Date of Request: October 1, 2020 | Request No. SC-004
Due Date: October 12, 2020 | NMPC Req. No. NM-992

NIAGARA MOHAWK POWER CORPORATION d/b/a NATIONAL GRID
Case Nos. 20-E-0380 and 20-G-0381
Electric and Gas Rates

Request for Information

FROM: Sierra Club, Joshua Berman

TO: National Grid, Future of Heat Panel

SUBJECT: Future of Heat

Request:

Note: The following information request pertains to the gas filings for 20-G-0381.

4. With regard to the Company's CCUS proposal, please provide the Company's assessment of the following, along with all supporting materials and data. If the assessments are supported by workpapers, please provide the workpapers in native electronic format with formulas intact:

   a. The total percentage capture of carbon from the combustion of gas that can be achieved with a typical distributed CCUS installation;

   b. The total incremental energy use percentage associated with a typical distributed CCUS installation;

   c. The annual volume and cost of potassium hydroxide that would be required for each such installation; and

   d. The cost per ton of carbon captured using distributed CCUS.

Response:

1. Based on discussions with CleanO_2, the Company offers the following:

   a. Independent reports have shown an average of 20 percent reduction in GHG emissions as these early systems were configured. The Company's review indicates the possibility of a much higher rate of extraction of CO_2, and determining the upper limit under local conditions is one of the key objectives of this project. It is important to point out that due to the variance in heating systems' design and configurations, this average will change as the data sets increase in volume. A draft life-cycle analysis ("LCA") from the University of British Columbia is included as Attachment 1.

b. The estimated average is around 250 to 300 kWh per year per unit and varies with the size of the system.

c. Each CARBiN-X unit as configured will require 2.85 metric tonnes of potassium hydroxide per year. This cost is carried by CleanO_2 and not the customer.

d. The premise of CleanO2's business model is based on profit per tonne, rather than cost per tonne. The forecast operating profit is $223 per tonne of CO2

<u>Name of Respondent</u>: Christopher A. Cavanagh, PE

<u>Date of Reply</u>: October 9, 2020

Micro Carbon Capture and Utilization: Life Cycle Assessment

Prepared for

CleanO2

Pacific Northern Gas

FortisBC

Northern Lights College

City of Dawson Creek

ATCO Gas and Pipelines Ltd.

By,

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June 21, 2020

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Abbreviations

GWP	Global Warming Potential
GHG	Greenhouse gases
CO_2	Carbon Dioxide
CFC11	Trichlorofluoromethane
Co-60	Cobalt 60
NOx	Oxides of Nitrogen
PM2.5	Particulate matter with a diameter of less than 2.5 µm
SO_2	Sulphur Dioxide
P	Phosphorus
N	Nitrogen
DCB	Dichlorobenzene
MCCU	Micro Carbon Capture and Utilization
K_2CO_3	Potassium Carbonate
KOH	Potassium Hydroxide
KCl	Potassium Chloride
LCA	Life cycle assessment
DWH	Domestic Hot Water
DCB	Dichlorobenzene
AB	Alberta
BC	British Columbia
MB	Manitoba
NB	New Brunswick
NS	Nova Scotia
ON	Ontario
QC	Quebec
SK	Saskatchewan

Units

kg	Kilogram
kg CO2 eq	Kilograms of equivalent Carbon Dioxide

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kg CFC11 eq	Kilograms of equivalent Trichlorofluoromethane
kBq Co-60 eq	Kilo Becquerel of equivalent Cobalt 60
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 P eq	Kilograms of equivalent Phosphorus
kg N eq	Kilograms of equivalent Nitrogen
kg 1,4-DCB	Kilograms of equivalent Dichlorobenzene
m^{A2} crop eq	Equivalent species loss per square meter of annual crop production
kg Cu eq	Kilograms of equivalent Copper
kg oil eq	Kilograms of equivalent crude oil
m^3	Cubic meter
kJ/kg	Kilo Jules per Kg of water

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Executive Summary

The goal of this report is to present the findings of a holistic environmental impact assessment conducted on a commercially available carbon capturing system designed for building level operation. The company "CleanO2" has developed a carbon capturing device to be used with natural gas building heating systems [1]. This technology is known as Micro Carbon Capture and Utilization (MCCU). The above system is capable of capturing CO_2 from the flue gas in natural gas heating systems using solid Potassium Hydroxide (KOH). The reaction produces Potassium Carbonate (K_2CO_3). The K_2CO_3 is removed after KOH is fully exhausted, at which point KOH is refilled. The MCCU system uses a heat recovery system to make use of the reaction energy and the waste heat of flue gas. The recovered heat is transferred to a domestic hot water system. Therefore, the system reduces the CO_2 emissions from flue gas while simultaneously reducing the overall heating energy demand of the building.

In this study, a "cradle-to-gate" life cycle assessment was conducted by considering the material extraction, manufacturing, and operational phases of the MCCU technology. The study estimated the life cycle environmental impacts of integrating the MCCU system with a space heating system in a residential building (Scenario A1) and with a Domestic Hot Water heating (DHW) system in a commercial building (Scenario B1). The technical performance of the MCCU system was evaluated by conducting an experimental study, where actual performance data was collected. The MCCU system was integrated with 250,000 BTU DHW heating system located in ATCO gas facility in Calgary (AB). Two Scenarios, A1 and B1 were defined by considering the above heating systems with MCCU technology. The regional variability is included in the study by assuming the buildings 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). Also, reference scenarios A2 (residential buildings) and B2 (commercial buildings) were defined to represent the conventional methods of producing the same amount of heat energy and industrial production of the equivalent quantity of K_2CO_3 generated through the MCCU process.

The LCA results show that Scenario A1, where the maximum reduction was observed in BC and the minimum reductions are in AB, SK, and NS, significantly reduces the Global Warming Potential (GWP) compared to Scenario A2. Scenario B1 too reduces GWP, and the maximum reduction was observed in the buildings in BC and the minimum reduction is in NS. Further, the reduction of GWP is highly influenced by the electricity mix of the province, and higher reductions can be observed in the provinces that are primarily reliant on high-carbon energy (i.e. fossil fuels). The study also revealed that the avoided industrial production of the K_2CO_3 contributes more to the overall GWP reduction compared to the reduction of natural gas combustion and the capturing of CO_2 from the flue gas. While some of the other environmental impact categories showed an increase by using MCCU systems in certain provinces. However, only mineral resource scarcity is increased in both building types in all provinces.

Based on the results, it can be concluded that the MCCU system has a high potential to reduce life cycle global warming potential of building heating systems. The MCCU system has higher potential for environmental impact reduction when integrated with DHW systems as opposed to space heating. This is because there is a consistent energy consumption for hot water throughout the year, while space heating has seasonal variations. In addition, the study revealed that increasing the capacity of the MCCU system helps to increase the environmental benefits further. Furthermore, the manufacturer should consider reducing electricity consumption of the MCCU system as electricity has a large role in generating environmental impacts.

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1 Introduction

Micro-scale carbon capturing and utilization (MCCU) is an innovative technology that could contribute towards net-zero or low emission buildings. This technology can be integrated with natural gas heating systems to reduce the Green House Gases (GHG) emissions during the combustion process and to reduce the natural gas combustion by recovering heat. While this technology has apparent potential to help in the climate change mitigation efforts, a thorough environmental impact assessment with a holistic vision based on life cycle thinking is necessary to establish whether building-level MCCU integration is truly sustainable. The goal of this report is to present the findings of a holistic environmental impact assessment conducted on a commercially available carbon capturing system designed for building level operation. This is a part of a three-year research project focusing on an overall system analysis of micro carbon capture systems in buildings.

