-7, to estimate the transportation medium and distances from manufacturers in the US to importers in Canada. In addition, it was assumed that KOH is transported to cities where the buildings are located close to the nearest importer in Canada. The distances were calculated using the "Google Map" online map interface and are shown in Table 5-8. In addition, it was assumed that KOH is transported from the importers to the city using a 16-32 ton truck.

Table 5-8: KOH transportation distances

Province	***City***	***Distance from Toronto***	***Distance from Montreal***	***Distance from Edmonton***	***Minimum distance***	***The city of the importer***
ON	Ottawa	451	983	3456	451	Toronto
QC	Montreal	540	0	3583	0	Montreal
BC	Vancouver	4206	4557	1160	1160	Edmonton
AB	Calgary	3238	3527	300	300	Edmonton
MB	Winnipeg	2055	2269	1305	1305	Edmonton
SK	Saskatoon	2781	3059	525	525	Edmonton
NS	Halifax	1783	1242	4814	1242	Montreal
NB	Moncton	1523	983	4554	983	Montreal

5.2.1.3 Life cycle impact assessment

Since the case study considered the application of carbon capturing systems in Canadian provinces, impact assessment methods based on US and Canada databases are most suitable. Therefore, the study considered TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) version 2.1 as the life cycle assessment method [128]. The method was incorporated with normalization factors of average impact per year and impact per person per year [129] in US and Canadian regions. The TRACI 2.1 impact assessment method consists of 10 impact categories. The overview of the impact categories is shown in Table 5-9 below.

Table 5-9: Overview of the life cycle impact categories

Impact category	***Overview***
Ozone depletion *(kg CFC-11 eq)*	Ozone depletion is related to the increase of UVB radiation caused by ozone depletion due to the Ozone Depleting Substances. The characterization factor used for Stratospheric ozone depletion is known as Ozone Depleting Potential. The Ozone Depleting Potential of a substance is expressed by the equivalent amount of CFC11 in the given time frame.
Global warming *(kg CO2 eq)*	The global warming impact is related to the increase of global mean temperature caused by GHGs. The indicator used to measure global warming is the increase of infra-red radiative forcing. Global warming potential of a substance is expressed by the equivalent amount of CO_2 in the given time frame.
Smog *(kg O3 eq)*	Photochemical reactions of NOx and non-methane volatile organic compounds form ozone in the atmosphere. Ozone formation is expressed as an equivalent amount of ozone (O3).
Acidification *(kg SO2 eq)*	Acidification is caused by the addition of acids such as hydrochloric and sulphuric, or substances such as ammonia that increase the acidity in the environment. The substances can damage building materials, rivers, and eco-systems. The acidification potential of a substance/emission is expressed by the equivalent amount of SO_2 emissions.
Eutrophication *(kg N eq)*	Eutrophication is related to the rise of nutrition of freshwater bodies caused by discharge of nutrients such as nitrogen (N). The eutrophication potential of a substance/emission is expressed by the equivalent amount of N.

Impact category	**Overview**
Carcinogenics (CTUh)	The carcinogenics impact category refers to human health cancer potential caused by urban air emissions. The carcinogenics potential is measured using Comparative Toxicity Unit (CTU).
Non-carcinogenics (CTUh)	The non-carcinogenics impact category refers to human non-cancer potential caused by urban air emissions. The non-carcinogenics potential is measured using Comparative Toxicity Unit (CTU).
Respiratory effects (kg PM2.5 eq)	The respiratory effects impact category is related to primary and secondary aerosols in the atmosphere formed by air pollution. The particulate matter formation potential of a substance/emission is expressed by the equivalent particulate matter with a diameter less than 2.5 µm in the given time frame.
a Ecotoxicity (CTUe)	Toxicity accounts for the damage to the ecosystem and human health caused by the persistence and toxicity of a chemical. The ecotoxicity potential is measured using Comparative Toxicity Unit (CTU)
Fossil fuel depletion (MJ surplus)	Fossil fuel depletion refers to the potential of reducing the availability of fossil fuel supplies. It is measured using the equivalent fossil fuel energy use of the process.

5.2.2 Life cycle costing

The system boundary of the life cycle costing consists of the capital cost of the equipment and 20 years of the operational phase of the heating system. The life cycle cost of the systems are calculated using Equation 5-2, which is derived using the LCC formula of building energy and water conservation projects presented in the life-cycle costing manual for the federal energy management program [24].

$$LCC = AQC - RES + FC + RM + OM - \mathrm{RG} \qquad \text{---- Equation 5-2}$$

Where,

LCC is life cycle cost of the heating system

AQC is present value of the acquisition cost of the system

FC is present value of the total fuel cost. (Annual fuel cost is replaced by annual operational cost in carbon capturing scenario)

RES is present value of residual value of the system

OM is present value of maintenance cost

RG is the revenue generated by selling by-products

5.2.2.1 Capital cost estimation

The study used the order-of-magnitude method, which is also known as the viola method [30] to estimate the equipment cost of the carbon capturing system. This method is widely used in preliminary estimations of capital costs in the chemical industry. The estimation of capital cost is calculated using Equation 5-3 [29].

$$C_{eq} = C_{eq,ref} \times \left[\frac{Ca_{eq}}{Ca_{eq,ref}}\right]^{n} \quad \text{--------------------- Equation 5-3}$$

Where,

C_{eq} is the cost of the equipment

$C_{eq,ref}$ is the cost of the reference equipment

Ca_{eq} is the capacity of the equipment

$Ca_{eq,ref}$ is the capacity of the reference equipment

n is the exponent (0.5 – 1.0)

The exponent is considered as 0.6, which is widely used in chemical engineering equipment costing [30]. The reference flow that represents the capacity of the equipment differs according to the type of process. The reference flows used to calculate the equipment cost are shown in Table 5-10 [29]. It was assumed that the liquid to gas ratio of System C1 (solvent rate l/s / flue gas rate m^3/s) is 2, CO_2 concentration of flue gas is 10%, flue gas temperature is 50 °C, and the flue gas pressure is 1 atm when calculating exhaust gas flow rate and solvent gas flow rate. The maximum CO_2 flow rate that enters through the carbon capturing system (in Scenario C1.4) was calculated using the capacities of the heating systems and natural gas emission factor. The carbon capturing systems in Scenario C1.1, Scenario C1.2, and Scenario C1.3 do not need the maximum CO_2 flow rate used in Scenario C1.4, as these systems have limited CO_2 flow rates. Therefore, it was assumed that the maximum CO_2 flow rates in Scenarios C1.1, Scenario C1.2, and Scenario C1.3 were 25%, 50%, and 75% of the maximum CO_2 flow rates of Scenario C1.4.

Table 5-10: Reference equipment costs of the carbon capturing systems [29]

Equipment	*Reference flow type*	*Equipment cost*	*Unit*
Absorber	Exhaust gas flow rate	5.038	Millions of Euro - 2014
Regenerator	Solvent flow rate	2.514	Millions of Euro - 2014
Exhaust fan	Exhaust gas flow rate	0.748	Millions of Euro - 2014
Rich Amine pump	Solvent flow rate	0.235	Millions of Euro - 2014
Lean/Rich Heat exchanger	Solvent flow rate	1.558	Millions of Euro - 2014
Lean amine cooler	Solvent flow rate	0.248	Millions of Euro - 2014
Reflux condenser	Solvent flow rate	0.413	Millions of Euro - 2014
Stripper reboiler	Solvent flow rate	1.832	Millions of Euro - 2014
Lean amine pump	Solvent flow rate	0.711	Millions of Euro - 2014
Compressor and refrigerator	CO_2 flow rate	6.07	Millions of Euro - 2016

The equipment costs of past years are converted to 2018 using the Chemical Engineers Plant Cost Index [130] and Equation 5-4 [131].

$$Cost_A = Cost_B \times \left[\frac{CI_A}{CI_B}\right] \qquad \text{---------------------} \quad \text{Equation 5-4}$$

Where,

$Cost_A$ is the cost of the equipment in year A.

$Cost_B$ is the cost of the equipment in year B.

CI_A is the cost index in year A. (CEPCI in 2018 is 603.1)

CI_B is the cost index in year B. (CEPCI in 2016 is 541.8 and CEPCI in 2014 is 556.8)

After calculating the process equipment cost, the total capital cost was calculated using Table 5-11 [132]. The capital costs of the building heating systems are estimated using RsMeans building cost data.

Table 5-11: Capital cost parameters [132]

Parameter	***Value***
Process equipment cost	Total cost of the equipment
General cost	30% of the process equipment cost
Total equipment cost	Sum of the process equipment cost and general cost
Instrumentation	15% of the total equipment cost
Electrical	7% of the total equipment cost
Piping	20% of the total equipment cost
Total installed cost	The sum of total equipment cost, instrumentation cost, electrical cost, and piping cost

5.2.2.2 Operational cost estimation

The operational cost consists of electricity cost, natural gas cost, maintenance cost, and the revenue generated by selling the by-products. Electricity cost is estimated using the average electricity bill in residential houses in Canadian provinces using the data provided in Table 5-3 [120] [121].

Table 5-12: Energy costs in Canadian provinces [120] [121]

Province	***Electricity cost (CAD/ MJ)***
Ontario	*0.04*
Quebec	*0.02*
British Columbia	*0.03*
Alberta	*0.04*

Province	**Electricity cost (CAD/ MJ)**
Manitoba	*0.03*
Saskatchewan	*0.05*
Nova Scotia	*0.05*
New Brunswick	*0.04*

The cost of KOH is given by the manufacturer of carbon capturing system C2, which is 1.4 CAD/ kg. The cost of the rest of the material is taken from IECM software [28], [133]. The cost of activated carbon is 2193 $/ton, sodium hydroxide (NaOH) is 452.9 $/ton, and MEA is 2349 $/ton. The annual cost of maintenance including labour and material was considered as 2.5% of the total capital cost.

5.2.2.3 Summary of assumptions

Table 5-13 shows a summary of the assumptions made for the analysis in LCA and LCC.

Table 5-13: Summary of the assumptions in Chapter 5

Section	*Assumptions*
LCA – Goal and scope definition	– The cities have adequate demand for the generated by-products. – The natural gas savings from the heat recovery process in System C2.2 is attributed to the heating system that is combined with the carbon capturing system. – The lowest selling price of the K_2CO_3 represents its economic value. – The economic value of the captured CO_2 is represented by the selling price of the CO_2 in the Enhanced Oil Recovery industry. – The economic value of heat energy is represented by the cost of natural gas.

Section	Assumptions
LCA – Inventory development	– The maximum CO_2 flow rates through System C1 are proportional to the CO_2 storage capacity. – The by-products (CO_2 or K_2CO_3) are transported to a utilization facility at a distance of 50 km. – Transportation distances and mediums based on USA commodity flows were considered when actual distances are unknown. – The material requirement for the construction of equipment of System C1 is proportional to the reference flows mentioned in Table 5-4. – The raw material in the operational phase of System C1 is extracted according to the global average data. – The raw material in the operational phase of System C2 is manufactured in the US.
LCC – Capital cost estimation	– The equipment cost of System C1 follows the order of magnitude equation, where the exponent is 0.6. – Capital cost components such as electrical cost, instrumentation cost, and the general cost in System C1 are a fixed percentage of the equipment cost as indicated in Table 5-11.
LCC – Operational cost estimation	– The annual maintenance cost of System C1 is a fixed percentage of the capital cost.

5.3 Results

This section presents the LCC and LCA results obtained in the study.

5.3.1 LCA results for integrating carbon capturing into space heating systems

The contribution of each phase of the process, such as raw material extraction, construction of the carbon capturing system, heating system, and by-product transportation, to the relevant impacts are presented by considering Scenario C1.4, Scenario C2.1, and Scenario C2.2. The life cycle impacts of all the scenarios are presented as normalized and allocated between heat generation and by-products.

5.3.1.1 Ozone depletion

Figure 5-5 shows the ozone depletion of Scenario 0, Scenario C1.4, Scenario C2.1 and Scenario C2.2. Integrating System C1 and C2 on the space heating systems shows an increase in ozone depletion without considering allocation.

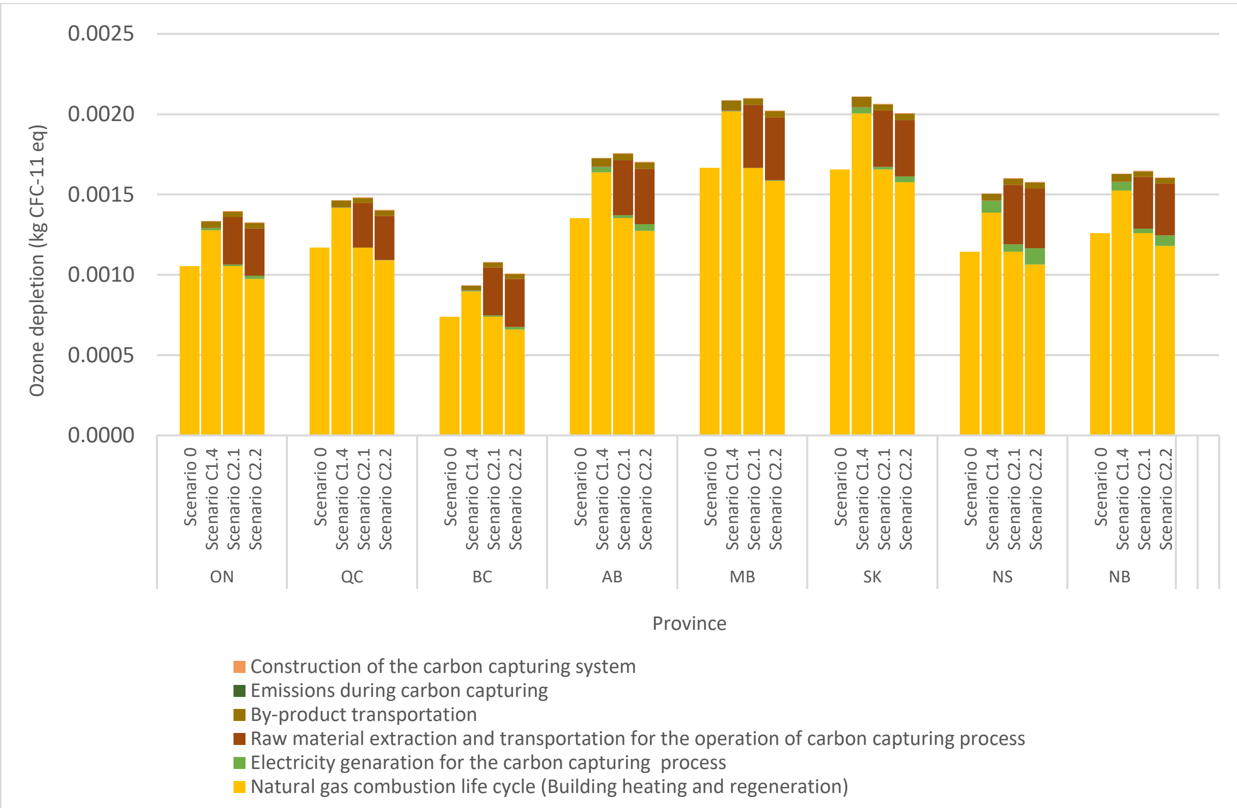

Figure 5-5: Contribution of process phases to life cycle ozone depletion

Figure 5-5 clearly shows that the natural gas combustion life cycle contributes substantially to ozone depletion. The reason is that natural gas consists of methane, which has a high ozone depletion potential [134]. Figure 5-5 indicates that the life cycle of natural gas combustion contributed 92% to 97% of the ozone depletion in Scenario C1.4, 69% to 80% of ozone depletion in Scenario C2.1, and 65% to 79% in Scenario C2.2. The raw material extraction phase of Scenario C2.1 contributed 17% to 28% and Scenario C2.2 contributed 17% to 30%. This can be a result of natural gas combustion that was used to supply thermal energy during KOH production. The by-product transportation phase of Scenario C1.4 contributed 3% of the total ozone depletion. It may be the refrigeration gases used in production of refrigeration systems when transporting liquefied

CO_2 [135]. The by-product transportation process of Scenario C2.1 and Scenario C2.2 has negligible impact on ozone depletion. Electricity generation contributed to ozone depletion by 1% to 6%, where the highest contribution was observed in NS. Construction of the carbon capturing systems and emissions during the carbon capturing processes had negligible contribution to ozone depletion.

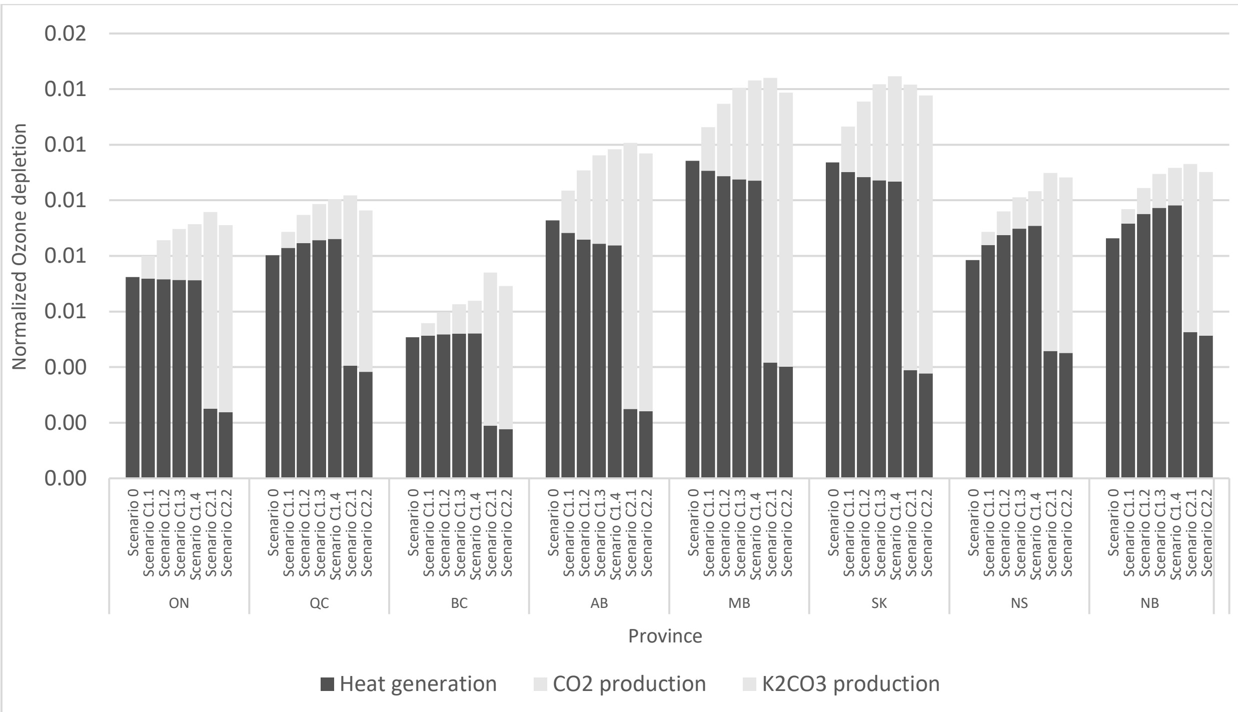

Figure 5-6: Normalized life cycle ozone depletion with economic allocation

Figure 5-6 shows the allocation of ozone depletion impact between heat generation and by-products of all scenarios using economic allocation. The heat generation process from Scenario C1.1 to C1.4 had no considerable effect on ozone depletion in ON and BC. The house located in Vancouver-BC had the lowest Ozone depletion due to the lower energy consumption. A reduced ozone depletion trend in heat generation can be seen in AB, MB, and SK, from Scenario C1.1 to C1.4, ranging from 3% to 10%. AB, MB, and SK had significant requirements of thermal energy and increased the yield of CO_2, thus increasing the fraction of environmental impacts from CO_2 production. However, QC, NS, and NB had an increasing trend in heat generation from Scenario C1.1 to C1.4. The ozone depletion of the heat generation process in Scenario C2.1 was decreased by 39% to 73%, and in Scenario C2.2 it decreased by 44% to 73%, with AB showing the highest reduction in ozone depletion.

5.3.1.2 Global warming

Figure 5-7 shows how the process phases of the heating system scenarios contributed to global warming. Scenario C1.4 reduced global warming by 40% to 54%, Scenario C2.1 increased global warming by 27% to 45%, and Scenario C2.2 increased global warming by 23% to 49%, when allocation and avoided production of by-products were not considered. The highest reduction of global warming in Scenario C1.4 is observed in QC and the lowest is observed in NS. The highest increase of global warming in Scenario C2.1 and Scenario C2.2 are also shown in NS.

Electricity generation for the operation of carbon capturing systems was considerably increased (19% to 24%) in AB, SK, and NS in Scenario C2.1. These provinces had higher overall global warming compared to all the other provinces and mainly depend on fossil fuel for electricity generation [119]. In addition, for the same scenario, the electricity consumption of the carbon capturing system in NB contributes 12% of total global warming. NB uses fossil fuel combustion to generate 35% of its electricity and the rest is generated using nuclear and renewable energy [119]. By-product transportation in Scenario C1.4 was 4% to 5% of total global warming, while Scenario C2.1 and Scenario C2.2 had negligible contribution to global warming. Energy consumption for the refrigeration process when transporting CO_2 can be a reason for the increased global warming potential of by-product transportation in Scenario C1.4. The contribution to global warming by the raw material extraction in Scenario C1.4 was negligible, while the raw material extraction in Scenario C2.1 was 22% to 35% and in Scenario C2.2 was 22% to 37% of the total global warming potential. That was a result of the substantial use of thermal energy and electricity in KOH production. Construction of the carbon capturing systems and emissions during the carbon capturing process had negligible impacts on global warming.

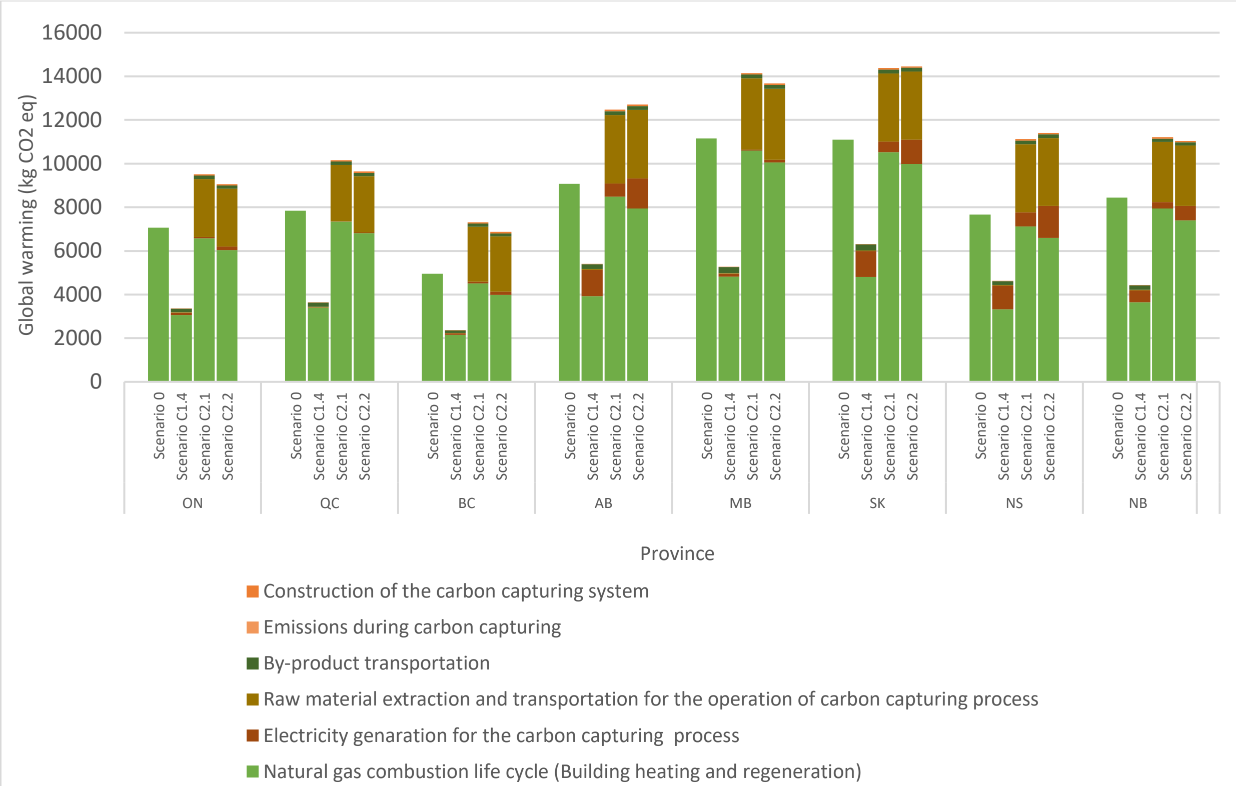

Figure 5-7: Contribution of process phases to life cycle global warming

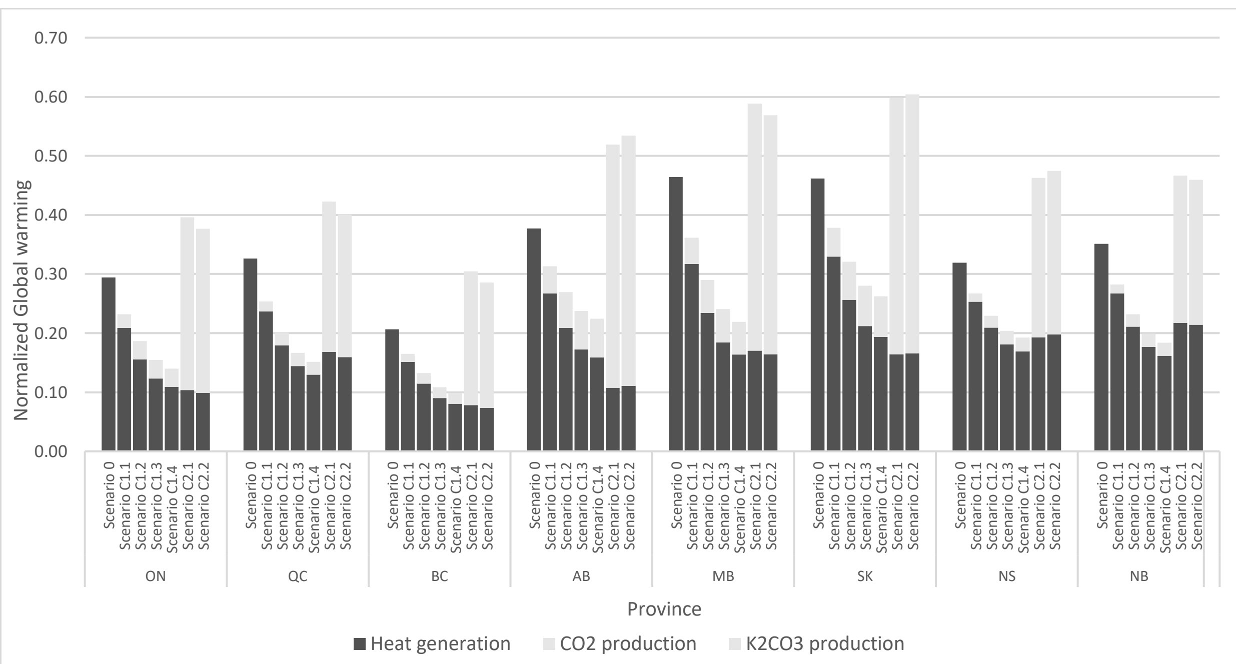

Figure 5-8: Normalized life cycle global warming with economic allocation

Figure 5-8 shows the allocation of the impact of global warming between heat generation and by-products of all scenarios using economic allocation. The overview of Figure 5-8 shows that all the carbon capturing scenarios show a decrease in global warming potential in heat generation in all eight provinces. Decreasing trend of global warming in C1 scenarios can be summarized as follows: C1.1 decrease ranges from 21% to 32%, C1.2 decrease ranges from 35% to 50%, C1.3 decrease ranges from 43% to 60%, and C1.4 decrease ranges from 47% to 65%. MB has the best trend in reducing global warming, from 32% to 65%, in C1 scenarios. When considering Scenario C2.1 and Scenario C2.2, a significant decrease can be observed (38% to 72%) in all provinces, and AB has the highest decrease in global warming at 72% according to the Figure 5-8. Scenario C2 performed better in reducing global warming in provinces except MB, NS, and NB. This can be a result of higher natural gas cost, which increases the fraction of impacts related to heat generation.