1.1 Project Description

In this project, the researchers from the Life Cycle Management laboratory of the University of British Columbia's Okanagan Campus are collaborating with CleanO2, FortisBC, Pacific Northern Gas (an AltaGas subsidiary), ACTO gas, Northern Lights College, and the City of Dawson Creek. The project seeks to understand the feasibility of adopting MCCU in the Canadian building sector, and to generate the much-needed knowledge on using carbon capturing applications for advancing the sustainability of building energy use. A life cycle thinking-based methodological framework is being developed to assess the feasibility of using MCCU systems in different building types under varying climatic and socio-economic conditions in Canada. The research outcomes will be used to develop a comprehensive decision support tool for climate action planning in organizations and communities. Furthermore, implementation guidelines and best management practices will be developed for MCCU in Canada. The research will produce research outcomes that will be immediately transferable to the natural gas consortium members. In addition, they will have a direct impact on performance improvement, cost reduction, and manufacturing of MCCU systems. The outcomes of the research will assist in GHG emissions reduction, improving air quality, and providing social, environmental and health benefits to all Canadians.

The Carbon Dioxide (CO_2) emissions from combustion processes can be captured using post-combustion carbon capturing [2]. This technology is mainly used in fossil fuel power generation plants. The commonly used procedure is to separate CO_2 from flue gas by means of CO_2 separation methods [3]. The separated CO_2 is then transported to storage or utilization facilities [4]. In addition, CO_2 can be converted into a useful product during the capturing process [5]. Adopting the carbon capturing process in natural gas-based building heating systems has been brought into the discussion recently. "CleanO2" has newly developed building scale carbon capturing devices for use in natural gas building heating systems [1]. This technology used Potassium Hydroxide (KOH) to capture CO_2 from flue gas. The reaction produces Potassium Carbonate (K_2CO_3). The K_2CO_3 is removed after KOH is fully reacted, and then KOH is refilled. In addition, the reaction between KOH and CO_2 is exothermic. Therefore, the MCCU system uses a heat recovery system to make use of the reaction energy and the waste heat of flue gas. The recovered heat is transferred to a domestic indoor hot water system. The system reduces the CO_2 content in the flue gas emitted to atmosphere and also reduces the overall heating energy demand of the building.

1.2 Study objectives

This study aimed to investigate the life cycle environmental impacts of integrating MCCU system in building heating systems in Canada. The specific sub-objectives are as follows:

- Evaluate the technical performance of MCCU system based on an experimental study

- Estimate the annual heating energy required for space heating in residential buildings and non-residential domestic hot water heating in commercial buildings
- Conduct a life cycle assessment of MCCU system integrated with building heating systems in different regions of Canada

1.3 Importance of this study for CleanO2

The MCCU system requires an extensive amount of raw materials for its operation as the material consumed in capturing CO_2 cannot be reused. The production of the raw material, i.e., KOH is produced by electrolyzing Potassium Chloride (KCl), which requires a significant amount of energy. Therefore, the material input to the MCCU process may cause significant environmental impacts [6]. In contrast, the industrial method to produce K_2CO_3 (which is the by-product of the MCCU process) uses KOH and liquid CO_2 as the main raw materials [7]. Although the same chemical reaction occurring in the MCCU system is used in the industrial method, the required CO_2 for the industrial production is transported in the form of liquid CO_2. The production and transportation of liquid CO_2 can have a considerable energy requirement. K_2CO_3 production from the MCCU system avoids the industrial manufacturing of an equivalent amount of K_2CO_3, thus in turn eliminating considerable amounts of energy use and associated environmental impacts. This shows the potential benefits of the MCCU system, which can play a significant role in attracting customers.

Life cycle assessment (LCA) technique is widely used in decision making to improve product designs and selecting alternatives in products and services. Since LCA includes all stages of the product life cycle, it can provide more realistic and complete picture of the environmental performance. Yet, LCA has never been conducted for MCCU systems and any building-level carbon capture system in the world. This study will provide a holistic technical metric on environmental performance of MCCU system by addressing the above gap. The results can be used by CleanO2 for further improving the product design of MCCU and its performance metric can be used for public awareness and marketing of the MCCU system.

2 Background information

This section provides details on the LCA process in general as well as the technical details related to the MCCU system under investigation.

2.1 LCA study

Life cycle assessment (LCA) is a standardized technique used to quantify the environmental impacts associated with a product throughout its life cycle. The complete life cycle of a product or a system comprises of raw material extraction and energy consumption for the production, operational phase, and the demolition and final disposal of the product. The study uses the guidelines provided by ISO 14040 framework to evaluate the life cycle impacts [44].

The life cycle assessment procedure consists of following major phases as shown in the Figure 1, and those phases are described below.

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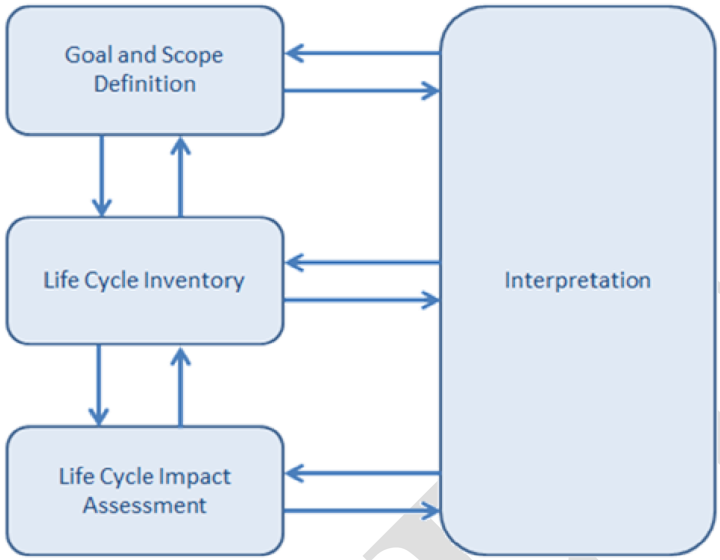

Figure 1: LCA stages (ISO 14040, 2006)

- **Goal and Scope definition:** Defining the objectives of the study and parameters that guide how the study is conducted, including the functional unit, system boundary, study scope, and intended application.
- **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 numerical 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.

2.2 MCCU System

The schematic diagram of the MCCU system is shown in the Figure 2. The MCCU system 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 byproducts. 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 1. In addition, the water is circulated through the heat exchanger. The heat exchanger is used to transfer thermal energy from flue gas to the water, when lean flue gas passes through the heat exchanger.

$$2KOH(s) + CO_2(g) \rightarrow K_2CO_3(s) + H_2O(l) \quad \text{-------------- Equation 1}$$

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The chemicals must be agitated using an agitator while KOH is converted into K_2CO_3. This agitator operates for 1 to 2 minutes during every 15-minute interval. 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 is used to circulate the water through the heat exchanger to the water storage. The carbon capturing system is not directly connected to the boiler outlet, and instead the flue gas is diverted to a separate duct as shown in the Figure 2. The blower is used to draw gas from the main stream of flue gas to the flue gas intake duct.

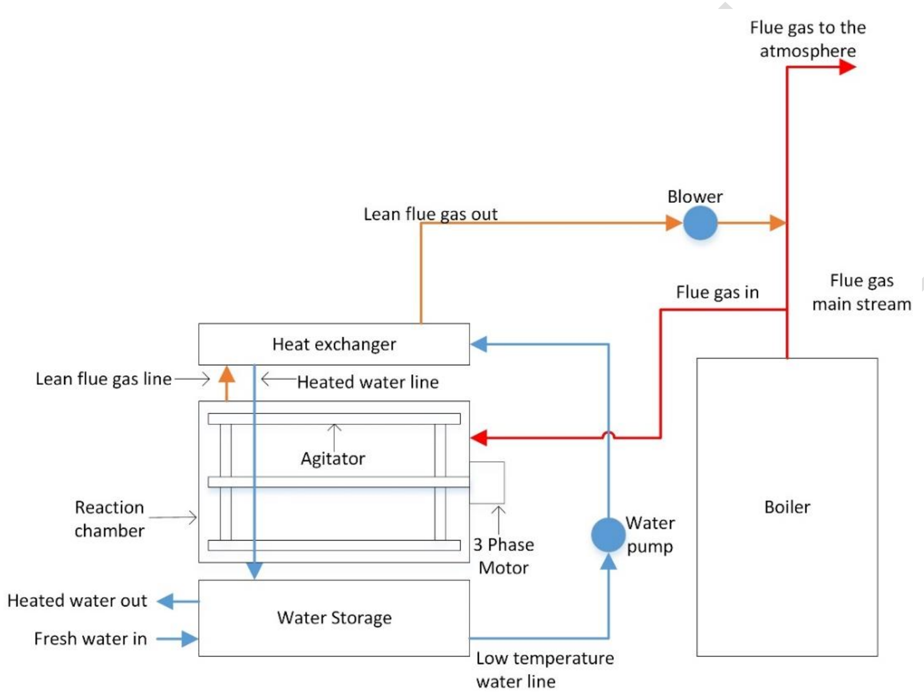

Figure 2: Schematic diagram of the carbon capturing system

3 Methodology

The study aimed to evaluate the life cycle environmental impacts of integrating MCCU in residential and commercial building heating systems. In order to incorporate regional variability in the study, buildings are assumed to be located in in major cities in eight different provinces, namely 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).

An experimental study was carried out to evaluate the technical performance of the MCCU system. The major technical performance indicators considered for MCCU system were carbon capturing efficiency, maximum CO_2 flow rate, and the flue gas heat recovery rate. The study assumed that the technical performance indicators are same for all the buildings despite the changes of climatic regions. The monthly energy load and the efficiencies of the building heating systems were used to evaluate the monthly CO_2 emissions of the buildings. The monthly space heating energy requirement of a single-family detached residential house was estimated using HOT2000, a building energy simulation software. The water heating energy load of commercial building was estimated using the average natural gas energy intensity for water heating of office buildings in USA [8], as the water heating requirement is mostly dependent to the number of occupants in the building instead of the climatic region [9]. The above information was used in LCA as explained in the subsequent sections. The overall methodology flow is shown in the Figure 3.

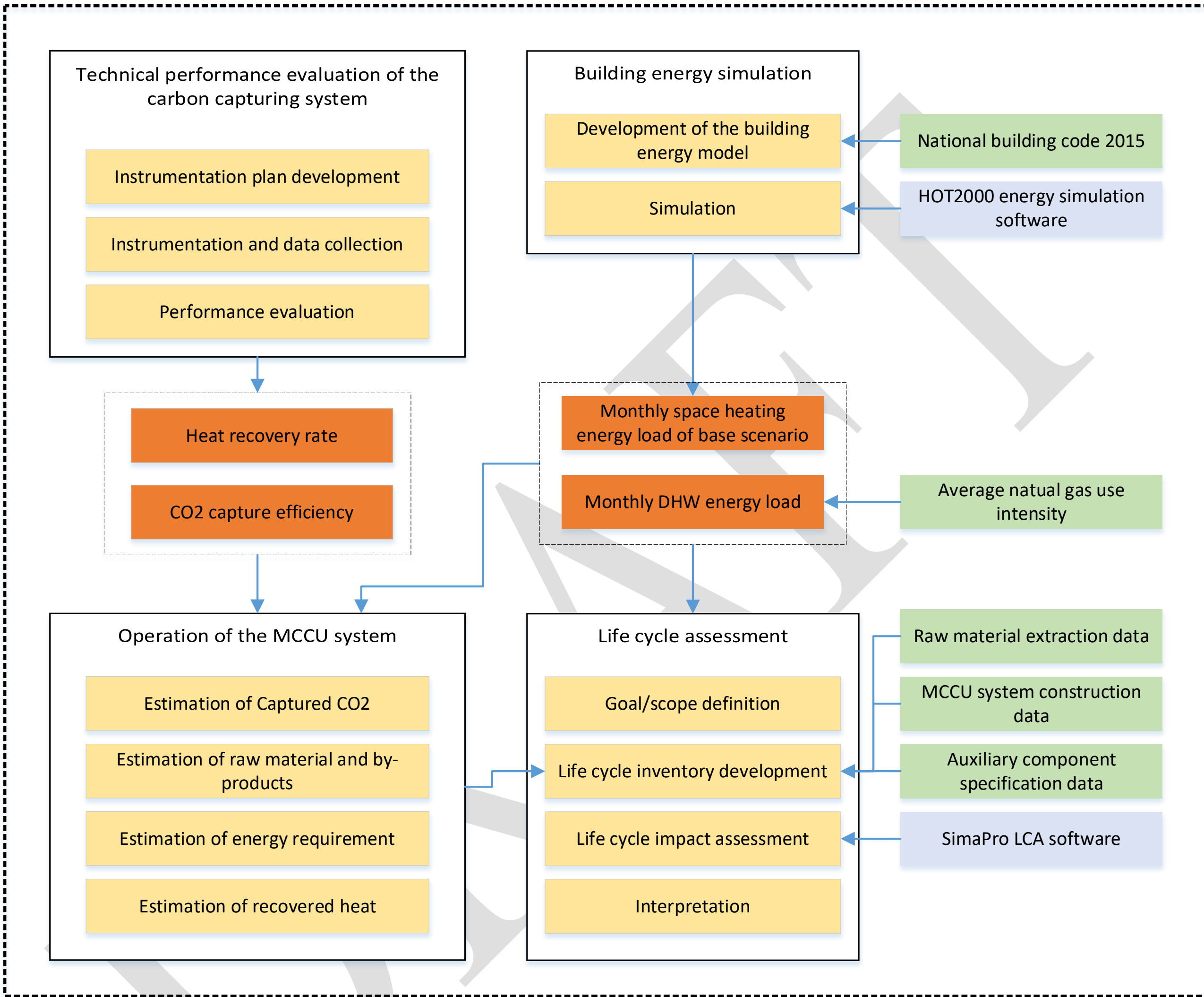

Figure 3: Overall methodology

3.1 Experimental study

The MCCU system was connected to a 250,000 BTU DHW boiler in an office building located in Calgary, AB. The boiler is non-modulating, which generates heat at its maximum power when operating. Figure 4 shows an instrumentation setup developed to estimate the technical performance of the carbon capturing system. 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 calculation procedure is shown below.

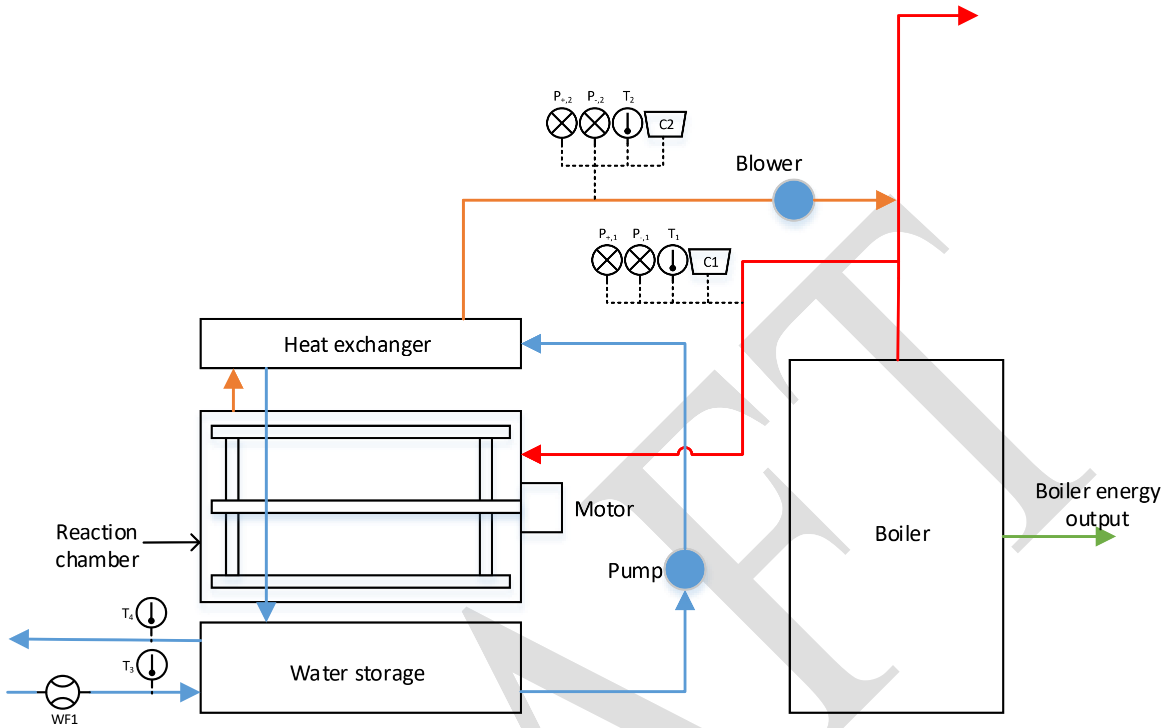

Figure 4: Instrumentation setup of technical performance evaluation

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The flue gas flow rate was calculated using the Equation 2, Equation 3, and Equation 4. Ideal gas equations were used to evaluate the gas properties.