5.3.1.3 Smog

Figure 5-9 shows the annual smog caused by Scenario 0, Scenario C1, and Scenario C2. Scenario C1.4, Scenario C2.1, and Scenario C2.2 all increased smog without allocating the impacts between heat generation and the carbon capturing process. The combustion of natural gas increases the smog as combustion products contain NO_x (emission factor of uncontrolled combustion of natural gas is 132 lb/10^6 scf) [136]. Since Scenario C1.4 increases natural gas combustion due to the regeneration process, the results show increased smog in Scenario C1.4 related to natural gas combustion. Transportation of by-products contributes 12% to 15% in Scenario C1.4, and 5% to 7% in both Scenario C2.1 and C2.2 as a result of fossil fuel combustion during transportation. The raw material extraction in Scenario C2.1 contributes 39% to 56% and Scenario C2.2 contributes 37% to 57% to the total smog. That can be a result of significant use of electricity and fossil fuel combustion during the production of KOH [137]. The electricity generation of the process contributed a less than 3% increase of smog in ON, QC, BC and MB, which use renewable energy for electricity generation. Electricity generation in Scenario C1.1 in provinces that use fossil fuel combustion contributed to smog by 13% to 25%, while electricity generation in Scenario C2.1 contributed 5% to 11% and Scenario C2.2 contributed 12% to 22%. Construction of the carbon capturing system and the emissions during the carbon capturing process contributed less than 2% of the smog for all the scenarios.

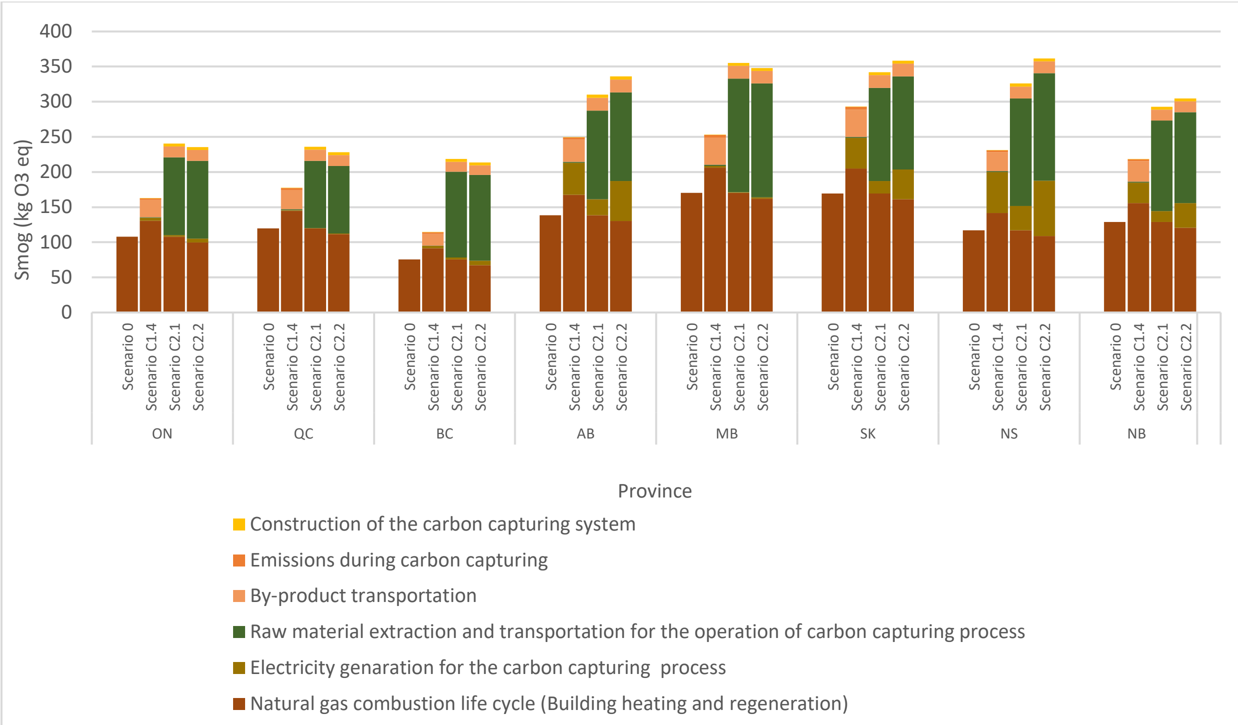

Figure 5-9: Contribution of process phases to the Smog

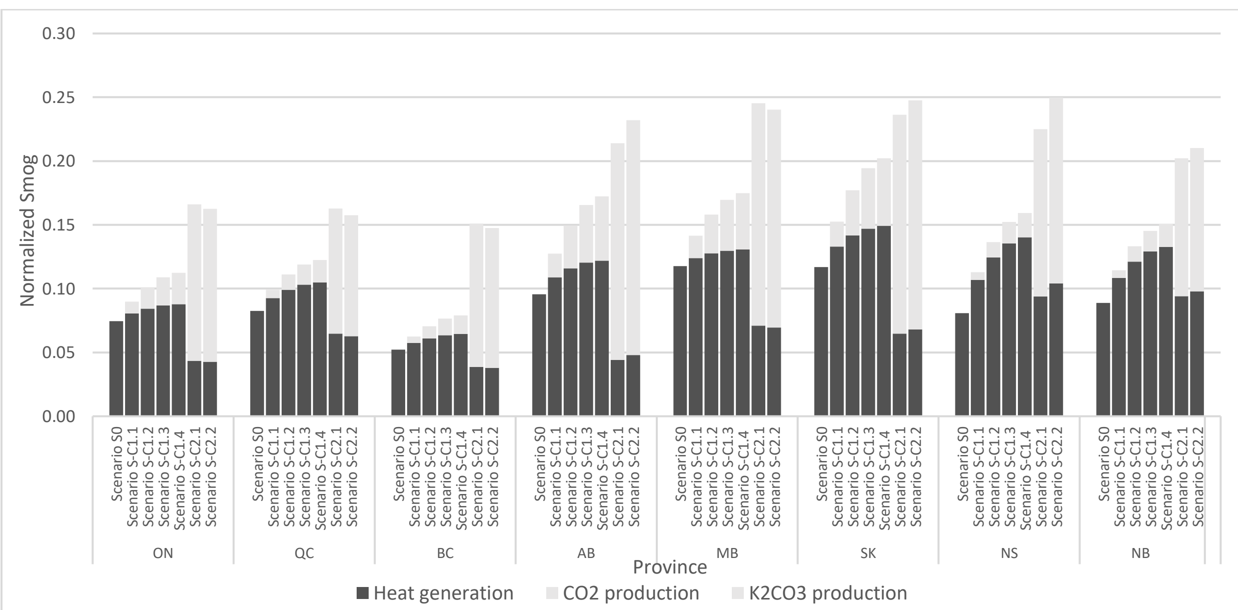

Figure 5-10: Normalized life cycle smog with economic allocation

Figure 5-10 shows the allocation of impact of smog between heat generation and by-products of all scenarios using economic allocation. The overview of Figure 5-10 shows that the heat generation of the C1 Scenarios increased smog in all provinces compared to Scenario 0. In addition, the smog of the C1 scenarios has an increasing trend from C1.1 to C1.4. The increasing trend can be summarized as follows: C1.1 has increased the smog from 5% to 32%, C1.2 has increased the smog from 9% to 54%, C1.3 has increased the smog from 10% to 67%, and C1.4 has increased the smog from 11% to 73%. MB has the lowest trend in increasing smog, from 5% to 11% in the C1.1 to C1.4 scenarios, and NS shows the highest trend in increasing smog, ranging from 32% to 73% in C1.1 to C1.4 scenarios. The reason for the significant increase in smog in NS can be a result of using heavy fuel oil for electricity generation [138]. MB has a higher energy load compared to other provinces, while Manitoba's electricity generation is based on renewable energy sources. As a result, a higher component of environmental impacts are allocated to CO_2 production. When comparing Scenario C2.1 and Scenario C2.2 against Scenario 0, a significant decrease can be observed in all provinces (a reduction of 22% to 54% and 24% to 50% respectively in each scenario) except for NS and NB, and the highest decrease in smog in AB of 54% and 50%. However, the percentage increase of smog in Scenario C2.1 and Scenario C2.2 in NS and NB are less than all of the C1 scenarios.

5.3.1.4 Acidification

Figure 5-11 shows the process phase contribution to acidification. Scenario C1.4, Scenario C2.1, and Scenario C2.2 increased the acidification without considering the allocation. Although natural gas combustion does not emit a significant amount of gases that cause acidification, the complete life cycle of natural gas combustion includes extraction of natural gas involved with energy use and gas emissions during purification [139]. By-product transportation caused 6% to 10% of the acidification caused by Scenario C1.4 due to the emissions of fuel combustion and the production of fuel required during transportation [140]. The by-product transportation phases in Scenario C2.1 and Scenario C2.2 have relatively low contribution to acidification compared to the acidification in Scenario C1.4, as transporting liquid CO_2 is an energy intensive process. Therefore, it increases fuel consumption and consequently increases acidification. Raw material extraction in Scenario C2.1 contributed 45% to 61%, and C2.2 contributed 39% to 62%. Significant use of electricity for the electrolysing process used to produce KOH can be a reason for the increase of acidification as the US electricity grid consists of 50% fossil fuel combustion [141]. The emissions during the carbon capturing process in Scenario C1.4 also contributed 3% to 4% of the acidification as a result of NH_3 emissions due to degradation of MEA [68].

Electricity generation for the carbon capturing process contributed to acidification by less than 3% in ON, QC, MB, and BC as a result of using renewable energy [119]. The increased contribution of electricity generation for acidification can be clearly observed in AB, SK, NS, and NB. AB, SK, and NB use coal for electricity generation, which has high SO_2 content in the flue gas [142]. In addition, NS uses heavy fuel oil for electricity production, which results in a higher SO_2 content in flue gas [138]. SO_2 gas mixes with rain water and creates sulphates, which in turn cause acidification of the soil [143].

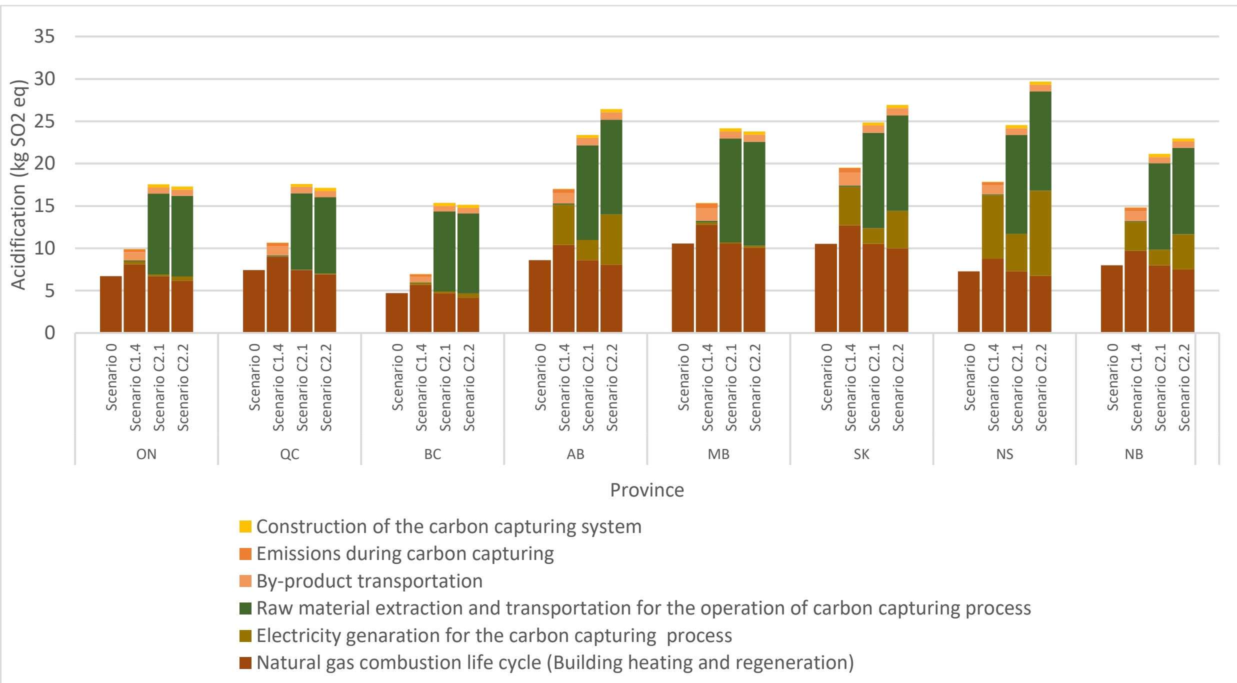

Figure 5-11: Contribution by process phases to increased acidification

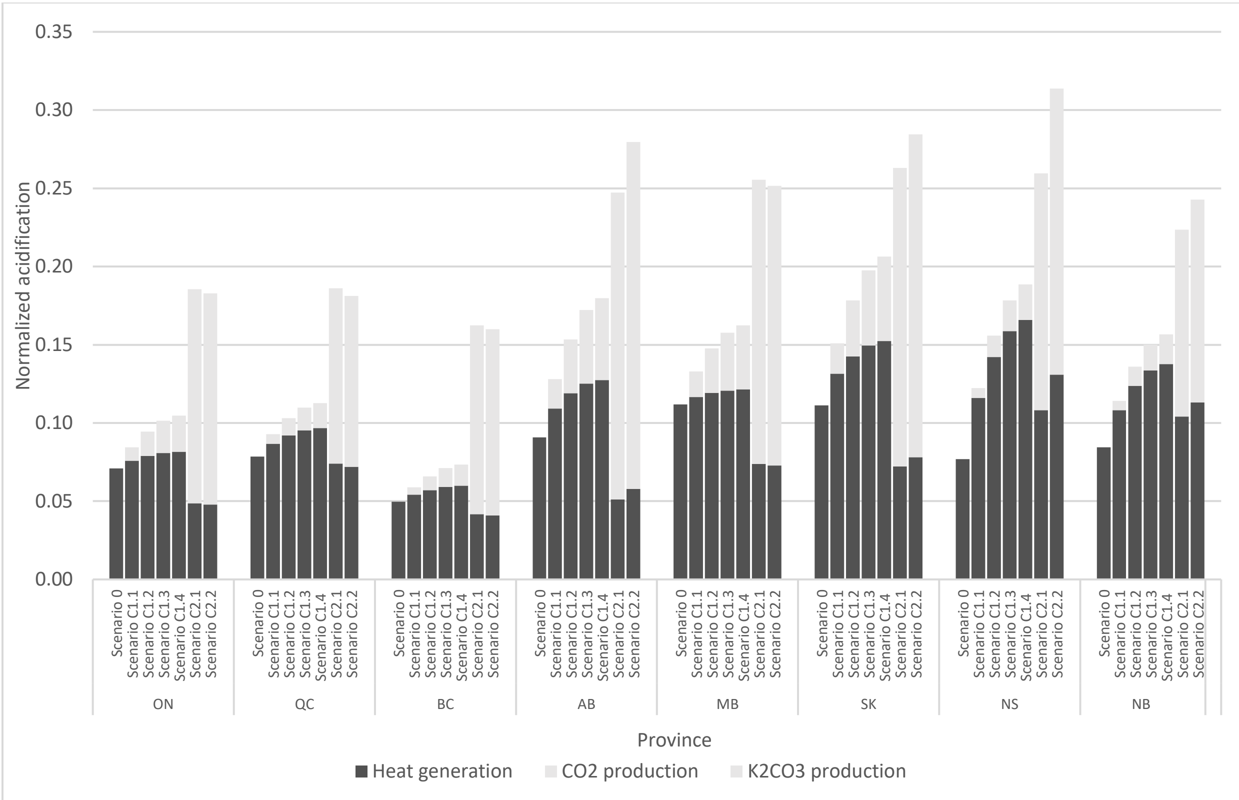

Figure 5-12: Normalized values of acidification with economic allocation

Figure 5-12 shows the allocation of the impact of acidification between heat generation and by-products of all scenarios using economic allocation. The overview of Figure 5-12 shows that all eight provinces show increase in acidification related to the heat generation in C1 Scenarios. There is an increasing trend of acidification from Scenario C1.1 to Scenario C1.4. The increasing trend can be summarized as follows: the C1.1 increase ranges from 4% to 51%, the C1.2 increase ranges from 7% to 85%, the C1.3 increase ranges from 8% to 106%, and the C1.4 increase ranges from 9% to 116%. BC has the lowest trend in increasing acidification, and NS shows the highest trend in increasing acidification. When comparing Scenario C2.1 and Scenario C2.1 against Scenario 0, a decrease in acidification can be observed in all provinces except for NS and NB, and the highest decrease in acidification is in AB with 44% and 36% respectively for each scenario. Scenario C2.1 in NS and NB decreased acidification by 7% and 4% respectively, when compared to C1 scenarios.

5.3.1.5 Eutrophication

Figure 5-13 shows the process phase contribution to the increase in eutrophication. Scenario C1.4, Scenario C2.1, and Scenario C2.2 increased eutrophication compared to Scenario 0 without considering allocation. Electricity generated to operate the carbon capturing process contributed significantly in AB and SK. AB and SK generate electricity primarily using coal combustion [119], and coal combustion products are responsible for immobilization of phosphorus, which creates eutrophication in fresh water [144]. The raw material extraction in Scenario C2.1 increased eutrophication by contributing 61% to 84%, and Scenario C2.2 increased eutrophication by contributing 43% to 84% of the total eutrophication due to energy consumption during the production of KOH [141]. Transportation of by-products contributed 1% to 7% in Scenario C1.4, and less that 2% in Scenario C2.1 and Scenario C2.2. Construction of the carbon capturing systems and the emissions during the carbon capturing process did contribute significantly to eutrophication.

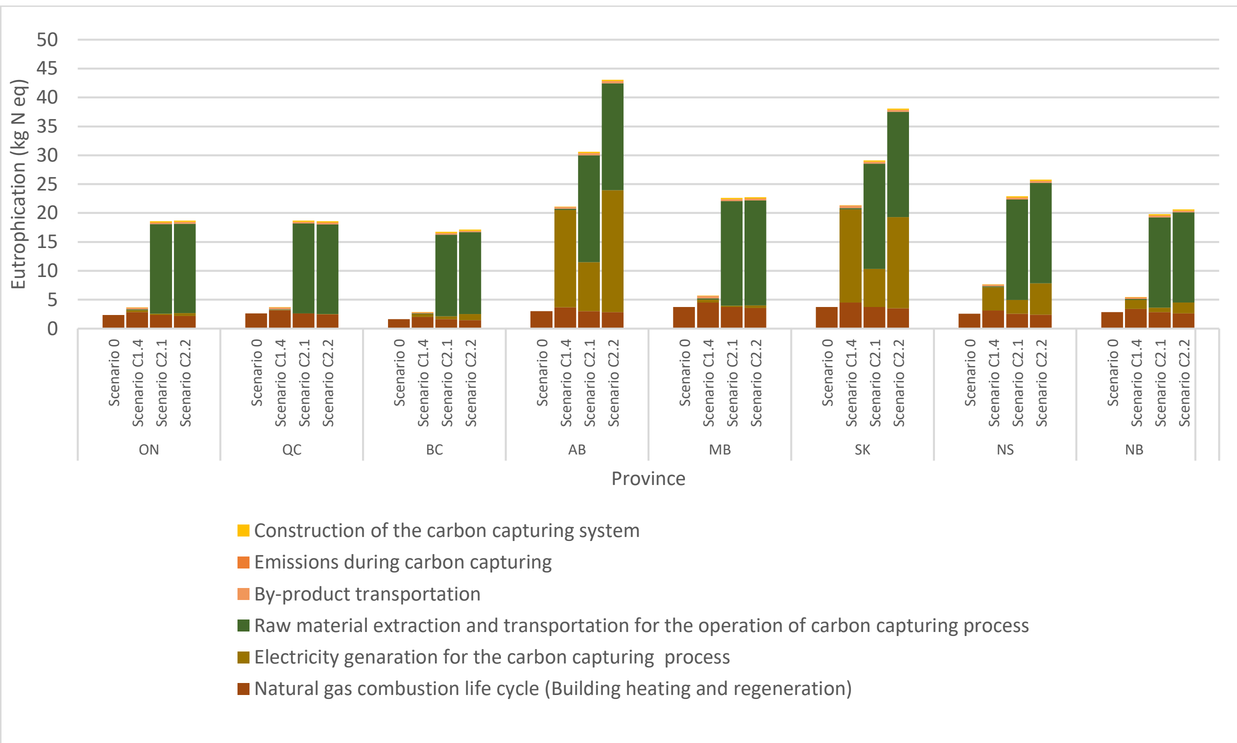

Figure 5-13: Contribution of the process phases to the increase of eutrophication

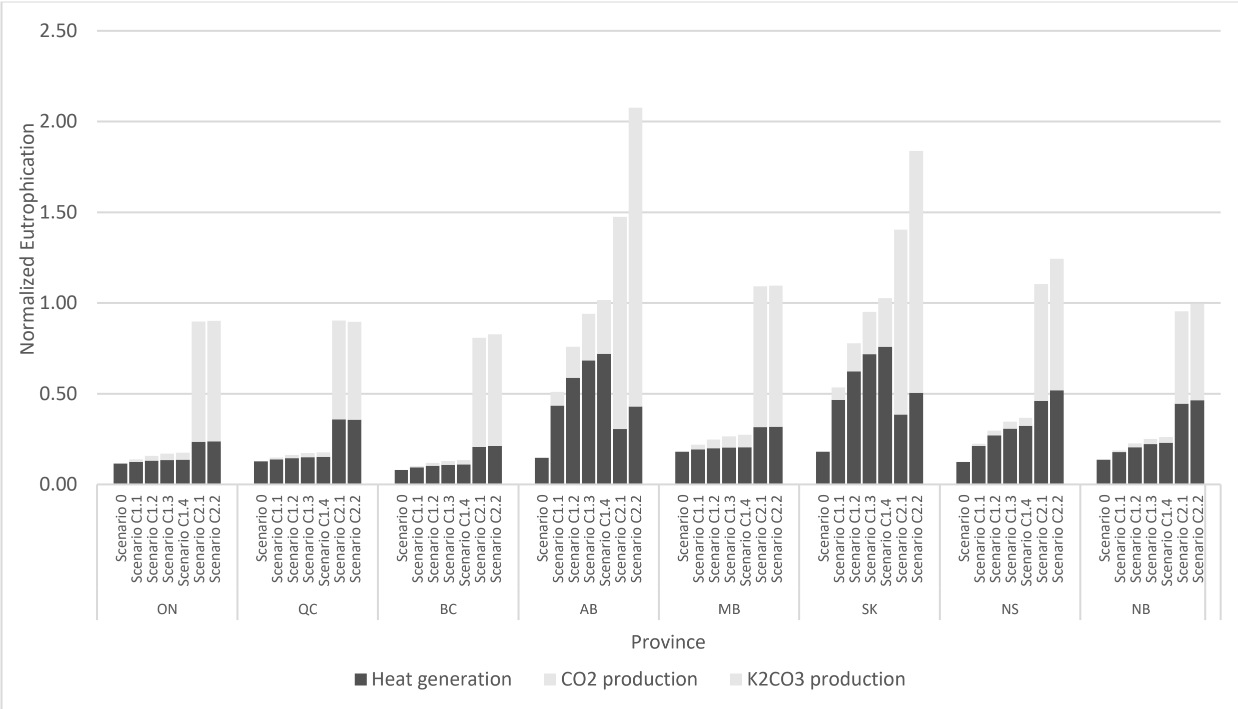

Figure 5-14: Normalized values of eutrophication with economic allocation

Figure 5-14 shows the allocation of impact of eutrophication between heat generation and by-products of all scenarios using economic allocation. The overview of Figure 5-14 shows that all eight provinces show increase in eutrophication for C1 Scenarios. The increasing trend can be summarized as follows: the C1.1 increase ranges from 6% to 196%, the C1.2 increase ranges from 10% to 300%, the C1.3 increase ranges from 12% to 365%, and the C1.4 increase ranges from 13% to 390%. AB and SK show significantly higher trends in increasing eutrophication from Scenario C1.1 to Scenario C1.4. When comparing Scenario C2.1 and Scenario C2.2 against Scenario 0, a significant increase in eutrophication can be observed in all provinces ranging from 75% to 271% and 75% to 317% respectively, with NS showing the highest increase. In addition, the percentage increase of eutrophication in Scenario C2.1 and Scenario C2.2 is higher than the C1 scenarios in all provinces except AB and SK.

5.3.1.6 Carcinogenics

Figure 5-15 shows process phase contribution to the increase of carcinogenics. Scenario C1.4, Scenario C2.1, and Scenario C2.2 increased carcinogenics without considering economic allocation. Although natural gas combustion does not emit carcinogenics, natural gas extraction and transportation may include carcinogenics due to energy use. Electricity generation in AB, SK, NS, and NB increased the carcinogenics significantly. These provinces depend on coal combustion for electricity generation [119], and the coal mining process is known to be associated with cancer risks such as lung cancer due to inhalation of coal particles [145]. The raw material extraction process contributed to carcinogenics by 50% to 61% in Scenario C2.1 and 41% to 60% in Scenario C2.2, while the raw material extraction in Scenario C1.4 has negligible contribution. Although formaldehyde and acetaldehyde are known carcinogenics [146], emissions during the carbon capturing process in Scenario C1.4 did not contribute to the carcinogenics due to low emissions. Construction of the carbon capturing system in Scenario C2.1 and Scenario C2.2 contributed by 8% to 16% as a result of cancer risks in the mining industry [147].