$$\rho = \frac{P\_ \times M_{air}}{R(T + 273)} \quad \text{--------------------} \quad \text{Equation 2}$$

$$U_{mean} = \sqrt{\frac{2(P_+ - P\_)}{\rho}} \quad \text{--------------------} \quad \text{Equation 3}$$

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

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 masses were 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 5 only indicates the reduction of CO_2 in the flue gas that is diverted through the MCCU system.)

$$\eta_{CO2} = \frac{\sum_{i=1}^{n} M_{in,i} - \sum_{i=1}^{n} M_{out,i}}{\sum_{i=1}^{n} M_{in,i}} \quad \text{--------------------- Equation 5}$$

Where,

η_{CO2} is the carbon capture efficiency.
i is the day 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).

The heat recovery rate was calculated using Equation 6.

$$Q_{heat} = \rho_{water} \times \dot{V}_w \times S_{water} \times (T_{out} - T_{in}) \quad \text{--------------- Equation 6}$$

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 the water flow rates were recorded continuously at constant time intervals. Then, cumulative recovered heat and the amount of water flowed through the system were evaluated using numerical integration method (Trapezoidal method) on a daily basis. The average heat recovery rate (heat recovered per 1 liter of water) was calculated using Equation 7 as given below.

$$\eta_{heat} = \frac{\sum_{i=1}^{n} Q_{in,i}}{\sum_{i=1}^{n} V_{in,i}} \quad \text{--------------------- Equation 7}$$

η_{heat} is the heat recovery rate (kJ/l).
$Q_{in,i}$ is the recovered in i^{th} day (kJ).
$V_{in,i}$ is the volume of water flowed through the system on i^{th} day.

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In addition to the above technical parameters, the study also measured the ratio of the flue gas diverted from the main flue gas line of the boiler. This ratio helps to determine the maximum amount of the 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, it considered the time between the points where temperatures starts to increase and to decrease as the time interval during which the boiler operates. It is assumed that the boiler operates at its maximum power during this time. Emission factor data were used to estimate the CO_2 mass output.

3.2 Building energy modeling

The study used HOT2000 v11.7b23 building energy simulation software for residential building energy modeling. The HOT2000 software is widely used for building energy simulations in single-family detached residences. The study considered a single-family detached house with an area of 2000 ft^2 located in each of the eight provinces: ON, QC, BC, AB, MB, SK, NS, and NB. Since these eight provinces contain more than 90% of the population in Canada, only those provinces were considered in this study. Furthermore, the buildings were considered to be located in the most highly populated cities in the selected provinces. The details of the developed building model are shown in the Table 1 given below. Table 2 shows the heating degree days and the climatic regions of the selected cities, which were obtained from HOT2000.

Table 1: Building model information

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

Table 2: Heating degree days and Climatic regions of the selected cities

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

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The energy model of the residential house was developed in HOT2000 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 based on the building energy code of 2015 [10] as shown in Table 3. It was assumed that the space heating system is a natural gas induced draft furnace with 80% of steady state efficiency.

Table 3: Overall thermal transmittance values of building components [10]

Building component	***Overall thermal transmittance* [*W/ (m²̄.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
Other components				
Doors			2.2	
All fenestration	2.4	2.2	2.2	2.2

A medium-size commercial building in Canada has 10001 ft^2 to 50000 ft^2 floor area [11]. Therefore, the study was conducted assuming a commercial building with an office space of 30000 ft^2 [11] . The average natural gas energy intensity for water heating annually was considered as 4.8 thousand BTU/ft^2 [8] in all the buildings. Similar to the residential buildings, the commercial buildings were assumed to be located in ON, QC, BC, AB, MB, SK, NS, and NB. However, the regional variation of the energy intensity was not considered in this study as the main objective was to evaluate the performance of the MCCU system with natural gas heating systems used for domestic water heating. It was assumed that the energy factor of the domestic water heating system is 0.67, which is the minimum energy factor recommended by the 2015 building energy code [12]. In addition, the temperature difference of the inlet and the outlet water flows was considered to be 50 °C [12]. This is the temperature difference recommended by the 2015 building energy code when designing the hot water systems. The above data and the specific heat capacity of water were used to calculate the annual heat energy consumed by water for water heating in an office building of this nature.

3.3 Life cycle assessment

The life cycle assessment of MCCU system was conducted by using the framework provided by ISO 14040 [44]. This study considered cradle to gate life cycle of MCCU system, which covers raw material extraction and energy consumption for the production and operational phases of the product system.

3.3.1 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 in building level natural gas heating systems in Canada.

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The major reason to carry out the LCA was to evaluate the carbon capturing technology as it consumes considerable amount of material and electrical energy in the operational phase. In addition, the system produces K_2CO_3 that can replace commercially manufactured K_2CO_3. Therefore, it is important to consider the life cycle environmental impacts associated with the manufacturing phases of the chemicals.

3.3.1.1 Definitions of the Scenarios and functional units

When the heating system is combined with the MCCU unit, the combined system produces two main products: thermal energy and K_2CO_3. Therefore, the product system of the heating system combined with the MCCU system must be studied by considering it as a multifunctional process as advised by the ISO 14040 guidelines. Four Scenarios were considered in this study. Scenario A1 and Scenario B1 were defined by considering the residential space heating system and the commercial DHW systems integrated with an MCCU system where K_2CO_3 is generated as a byproduct. The reference scenarios were defined as Scenario A2 and Scenario B2. Since the study used system expansion to address the multi functionality of the product system, the reference scenarios have combined heat generation and equivalent commercial K_2CO_3 production. Scenario A2 was defined for the residential heating system without MCCU with the production of an equivalent amount of the K_2CO_3 by the conventional method. Scenario B2 was defined for the commercial building DHW system without MCCU with the production of an equivalent amount of K_2CO_3 by conventional method. The scenarios with their functional units are summarized in the Table 4.

Table 4: Functional units and heating system scenarios

Building Type	***Scenarios***	***Function Unit***
Residential	A1	The annual space heating energy requirement of a 2000 ft^2 single-family detached house having space heating system coupled with the MCCU system that generates K_2CO_3 as a by-product.
	A2	The annual space heating energy requirement of a 2000 ft^2 single-family detached house having space heating system without the MCCU system and industrial production of equivalent amount of K_2CO_3 (Reference)
Commercial	B1	Annual DHW energy requirement of a medium sized office building (30000 ft^2) coupled with MCCU system that generates K_2CO_3 as a by-product.
	B2	Annual DHW energy requirement of a medium sized office building (30000 ft^2) without MCCU system and industrial production of equivalent amount of K_2CO_3 (Reference)

3.3.1.2 System boundary of the Scenario A1 and Scenario B1

The study considered the manufacturing phase and the operational phase of the building heating systems including carbon capturing systems. The manufacturing phase is comprised of raw material extraction, and energy consumption for the manufacturing of heating systems and MCCU systems. The operational phase of the heating system includes the energy necessary for generating the required thermal energy. The operational phase of the MCCU system considers the amount of KOH consumed during operation, reduction (avoidance) of CO_2 by capturing process, and electricity consumption by the auxiliary equipment. Furthermore, the study considered the transportation of the required chemicals and by-products. The system boundary of MCCU scenarios in residential buildings (Scenario B1) is shown in Figure 5. The system boundary of the MCCU integration scenario in a commercial building (Scenario B2) is shown in Figure 6.

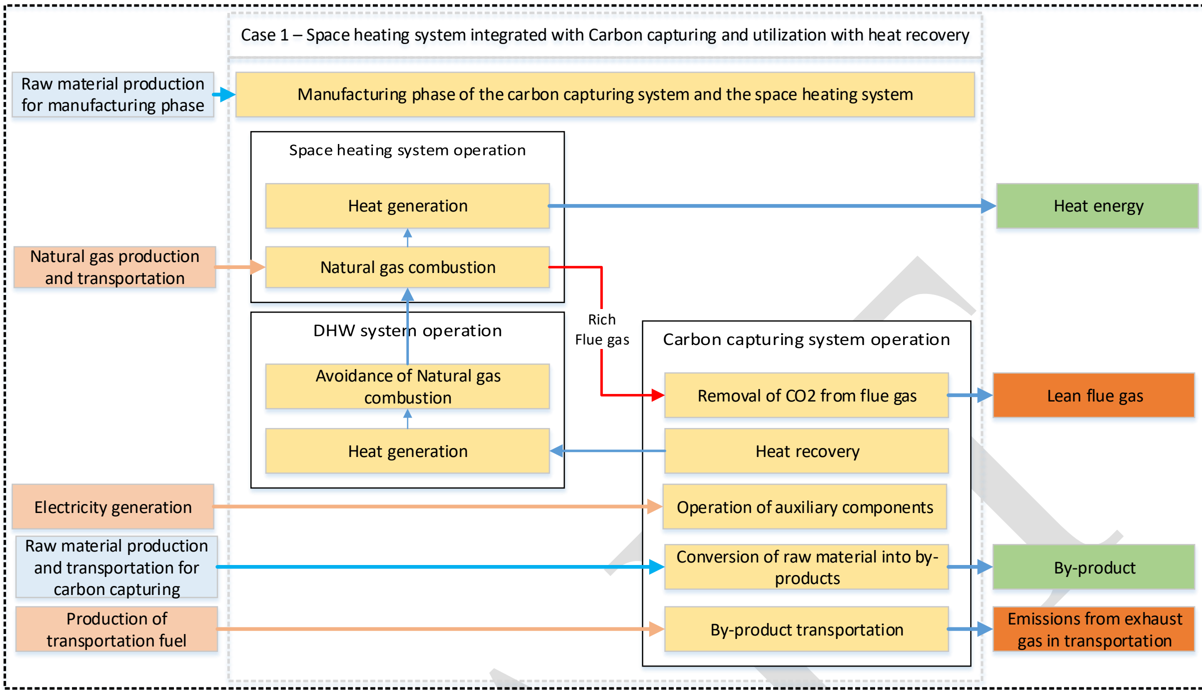

Figure 5: System boundary of the Residential space heating system integrated with MCCU (Scenario B1)

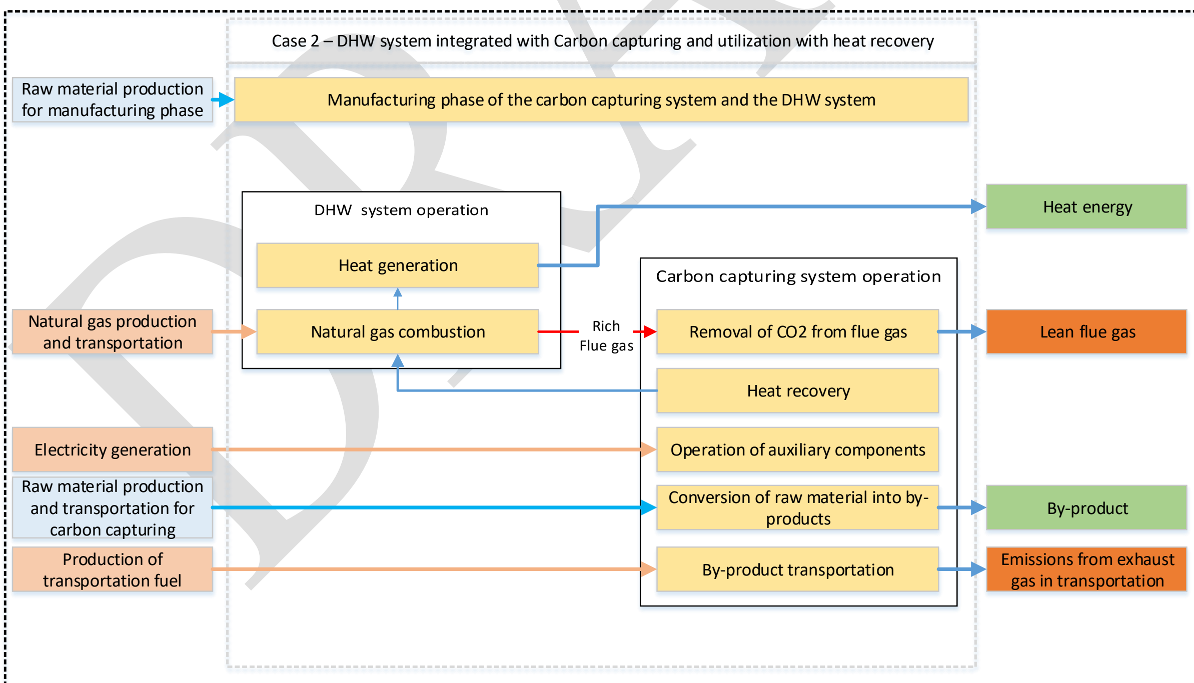

Figure 6: System boundary of the Commercial DHW system integrated with MCCU (Scenario B2)

3.3.1.3 System boundary of the Scenario A2 and Scenario B2

Figure 7 shows the system boundary of Scenario A2 and Scenario B2. The system boundary consists of two main subsystems: Generating heat using the respective heating system (Residential space heating system or Commercial DHW system) and production of K_2CO_3 in a commercial chemical production facility. The building heating process includes the manufacturing of the heating system, natural gas production, and the emissions associated with the combustion process. The conventional production of K_2CO_3 consists of raw material extraction including natural gas, electricity consumption for the auxiliary components, waste material, and transportation of K_2CO_3. In addition, the construction phase of the chemical facility is allocated to the total production volume of the K_2CO_3.

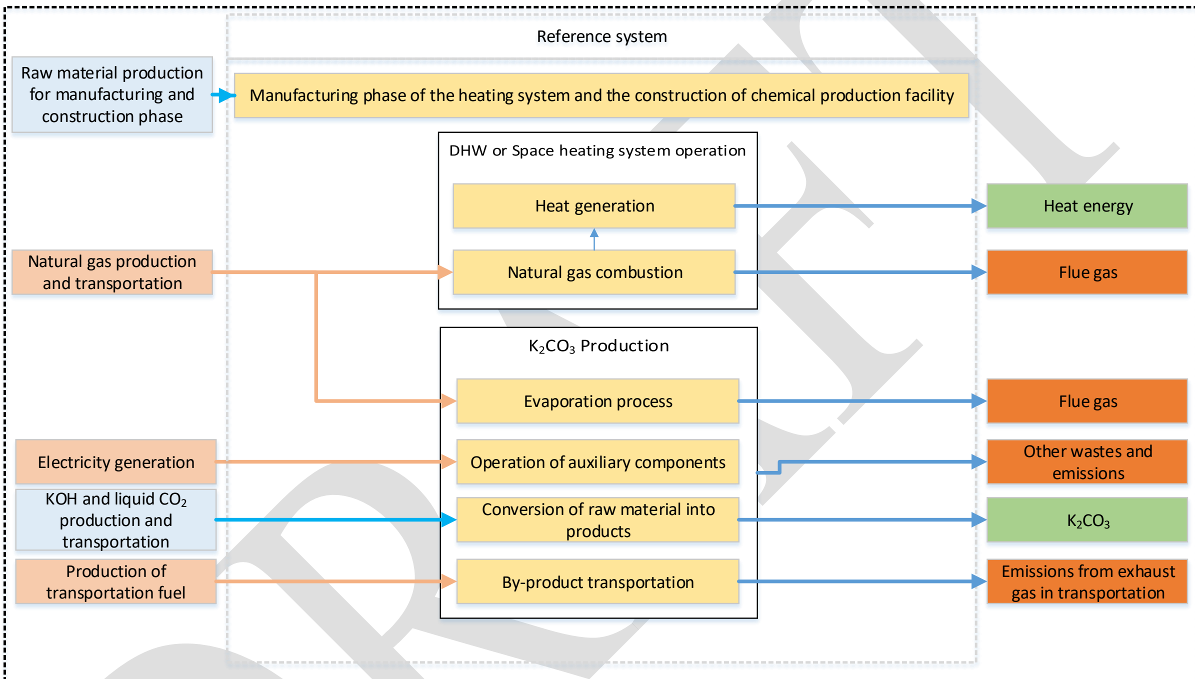

Figure 7: System boundary of the reference system (Scenarios A1 and A2)

3.3.2 Life cycle inventory

The life cycle inventory data generated for the LCA study is elaborated below.