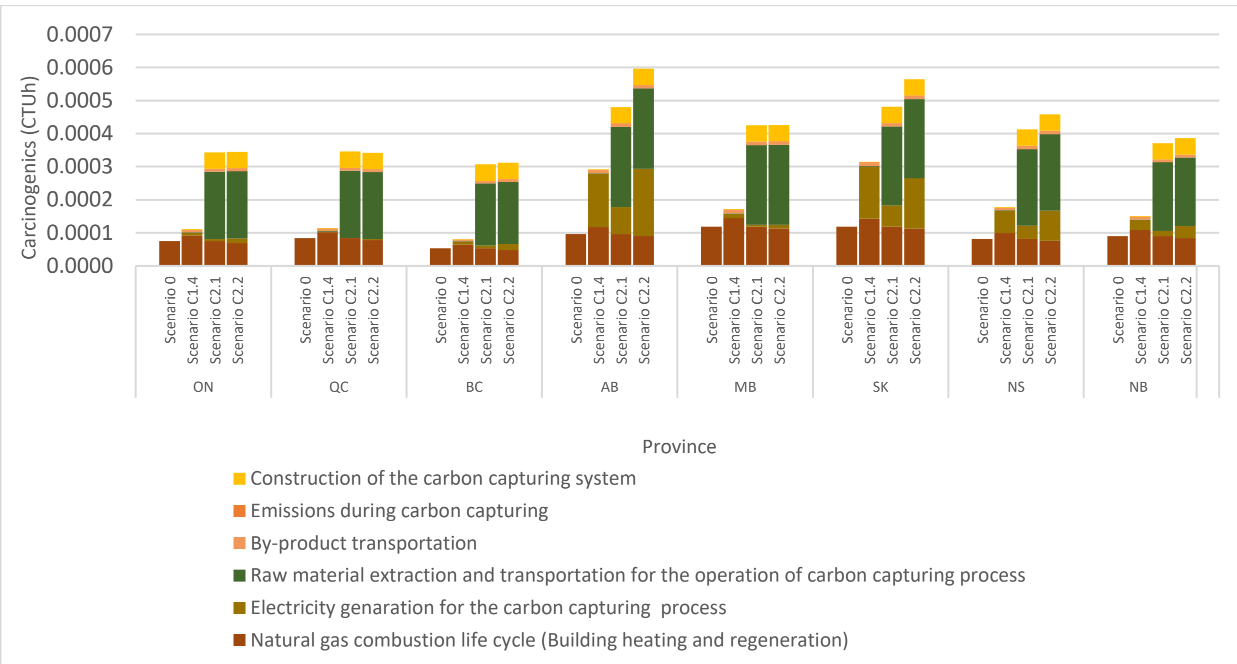

Figure 5-15: Contribution of the process phases to the increase of carcinogenics

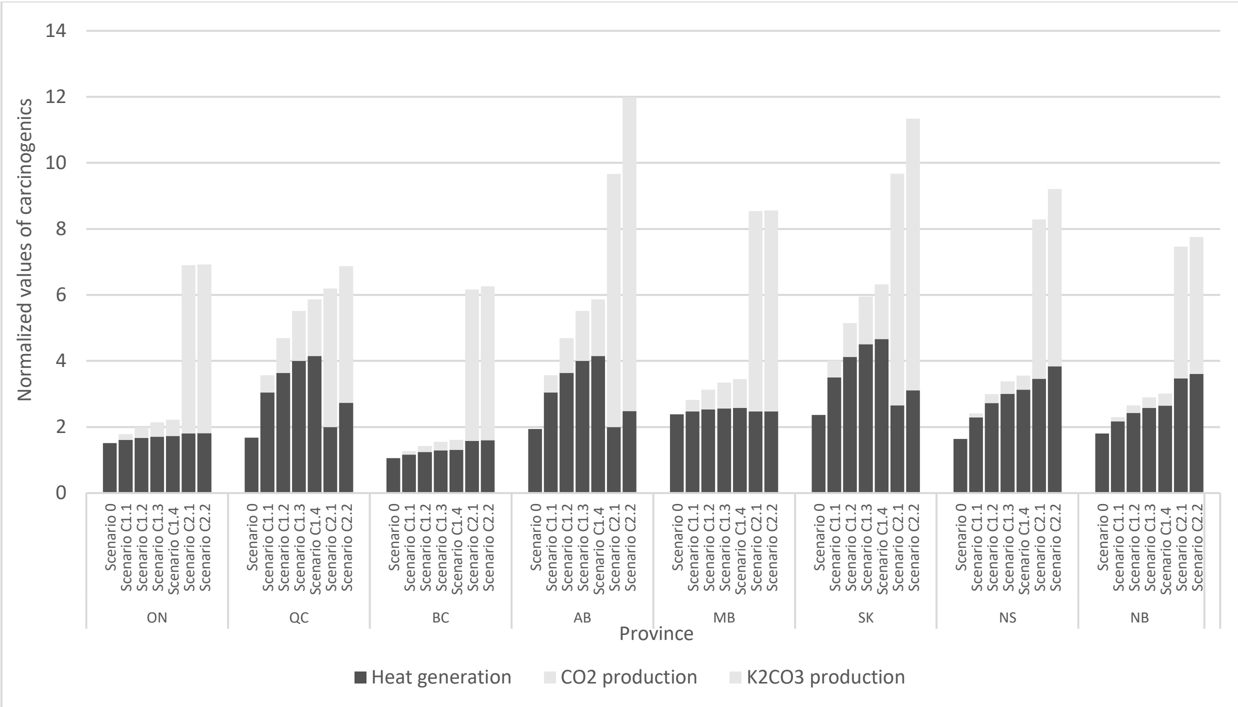

Figure 5-16: Normalized values of carcinogenics with economic allocation

Figure 5-16 shows allocation of the impact of carcinogenics between heat generation and by-products of all scenarios using economic allocation. The overview of Figure 5-16 shows that heat generation in all C1 scenarios and Scenario C2 increases carcinogenics. ON has the lowest trend in increasing carcinogenics, ranging from 6% to 15% in C1.1 to C1.4 scenarios. In addition, SC2.1 has increased from 3% to 111% and C2.2 has increased from 4% to 134%.

5.3.1.7 Non-carcinogenic

Figure 5-17 shows the process phase contribution to the increase of non-carcinogenics. The variations in contribution for non-carcinogenics is similar to the carcinogenics described in the previous section. However, the construction phase of the carbon capturing system in Scenario C1.4 was 0% to 4%. By-product transportation contributed to non-carcinogenics by 3% to 10%. The raw material extraction in Scenario C2.1 contributed to non-carcinogenics by 60% to 74%, and Scenario C2.2 contributed to non-carcinogenics by 50% to 72%, while the contribution of Scenario C1.4 is negligible. Electricity generation in ON, QC, BC, and MB contributed to non-carcinogenics by 3% to 16%, while electricity generation in AB, SK, NS, and NB contributed to non-carcinogenics by 24% to 56% in Scenario C1.4. Electricity generation in Scenario C2.1 and

Scenario C2.2 had negligible contribution in QC, while there was a contribution of 2% to 15% in other provinces. The maximum contribution of the electricity generation in both Scenario C2.1 and Scenario C2.2 was observed in the house located in AB.

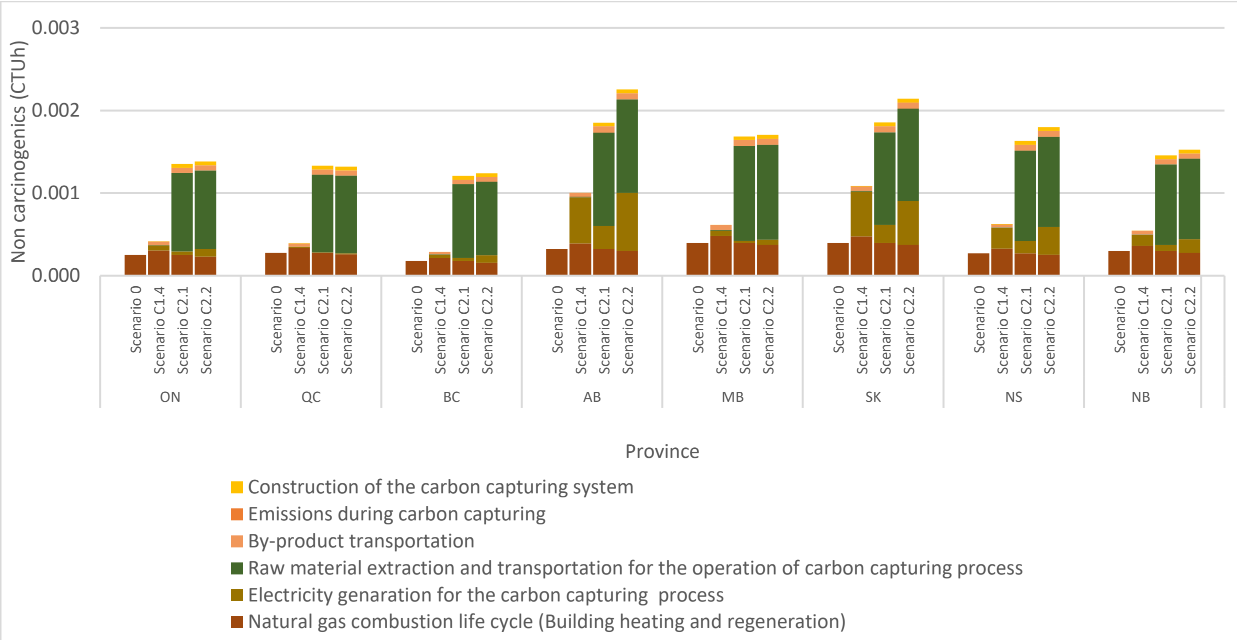

Figure 5-17: Contribution of the process phases to the increase of non-carcinogenics

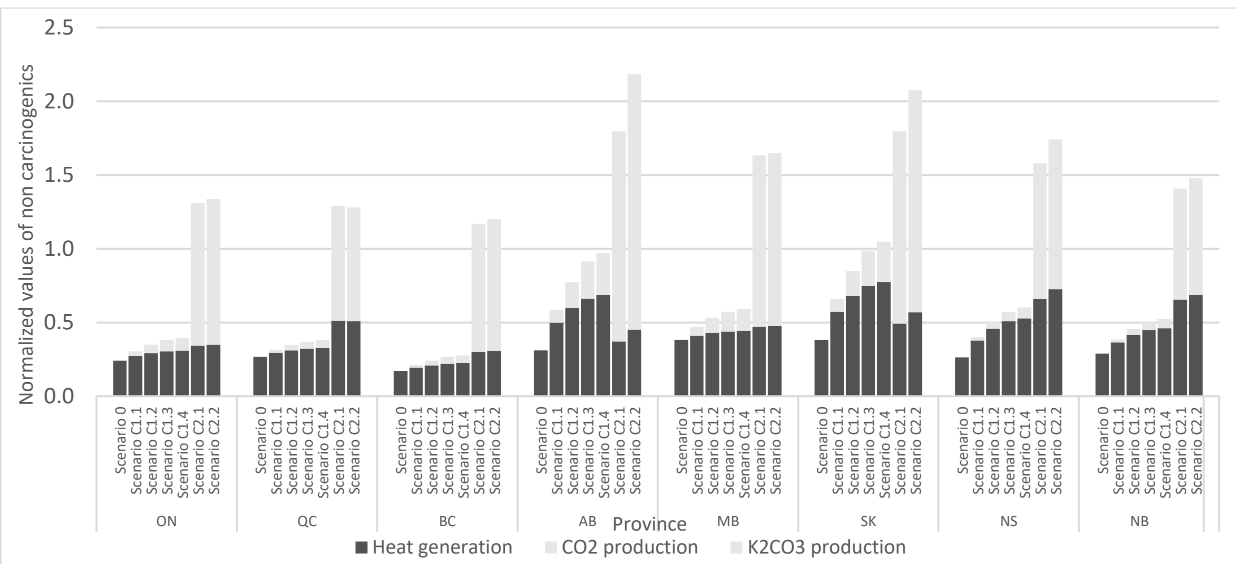

Figure 5-18: Normalized values of non-carcinogenics with economic allocation

Figure 5-18 shows the allocation of impact of non-carcinogenics between heat generation and by-products of all scenarios using economic allocation. The overview of Figure 5-18 shows that all carbon capturing scenarios increased the non-carcinogenics. In addition, there is an increasing trend when considering Scenario C1.1 to Scenario C1.4, respectively. The increasing trend can be summarized as follows: the C1.1 increase ranges from 8% to 61%, the C1.2 increase ranges from 12% to 93%, the C1.3 increase ranges from 15% to 114%, and the C1.4 increase ranges from 16% to 121%. MB has the lowest trend in increasing non-carcinogenics, ranging from 8% to 16% in C1.1 to C1.4 scenarios. AB and SK show significantly higher values in increasing non-carcinogenics in the C1.1 to C1.4 scenarios, since these two provinces depend on fossil fuel combustion for electricity generation. Scenario C2.1 and Scenario C2.2 show an increase in non-carcinogenic potential in all provinces, with NS showing the highest increase of 151% and 176% respectively.

5.3.1.8 Respiratory effects

Figure 5-19 shows the contribution of process phases to the increase of respiratory effects. Scenario C1.4, Scenario C2.1, and Scenario C2.2 all increased respiratory effects compared to Scenario 0, while Scenario C2.1 and Scenario C2.2 increased the respiratory effects significantly. The raw material production in Scenario C2.1 and Scenario C2.2 contributed to respiratory effects by 77% to 82% in both scenarios. This can be a result of electricity use for KOH production, as the US electricity grid consists of 50% fossil fuel combustion [141].

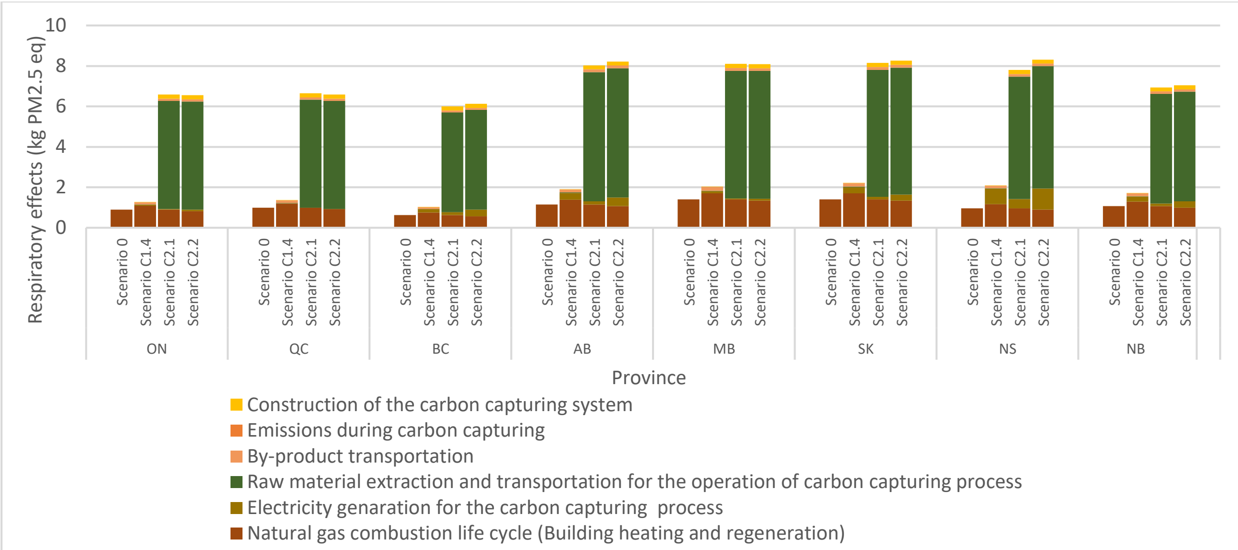

Figure 5-19: Contribution of the process phases to the increase of respiratory effects

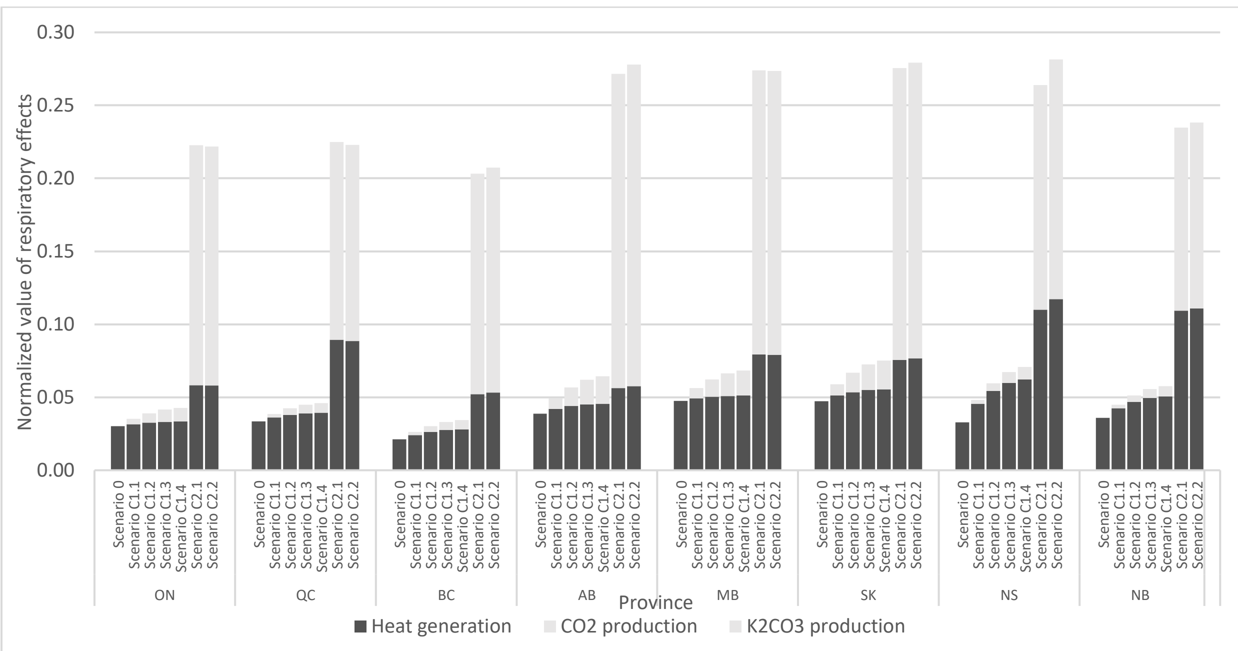

Figure 5-20: Normalized values of respiratory effects with economic allocation

The Figure 5-20 shows the allocation of impact of respiratory effect between heat generation and by-products of all scenarios using economic allocation. The heat generation in Scenario C1.1 to Scenario C1.4 shows less than 33% increase in all provinces except NS and NB. The increase of respiratory effect in NS is 90%, while NB shows an increase of 41%. The heat generation in

Scenario C2.1 increased respiratory effects by 45% to 236%, and in Scenario C2.2 by 49% to 259%.

5.3.1.9 Ecotoxicity

Figure 5-21 shows the process phase contribution to an increase of ecotoxicity. It shows that ecotoxicity was increased in both Scenario C1 and Scenario C2 compared to Scenario 0.

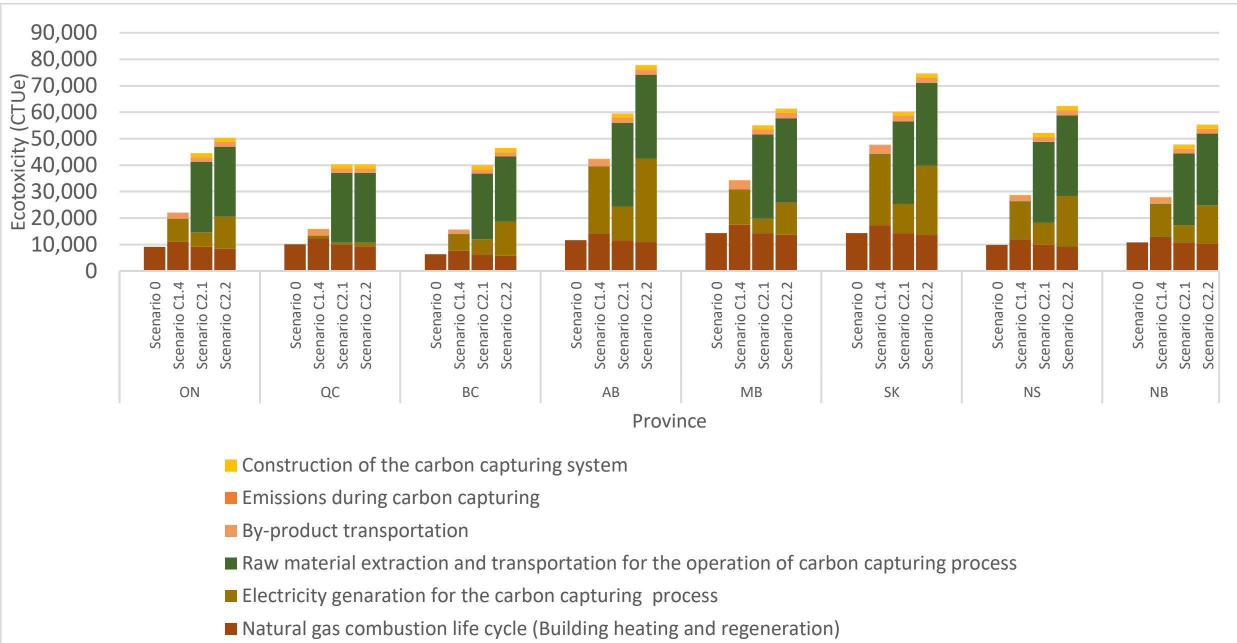

Figure 5-21: Contribution of the process phases to the increase of ecotoxicity

Figure 5-21 shows that the natural gas combustion life cycle increased the ecotoxicity significantly. This can be a result of water pollution during the natural gas extraction process. Electricity generation contributed 39% to 60% in all provinces. The raw material extraction in Scenario C2.1 contributed 52% to 65%, and in Scenario C2.2 contributed 41% to 65% for total ecotoxicity. By-product transportation in Scenario C1.4 contributed 6% to 15%, while by-product transportation in Scenario C2.1 and Scenario C2.2 contributed to ecotoxicity by 3% to 4%. The construction phase of Scenario C2.1 and Scenario C2.2 increased the ecotoxicity by 3% to 4%, and the construction phase in Scenario C1.4 had negligible contribution.

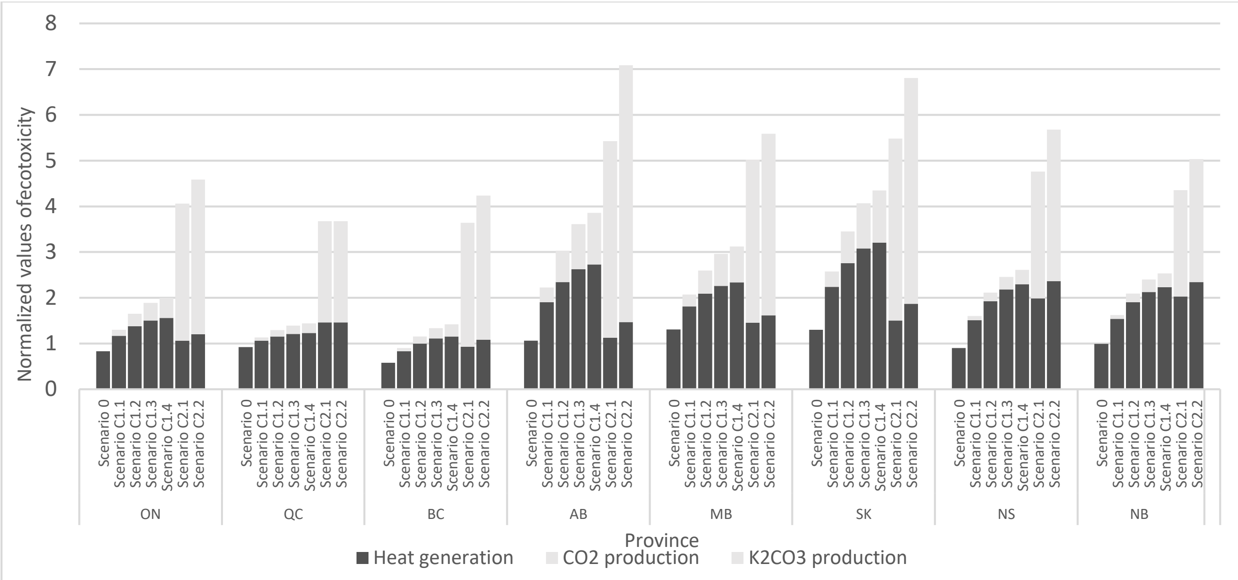

Figure 5-22: Normalized values of ecotoxicity with economic allocation

Figure 5-22 shows the allocation of impact of ecotoxicity between heat generation and by-products of all scenarios using economic allocation. The overview of Figure 5-22 shows all carbon capturing scenarios increased the ecotoxicity in heat generation compared to Scenario 0. The ecotoxicity in heat generation is increased when considering Scenario C1.1 to C1.4 accordingly. The increasing trend can be summarized as follows: the C1.1 increase ranges from 15% to 79%, the C1.2 increase ranges from 25% to 120%, the C1.3 increase ranges from 31% to 146%, and the C1.4 increase ranges from 34% to 156%. QC has the lowest trend in increasing ecotoxicity, ranging from 15% to 34% in C1.1 to C1.4 scenarios. Scenario C2.1 and Scenario C2.2 show an increase in ecotoxicity in all provinces, with NS showing the highest increase of 120% and 163% respectively for each province. The heat generation in Scenario C2 has a lower increase compared to C1 scenarios in all provinces except QC.

5.3.1.10 Fossil fuel depletion

Figure 5-23 shows the process phase contribution to fossil fuel depletion. Natural gas combustion contributed the majority of the fossil fuel depletion, and Scenario C1.4 had higher fossil fuel depletion compared to Scenario 0 and Scenario C2 as a result of using natural gas for the regeneration process. The raw material extraction in Scenario C2.1 and Scenario C2.2 contributed to fossil fuel depletion by 12% to 20%. This is a result of using natural gas for the thermal energy required for KOH production.