3.3.2.1 Manufacturing phase of the MCCU system

The LCI of the MCCU system infrastructure consists of the material required to manufacture the system. The material requirement is derived from the engineering drawings of the carbon capturing systems. It was also assumed that the MCCU system is operated for 20 years.

Table 5: LCI of manufacturing phase of the MCCU system

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

3.3.2.2 Operational phase of the MCCU system

The LCI of the operational phase of Scenarios B1 and B2 consists of raw material input (KOH), by-product (K_2CO_3) formation, electricity consumption by the axillary components, and transportation of raw materials and by-products. It was also assumed that heat recovery saves natural gas used for heating.

The raw material requirement and the formation of the by-products can be calculated using the stoichiometry of the chemical reaction. The study assumes that 2.54 kg of raw material is required per kg CO_2 captured and 3.13 kg of by-product is generated per kg CO_2 captured during the carbon capture process based on the stoichiometry of the chemical reaction. The electricity consumption of the carbon capturing system was evaluated using the technical specifications and the operating time of the components as shown in the Table 6. The data for the Table 6 was obtained from a technical report on the carbon capturing system provided by the manufacturer.

Table 6: Specifications of the Auxiliary components in the MCCU unit

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 life cycle inventory of KOH production was adapted from Ecoinvent database [6]. In this database, it was assumed that the Potassium Chloride and water were used as the main raw materials when producing KOH. It was estimated that 823 kg of Potassium chloride and 2195 kg of water are consumed during the production of 1 ton of KOH. It was assumed that 6.52 MJ of electricity with 6.2 MJ of thermal energy that was in the medium of steam was required for producing 1kg of KOH production. The process emits 0.023 kg of insolubles, 0.257 kg of filter waste, and 1.814 kg of evaporated water. The production of 1 kg of K_2CO_3 required 0.854 kg of KOH and 0.336 kg of liquid CO_2. In addition, 2 MJ of heat and 0.33 kWh of electricity were used for the production process. It was assumed that all the electricity used in the process is converted into waste heat. In addition, excess CO_2 is released to the atmosphere and excess KOH is released to the water [7].

The Canadian importers' database indicates that the KOH is imported mainly from USA, Germany and China, while K_2CO_3 is imported from USA and China [13]. Although the information on major importers in Canada are available, the exact locations of the exporters and transportation mediums are not available. Therefore, the study used global default transportation statistic data on basic chemicals in Ecoinvent library [14][15][16]. These statistics are based on commodity flow surveys from United States Department of Transportation. The details of the transportation data are shown in Table 7. In addition, it was assumed that the raw material and by-products were transported at a distance of 50 km using light commercial vehicle [14] for the collection of by-production and refilling the chemicals of the MCCU process.

Table 7: Details of Transportation

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

3.3.3 Life cycle impact assessment

The potential environmental impacts were estimated using ReCiPe 2016 as the life cycle impact assessment method. The overview of the life cycle impact categories in ReCiPe 2016 is provided in the Table 8.

Table 8: Overview of the Life Cycle Impact categories

Impact category	***Overview***	***Unit of the characterization factor***
Climate change	The Climate Change impact is related to the increase of global mean temperature caused by GHGs. The indicator used to measure the Climate Change is the increase of inftra-red radiative forcing. Global warming potential of a substance is expressed by the equivalent amount of CO_2 in the given time frame.	kg CO_2 eq
Stratospheric ozone depletion	The Stratospheric ozone depletion is related to the increase of UVB radiation caused by the 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.	kg CFC11 eq
Ionizing radiation	The ionizing radiation is caused by the anthropogenic emissions of radionuclides. These emissions are generated during the nuclear fuel cycle, combustion of Coal, and extraction of phosphate. Ionizing radiation potential is used as the Characterization factor in ionizing radiation. The ionizing radiation potential of substance/emission is expressed by the equivalent radiation (kBq) of Co-60 in the given time frame.	kBq Co-60 eq

Ozone formation, human health, Terrestrial ecosystems	Photochemical reactions of NOx and Non-methane Volatile Organic Compounds form Ozone in the atmosphere. The ozone formation is expressed as an equivalent amount of NOx.	kg NOx eq
Fine particulate matter formation	Fine particulate matter formation is related to the primary and secondary aerosols in the atmosphere formed by the air pollution. The particulate matter formation potential of substance/emission is expressed by the equivalent particulate matter with a diameter less than 2.5 µm in the given time frame.	kg PM2.5 eq
Terrestrial acidification	Terrestrial acidification is related to the acidity of the Soil created by the inorganic substances such as sulphates. Acidification potential is used as the characterization factor to represent the Terrestrial acidification. The acidification potential of a substance/emission is expressed by the equivalent amount of SO_2 emissions.	kg SO_2 eq
Freshwater eutrophication	Freshwater eutrophication is related to the rise of nutrition of freshwater bodies caused by the discharger of nutrients such as P. Eutrophication potential is used as the characterization factor to represent Freshwater eutrophication. The Eutrophication potential of a substance/emission is expressed by the equivalent amount of P.	kg P eq
Marine eutrophication	Marine eutrophication is related to the rise of nutrition of freshwater bodies caused by the discharger of nutrients such as N. Marine Eutrophication potential is used as the characterization factor to represent marine eutrophication. The marine eutrophication potential of a substance/emission is expressed by the equivalent amount of N.	kg N eq
Ecotoxicity (Terrestrial, Freshwater, Marine,) and *Human Toxicity (carcinogenic/ non-carcinogenic toxicity)*	The Toxicity accounts the damage to the ecosystem and human health caused by the persistence and toxicity of a chemical. The terrestrial ecotoxicity is expressed as equivalent emission of 1,4-dichlorobenzene (1,4-DCB) to industrial soil, whereas the freshwater and marine ecotoxicity is expressed as equivalent emission of 1,4-dichlorobenzene (1,4-DCB) to the fresh water and seawater accordingly. The human Toxicity is expressed as equivalent emissions of 1,4-dichlorobenzene (1,4-DCB) to the urban air.	kg 1,4-DCB
Land use	The land use impact category accounts for the relative species losses due to land transformation and occupation. It is expressed as the equivalent relative species loss resulting from annual crop production.	m^{A2} crop eq
Mineral resource scarcity	The mineral resource scarcity is related to the extra amount of ore need to be produced when extracting materials (as the reduction of ore grade). Surplus Ore potential is used as the characterization factor. The Surplus Ore potential of a substance is expressed by the equivalent amount of extraction of Cu.	kg Cu eq
Fossil resource scarcity	Fossil fuel potential of the fossil resource is used as the characterization factor for fossil resource scarcity. The fossil fuel potential is expressed by the equivalent amount of crude oil.	kg oil eq
Water consumption	The water that is evaporated, included in a product, transferred to other water fields, and flowed in to sea during a process is accounted by the water consumption impact category.	m^3

3.3.4 Interpretation

The findings from the life cycle inventory analysis and the life cycle impact assessment are interpreted during this phase. The change in life cycle environmental impacts by the use of MCCU system in each residential and commercial building were statistically tested by employing one-tail t-test using Microsoft Excel 2016. The null hypothesis for the test was defined as there being no significant reduction in the mean environmental impacts of heating systems when using carbon capturing compared to the reference (baseline) heating systems. The alternative hypothesis is defined as there being significant change in the mean environmental impacts of heating systems when using carbon capturing compared to the reference (baseline) heating systems.