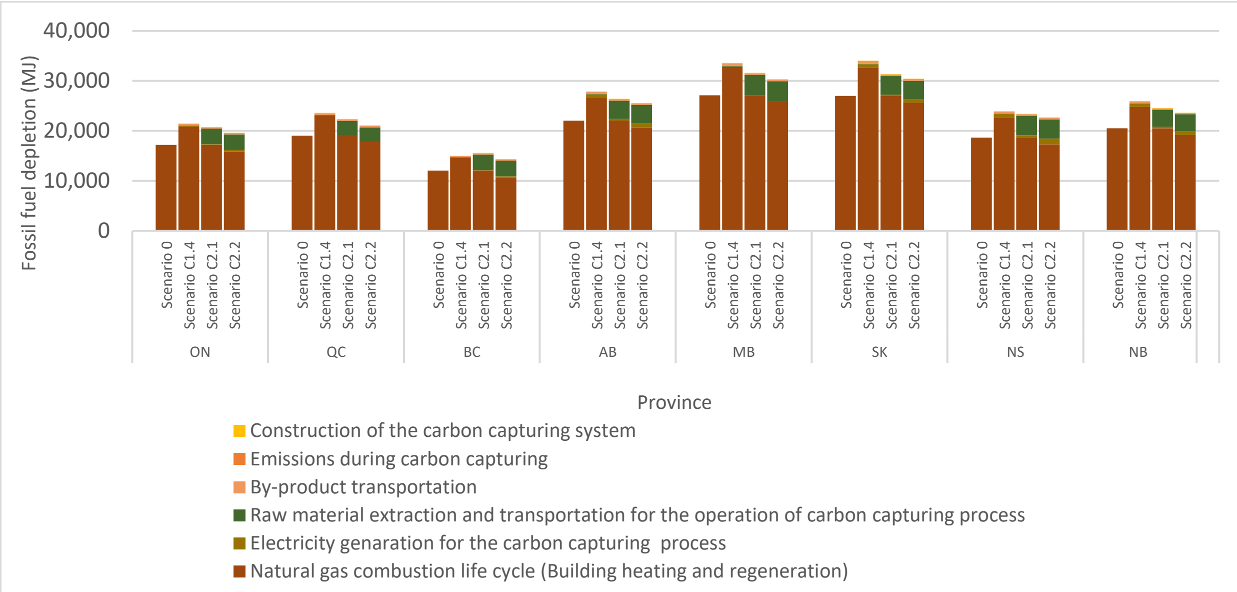

Figure 5-23: Contribution of the process phases to the increase of fossil fuel depletion

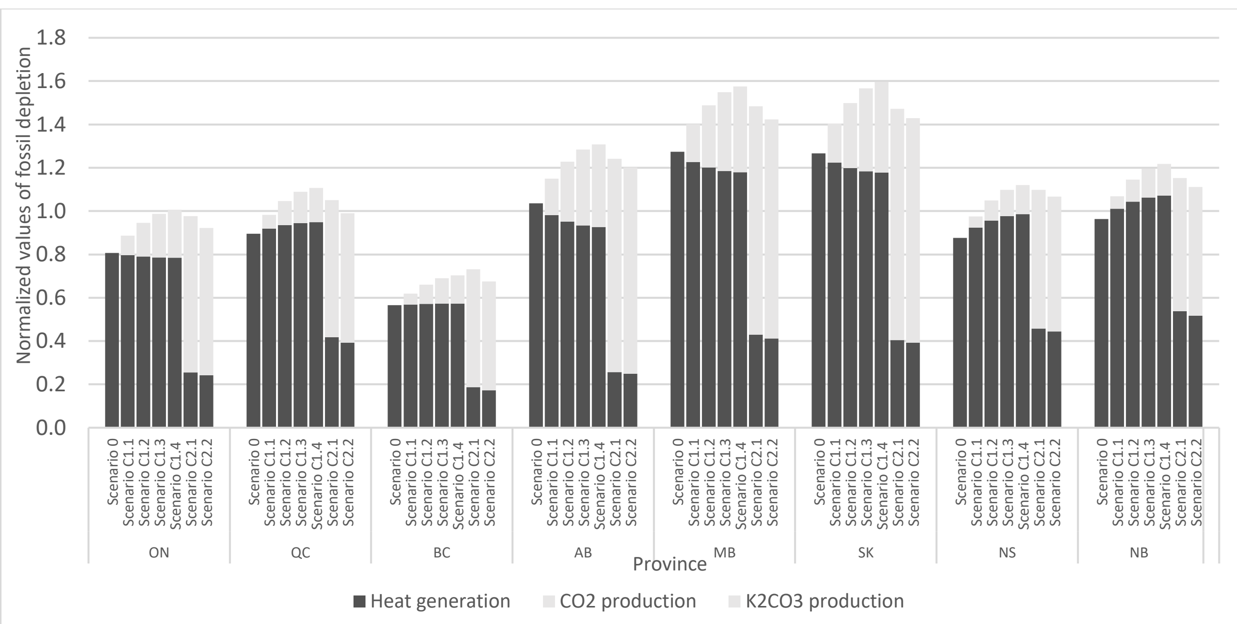

Figure 5-24: Normalized values of fossil fuel depletion effects with economic allocation

Figure 5-24 shows allocation of the impact of fossil fuel depletion between heat generation and by-products of all scenarios using economic allocation. The heat generation in C1 scenarios reduced fossil fuel depletion in ON, AB, MB, and SK. BC has negligible change from C1.1 to C1.4, with an increase of 1% for all four scenarios. The heat generation in C1 scenarios increased the fossil fuel depletion in QC, NS, and NB. The heat generation in Scenario C2.1 and Scenario C2.2 decreased fossil fuel depletion in all provinces with AB showing the highest decrease of 75% for both C2 scenarios.

5.3.1.11 Summary of the LCA results

Table 5-14 shows the percentage change of the life cycle environmental impacts of carbon capturing scenarios compared to the base scenario. It shows that the global warming is reduced substantially in carbon capturing scenarios. Higher reduction of global warming can be observed in provinces that are depend on renewable energy for electricity generation, while lower generation can be observed in provinces that depend fossil fuel for electricity generation. However, Eutrophication, Carcinogenics, Non carcinogenics, respiratory effects, and ecotoxicity are increased in all scenarios. Smog and acidification of heat generation in Scenario C1.1 to Scenario C1.4 were increased in all provinces. However, those impacts of heat generation in Scenario C2.1 and Scenario C2.2 were reduced in most of the provinces except NS and NB. Fossil fuel depletion of heat generation in Scenario C1.1 to Scenario C1.4 is reduced in ON, AB, MB, and SK compared to the base scenario. It is reduced substantially in Scenario C2.1 and Scenario C2.2 in all provinces.

Table 5-14: Percentage change of environmental impacts when integrating carbon capturing

Province	Scenarios	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
ON	C1.1	-1%	-29%	8%	7%	9%	6%	13%	5%	41%	-1%
	C1.2	-1%	-47%	13%	11%	14%	11%	21%	8%	66%	-2%
	C1.3	-1%	-58%	16%	14%	17%	13%	25%	10%	81%	-3%
	C1.4	-1%	-63%	18%	15%	19%	15%	28%	11%	88%	-3%
	C2.1	-65%	-65%	-42%	-31%	105%	20%	42%	94%	28%	-68%
	C2.2	-67%	-66%	-43%	-32%	106%	20%	45%	93%	45%	-70%

Province	Scenarios	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
QC	C1.1	3%	-27%	12%	10%	9%	82%	10%	8%	15%	3%
	C1.2	5%	-45%	20%	17%	15%	117%	16%	13%	25%	4%
	C1.3	7%	-56%	25%	21%	18%	139%	20%	16%	31%	6%
	C1.4	7%	-60%	27%	23%	20%	148%	21%	18%	34%	6%
	C2.1	-50%	-48%	-22%	-6%	182%	19%	91%	167%	59%	-53%
	C2.2	-54%	-51%	-24%	-8%	180%	63%	89%	165%	59%	-56%
BC	C1.1	1%	-27%	10%	9%	16%	10%	14%	14%	43%	1%
	C1.2	2%	-44%	17%	15%	27%	17%	24%	24%	71%	1%
	C1.3	3%	-56%	21%	19%	34%	22%	30%	30%	91%	1%
	C1.4	3%	-61%	23%	20%	37%	24%	33%	33%	98%	1%
	C2.1	-63%	-62%	-26%	-16%	158%	49%	77%	146%	60%	-67%
	C2.2	-66%	-65%	-28%	-18%	164%	52%	81%	151%	86%	-69%
AB	C1.1	-5%	-29%	14%	20%	196%	57%	61%	9%	79%	-5%
	C1.2	-7%	-45%	21%	31%	300%	88%	93%	14%	120%	-8%
	C1.3	-9%	-54%	26%	38%	365%	107%	114%	17%	146%	-10%
	C1.4	-10%	-58%	28%	40%	390%	114%	121%	18%	156%	-10%
	C2.1	-73%	-72%	-54%	-44%	108%	3%	20%	45%	5%	-75%
	C2.2	-73%	-71%	-50%	-36%	192%	28%	45%	49%	38%	-76%
MB	C1.1	-3%	-32%	5%	4%	6%	4%	8%	4%	38%	-4%
	C1.2	-5%	-50%	9%	7%	10%	6%	12%	6%	60%	-6%
	C1.3	-6%	-60%	10%	8%	12%	8%	15%	7%	73%	-7%
	C1.4	-6%	-65%	11%	9%	13%	8%	16%	7%	78%	-7%
	C2.1	-64%	-63%	-40%	-34%	75%	4%	24%	66%	11%	-66%
	C2.2	-64%	-65%	-41%	-35%	75%	4%	25%	66%	23%	-68%
SK	C1.1	-3%	-29%	14%	18%	159%	48%	51%	8%	72%	-3%
	C1.2	-5%	-44%	21%	28%	246%	74%	79%	13%	112%	-5%
	C1.3	-6%	-54%	26%	34%	300%	90%	96%	16%	136%	-7%
	C1.4	-6%	-58%	28%	37%	322%	97%	104%	17%	146%	-7%
	C2.1	-66%	-64%	-45%	-35%	114%	12%	30%	60%	15%	-68%
	C2.2	-66%	-64%	-42%	-30%	180%	31%	50%	62%	43%	-69%
NS	C1.1	7%	-21%	32%	51%	70%	40%	44%	39%	68%	5%
	C1.2	11%	-35%	54%	85%	117%	67%	74%	66%	114%	9%
	C1.3	14%	-43%	67%	106%	147%	84%	93%	83%	143%	12%
	C1.4	16%	-47%	73%	116%	160%	91%	101%	90%	155%	13%
	C2.1	-42%	-40%	16%	41%	271%	111%	151%	236%	120%	-48%
	C2.2	-46%	-38%	29%	70%	317%	134%	176%	259%	163%	-49%

Province	Scenarios	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
NB	C1.1	6%	-24%	22%	28%	30%	21%	26%	18%	55%	5%
	C1.2	10%	-40%	36%	46%	50%	35%	44%	30%	92%	8%
	C1.3	13%	-50%	45%	58%	63%	43%	55%	37%	115%	10%
	C1.4	14%	-54%	49%	63%	68%	47%	60%	41%	125%	11%
	C2.1	-39%	-38%	6%	23%	225%	93%	127%	204%	105%	-44%
	C2.2	-44%	-39%	10%	34%	239%	101%	138%	208%	137%	-46%

5.3.2 LCC results

This section elaborates on the results obtained from the life cycle costing. In addition, the operational cost and capital cost of all the heating system scenarios are explained.

5.3.2.1 Capital cost

Figure 5-25 shows the capital cost of Scenario C1 scenarios. The purchase cost of the carbon capturing equipment (including the carbon capturing system with compression and liquefaction systems) in Scenario C1 ranged from CAD 24,000 to 37,000, where the lowest was in BC and the highest was in SK. The purchase cost of the carbon capturing equipment in Scenario C1.2 was CAD 36,500 to CAD 56,000, while in Scenario C1.3 it ranged from CAD 46,500 to CAD 71,500. In Scenario C1.4, the cost of the highest-capacity carbon capturing system ranged from CAD 55,000 to CAD 85,000. However, the total investment cost of the carbon capturing systems includes general cost, piping and instrumentation cost, electrical cost, and natural gas furnaces. Therefore, the total investment cost is 85% higher than the purchase equipment cost. The total investment cost of the carbon capturing system in Scenario C1.2 was CAD 15,000 based on the manufacturer of the commercial system.

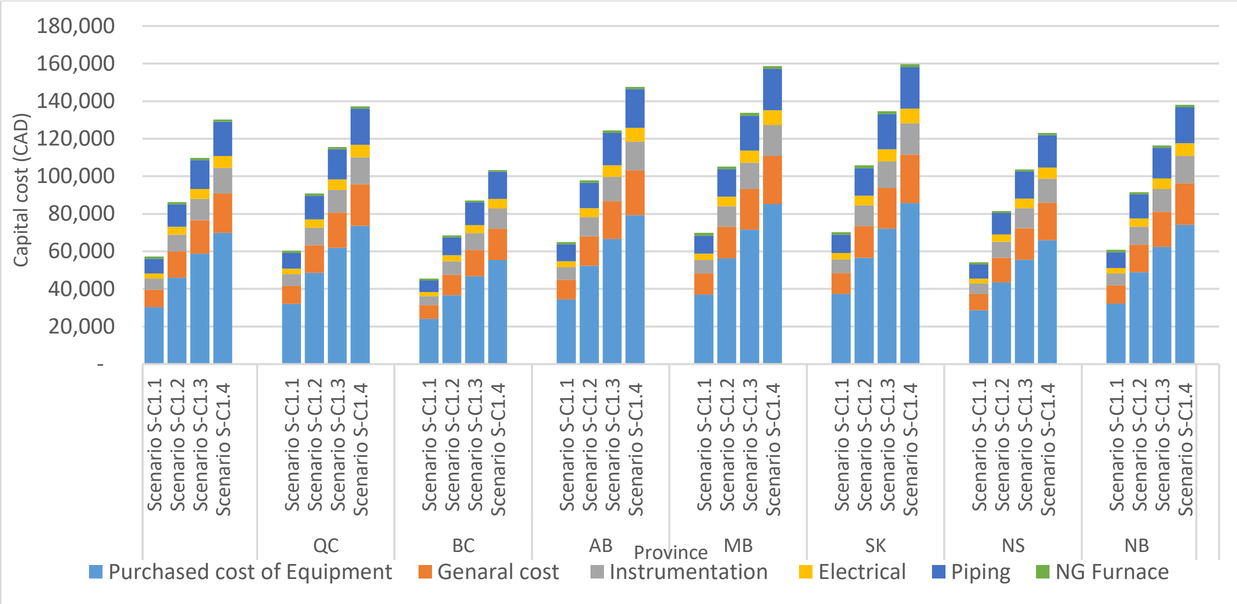

Figure 5-25: Capital cost of the carbon capturing systems in Scenario C1.1 to C1.4

5.3.2.2 Operational cost

Figure 5-26 shows the operational cost of Scenario 0, Scenario C1.1 to C1.4, and Scenario C.2. The annual operational cost of the C1 scenarios consists of raw material cost, maintenance cost, natural gas cost for heating and regeneration, electricity cost, and transportation cost. The results show that maintenance cost is the largest fraction of annual operational cost in all carbon capturing scenarios. The maintenance cost of Scenario C1.1 is 42% to 62% of the total operational cost. The fraction of the maintenance cost is increased from Scenario C1.1 to Scenario C1.4 accordingly. The natural gas requirement for building heating is 29% to 49% in Scenario C1.1, which is reduced to 15% to 30% from Scenario C1.1 to Scenario C1.4 accordingly. The annual cost of natural gas consumption for the regeneration process and CO_2 transportation cost of the carbon capturing system is 2% to 6% of the total operational cost separately. The annual raw material cost is a negligible fraction of the total annual operational cost at less than 0.6%. The revenue generated by selling the captured CO_2 reduced the total operational cost by 3% to 6%. The electricity cost is 1% to 2.7% of the operational cost.

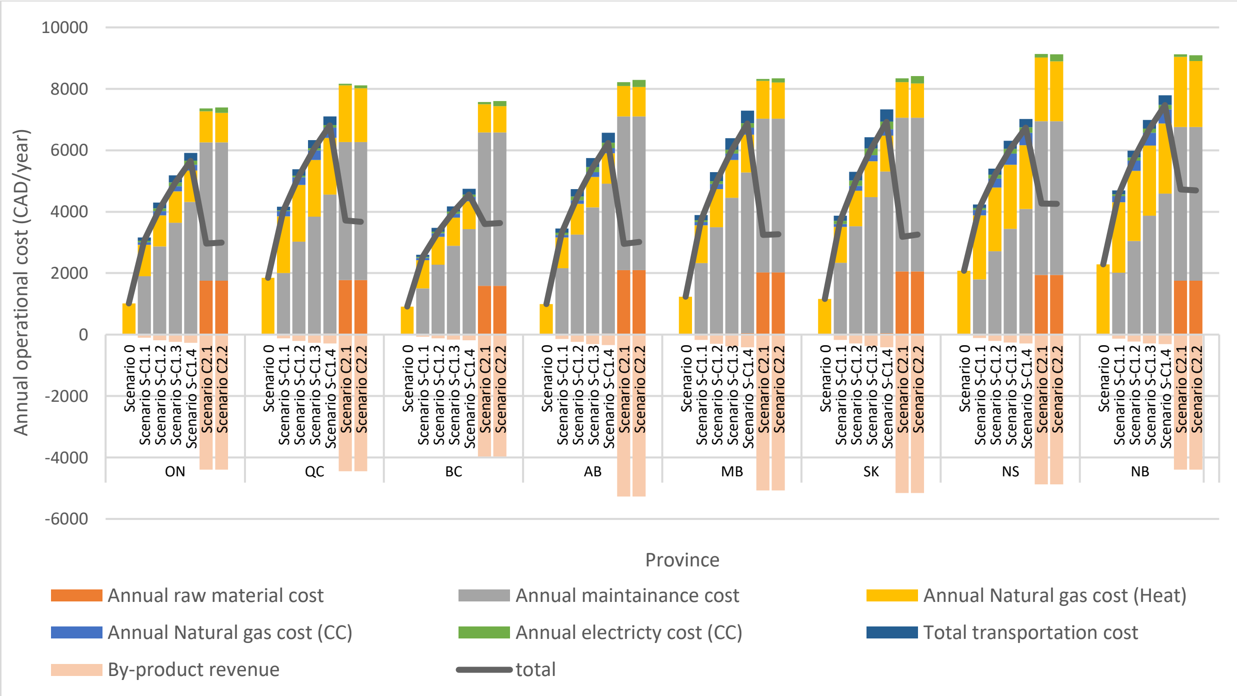

Figure 5-26: Annual operational cost

The maintenance cost of Scenario C2 is also the highest fraction of the operational cost and it is 55% to 66% of the total operational cost. The natural gas for building heating is 13% to 25%, while the raw material cost is 19% to 26%. Furthermore, the cost of electricity of Scenario C2 is less than 1% of the total operational cost in all provinces. Although the annual operational cost of Scenario C2 is higher than all the C1 scenarios, the revenue generated by selling the by-products can reduce the annual operational cost by 50% to 65%. Although Scenario C1.2 reduces the operational cost by saving natural gas, the operational cost in Scenario C1.2 was slightly higher than C1.1 in provinces except BC, due to higher electricity cost.

5.3.2.3 Life cycle cost

Figure 5-27 shows the life cycle cost for residential space heating in the 20 years of Scenario 0, Scenario C1.1 to Scenario C1.4, and Scenario C2.1 to Scenario C2.2 and the LCC for the reduction of 1kgCO_2 of global warming. The results clearly show that the life cycle costs of C1 scenarios are substantially higher than all the other Scenarios due to significant investment cost, operational cost, and lower value generation of captured CO_2. In addition, the investment costs of the C1 scenarios are more than 50% of the life cycle cost after 20 years from the initial investment. The life cycle cost of Scenario C2.1 and C2.2 was 2 to 4 times higher than the life cycle cost of Scenario 0. The investment cost of Scenario C2.1 and C2.2 varies from 15% to 23%. In addition, the LCC per reduction of 1 $kgCO_2$ of global warming in Scenario C2.1 and Scenario C2.2 is less than 1 CAD, while it is 2 – 3.5 CAD in Scenario C1.1 to C1.4. The Scenario C1.2 has the lowest LCC per reduction of 1$kgCO_2$ of global warming among the Scenarios C1.1 to C1.4.

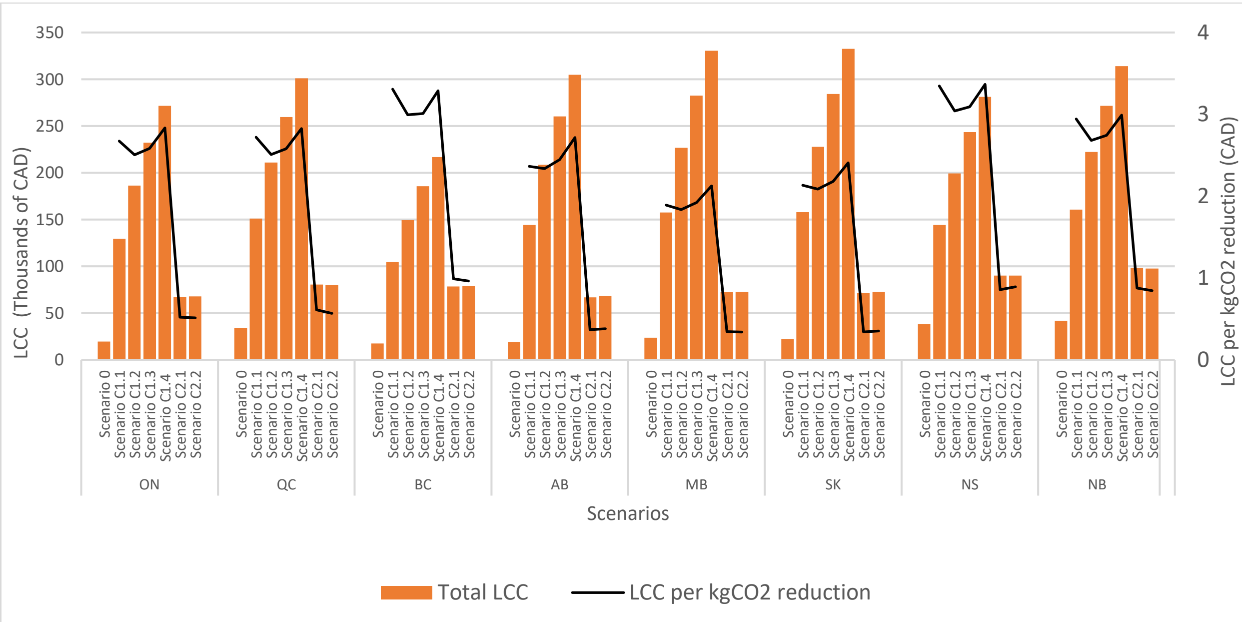

Figure 5-27: Life cycle cost

5.4 Discussion

In this section, the results obtained from the LCA and the LCC and their overall implications are discussed in detail.

5.4.1 Life cycle environmental impacts

The results show that integrating carbon capturing technologies in building heating systems reduced the life cycle global warming potential significantly. The life cycle results indicated that the reduction of life cycle global warming by integrating MEA-based chemical absorption carbon capturing technology was substantially lower than the reduction of operational GHG emissions estimated in Chapter 4. The considerable differences of operational and life cycle GHG emission reduction in Scenario C1.1 to Scenario C1.4 were caused by the GHG emissions in different process phases in the life cycle of the carbon capturing technology. In addition, integrating a KOH-based commercial building-level carbon capturing system increased the overall global warming potential without considering any allocation. However, when global warming was allocated into heat generation, the KOH-based carbon capturing technology reduced global warming significantly and the reduction of global warming was higher than the operational GHG emissions reduction. That was caused by the higher economic value of the by-products generated in the KOH-based carbon capturing technology, which allocates the majority of environmental impacts to by-product generation. This was due to the assumption in the economic allocation that energy use is proportional to the economic value of the product.

In addition, it is important to consider the actual production process of by-products in the industry. The literature shows that K_2CO_3 production uses the same reaction as in the KOH-based building-level carbon capturing process. In addition, a considerable amount of thermal and electric energy is required for the production process as the reaction occurs in an aqueous medium and the K_2CO_3 must be crystalized continuously [137]. Therefore, allocating a majority of the environmental impacts to K_2CO_3 production is justifiable. When considering CO_2 production, a majority of the CO_2 is recovered from highly concentrated gas mixtures [148]. Ammonia production is an industry that produces CO_2 as a by-product [149]. Since the CO_2 is captured from a highly concentrated source, it can be assumed that the energy and raw material requirement is low for the production of CO_2, as opposed to capturing CO_2 from low concentration gases such as flue from natural gas combustion [148]. Therefore, the cost of CO_2 must reflect the impacts behind conventional production of CO_2 that can be replaced by CO_2 captured from building heating systems.

Although both types of carbon capturing systems reduce global warming potential, most of the non-GHG impacts were considerably increased when economic allocation was not considered. In particular, the KOH-based building-level carbon capturing scenarios have higher non-GHG impacts than the chemical absorption-based CO_2 separation systems, except for the fossil fuel depletion. However, when the environmental impacts were allocated to heat generation, the KOH-based carbon capturing system decreases impacts such as ozone depletion, smog, and fossil fuel depletion due to the higher economic value of the by-products. Chemical absorption based CO_2 separation systems increased all the non-GHG impacts even when considering economic allocation.

The LCA study also revealed that the MEA based carbon capturing system emits gases such as NH_3 and Formaldehyde during the carbon capturing process. These emissions can cause safety issues in the residential building environment, unlike controlled environment such as fossil fuel power generation plants. Therefore, additional safety measures must be established on carbon capturing technologies when implementing in the building scale.

It can be observed that the variable cost of natural gas in NS, QC, and NB was higher than in other provinces. As a result, the environmental impacts allocated to heat generation were higher than in other provinces. The higher variable cost reflects the required energy and materials for natural gas transportation from the producers to these provinces, as NS and NB produce less natural gas compared to other provinces [150].

The study considered the global average data for most of the raw material production except KOH. It was considered that KOH was produced in the USA, as the majority of KOH was imported from USA to Canada and the KOH-based building-level carbon capturing system consumes a substantial amount of KOH during the carbon capturing process [127]. However, it is important to consider that life cycle impacts can be considerably different depending on the region where the material is produced. The production of KOH consumes a substantial amount of electricity for the electrolysis process, where the environmental impacts of electricity generation are significantly changed with the energy sources used in a particular region. Therefore, the results may alter with the region where materials such as KOH are produced.

The study also considered global average data for the transportation of raw material, based on US commodity flows, due to lack of specific data. The transportation data can also vary significantly. However, the raw material requirement of the chemical absorption CO_2 separation system is notably low when the system starts to operate as the chemical was reused in the carbon capturing process. In contrast, the transportation data may affect the KOH-based building-level carbon capturing system as there is no reuse of the KOH raw material. In addition, it was considered that the by-products (CO_2 and K_2CO_3) travelled a distance of 50 km from the buildings [124]. It was assumed that cities have enough demand for the by-products generated from the building-level carbon capturing; however, if demand is low, the by-products may have to be transported long distances, thereby increasing the environmental impacts.

5.4.2 Life cycle cost

The capital cost estimation method used in this study to estimate the cost of different capacities of the MEA-based chemical absorption carbon capturing system is known as the order-of-magnitude method [30]. It is commonly used in chemical engineering applications for initial feasibility assessment and technology screening [30]. Although the method can be used to estimate the capital cost of the whole plant, the study considered estimating the specific equipment costs first to estimate the total equipment cost [151] [30], as the capital cost of a large carbon capturing facility may include other components such as construction of buildings [33]. This method is known to have low accuracy, which can result in error of ± 40% [30]. Therefore, the uncertainty of the model must be considered in future studies. In addition, the components of the total capital cost, such as electrical systems and instrumentation, were considered as a percentage of equipment cost [132]. Therefore, the uncertainty of the equipment cost also transferred to other components of the capital cost.

The results indicate that the operational costs of all the carbon capturing scenarios were increased substantially. The KOH-based building-level carbon capturing systems had lower net annual operational cost compared to the MEA-based chemical absorption system. This was a result of the significant amount of revenue generated by the by-products in KOH-based building-level carbon capturing systems. The revenue generated from the captured CO_2 in MEA-based chemical absorption systems was significantly lower than the overall operational cost. The results also clearly show that the maintenance cost of the carbon capturing scenarios was significant and only second to the annual natural gas cost of the building heating systems. The maintenance cost of the MEA-based chemical absorption systems was estimated as a fixed (2.5%) percentage of the capital cost. Therefore, the uncertainty of the capital cost estimation method must be considered in the feasibility assessment process. Although the KOH-based system with heat recovery process saved natural gas by heat recovery, it can be seen that the overall operational cost is higher when compared to the same carbon capturing system without heat recovery in most provinces, due to increased electricity consumption. The results may also alter when the KOH-based system is connected to a building with a higher domestic hot water consumption than residential buildings, as the electricity consumption remains constant.

The study included the carbon tax associated with the natural gas price when calculating the operation cost (only in ON, QC, BC, and AB). However, natural gas combustion only released a fraction of the CO_2 emissions from the combustion products due to the carbon capturing system integration. Therefore, operational cost must be lower for natural gas due to this fact. In addition, provinces such as BC in Canada reduce the carbon-tax cost of systems that have lower emissions than the benchmark systems. These policies must be considered when evaluating the operational cost calculations as they may reduce the operational cost. In addition, extremely high investment cost may be a barrier for implementation of carbon capturing systems. Therefore, it is important to develop policies to provide rebates and incentives for implementing carbon-capturing in building-level.

Although the CO_2 storage sizes of MEA based chemical absorption carbon capturing systems were determined by considering the maximum CO_2 emissions in the buildings, the by-product storage size of KOH based carbon capturing system was considered to be fixed. Therefore it is important to notice that the percentage change of environmental impacts and LCC can be changed with the building energy load, which is affected by the building size, heating system efficiency, and the climatic region where the building is located.

The results show that integrating carbon capturing reduced the GHG emissions while increasing life cycle cost and most of the non-GHG environmental impacts compared to conventional natural gas heating systems. In addition, there is considerable uncertainty with the results due to the lack of data and model inaccuracies, while the decision-making process is also uncertain as it includes the decision maker’s preferences. Therefore, implementing carbon capturing at the building level must be considered using a holistic and flexible decision making approach that includes the effect of the above mentioned indicators, uncertainties, and different stakeholder preferences simultaneously.

5.5 Summary

Although carbon capturing technologies can reduce the carbon foot print by capturing CO_2 from fossil fuel combustion, there are many adverse environmental and economic impacts related to this technology. The main goal of this section is to identify those impacts based on life cycle thinking. This section developed life cycle assessment (LCA) and life cycle cost models (LCC) based on the suitable carbon capturing, storage, and utilization strategies identified through the comprehensive literature review. The study also demonstrated those models using the case study presented in Chapter 4 and compiled as a life cycle environmental and cost database.

The results show that the C1 scenarios have lower life cycle global warming potential compared to the operational GHG emission reduction. The C2 scenarios have higher reduction in global warming potential due to the allocation of total environmental impacts to the by-product. The results also indicate that the carbon capturing scenarios increased several non-GHG environmental impacts. The LCC results showed that the C1 and C2 scenarios increased the LCC considerably compared to natural gas conventional heating systems. Therefore, it is important to consider environmental and economic impacts together when assessing the applicability of carbon capturing technologies at the building scale.

The economic allocation method was used to allocate the environmental impacts between heat generation and by-products. However, the economic value can change with the demand for the product (in this case study, products are CO_2 and K_2CO_3). In addition, the capital cost estimation method is known to have significant uncertainty in the results. Therefore, it is necessary to consider that uncertainty when evaluating the applicability of the carbon capturing technologies.

Chapter 6: Comparison of Environmental and Economic Impacts of Carbon Capturing against Commonly Used Heating Systems

6.1 Background

Natural gas heating systems that are integrated with building-level carbon capturing technologies can be considered as alternative energy sources with lower GHG emissions. On the other hand, there are commonly used building heating systems that may have the potential to reduce GHG emissions by reducing the energy load or using cleaner energy sources. Therefore, it is necessary to compare the performance of building-level carbon capturing systems against commonly used heating systems.

Using renewable energy sources for building heating is a widely adopted method to reduce energy costs and building energy-related GHG emissions. Although solar energy is used for electricity generation in building and water heating, it is not commonly used for space heating applications due to limited solar energy in extreme climates [8]. Geothermal energy is considered renewable energy [9]. In addition, electricity is generated using renewable energy in some provinces in Canada. Using electricity in these provinces would be more environmentally friendly than using fossil fuel combustion to generate heat, although it increases energy costs due to electricity's higher price compared to natural gas.

Since the case study in Chapter 4 and Chapter 5 was related to residential space heating in Canadian provinces, it is important to consider commonly used heating systems in Canada. The 2015 energy use data handbook shows that 47% of residential buildings use natural gas, while 29% of residential buildings used electricity for space heating systems [117]. In addition, 5% of residential buildings are equipped with heat pumps, while the remaining heating systems use coal, wood, and heating oil [117].

Canada has mainly focused on changing its building heating energy sources from conventional natural gas heating systems to more efficient electric heat pumps. Air source heat pumps require approximately 50% less electric energy to produce heat than electric baseboards [116]. Moreover, ground source heat pumps require one third of the electricity to produce heat due to the higher coefficient of performance [116]. The report known as "Canada's Energy Future 2018" indicates that the adoption of heat pumps is expected to increase from 10% to 20% by 2030. In many provinces, this will reduce energy consumption and operational cost. In addition, GHG emissions from building heating can be reduced if provinces have cleaner energy sources when producing electricity.

Although carbon capturing technologies reduce GHG environmental impacts, they show an increase of non-GHG environmental impacts and economic impacts when integrated with current energy systems. Therefore, considering all this information in different stakeholder perspectives is important when comparing the performance of building carbon capturing against commonly used building heating systems.

Multi-criteria decision making (MCDM) is commonly used to assess sustainability in energy systems and energy saving measures [152] [153]. It is a decision support technique that is used when there are multiple conflicting objectives, different perspectives of the decision makers, and different types of data at the same time [102]. In addition, there are often data and information uncertainties, and many studies use fuzzy logic-based MCDM techniques to account for these uncertainties [154] [102]. Considering the above information, the study developed a comparative performance assessment framework to assess the regional applicability of building-level carbon capturing systems based on life cycle environmental and economic impacts using fuzzy MCDM techniques.

6.2 Methods and Procedure

Chapter 5 showed the performance of implementing carbon capturing systems in natural gas heating systems based on life cycle environmental impacts and life cycle cost. The aim of this section is to evaluate the regional applicability of integrating carbon capturing systems based on the life cycle environmental and economic impacts by comparing them with commonly used heating systems. A comparative performance evaluation framework was developed to aggregate the life cycle environmental and economic impacts of heating systems in different regions. The multi-attribute decision making method was used to aggregate the impacts and rank the heating system scenarios. It helps to identify the regional applicability of the carbon capturing scenarios. The overall methodology is shown in Figure 6-1. The subsequent sections elaborate on the specific details of the methods and procedures followed to establish the model.

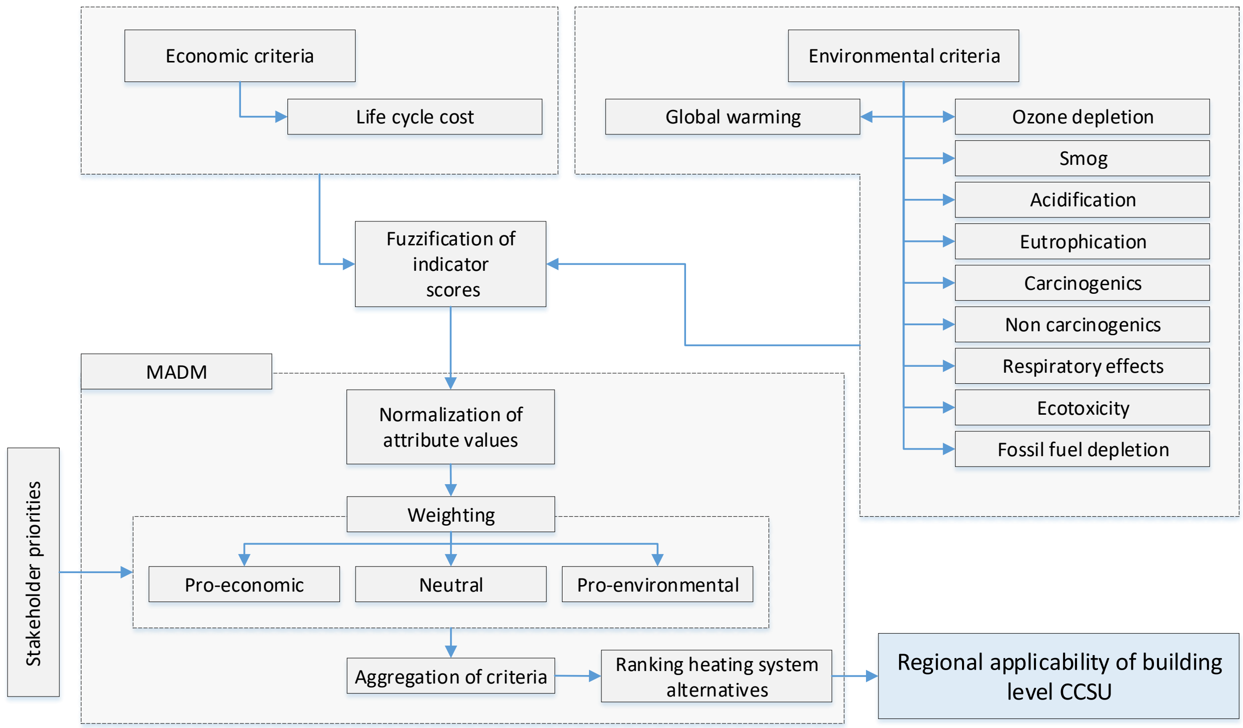

Figure 6-1: Comparative performance assessment model for building heating systems integrated with carbon capturing

6.2.1 Multi-criteria decision making

Since this study considered economic and environmental impacts of carbon capturing systems, the impacts must be evaluated by considering multiple stakeholder priorities. Multi-attribute decision making (MADM) can be used to compare alternatives against each other by considering multiple attributes [155]. The 10 life cycle impact categories and the life cycle cost values are considered as attributes, and the 8 scenarios were considered as alternatives.

6.2.1.1 Decision making under uncertainty

Most decision-making problems consist of uncertainties of data, model, and parameters. It is important to consider the uncertainties in the decision-making process. The study used fuzzy data to consider the uncertainty, and the data are represented by triangular fuzzy numbers. A fuzzy number is defined as a triangular fuzzy number (l, m, u), when its membership function is equal to Equation 6-1 below [156].

$$\mu(x) = \begin{cases} \frac{1}{m-l}x - \frac{1}{m-l}, & x \in [l,m], \\ \frac{1}{m-u}x - \frac{1}{m-u}, & x \in [m,u], \\ 0 & otherwise \end{cases}$$ ----------- Equation 6-1

Where,

$\mu(x)$ = The membership function of the fuzzy set

l = Lowermost value of the support of the fuzzy number

u = Uppermost value of the support of the fuzzy number

m = Most probable or modal value

$l \leq m \leq u$

Table 6-1 below shows the operations on the fuzzy triangular numbers $\widetilde{n_1}$ = (n_{1l}, n_{1m}, n_{1u}) and $\widetilde{n_2}$ = (n_{2l}, n_{2m}, n_{2u}) [156] [154].

Table 6-1: Triangular fuzzy number operation

Operation	***Equation***
Addition	$\tilde{n}_1 + \tilde{n}_2 = (n_{1l}+n_{2l}, n_{1m} + n_{2m}, n_{1u} + n_{1u})$
Multiplication	$\tilde{n}_1 \times \tilde{n}_2 = (n_{1l} \times n_{2l}, n_{1m} \times n_{2m}, n_{1u} \times n_{1u})$
Negation	$-\tilde{n}_1 = (-n_{1u}, -n_{1m}, -n_{1l})$
Division	$1/\tilde{n}_1 \cong (1/n_{1u}, 1/n_{1m}, 1/n_{1l})$
Scalar multiplication	$\tilde{n}_1 = (kn_{1l}, kn_{1m}, kn_{1u})$; if k > 0
	$\tilde{n}_1 = (kn_{1u}, kn_{1m}, kn_{1l})$; if k < 0

<u>Ranking Fuzzy Numbers</u>

Ranking fuzzy numbers with maximizing set and minimizing set [157] [158] is a commonly used method to rank fuzzy numbers [159] [160]. The procedure of ranking is shown below [161].

Let, $\mu_i(x)$ be the membership function of i^th fuzzy number from the set of fuzzy numbers that must be ranked. Then, Equation 6-2 and Equation 6-3 can be used to calculate the maximizing set and minimizing set.

$$\mu_M(x) = \begin{cases} \left[\dfrac{w_i(x - x_{min})}{(x_{max} - x_{min})}\right]^r, & x_{min} < x < x_{max} \\ 0 \ , & Otherwise \end{cases} \quad \text{------ Equation 6-2}$$

$$\mu_m(x) = \begin{cases} \left[\dfrac{w_i(x - x_{max})}{(x_{max} - x_{min})}\right]^r, & x_{min} < x < x_{max} \\ 0 \ , & Otherwise \end{cases} \quad \text{------ Equation 6-3}$$

Where,

$\mu_M(x)$ = Maximizing set

$\mu_m(x)$ = Minimizing set

x_{min} = inf (x)

x_{max} = sup (x)

w_i = sup (μ_i (x))

r = constant = 1 (r = 1 : Decision maker is conservative; r = 0.5 : Decision maker is a risk taker, r = Decision maker is a pessimist)

Let's define the $U_M(A)$ as the right utility value and $U_m(A)$ as the left utility value using Equation 6-4 and Equation 6-5 shown below.

$$U_M(A) = \sup(\mu_i(x) \cap \ \mu_M(x)) \quad \text{------ Equation 6-4}$$

$$U_m(A) = \sup(\mu_i(x) \cap \ \mu_M(x)) \quad \text{------ Equation 6-5}$$

The total utility value of the i^th fuzzy number that is used to rank the fuzzy numbers can be calculated using Equation 6-6 below.

$$U_T(A) = (U_M(A) + w - U_m(A))/2 \qquad \text{------ Equation 6-6}$$

Where,

$U_T(A)$ = Overall utility value

w = inf (w_i)

Normalization of Fuzzy Numbers

The normalization of fuzzy numbers is defined as follows [158].

Let $\hat{n}_{ij} = (n_{ijl}, n_{ijm}, n_{iju})$ the performance score of the ith alternative in jth criteria, $n_{max} = \max(n_{iju})$, and $n_{min} = \min(n_{ijl})$. Then the normalized performance score can be calculated by using Equation 6-7 below.

$$\hat{P}_{ij} = \begin{cases} \left(\dfrac{n_{ijl} - n_{min}}{n_{max} - n_{min}}, \dfrac{n_{ijm} - n_{min}}{n_{max} - n_{min}}, \dfrac{n_{iju} - n_{min}}{n_{max} - n_{min}}\right); for\ benefit\ criteria \\ \left(\dfrac{n_{max} - n_{iju}}{n_{max} - n_{min}}, \dfrac{n_{max} - n_{ijm}}{n_{max} - n_{min}}, \dfrac{n_{max} - n_{ijl}}{n_{max} - n_{min}}\right); \quad for\ cost\ criteria \end{cases} \qquad \text{--- Equation 6-7}$$

Where,

$\hat{P}_{ij}$= Normalized score in the form of $\hat{P}_{ij} = (p_{ijl}, p_{ijm}, p_{iju})$

Uncertainty Tolerance

The study considered 40% tolerance in the equipment cost estimation method used on System C1 to construct the triangular fuzzy numbers. In addition, the investment cost and maintenance cost were recalculated accordingly by considering the lower and upper bound of the equipment cost. The price of the by-product (K_2CO_3) was varied from CAD 1.70 to CAD 4.00 according to the manufacturer of System C2. It was assumed 10% tolerance level for the remaining parameters according to previously published literature [20].

6.2.1.2 Aggregation of indicator scores

The fuzzy Weighted-Sum Model was used to aggregate the indicator scores. It is considered the most well-known and most commonly used method [101] in decision making applications [156]. The procedure used to aggregate the fuzzy performance scores of the alternatives is shown below.

Let $\tilde{P}_{ij} = (p_{ijl}, p_{ijm}, p_{iju})$ be the performance score of the i[th] alternative in j[th] criterion and $\tilde{w}_j = (w_{jl}, w_{jm}, w_{ju})$. Then the aggregated performance score can be calculated using Equation 6-8 below.

$$P^*_{FWSM} = max \sum_{j=1}^{N} \hat{p}_{ij} \widehat{W}_j \qquad \text{------ Equation 6-8}$$

Where, P^*_{FWSM} is the aggregated performance score and N is the number of criteria used in the study. The aggregated performance scores of alternatives are ranked using a suitable ranking method (This study considered ranking fuzzy numbers with maximizing set and minimizing set).

Weighting

Weights were assigned for the attributes based on the decision maker's priorities [155]. The model, therefore, provides a holistic view of the regional applicability of integrating carbon capturing systems based on different stakeholder perspectives. The study used three different weighting schemes to address different stakeholder priorities.

- *Pro-economic*: The economic performance of the heating systems was considered as more important. 80% of the weight was assigned for the LCC of the heating systems and 20% was assigned for life cycle environmental impacts.
- *Neutral*: Both economic and environmental performance of the heating systems were considered equally important. Therefore, each of the LCC and life cycle environmental impacts were assigned 50% of the weight.
- *Pro-environmental*: The environmental performance of the heating systems was considered more important. 80% of the weight was assigned for the life cycle environmental impacts of the heating systems and 20% was assigned for LCC.

The summary of the weighting schemes is shown in Table 6-2.

Table 6-2: Weighting schemes

Weighting Scheme	***LCC***	***LC Impacts***
Pro-economic	0.8	0.2
Neutral	0.5	0.5

Weighting Scheme	**LCC**	**LC Impacts**
Pro-environment	0.2	0.8

The TRACI 2.1 life cycle impact assessment method provides 10 life cycle environmental impact categories. Therefore, it is important to consider the importance of the environmental impacts when assigning the weights. The study considered the life cycle environmental assessment weights based on percentage importance given by LCA experts [162] as shown in the Table 6-3. Since [162] did not consider respiratory effects, the importance given for air pollutants was considered to represent the importance of respiratory effects.

Table 6-3: Weights assigned for life cycle environmental impacts

Weighting Scheme	***Weight (Between life cycle impacts)***
Ozone depletion	0.01
Global warming	0.55
Smog	0.02
Acidification	0.01
Eutrophication	0.03
Carcinogenics	0.07
Non carcinogenics	0.02
Respiratory effects	0.14
Ecotoxicity	0.03
Fossil fuel depletion	0.11

6.2.2 Case specific methods

The study considered electric heating system (electric baseboard), air-source heat pump, and ground-source heat pump to compare performance with the natural gas heating systems that are combined with carbon capturing systems. This section introduces Scenario E1, Scenario E2, and Scenario E3 to represent the above-mentioned heating systems respectively in addition to the scenarios mentioned in Chapter 4 and Chapter 5. The comparative performance assessment framework was used to evaluate the regional applicability of the above scenarios and Scenario 0, Scenario C1.1 to Scenario C1.4, Scenario C2.1, and Scenario C2.2 using life cycle impacts and the life cycle cost obtained in Chapter 5. The summary of the scenarios is shown in Table 6-4 below.

Table 6-4: Summary of the scenarios

Scenario type	***Scenario***	***Description***
Base Scenario	Scenario 0	Residential space heating system that is equipped with a natural gas condense furnace.
Natural gas heating system is equipped with carbon capturing technology	Scenario C1.1	Residential space heating system that is equipped with a natural gas condense furnace and MEA based chemical absorption technology that has 25% of the maximum CO_2 storage capacity. (90% carbon capturing efficiency)
	Scenario C1.2	Residential space heating system that is equipped with a natural gas condense furnace and MEA based chemical absorption technology that has 50% of the maximum CO_2 storage capacity. (90% carbon capturing efficiency)
	Scenario C1.3	Residential space heating system that is equipped with a natural gas condense furnace and MEA based chemical absorption technology that has 75% of the maximum CO_2 storage capacity. (90% carbon capturing efficiency)
	Scenario C1.4	Residential space heating system that is equipped with a natural gas condense furnace and MEA based chemical absorption technology that has the maximum CO_2 storage capacity. (90% carbon capturing efficiency)
	Scenario C2.1	Residential space heating system that is equipped with a natural gas condense furnace and KOH based commercial building-level carbon capturing technology without heat recovery. (13% carbon capturing efficiency)

Scenario type	**Scenario**	**Description**
	Scenario C2.2	Residential space heating system that is equipped with a natural gas condense furnace and KOH based commercial building-level carbon capturing technology with heat recovery. (13% carbon capturing efficiency)
Alternative building heating energy sources	Scenario E1	The natural gas heating system is replaced with electric baseboard system
	Scenario E2	The natural gas heating system is replaced with electric air-source heat-pump.
	Scenario E3	The natural gas heating system is replaced with electric ground-source heat-pump.

The building energy models considered in Chapter 4 were used to evaluate the building space heating energy performance when using the electric heating system, air-source heat pump, and ground-source heat pump. The air source and ground source heating systems may not be able to supply heat if the outside air temperature (for air-source heat pumps) or ground (for ground-source heat pumps) is below the temperature rating. Therefore, the heating systems must include secondary heating systems. It was assumed that the buildings are equipped with electric baseboard as the secondary heating system when using heat pumps. In addition, the study did not consider the cooling capability of the heat pumps, as the main focus of this study is the GHG emission reduction of space heating systems. It was considered that the efficiency of the electric baseboard is 100%, coefficient of performance (COP) of air-source heat pump is 2.3 [163], and the COP of the ground-source heat pump is 3.15 according to average performance data [164].

<u>Life Cycle Cost Estimation</u>

The building energy model was used to estimate the capacity of the heating systems in Scenario E1, Scenario E2, and Scenario E3. RSMeans construction cost estimation database was used to estimate the investment cost (acquisition cost) of the heating systems. The electricity cost was calculated using the energy consumption results obtained from the energy simulation in each scenario and the provincial electricity prices shown in Table 5-3. The life cycle cost was estimated using the life cycle estimation model used in Equation 5-3 in Chapter 5.

Life Cycle Inventory Development and Impact Assessment

The life cycle inventory of the construction of the heating systems was developed using the Ecoinvent 3.1 database. It was used to estimate the life cycle impacts related to a 30 kW heat pump, which is used to estimate the construction of both air-source and ground-source heat pumps by assuming that material and energy flows of the construction of the heating systems are proportional to the capacity. In addition, the ground-source heat pump consists of bore holes that must be constructed when installing heat pumps. The life cycle inventory of the construction of bore holes was also developed using the Ecoinvent 3.1 database. The scenarios were then simulated in the SimaPro LCA software with the help of operational energy equipment obtained from the building energy simulation. The TRACI 2.1 life cycle impact assessment method was used to evaluate the life cycle impacts, similar to the LCA conducted in Chapter 5.

6.3 Results

This section presents the regional applicability of the heating system scenarios in different provinces in Canada based on the case study presented in Chapter 4 and Chapter 5. In addition, the results obtained from the energy simulation and life cycle costing of Scenario E1, E2, and E3 used to compare with carbon capturing scenarios are also presented. The life cycle environmental impacts of Scenario E1, E2, and E3 are not included in this section as the operational environmental impacts are mainly based on the electricity sources used in provinces that have been discussed in-depth in Chapter 5.

6.3.1 Energy consumption and life cycle cost of building heating systems

Figure 6-2 shows the annual energy consumption of Scenario E1, Scenario E2, and Scenario E3. The results show that air source heat pumps (Scenario E2) can reduce energy consumption by 9% to 40% compared to electric baseboards. The results show that provinces such as BC have higher energy reduction when using air source heat pumps compared to provinces such as AB. This can be a result of much lower atmospheric temperature in provinces such as AB, which is located in zone 7A climatic region, while BC is located in zone 4. However, the results show that ground source heat pumps reduce the space heating energy consumption by 59% to 61% as the ground temperature is not considerably changed with the climatic regions.

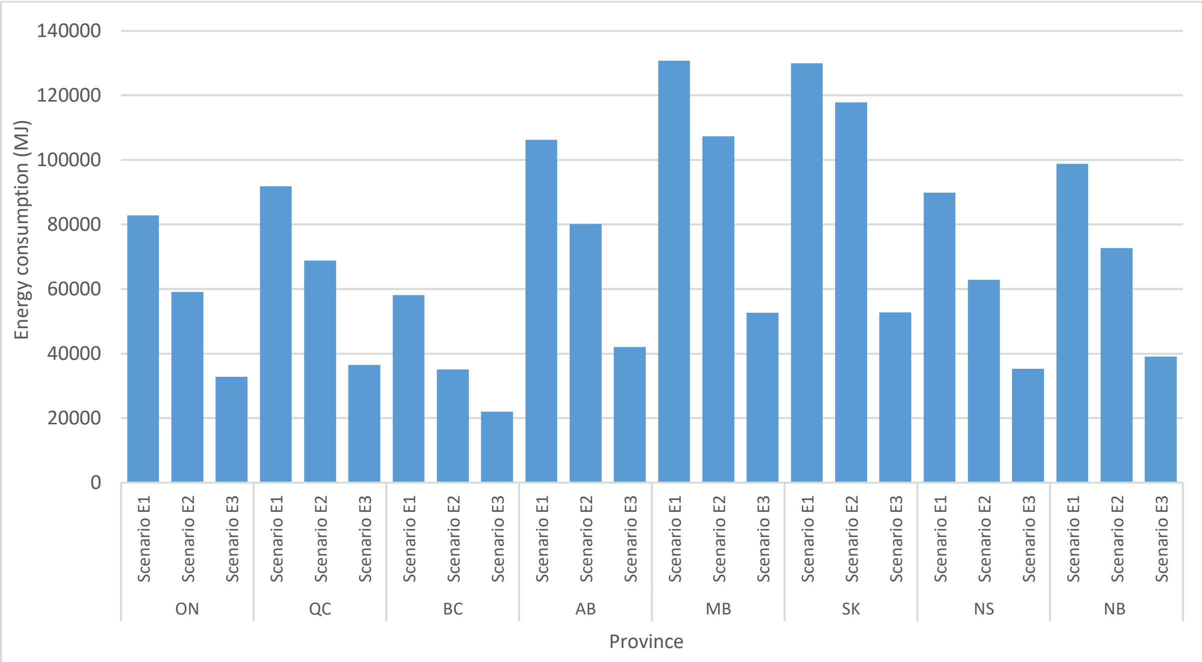

Figure 6-2: The energy consumption of energy systems in Scenario E1, Scenario E2, and Scenario E3

Figure 6-3 shows the average life cycle cost of the building heating scenarios. It shows that the air source heat pumps increase the life cycle cost in most provinces except NS, which has 5% of reduction. Ground source heat pumps reduce the LCC by 2% to 23% in ON, AB, SK, NS, and NB, while increasing the LCC cost in QC, BC, and MB by 4% to 43%. The highest increase is in QC. Although the operational cost is significantly reduced in heat pump scenarios due to the lower energy consumption, higher investment cost may increase the life cycle cost compared to Scenario E1.

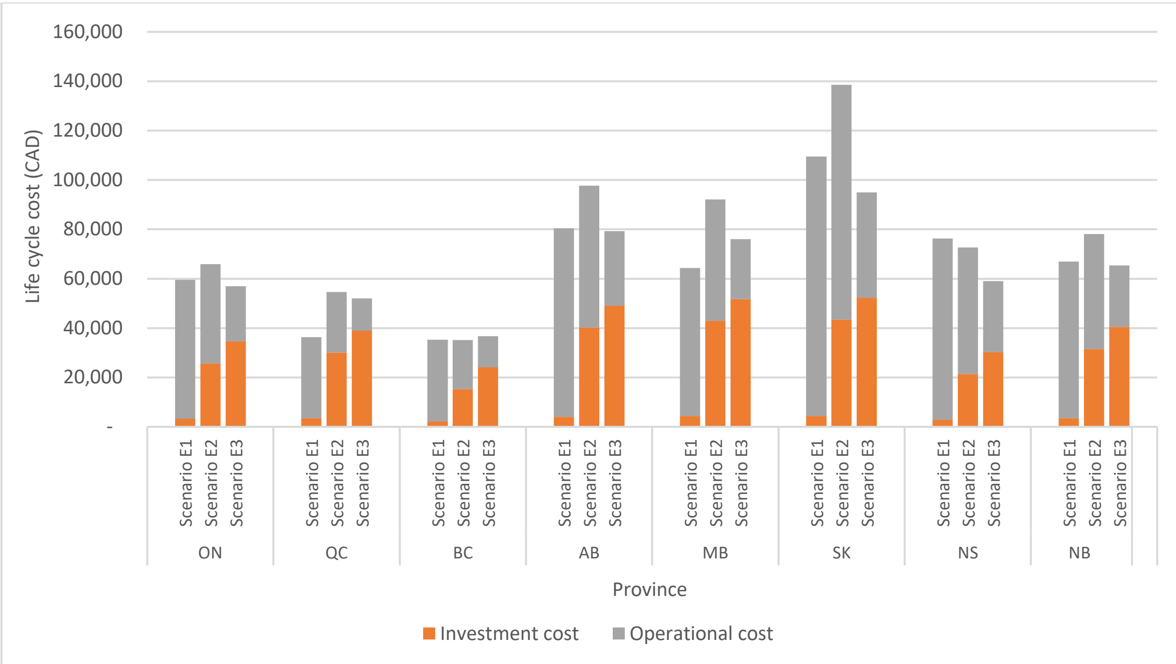

Figure 6-3: Life cycle cost of energy systems

The results also show that the life cycle cost is higher than Scenario 0, while significantly lower than Scenario C1.1 to Scenario C1.4. The life cycle costs of Scenario E1, E2, and E3 are lower than Scenario C2.1 and C2.2 in provinces except AB and MB. The LCC of Scenario C2.1 and C2.2 is lower than all the electricity-based energy sources in AB, and lower than Scenario E2 and Scenario E1 in MB.