4 Results

This section presents the results obtained from the experimental study, energy simulation, and the LCA.

4.1 Technical performance of the MCCU system

The collected data of the CO_2 inflow, CO_2 capture rate, and heat transfer rate observed from 2020-07-02 to 2020-03-20 are shown in the Appendix: Table A1. The average CO_2 emissions from the furnace was 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 in to the MCCU system 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.

The percentage of the CO_2 mass diverted through the MCCU system was varied from 52 – 75%, with an average of 60%. The study calculated the maximum CO_2 intake through the MCCU system by considering the average fraction of the CO_2 mass diverted through the MCCU system and the CO_2 emission rate of the heating system. The maximum CO_2 intake was found as 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 entered through the MCCU system. The results show that CO_2 capture efficiency is 13% in average with the maximum value of 21.07%.

The water flow through the MCCU system in weekdays were observed to be 2 – 264 L/day. The average water flow was 94 L/day. The heat transfer rate was varied from 2– 60 kJ/L, with an average of 26 kJ/L. The results also indicate that the heat transfer rate was reduced when there is low water usage. In addition, the water flow rates in the weekends were observed as 0.14 – 23 L/day.

4.2 Performance of the residential space heating system

The energy simulation results showed that the design power of the residential space heating system was 13.5kW – 27kW. Therefore, the MCCU system considered in this study must be able to take all the exhaust gas produced by the heating system, as the maximum CO_2 produced during the combustion is less than the maximum CO_2 intake of the MCCU system. Figure 8 shows the monthly energy consumption of the residential space heating system. The results show that the 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 does not need thermal energy in July. The house located in AB requires space heating energy throughout the year. The month with maximum energy requirement was January in all the provinces. SK had the highest annual energy consumption while BC had the lowest.

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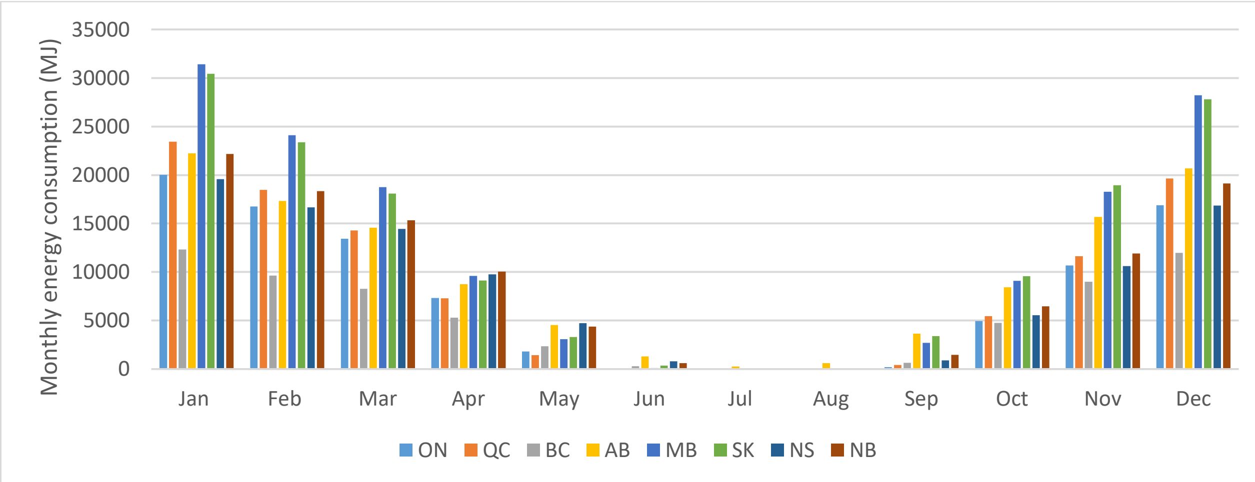

Figure 8: Monthly energy consumption of the Residential space heating system

4.3 Performance of the MCCU system in Scenario A1

The heat recovery system reduced 694 MJ/month of natural gas use from the DHW system in Scenario A1. Since the heat recovery can only be used in the DHW, it was assumed that the avoided use of natural gas is from this end use. The reduced combustion of the natural gas was not considered while calculating the captured CO_2 and the K_2CO_3 production from the space heating system.

Figure 9 shows the production of the K_2CO_3 by the MCCU system for Scenario A2. The study assumed that the maximum KOH consumption is 200 kg per month. Therefore, the maximum K_2CO_3 yield is 246 kg according to the stoichiometric ratios of the reaction. Figure 9 indicates that the K_2CO_3 production was more than 95% of its maximum in January, February, March, October, November, and December in all provinces except BC. In BC, the MCCU system produced maximum K_2CO_3 only in January and December. The K_2CO_3 production in June was less than 12 % of its maximum production in all provinces. Only AB and SK produce K_2CO_3 in August, which was less than 6% of the maximum capacity. Only AB produce K_2CO_3 in July, which was only 2% of the maximum capacity. The annual production of the K_2CO_3 was 1.4 tons – 1.8 tons, and the lowest K_2CO_3 production was from BC and the highest was from AB.

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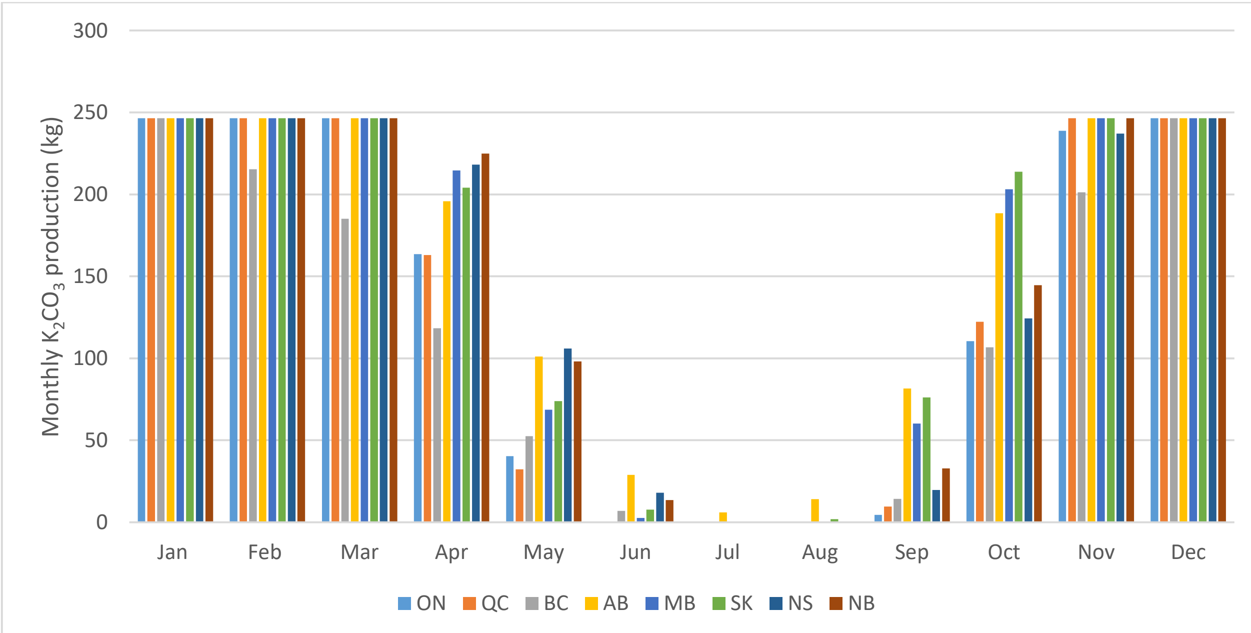

Figure 9: Monthly K_2CO_3 production in Scenario A1

4.4 Performance of the MCCU system in Scenario B1

The annual DHW energy requirement was calculated as 151,920 MJ using the average energy use of an office building. However, the heat recovery system reduced the heat load by 16%, resulting only in a combustion of natural gas equivalent to 126,868 MJ. The calculations show that the monthly K_2CO_3 production was 237 kg by assuming an equal DHW energy requirement in all eight provinces. The monthly production of K_2CO_3 in Scenario B1 is less than the maximum production of Scenario A1. However, the annual K_2CO_3 production was 2.8 tons, which was higher than the annual K_2CO_3 production in Scenario A1. It was due to the constant use of natural gas for DHW in all the months, in-contrast to space heating systems.