6.3.2 Regional applicability of building-level carbon capturing

Figure 6-4 shows the rank of each energy system based on the overall score gained from the comparative assessment model for pro-economic, neutral, and pro-environmental stakeholder perspectives. The figures clearly indicate that none of the C1 scenarios become the best alternative in all provinces and all stakeholder priorities.

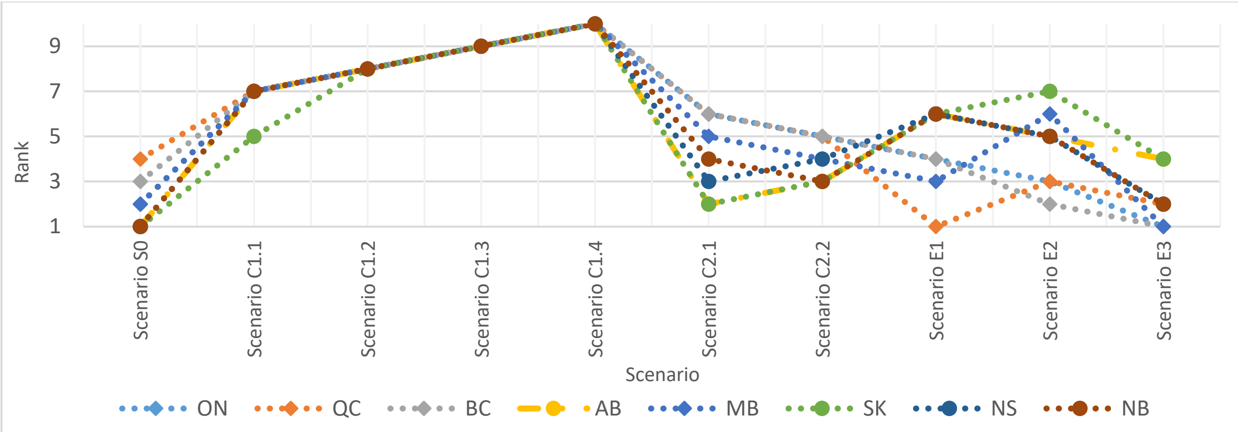

Figure 6-4: Regional applicability of building heating system – Pro-Economic

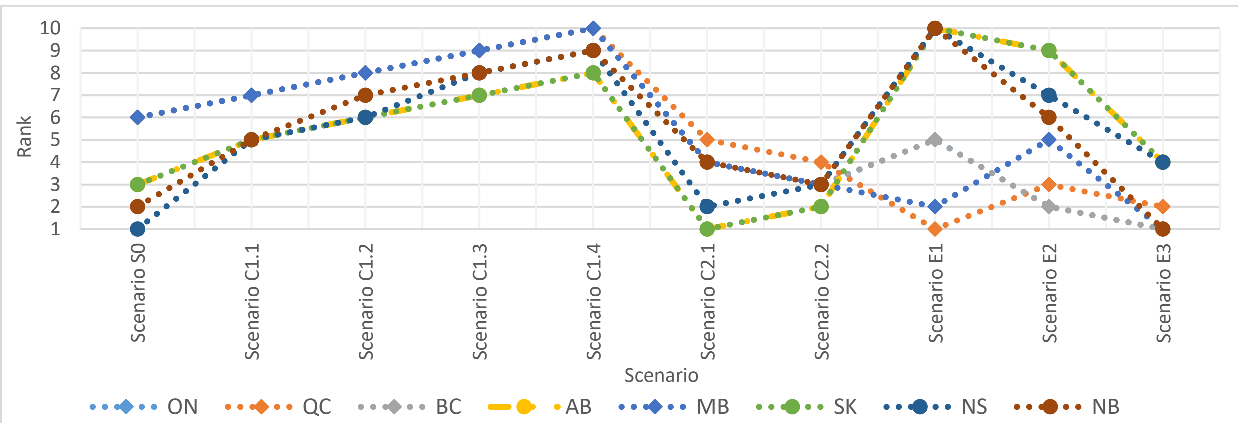

Figure 6-5: Regional applicability of building heating system – Neutral

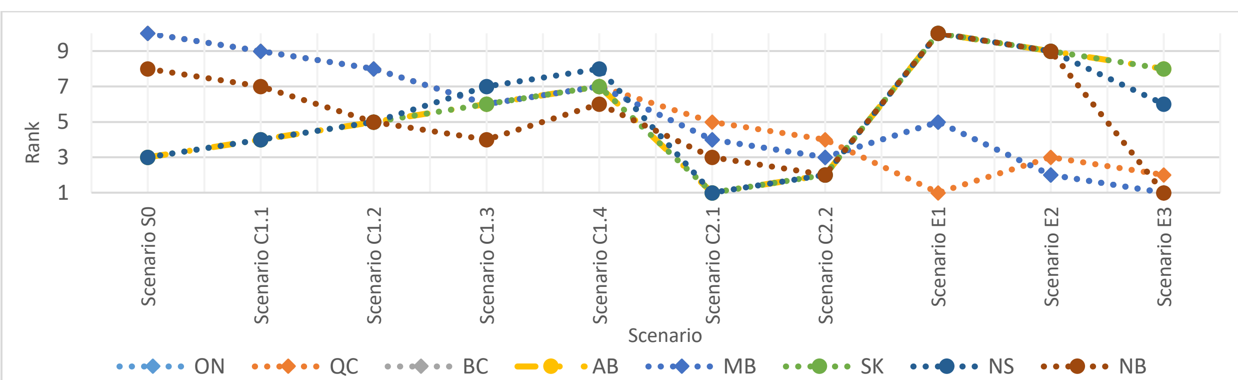

Figure 6-6: Regional applicability of building heating system – Pro-Environmental

The above figures show that ground source heat pump in Scenario E3 is the best alternative in ON, MB, and BC according to pro-economic, neutral, and pro-environmental stakeholder perspectives. That can be expected as these provinces depend mainly on renewable energy sources, and electricity has lower environmental impacts, which are considered more important. However, the best alternative in QC is electric baseboard (Scenario E1), due to its lower life cycle cost. Although electric baseboard consumes more energy, the life cycle cost is lower than both Scenario E2 and Scenario E3 as a result of much lower electricity prices in QC compared to all other provinces. In addition, QC has significantly lower global warming potential in electricity generation. As a result, it has less increase in life cycle environmental impacts compared to heat pump scenarios, which make it the best alternative.

In AB, conventional natural gas space heating systems become the best alternative from a pro-economic perspective. Scenario C2.1 is the best alternative from both a neutral and a pro-environmental perspective. The heating systems in SK also obtain the same rank as can be seen in AB. The rank can be explained as follows. Natural gas systems have significantly lower life cycle cost than all the other scenarios. In addition, they have better environmental performance than electricity-based heating systems in provinces that depend mainly on fossil fuel to generate electricity, according to the LCA results obtained from this study. Therefore, it becomes the best alternative in provinces such as AB and SK. Although Scenario C2.2 recovers heat and reduces natural gas consumption, Scenario C2.1 becomes the best alternative in AB from the neutral and pro-environmental perspectives. This can be expected as Scenario C2.2 increases electricity consumption significantly due to the operation of the water pump, which increase the environmental impacts in provinces that use fossil fuel for electricity generation.

In NS, Scenario 0 becomes the best alternative from the pro-economic and neutral perspectives, which is slightly different than in AB and SK. This can be a result of higher environmental impacts when producing electricity in NS compared to all other provinces, which increases the environmental impacts of Scenario C.2.1 and C2.2 and reduces the overall score compared to provinces such as AB and SK. However, the C2.1 and C2.2 scenarios have fewer life cycle environmental impacts than Scenario 0. As a result, Scenario 2.1 becomes the best alternative from a pro-environmental perspective. Scenario 0 becomes the best alternative from an economic perspective in NB. Since NB's electricity generation has lower environmental impacts, Scenario E3 becomes the best alternative from the neutral and pro-environmental perspectives.

6.4 Discussion

The above results show the regional applicability of building-level carbon capturing compared to the commonly used heating systems. The applicability of integrating MEA-based chemical absorption carbon capturing technologies was low compared to all the other scenarios due to the substantial increase in life cycle cost. None of the carbon capturing scenarios became the optimum choice in pro-economic scenarios in any province. Furthermore, the base scenario becomes the best scenario in provinces that use fossil fuel combustion for electricity generation when considering economic perspective. Integrating KOH-based building-level carbon capturing technology without heat recovery was the only scenario that becomes the best choice as a carbon capturing scenario from neutral and pro-economic perspectives, where the grid electricity depends on fossil fuel combustion. Ground source heating systems become the best alternative in provinces that depend on renewable energy, except QC. Electric baseboard systems become the best alternative in QC as a result of considerably lower electricity prices.

One of the interesting observations is that integrating MEA-based chemical absorption carbon capturing technology had a lower score than conventional natural gas heating systems in AB, SK, and NS, from a pro-environmental perspective. Integrating KOH-based building-level carbon capturing technology became the best scenario in the above provinces in neutral and pro-environmental perspectives. This can be a result of lower GHG emission reduction in MEA-based chemical absorption carbon capturing technologies in these provinces, while having significantly higher LCC. This can be further justified by the scores of MEA-based chemical absorption carbon capturing technologies in provinces such as ON, BC, and QC, which are higher than the conventional natural gas heating system as a result of higher GHG emission reduction. Although integrating KOH-based building-level carbon capturing technology with heat recovery reduced the environmental impacts and operational cost by saving natural gas consumption, the overall score was less than the system without heat recovery in provinces where fossil fuel is used to generate electricity. However, the overall score of KOH-based building-level carbon capturing technology with heat recovery was higher than the system without heat recovery in provinces where renewable energy is used to generate electricity. This result shows that the increase of electricity consumption in KOH-based building-level carbon capturing technology with heat recovery affects the overall score compared to the reduction of natural gas consumption.

Using fizzy based MADM approach helps the decision maker to observe the possibilities that the results can be changed by visualizing the final fuzzy scores of the alternatives. It can be seen that there is no or less overlap between the final scores of the heating systems integrated with MEA-based chemical absorption carbon capturing technologies and the best alternatives in all provinces, when considering the graphs of fuzzy numbers of the final scores (See Appendix A, Table A-1, Table A-2, and Table A-3). Therefore, the results clearly show that MEA-based chemical absorption carbon capturing technologies are not sustainable due to the higher LCC, although GHG emissions are reduced. The higher LCC of these technologies caused lower overall scores in all provinces, although the significant uncertainty of the capital cost estimation method is included.

In addition, the LCC results in Chapter 5 showed that the investment cost of the MEA-based chemical absorption carbon capturing technologies was a significant proportion of the life cycle cost. Nonetheless, the cost of the equipment also drops with the technical maturity of the technology. For example, PV solar system prices dropped from $4.9/W to 1.28/W (dropped by 74%) during the period of 1998 to 2011 [165]. Therefore, it is necessary to account for the technical maturity of the carbon capturing technologies when assessing their feasibility in future studies.

The results show that electricity-based heating systems are the best choice in provinces that use renewable energy. However, converting existing natural gas heating systems into electricity-based systems would cause additional issues. It would increase the electricity demand significantly as the majority of buildings in Canada are equipped with natural gas heating systems [117]. As a result, it may require constructing more power generation plants, which would require significant investment cost while creating environmental impacts and increase of electricity costs. Therefore, it is important to consider the overall change in demand and variations in electricity prices when considering implementation of electricity-based heating systems.

The study considered implementing carbon capturing technologies in Canada, where 82% of the electricity is generated using non-GHG emitting sources such as renewable energy and nuclear energy [166]. Canada is more focused on increasing the contribution of non-GHG energy sources for electricity generation and successful in becoming a leader in climate change mitigation. Therefore, technically matured electricity based heating systems have more potential to reduce the building GHG emissions compared to carbon capturing technologies when considering countries such as Canada. On the other, countries such as China, which depend on fossil fuel for electricity generation may require substantial time and investment when transferring into renewable energy. Therefore, implementing carbon capturing technologies in countries that depend on fossil fuel will be more feasible and will act as an interim solution reduce the GHG emissions.

CO_2 utilization technologies are emerging in the world. New technologies such as CO_2-cured concrete and CO_2-based fuels have significant potential for using large amounts of CO_2 [12]. Technologies such as CO_2-cured concrete are known to be superior to conventional concrete [167], and consequently the success of these technologies will increase demand for CO_2. In addition, higher demand for CO_2 may encourage local production of CO_2, where building-level carbon capturing may be more favourable.

Apart from the environmental and economic impacts of building-level carbon capturing technologies, it is necessary to consider the implications of carbon capturing technology in practical implementation. The building-level CCSU process involves different stakeholders such as building owners, CO_2 utilization industries, chemical industries that use the by-products generated in the carbon capturing process, transportation infrastructure suppliers, public authorities, and technology investors. In addition, the carbon capturing technology require intensive expertise for maintenance and operation. Therefore, frameworks for ownership structure and project financing mechanisms for the building-level CCSU must be considered, which may require governmental support and involvement for policy and infrastructure development. In addition, policies must be developed to provide subsidies and incentives for the technology developers and building owners as the current status of the building-level carbon capturing is not economically viable. Developing the carbon economy in the local community would be also needed to successfully implement carbon capturing at the building level.

The technology readiness of building-level CCSU technology is low due to a lack of research and development. Public funding schemes and research-program investments are more important to encourage development of such technologies in their early technology readiness [168]. In addition, the academic community has an important role to support technology investors in the decision making process [168]. It is necessary to evaluate the risks and benefits associated with different carbon capturing technologies from environmental, economic, and social perspectives by considering future scenarios such as changes in technology maturity, demand for by-products, and development of carbon utilization technologies.

6.5 Summary

This chapter discussed a life cycle thinking-based comparative assessment framework to evaluate the regional applicability of building-level carbon capturing technologies. The framework was demonstrated using a case study that is related to residential building space heating in Canadian provinces. The results showed that carbon capturing technology that separates CO_2 was not compatible in any provinces due to the significant LCC of the process. The carbon capturing technology that produces by-products becomes the best alternative compared to commonly used heating systems in provinces such as AB that use fossil fuel for electricity generation. However, electricity-based heating systems are more suitable for the operation compared to natural gas heating systems integrated with building-level carbon capturing systems in provinces that rely mainly on renewable energy.

Although the results show that separating CO_2 is not a viable method, the results can be affected by numerous factors that are not considered in this study. In particular, demand for CO_2 may increase in the future, while technical maturity reduces the investment and operational cost of the system. In addition, there are other carbon capturing technologies such as membrane separation that have potential to capture CO_2 with significant changes in flue gas recovery. Furthermore, it is essential to study the characteristics of different chemicals that can be used with the carbon capturing process that generate by-products. Studying this area helps to identify more feasible carbon capturing technologies that can be integrated with building-level heating systems.

Chapter 7: Conclusions and Recommendations

Increasing concerns about GHG emissions from the building sector raise the need for alternative GHG mitigation strategies for building heating energy sources. Building-level carbon capturing, storage, and utilization (CCSU) was considered as a GHG mitigation strategy. However, the building-level CCSU technology is in its early adoption stages due to a lack of feasibility studies. This study filled the gap in feasibility assessments of building-level carbon capturing by developing a life cycle thinking-based performance assessment framework and conducting a case study to consider residential space heating systems in Canadian provinces. The performance assessment framework can be used to evaluate the applicability of different building-level carbon capturing technologies compared to alternative GHG mitigation technologies used in building heating systems. The findings of the study also can be used by technology innovators and stakeholders in the building industry to consider fossil fuel heating systems integrated with carbon capturing as an alternative energy source when reducing building GHG emissions.

7.1 Summary and Conclusions

Below is a summary of the study sections and main conclusions derived in them.

In Chapter 3, a comprehensive literature review was conducted on carbon capturing technologies used in fossil fuel combustion sources, the adoptability of carbon capturing technologies at the building scale, and sustainable implementation of carbon capturing at the building scale. The findings of the literature review were used to identify the research gap and need for a life cycle thinking-based performance assessment of implementing carbon capturing at the building scale and defining the methodologies, models, and frameworks.

In Chapter 4, an assessment method was developed to estimate the operational characteristics of building-level carbon capturing technologies. The operational characteristics obtained from the study were annual CO_2 capture rate, annual electricity consumption, annual thermal energy consumption, and annual operational GHG emission reduction of the carbon capturing systems. The outcomes of this assessment method were used as input in the life cycle assessment and life cycle costing models developed in Chapter 5. The developed method can be used by decision makers to estimate the performance characteristics of building-level carbon capturing technologies. The method was demonstrated using a case study, which consisted of chemical absorption carbon capturing technology used in the fossil fuel power generation sector, and commercial KOH-based building-level carbon capturing technology where CO_2 is used to produce K_2CO_3. Although literature -based performance data was available for the chemical absorption technology, the study had to conduct an experimental study on KOH-based commercial building-level carbon capturing technology, due to a lack of data.

Chapter 5 presents the life cycle environmental and cost model that were developed for building-level carbon capturing technologies. The economic allocation method was used in the life cycle assessment model to partition the life cycle impacts between heat generation and by-products. The case study conducted in Chapter 4 was used to demonstrate the life cycle assessment and cost model. TRACI 2.1 LCA method was used to assess the life cycle impacts. The case study revealed that chemical absorption technology has less reduction of global warming compared to the operational GHG emission reduction obtained during Chapter 4. However, the commercial building-level carbon capturing technology has more reduction in global warming compared to operational GHG emission reduction. This is due to the ability of the commercial method to replace the conventional production of by-product. However, both carbon capturing scenarios showed an increase in the remaining environmental impacts without considering economic allocation.

Chapter 6 presents the developed comparative performance assessment model developed to assess the performance of building-level carbon capturing technologies, and compares it against the commonly available building heating systems from different stakeholder perspectives. The model consists of the fuzzy-based MADM method to aggregate the economic and environmental life cycle impacts while handing the uncertainty of data and models. The case study considered in Chapters 4 and 5 demonstrates the comparative performance assessment model. In addition, three alternative building heating energy sources were considered to compare against the carbon capturing scenarios. The results show that alternative energy sources were the best choice in provinces from all stakeholder perspectives, where renewable energy is mainly used for electricity generation. Natural gas conventional heating systems were the optimal choice from a pro-economic perspective in provinces where fossil fuel was used for electricity production. However, the commercial carbon capturing technology without heat recovery was the best choice from neutral and pro-environmental perspectives.

7.2 Originality and Contributions

This research delivers the following original contributions, which will assist in developing building-level carbon capturing technologies and implementation of climate change mitigation strategies.

Investigated carbon capturing technology adaptability and emission reduction potential at the building level: While carbon capturing technologies are used in the fossil fuel power generation sector, investigations of the adaptability of this technology at the building level are lacking. The study conducted a comprehensive literature review and investigated the technical feasibility of implementing different carbon capturing technologies at the building scale. In addition, the operational performance assessment method can be used in future studies to evaluate the performance of building-level carbon capturing technologies.

Established life cycle cost and impacts of building-level carbon capturing systems: Since building-level carbon capturing gains less attention in climate change mitigation studies, using life cycle thinking in performance assessment is overlooked in the literature. Therefore, life cycle cost and life cycle assessment models that were developed in this study contribute to the methodology of future studies. The results obtained from life cycle environmental and cost assessments conducted in this study can be considered a benchmark of building-level carbon capturing technologies. Furthermore, the systematic compilation of life cycle impacts and costs of building-level CCSU technologies is a novel contribution. The knowledge developed in this area will contribute to future research.

Proposed combined framework for comparative performance assessment of building-level carbon capturing: The study presents a comparative performance assessment model considering the economic and environmental performance of building-level carbon capturing technologies. The comparative performance assessment model combined with the operational characteristics estimation model, life cycle assessment model, and economic assessment models can be considered a life cycle thinking-based framework for comparative performance assessment of building-level carbon capturing technologies. This research addresses major limitations in the body of knowledge when considering building-level carbon capturing as a climate change mitigation method.

7.3 Limitations of the study

The following limitations and challenges were encountered when conducting the study. Adjustments were made to reduce the impacts of these limitations.

Uncertainties and gaps in life cycle impact and cost data: Life cycle assessment and costing require extensive amounts of data, and data collection is a challenging task in performance assessments. There is a significant degree of variability in the data available in the literature. In addition, the study conducted an experimental study to assess the performance of commercial building-level carbon capturing systems, which may have variabilities due to equipment errors. Fuzzy techniques were used to address the uncertainty of data in the comparative performance assessment model. In addition, it consisted of different stakeholder perspectives to address the variability of stakeholder preferences.

Limited investigations on realistic supply chains for carbon capturing: The study assumed that the supply chain of the carbon capturing process does not affect feasibility of implementation of building-level CCSU. However, the realistic supply chain of CCSU process may be governed by various factors such as local demand for by-products, local availability of raw materials, and transportation infrastructure development.

Technology acceptance of stakeholders was not evaluated comprehensively: Social acceptance of the technology is important for feasibility. However, social acceptance was not included in the performance assessment framework due to a lack of available data on social acceptance of building-level carbon capturing technologies.

Focus on residential communities: The case study considered applying carbon capturing technologies at the residential building scale. The results obtained from the case study included a life cycle environmental and cost database applicable only to residential buildings. The applicability of carbon capturing technologies may differ in commercial and institutional buildings due to energy use patterns and the scale of the energy system.

Environmental impacts of using the by-products was not considered: The study considered replacing the conventional production of by-products when evaluating the life cycle impacts. However, there can be adverse environmental impacts during the use of by-products depending on the application that uses the by-products. For example, if captured CO_2 is used as a chemical feedstock to produce urea, the CO_2 is ultimately released to the atmosphere when urea is used in agricultural industry.

7.4 Future research

The current study focused on assessing the environmental and economic performance of building-level carbon capturing and compared it to existing alternative GHG mitigation strategies used on building heating systems. However, the overall feasibility of building-level carbon capturing depends on various other factors. The study proposed the following research directions as detailed in Figure 7-1 to assess the overall feasibility of building-level CCSU technologies.

Technical performance assessment of building-level carbon capturing technologies: The literature review showed that the operational conditions of carbon capturing systems must comply with building-level heating systems. In addition, operational parameters such as CO_2 purity, reliability, and adaptability must be evaluated and threshold performance levels must be established to investigate the technical compliance of carbon capturing technologies at the building scale, as these parameters may differ at the building scale compared to fossil power plants. If the technology has the minimum requirements, it can then be evaluated in the comparative performance evaluation framework.

Future dynamics and potential changes in the macro environment: External factors such as variations in demand for by-products and development of new carbon utilization technologies must be considered when establishing the feasibility of carbon capturing systems. In addition, further studies must be conducted on the effect on the triple bottom line sustainability of building-level carbon capturing by changes in the macro environment, such as social acceptance, health risk of chemicals used, economic state, technology improvements, political involvements, carbon taxation, and carbon pricing.

In addition, this study assess the feasibility of the carbon capturing technologies based on the existing configurations. However, the model also can be adapted to identify and evaluate the requirements such as subsidies, by-product demand, and by-product revenue that make the building-level carbon capturing is feasible in the future compared to the other GHG emission reduction technologies.

Investigate the supply chain and stakeholder partnership: The supply chain of building-level carbon capturing technologies must be investigated in future studies. The feasibility of carbon capturing technologies depends on a properly established supply chain. In addition, the stakeholder partnerships within the complete carbon capturing process must be thoroughly studied. In particular, sharing responsibilities such as maintenance, infrastructure development, and by-product transportation must be considered when evaluating the effect of different stakeholder partnerships.

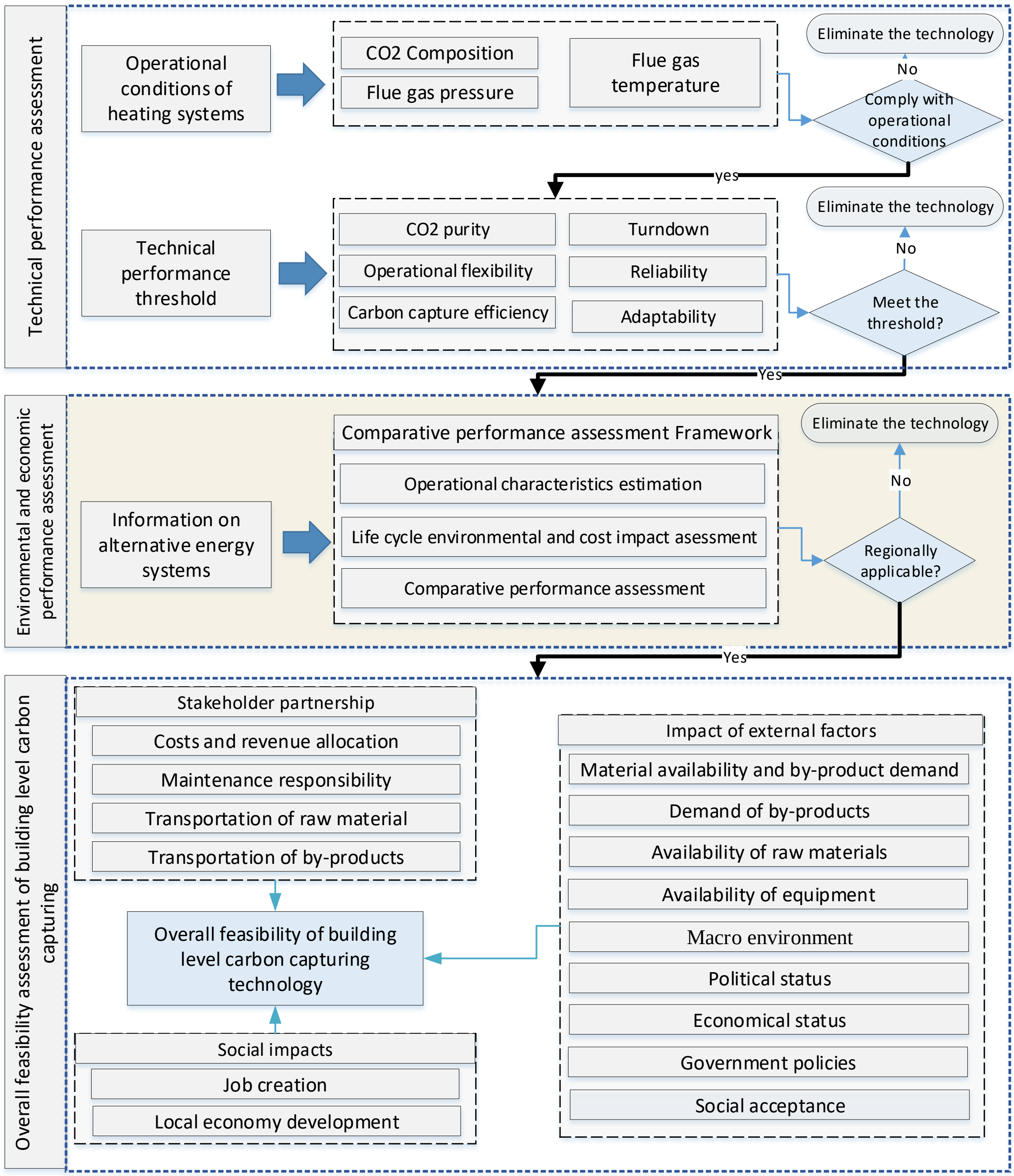

Figure 7-1: Overall vision of the feasibility assessment of building-level carbon capturing implementation

In addition, the following future research avenues were identified during the study.

Focus on modifications in existing heating systems: The study considered implementing carbon capturing in existing building heating systems. Therefore, only chemical absorption technology was screened out as a carbon capturing technology, as it is more suitable for capturing CO_2 in low concentrations. However, the literature review revealed that there are carbon capturing technologies such as membrane separation that can be used with combustion products that have higher composition. Techniques such as flue gas heat recovery can be used with building heating systems, which needs further research and development.

Comparison against other emission mitigation methods: The study considered the natural gas building heating system that is integrated with carbon capturing systems as a GHG mitigation strategy used on building heating systems. However, the carbon capturing technology can be considered a retrofit that can reduce GHG emissions of the building sector. Therefore, the study can be extended by considering other building energy retrofits such as improving building envelops and comparing it with the effect of carbon capturing systems.

Expand the system boundary of the study to include the use phase of by-products: There are different applications of the by-products, which have different environmental impacts. Therefore, it is essential to consider possible pathways to utilize the by-products and evaluate the environmental impacts by expanding the system boundary in this study to understand the holistic impact of building-level CCSU implementation.

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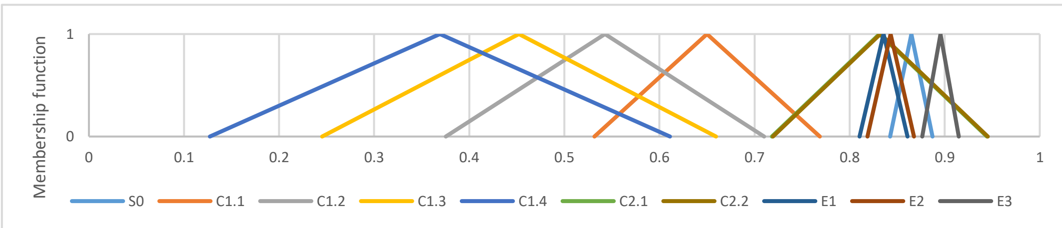
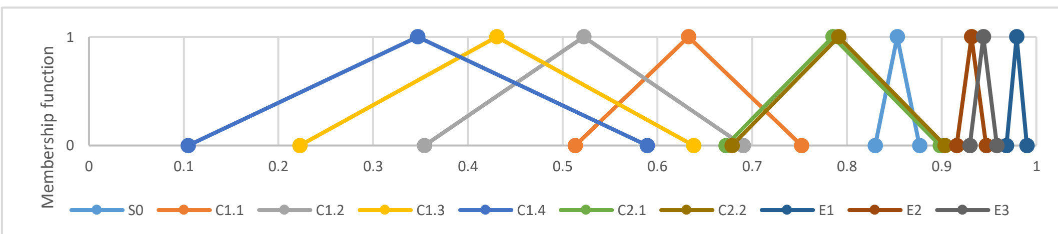
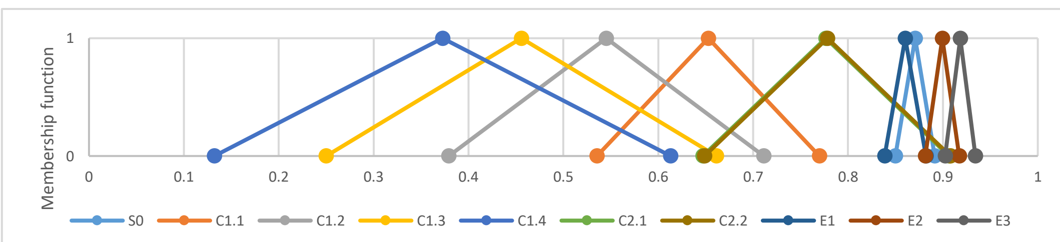
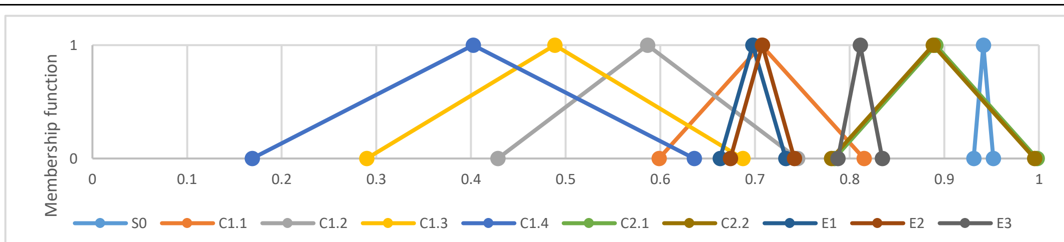
Appendices

Appendix A Performance scores of case study in comparative performance assessment

The Table A-1, Table A-2, and Table A-3 show the performance score of the scenarios in pro-economic, normal, and pro-environmental perspectives.

Table A-1: Overall performance score in pro-economic perspective

ON	
QC	
BC	
AB	

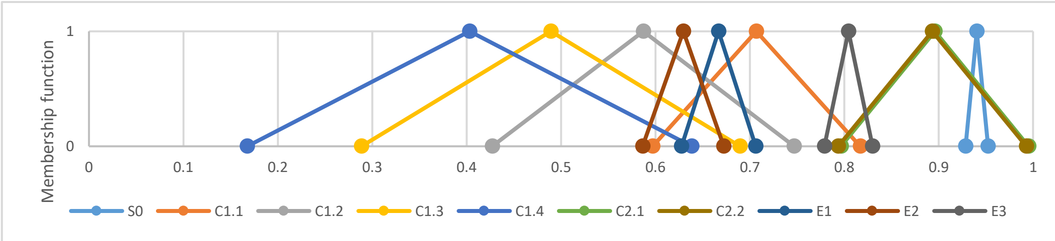
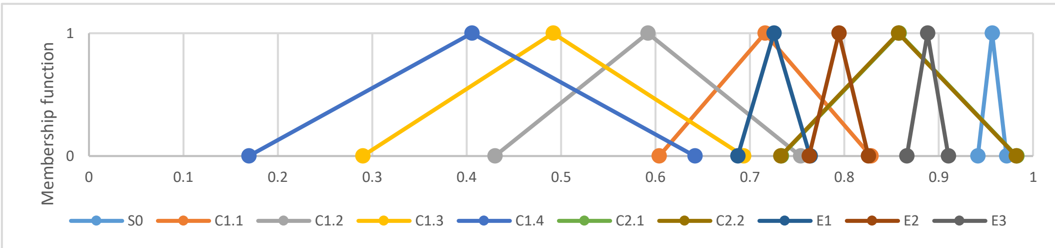
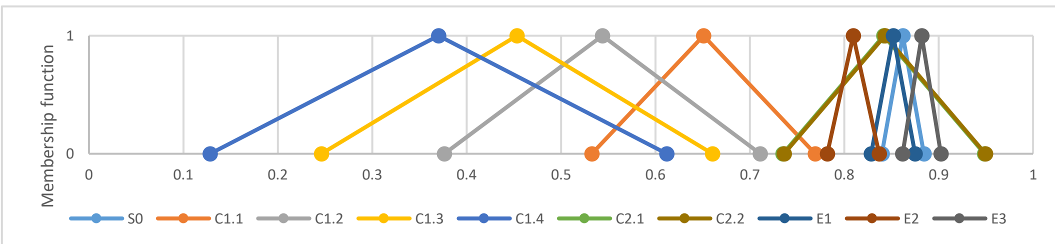
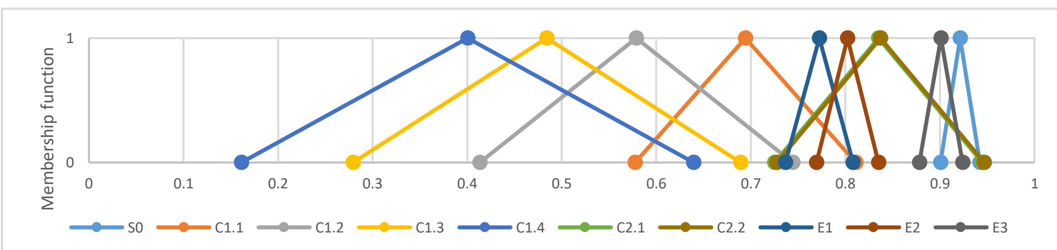
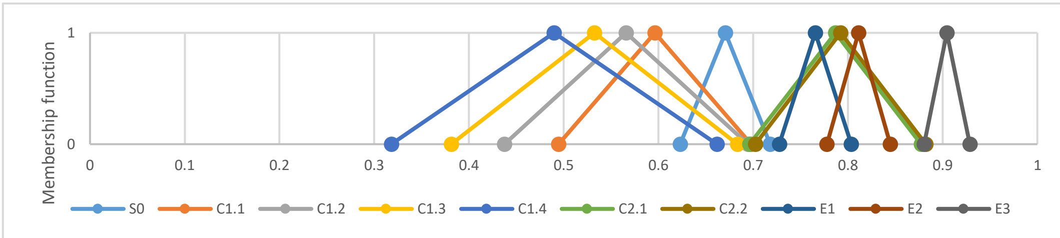
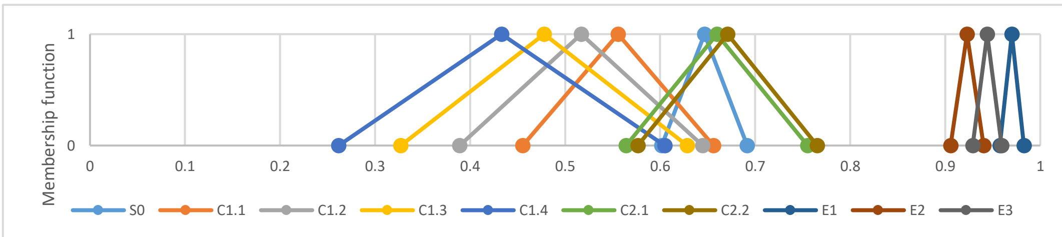
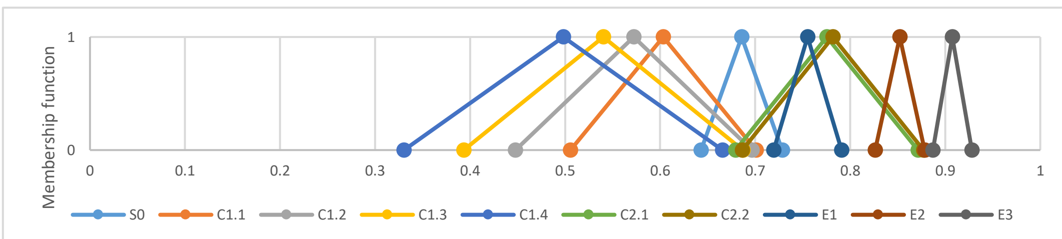
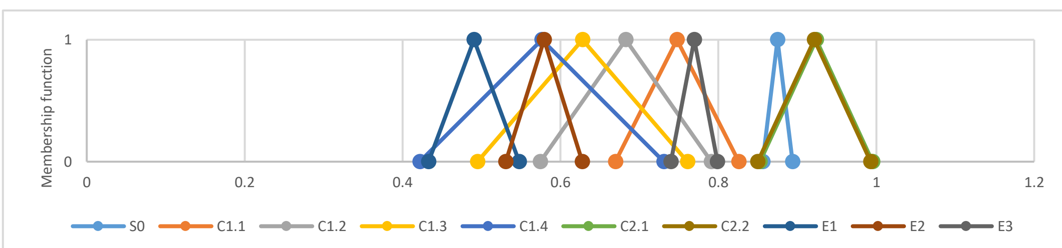
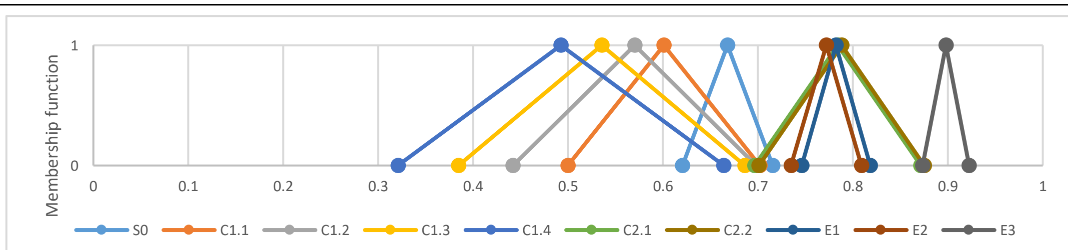
MB	 Membership function 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 S0 C1.1 C1.2 C1.3 C1.4 C2.1 C2.2 E1 E2 E3
SK	 Membership function 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 S0 C1.1 C1.2 C1.3 C1.4 C2.1 C2.2 E1 E2 E3
NS	 Membership function 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 S0 C1.1 C1.2 C1.3 C1.4 C2.1 C2.2 E1 E2 E3
NB	 Membership function 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 S0 C1.1 C1.2 C1.3 C1.4 C2.1 C2.2 E1 E2 E3

Table A-2: Overall performance score in normal perspective

ON	
QC	
BC	
AB	
MB	

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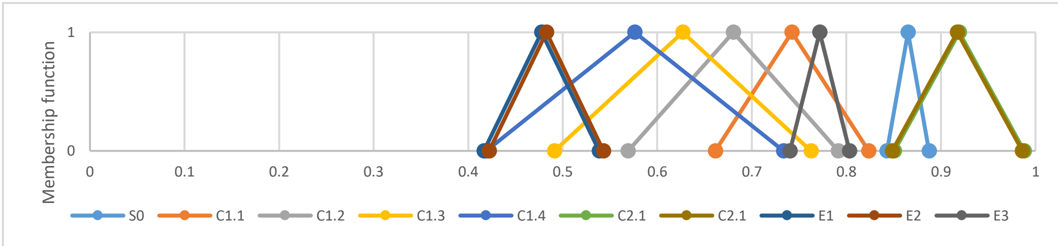

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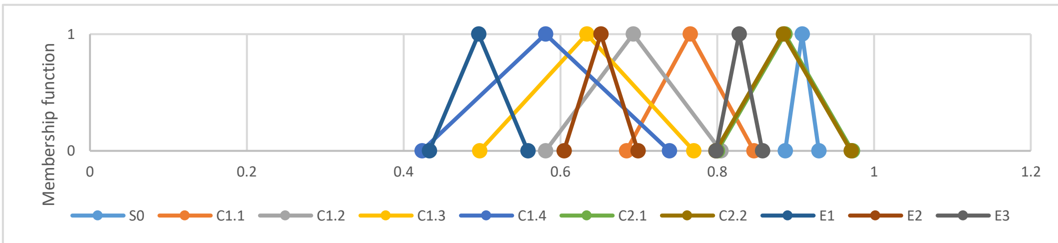

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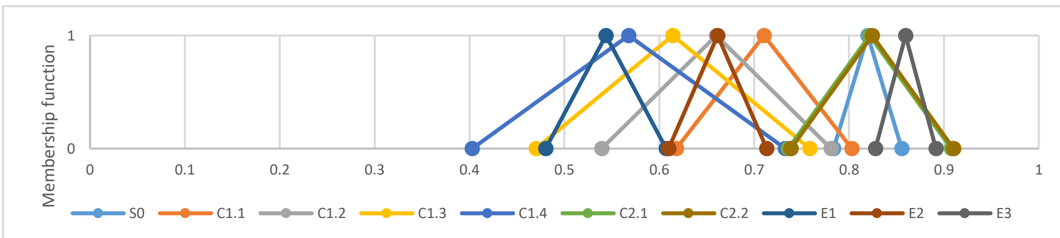

Table A-3: Overall performance score in pro environmental perspective

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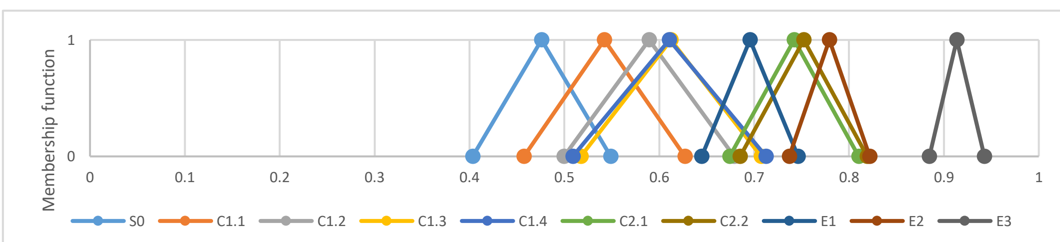

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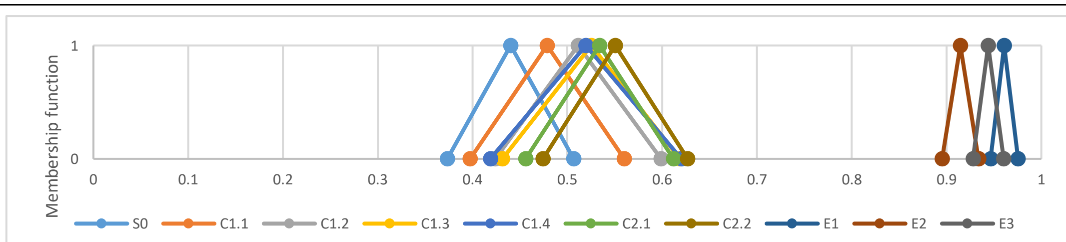

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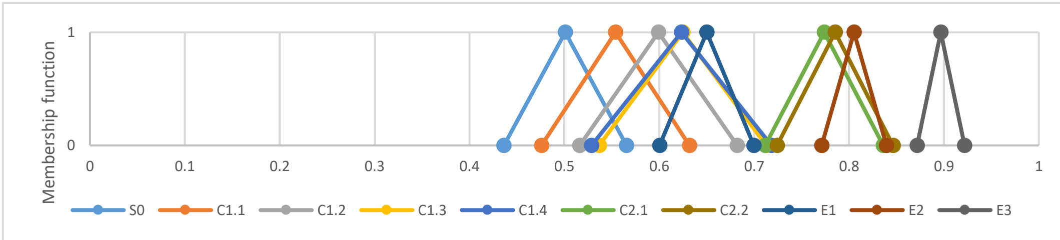
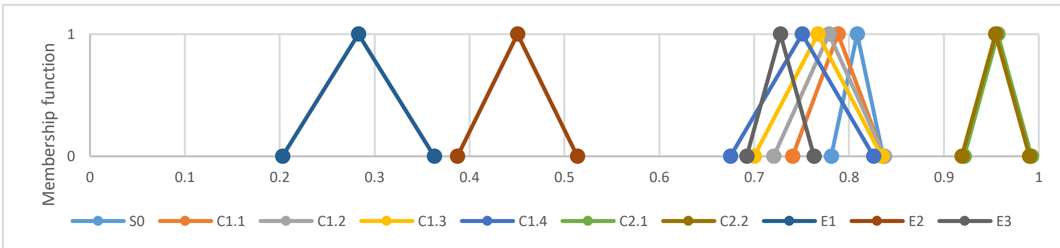

Membership function
1
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
S0 C1.1 C1.2 C1.3 C1.4 C2.1 C2.2 E1 E2 E3

AB


Membership function
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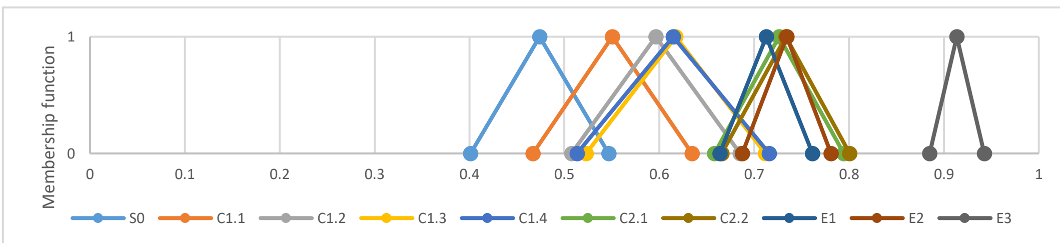
MB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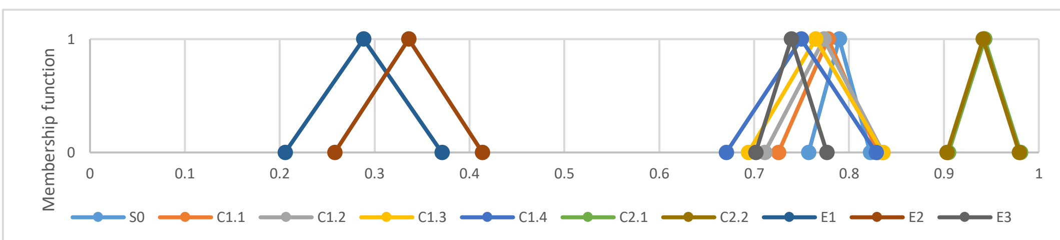
SK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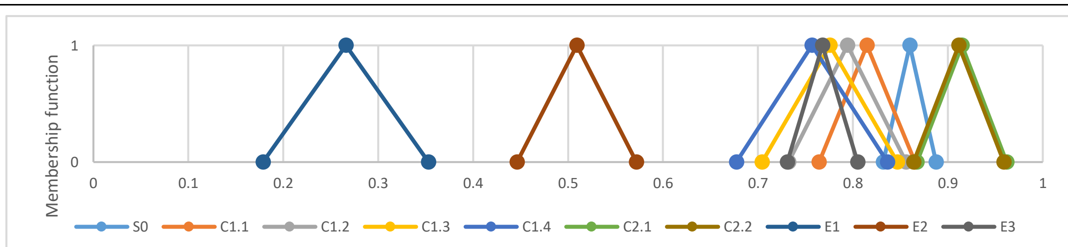
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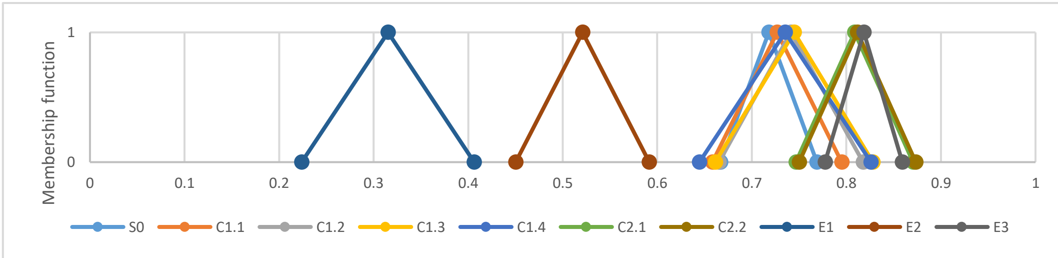
NB	

Appendix B Instrumentation of the commercial building-level carbon capturing system

The schematic diagram of the carbon capturing system with all the instruments is shown in the Figure B-1.

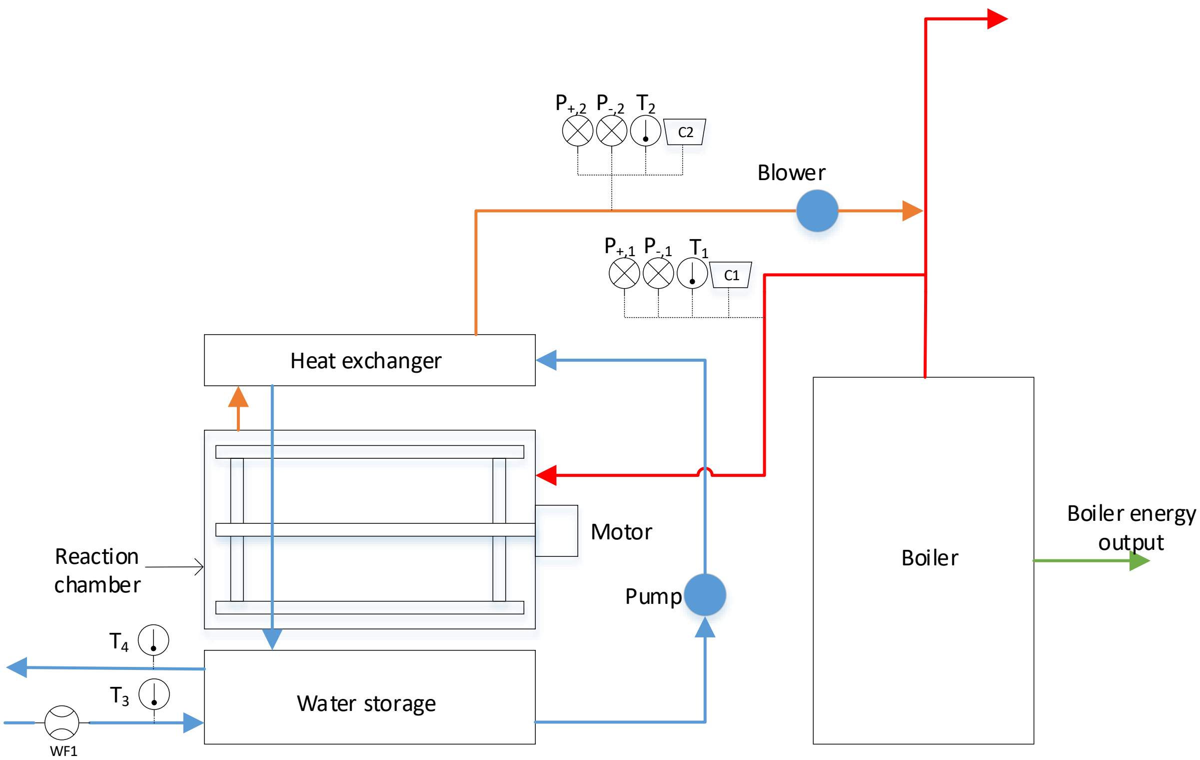


Figure B-1: Instrumentation diagram

Expected information and the required data points are shown in Table B-1, Table B-2, and Table B-3.

Table B-1: Data points used to estimate the CO_2 flow rate at the inlet of the reaction chamber

Data point	*Sensor output*	*Unit*
Pressure from the Total port of the pitot tube	$P_{+,1}$	Pa
Pressure from the static port of the pitot tube	$P_{-,1}$	Pa
Temperature of flue gas at the outlet of the boiler	T_1	°C
CO_2 concentration	C_1	ppm
Cross-sectional area of the tube	A_1	m^2

Table B-2: Data points used to estimate the CO_2 flow rate at the outlet of the reaction chamber

Data point	*Sensor output*	*Unit*
Pressure from the Total port of the pitot tube	$P_{+,2}$	Pa
Pressure from the static port of the pitot tube	$P_{-,2}$	Pa
Temperature of flue gas at the inlet of the reaction chamber	T_2	°C
CO_2 concentration of flue gas at the inlet of the reaction chamber	C_2	ppm
Cross-sectional area of the tube	A_2	m^2

Table B-3: Data points used to estimate the heat transfer rate to the domestic water supply

Data point	*Sensor output*	*Unit*
Water flow rate	V_w	m^3/s
Inlet water temperature	T_5	°C
Outlet water temperature	T_6	°C

This section describes the installation of sensors and the test rig to measure the performance of the carbon capturing system according to the instrumentation plan. Table B-4 shows the details of the sensors used to measure the performance.

Table B-4: Details of the sensors

Sensor Manufacturer	*Sensor model*	*Details of the sensor*
Honeywell Sensing and Productivity Solutions	Absolute pressure sensor - SSCDANN030PAAA5	The sensor measures the absolute pressure from 0 to 30psi and provide analog output from 0 to 5 V.
Honeywell Sensing and Productivity Solutions	Differential pressure sensor - HSCDRRN002NDAA5	The sensor measures the differential pressure from -2" H_2O to +2" H_2O and provide analog output from 0 to 5 V. The sensor was selected by considering the differential pressure that can be generated in the Pitot tubes when the suction fan operates in the highest flow rate.
Dwyer Instrumentation	Pitot tube - 167-6-CF	Pitot tube generate the static and the total pressure of flowing fluid.
CO2meter	CO_2 sensor - K33 ICB 10%	The sensor measures the CO_2 concentration in PPM and provide a digital output. The digital output operates using UART protocol.
Omega instruments	Thermocouple Probe - TC-K-1/8NPT-U-72	The sensor measures the temperature and provide analog voltage output. (The sensor is used to measure the temperature of water)
PerfectPrime	Thermocouple Probe – TL0400	The sensor measures the temperature and provide analog voltage output. (The sensor is used to measure the temperature of gas)
DIGITEN	Flow sensor – G3/4"	The sensor measures the water flow rate and provide digital output.

The data monitoring system is developed to collect all the sensor outputs. All the sensor outputs are connected to an Arduino micro controller interface that communicates with a laptop. The outputs of the pressure sensors are connected to a separate Analog to Digital Convertor (ADC), even though the Arduino board has built-in ADC. The reason is that the resolution of the ADC in the Arduino is not sufficient to measure slight changes in differential pressure in the Pitot tube. These ADCs are connected to the Arduino board using Inter-Integrated Circuit (I2C) protocol.

Both CO_2 sensors are connected to the Arduino board using Universal Asynchronous Receiver/ Transmitter (UART) protocol. Apart from that, the gas samples should be conditioned before entering to the CO_2 sensors. According to the specifications, the maximum temperature and the moisture content of the gas sample are 50°C and 90%, respectively. Since the temperature of the gas sample may reach 90°C, it needs to be cooled down before entering to the sensors. A thermoelectric cooler is used to cool the incoming gas. The temperature of the gas can be controlled by changing the duty cycle of the thermoelectric cooler. Reducing the temperature increases the humidity of the flue gas and may condense the water vapour. Therefore, moisture traps and hydrophobic filters are installed. The major components and their details are summarized in Table B-5.

Table B-5: Details of the components in the data collection system

Component	*Manufacturer and the model*	*Details of the component*
Thermoelectric cooler with heat sink	YIKESHU – TEC1-12706	Reduce the temperature of the flue gas
Moisture trap and gas filter	Mastercraft	Remove water vapour and other particulates from flue gas
Hydrophobic filter	CO2Meter	Remove water vapour left in the conditioned gas sample
Particulate filter	CO2Meter	Remove any particulates left in the conditioned gas sample
Power supply	12V – LEDMO 5V – ALITOVE 6V – CO2Meter	12V power supply is used for the thermoelectric cooler. CO_2 sensors are powered by the 6V power supply. All the other sensors are powered by the 5V power supply

Component	**Manufacturer and the model**	**Details of the component**
Thermocouple module	Robojax – MAX6675	This module is used to convert and amplify the analog signal of the thermocouple to a digital signal.
Analog to Digital (AD) converter	Akozon – ADS1115	These two AD convertors are used to convert the analog output of the pressure sensors to a digital output.
Arduino board	Arduino – MEGA 2560	The Arduino board is used to read all the senor outputs and communicate with the computer.

All the instruments are mounted inside a plastic enclosure as shown in the Figure B-2 to ensure that the components are protected from dust particles.

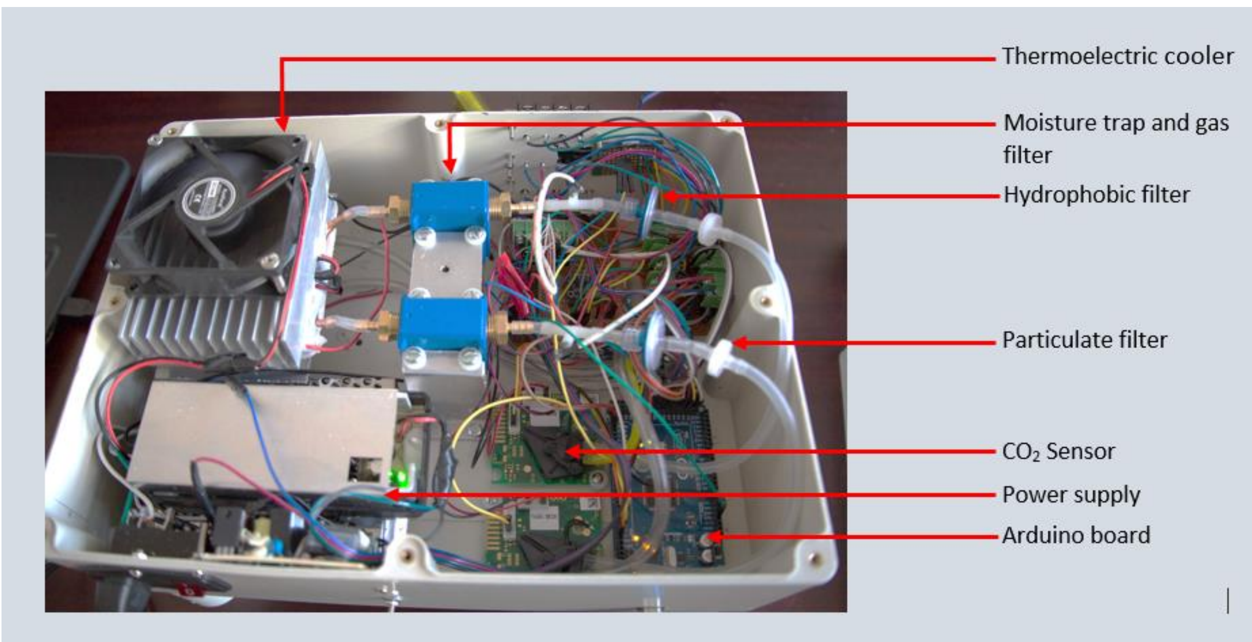


Figure B-2: Data collection system and components

The Pitot tubes, pressure sensors, thermocouple probes (to measure gas temperature), and gas sampling probes are connected to a sensor mount as shown in Figure B-3. There are two sensor mounts installed on the inlet and the outlet of the carbon capturing system.

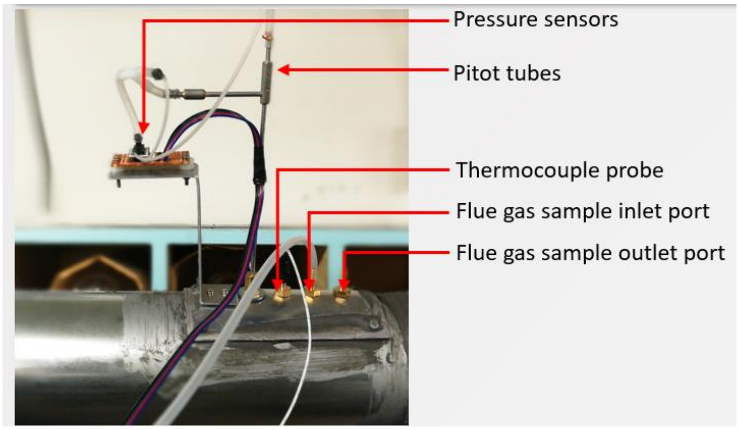


Figure B-3: Sensors installed in a flue gas duct

Figure B-4 shows thermocouples and water flow sensors installed in the piping system in the carbon capturing system. The thermocouples that are used to measure the water temperature are installed using pipe connectors. Furthermore, the water flow sensor is also installed at the inlet of the pipe. The water flows only when the pipes are operated in the office space.

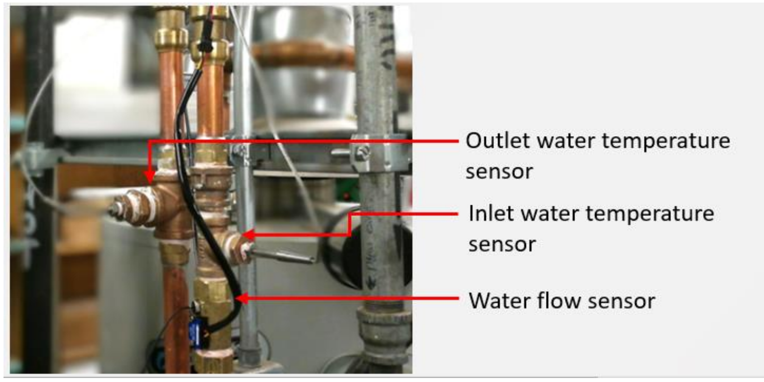


Figure B-4: Sensors installed in water lines

Figure B-5 shows the completed instrumentation of the carbon capturing system in the ATCO facility.

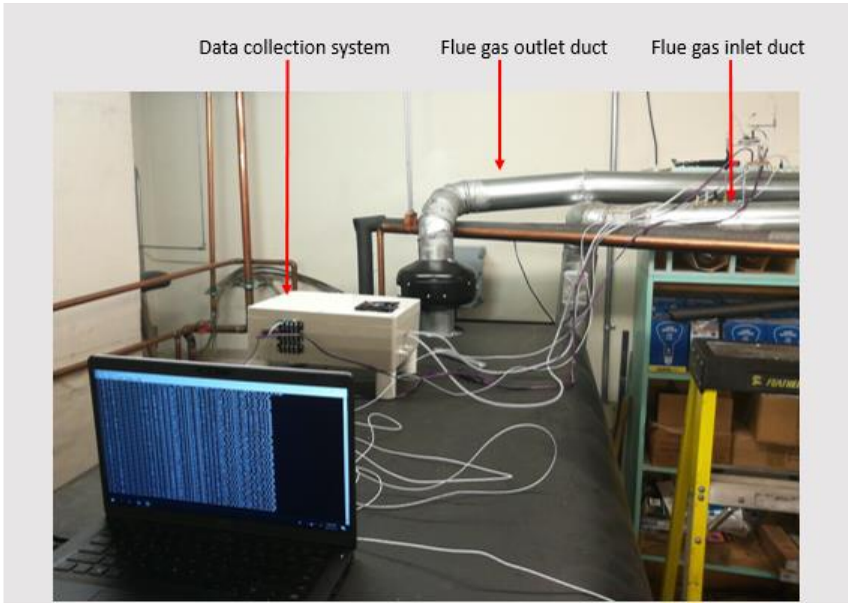


Figure B-5: Completed instrumentation setup

Appendix C Calibration of the sensors and initial data analysis

This section present the calibration of gas flow rate readings from the data collection system. In addition, this section presents the relationships of the inlet and outlet gas flow rates and validate the gas flow rates using a mass flow analysis.

C.1 Calibration of the airflow sensors

The sensors were installed in a 4 inch duct as shown in the Figure B-3 in Appendix B. The flowrate was controlled by changing the flow area at the fan inlet. Then, the average gas flow velocity was measured using the sensor outputs. In addition, an anemometer was used to obtain the average gas flowrate through the pipe. The results are shown in the Table C-1 below.

Table C-1: The flow velocity readings observed from the data collection system and the anemometer

Readings from the data collection system - V_s (ft/min)	*Readings from the anemometer – V_a (ft/min)*	*Percentage difference (%)*	*V_a / V_s (ft/min)*
350	452	22.5	1.29
334	433	22.8	1.30

Readings from the data collection system - V_s (ft/min)	Readings from the anemometer – V_a (ft/min)	Percentage difference (%)	V_a / V_s (ft/min)
295	350	15.7	1.18
198	257	22.9	1.29

The Table C-1 shows that the velocity observed from the data collection system was 15.7% to 22.8% lower than the reading observed from the anemometer. The possible reasons would be the voltage drop caused by the cables used to communicate the sensors and the data collection system and the noises occurred during the data collection period. As a solution for this, the study multiply the velocity readings from the data collection system by the average ratio between the readings from the anemometer and the readings of the data collection system.

C.2 Air flow rate of the carbon capturing system

Although currently it is possible to monitor the gas flow rate accurately, the pitot tubes can be clogged with the dust particles with the time. However, it is important to accurately measure the Inlet and outlet gas flowrates throughout the data collection process. The Figure C-1 shows the inlet and outlet air flow velocities through the carbon capturing system and the inlet gas temperature.

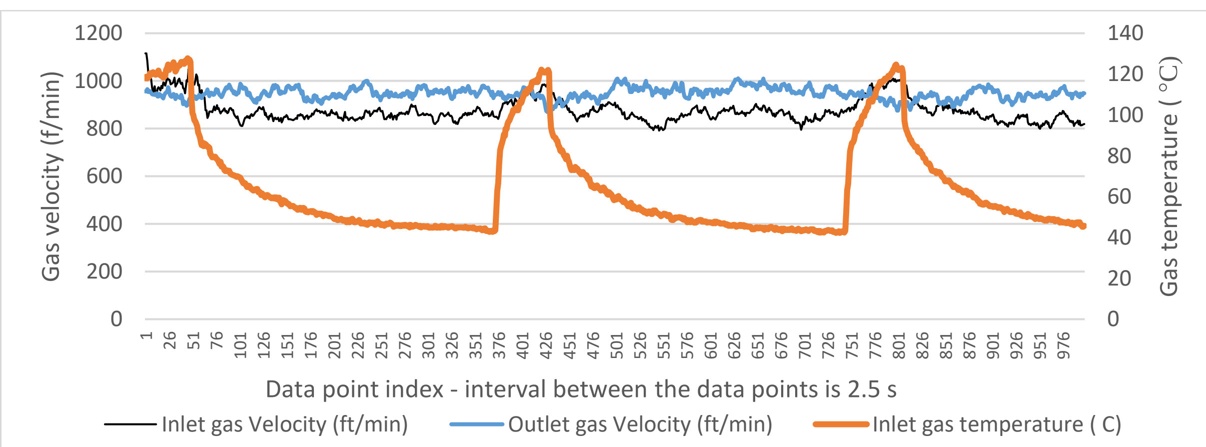


Figure C-1: Inlet and outlet gas velocities and inlet gas temperature variation with the time

The Figure C-1 shows the inlet gas flow is increased with the temperature. Therefore, there can be a relationship between the inlet gas flow and the temperature. To evaluate the relationship, the correlation coefficient between the temperature and gas flow rates are evaluated. The analysis used 5000 data points collected on 2019-12-13. The results of the correlation analysis are shown in Table C-2.

Table C-2: Correlation coefficients between gas velocities and gas temperatures

Variable	**Correlation coefficient - Inlet gas temperature vs gas velocity**	**Correlation coefficient – Outlet gas temperature vs gas velocity**
Inlet gas velocity	0.844	-0.094
Outlet gas velocity	-0.518	0.128

The results indicate that there is no evidence for a strong relationship between the outlet temperature and the gas velocities. However, there is strong positive correlation between the inlet gas velocity and the inlet gas temperature. Furthermore, there is a moderate negative correlation between the inlet gas temperature and the outlet gas velocity. The equation 1 and equation 2 are the relationships of inlet temperature and gas velocities that are developed using regression analysis. The R-sq values for the regression equation 1 and 2 are 26.78% and 71.15%.

$$V_{gas.in} = 774.8 + 1.703\ T_{gas,in} \qquad \text{---------- Equation 1}$$

$$V_{gas.out} = 983.2 - 0.6002\ T_{gas,in} \qquad \text{---------- Equation 2}$$

The fitted plots for equation 1 and 2 are shown in Figure C-2 and Figure C-3.

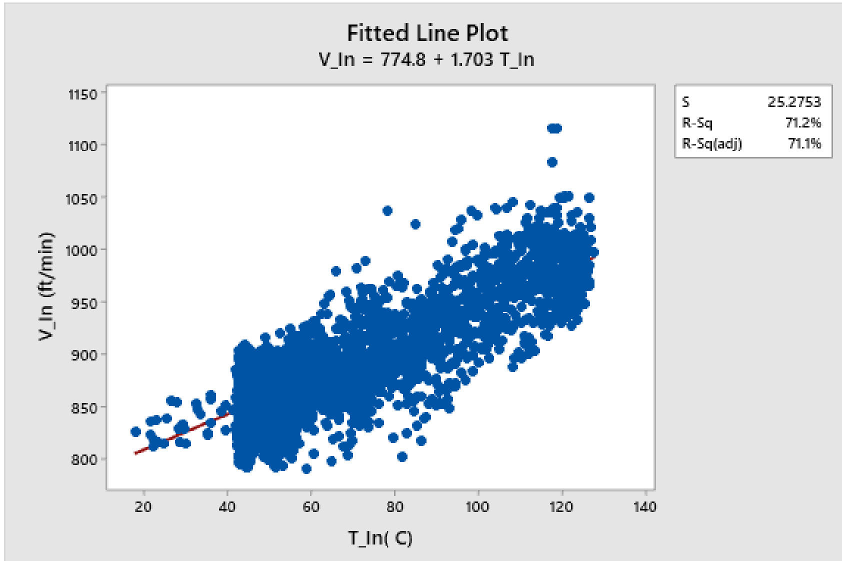


Figure C-2: Fitted line plot of regression analysis between inlet gas velocity and inlet temperature

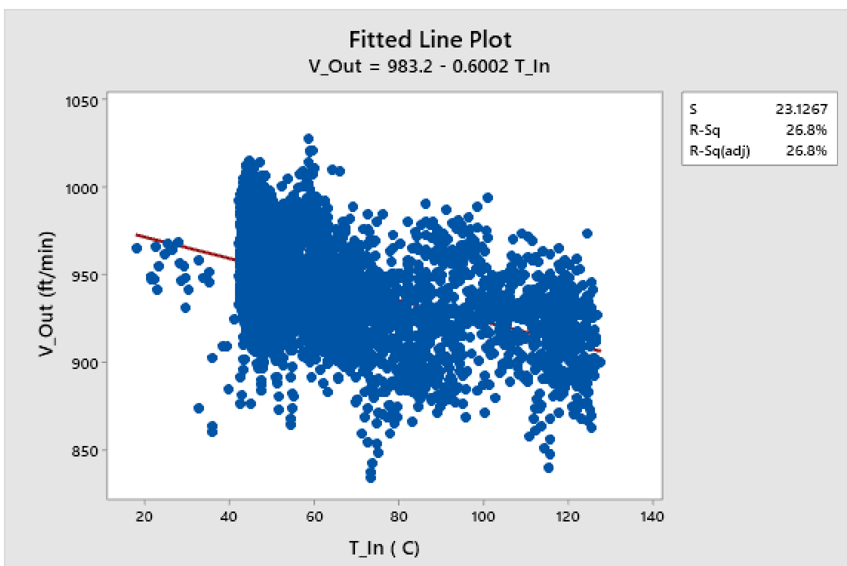


Figure C-3: Fitted line plot of regression analysis between outlet gas velocity and inlet temperature

The behaviour of the gas flowrate (gas velocity) can be explained as follows. The viscosity of the gas is reduced when increasing the temperature. Therefore, it can reduce the resistance for the gas flow and thus increase the velocity. However, increasing the gas temperature can reduce the density of the gas significantly, which reduces the inlet mass flow of the gas. Therefore, the outlet gas flow rate is reduced with the increase of the temperature at the inlet.

C.3 Mass flow analysis of carbon capturing system

It is necessary to analyse the mass flow through the carbon capturing system, to ensure the data are accurate enough for estimating the technical performance of the carbon capturing system. The study used 8000 data points collected using the data monitoring system. Furthermore, the absorbent chemical is completely converted in to by products during the data collection time period. Therefore, the inlet CO_2 mass went through the carbon capture system should be equal to the outlet CO_2 mass went through the carbon capturing system.

The Equation C-1 is derived using the ideal gas equation and used to calculate the CO_2 mass flow rate.

$$\dot{m_{CO2}} = M_{CO2} \times \frac{P.\dot{V}.C \times 10^{-6}}{R(273+T)} \qquad \text{---------- Equation C-1}$$

Where,

- m_{CO2} = CO_2 mass flow rate (kg/s)
- M_{CO2} = CO_2 molar mass (kg/mol)
- P = Gas pressure (Pa)
- V = Gas volume flow rate (m^3/ s)
- T = Gas temperature (°C)

The Figure C-4 and Figure C-5 show the variation of CO_2 concentration and CO_2 mass flow rates with time. The increase of the CO_2 concentration and CO_2 mass flow happens when the boiler operates. The Figure C-4 shows that the inlet CO_2 concentration is higher than the outlet CO_2 gas concentration. However, Figure C-5 shows that the area under the inlet CO_2 mass flow curve is approximately equal to the area under the outlet CO_2 mass flow.

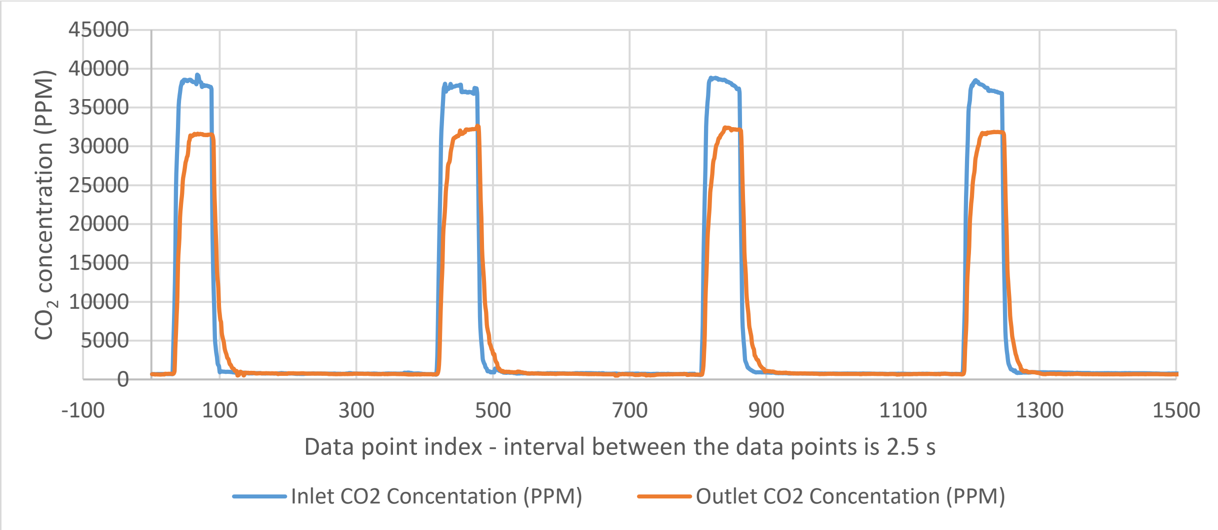


Figure C-4: Inlet and outlet CO2 concentration

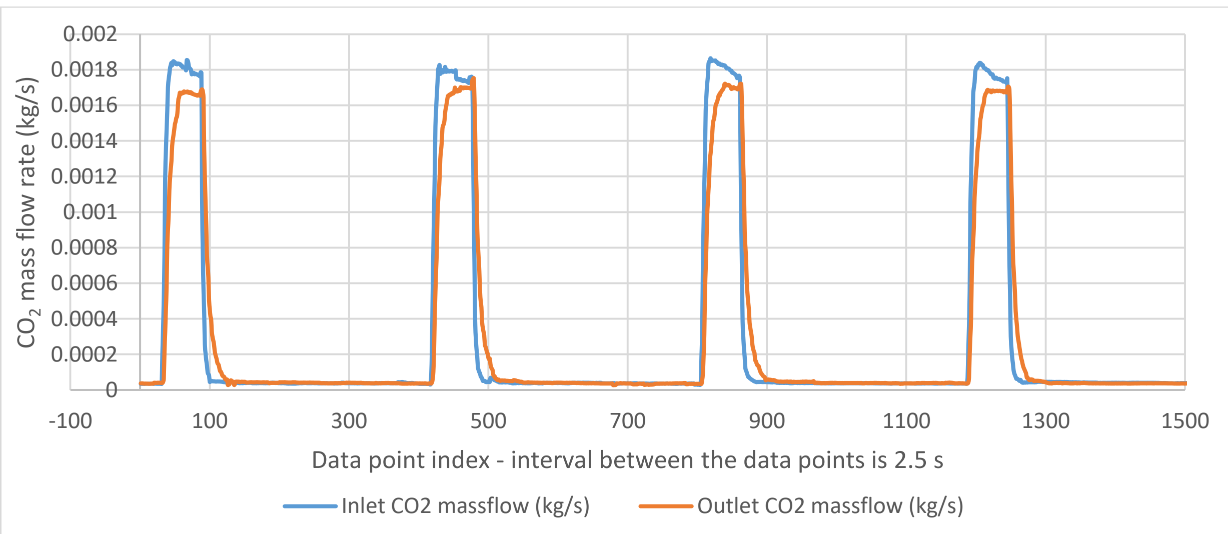


Figure C-5: Inlet and outlet CO2 mass flowrates

To accurately evaluate the mass flow through the system, the total mass of CO_2 went through the system is calculated. In this calculation, the time interval of the data points is 2.5 s. Trapezoidal rule was used to integrate mass flow rates and obtain the cumulative CO_2 mass flow.

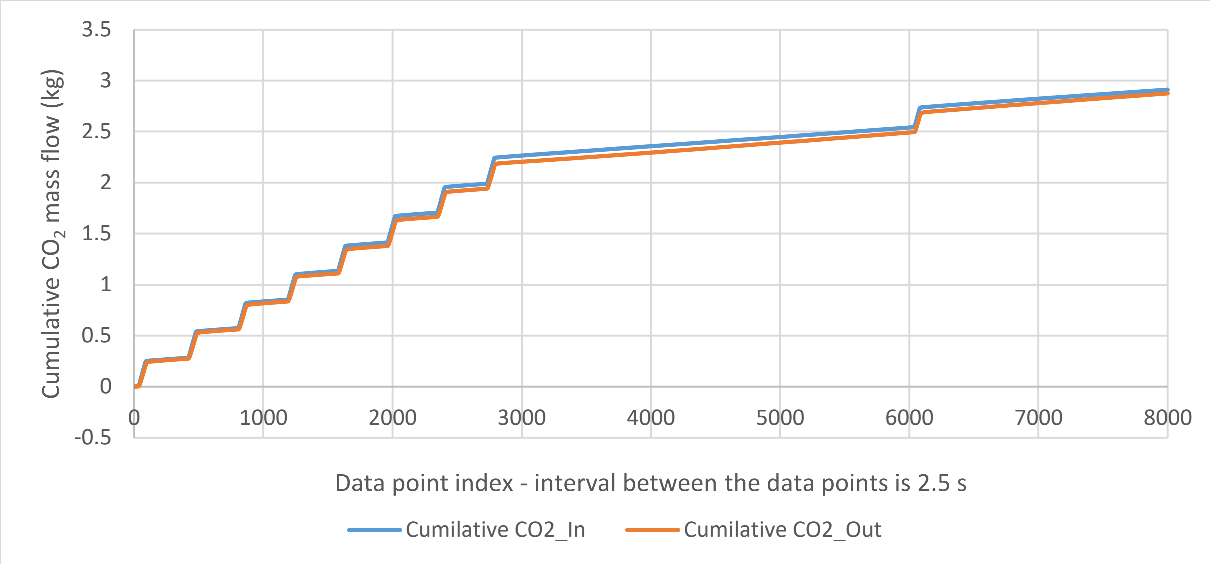


Figure C-6: Cumulative inlet and outlet CO_2 mass flow through the carbon capturing system

The Figure C-6 shows the total CO_2 inflow and outflow through the carbon capturing system. It indicates the percentage difference of the total CO_2 inflow and the outflow recorded during 5 hrs is only 1.21%.