4.5 Life cycle environmental impacts

Table 9 shows the values of functional units derived from the above analysis for difference provinces in Scenario A1 and Scenario A2. The functional unit obtained for Scenario B1 and B2 was generation of 151,920 MJ of thermal energy with production of 2,838 kg of K_2CO_3.

Table 9: Functional units used in Scenario A1 and Scenario A2

Province	*Thermal energy requirement (MJ/year)*	*Production of K_2CO_3 (kg/year)*
ON	92029	1543
QC	102068	1559
BC	64540	1393
AB	118052	1848
MB	145276	1781
SK	144444	1810

NS	99864	1709
NB	109821	1746
ON	92029	1543
QC	102068	1559
BC	64540	1393
AB	118052	1848

4.5.1 Life cycle impacts of MCCU system

The Table 10 shows the percentage and absolute differences of environmental impacts of Scenario A1 compared to Scenario A2 in different provinces. In addition, the table shows the mean values of environmental impacts and upper or lower bound of the absolute and percentage mean differences of environmental impacts. The LCA results for individual provinces are shown in the Appendix: Table A2, Table A3, Table A4, and Table A5). The results show that the mean global warming potential (GWP), stratospheric ozone depletion, ozone formation, fine particulate matter formation, terrestrial ecotoxicity, human non-carcinogenic toxicity, land use, and fossil resource scarcity were significantly reduced in all provinces.

The highest reduction of GWP in individual provinces was 24% and it was in the house located in BC. The houses located in AB, SK, and NS had reduction of 12% in GWP, which was the lowest in all provinces. The highest reduction of stratospheric ozone depletion was 15% and it was observed in BC, while the lowest reduction of 5% was observed in NS. The highest reduction of ozone formation was 20% and it was observed in BC and the lowest reduction of 3% was observed in NS. The highest reduction of fine particulate matter formation was 22% in QC and lowest reduction was 2% in NS. Similarly, the highest reduction of terrestrial ecotoxicity was 35% and it was also shown in QC, while the lowest that was 27% and it was in NS. QC also indicated the highest reduction of human non-carcinogenic toxicity that was 35%. The lowest reduction of human non-carcinogenic toxicity was observed in AB that is 3%. The highest reduction of land use was observed in MB and the lowest was observed in QC. The highest reduction of fossil resource scarcity that was 17% was in BC and the lowest that was 7% and it was shown in SK and NS.

A substantial increase in ionizing radiation can be seen in ON and NB, which was 51% to 140%. Terrestrial acidification was increased only in NS by 7%. The freshwater eutrophication, marine eutrophication, Freshwater ecotoxicity and marine ecotoxicity increased in AB and SK by 3% - 48%. Human carcinogenic toxicity was increased in AB, SK, and NS by 3% to 19%. The water consumption was increased by 33% - 74% in all provinces except AB, SK, and NB. Although there was a substantial increase of the above mentioned environmental impacts in different provinces, the mean differences between the environmental impacts of Scenario A1 and Scenario A2 compared to the respective reference scenarios were not statistically significant. The mineral resource scarcity increased in all provinces from 4% to 17%. The statistical analysis also indicates that the mean increase of mineral resource scarcity was significant.

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Table 10: Change in Environmental impacts in residential buildings by MCCU system

Impact category#	***Unit*** *(unless stated otherwise)*	***Change of Environmental impacts (%)***								***Mean difference***	***Upper bound of mean difference***	***Upper bound of mean % difference***
		ON	**QC**	**BC**	**AB**	**MB**	**SK**	**NS**	**NB**			
Global warming	kg CO_2 eq	-21	-20	-24	-12	-17	-12	-12	-17	-2236	-1822*	-13%
Stratospheric ozone depletion	kg CFC11 eq	-14	-14	-15	-9	-12	-9	-5	-9	-4.5E-4	-3.2E-04*	-8%
Ionizing radiation	kBq Co-60 eq	140	-25	-24	-26	-24	-25	-24	51	17.3	-	-
Ozone formation, human health	kg NOx eq	-18	-19	-20	-9	-17	-10	-3	-12	-1.99	-1.12*	-7%
Fine particulate matter formation	kg PM2.5 eq	-22	-22	-20	-13	-21	-15	-2	-15	-1.86	-1.07*	-9%
Ozone formation, terrestrial ecosystems	kg NOx eq	-18	-19	-20	-9	-17	-10	-3	-12	-2.03	-1.15*	-7%
Terrestrial acidification	kg SO_2 eq	-21	-22	-22	-8	-20	-10	7	-10	-2.99	-0.61*	-3%
Freshwater eutrophication	kg P eq	-26	-28	-23	48	-25	32	-6	-21	-0.11	-	-
Marine eutrophication	kg N eq	-26	-35	-31	28	-32	15	-16	-26	-0.03	-	-
Terrestrial ecotoxicity	kg 1,4-DCB	-31	-35	-32	-32	-33	-31	-27	-30	-5478	-4751*	-27%
Freshwater ecotoxicity	kg 1,4-DCB	-10	-26	-7	11	-12	6	-3	-9	-10.6	-	-
Marine ecotoxicity	kg 1,4-DCB	-12	-26	-10	8	-14	3	-5	-11	-20.6	-	-
Human carcinogenic toxicity	kg 1,4-DCB	-13	-16	-11	19	-14	12	3	-9	-6.9	-	-
Human non-carcinogenic toxicity	kg 1,4-DCB	-28	-31	-27	-3	-27	-8	-19	-25	-1035	-523*	-10%
Land use	m^2a crop eq	-21	-14	-18	-17	-23	-22	-12	-20	-22.30	-15.95*	-13%
Mineral resource scarcity	kg Cu eq	15	8	17	4	5	4	8	8	1.40	0.74*	4%
Fossil resource scarcity	kg oil eq	-14	-14	-17	-7	-11	-7	-7	-10	-450	-334*	-8%
Water consumption	m^3	74	37	64	-21	55	-2	-16	33	10.17	-	-

Note: # -ve values indicate decrease *significant at 99% confidence level

The life cycle impacts of the MCCU system in commercial buildings were estimated as the difference of the impacts between Scenarios B1 and B2 as shown in Table 11. The impact categories except ionizing radiation, freshwater eutrophication, and water consumption showed statistically significant mean reductions in Scenario B1 compared to Scenario B2. Furthermore, statistical analysis shows that there are insignificant increases in ionizing radiation, freshwater Eutrophication, and water consumption. The Table 11 also indicates that the percentage reductions of the environmental impacts in Scenario B1 were increased compared to Scenario A1. In addition, the terrestrial acidification, freshwater and marine ecotoxicity, and mineral resource scarcity, which have increased impacts in some provinces under Scenario A1 decrease in Scenario B1.

Table 11: Change in Environmental impacts in commercial buildings by MCCU system

Impact category#	***Unit** (unless stated otherwise)*	***Change of Environmental impacts (%)***								***Mean difference***	***Upper bound of mean difference***	***Upper bound of mean % difference***
		ON	**QC**	**BC**	**AB**	**MB**	**SK**	**NS**	**NB**			
Global warming	kg CO_2 eq	-27	-27	-26	-22	-27	-23	-21	-25	-5073	-4554*	-22%
Stratospheric ozone depletion	kg CFC11 eq	-20	-20	-20	-17	-20	-18	-14	-17	-1.16E-03	-1.0E-03*	-16%
Ionizing radiation	kBq Co-60 eq	64	-28	-27	-28	-27	-28	-27	21	-73.8	-	-
Ozone formation, human health	kg NOx eq	-22	-23	-22	-16	-23	-18	-12	-18	-4.687	-3.70*	-15%
Fine particulate matter formation	kg PM2.5 eq	-25	-25	-24	-19	-25	-21	-13	-21	-4.093	-3.23*	-17%
Ozone formation, terrestrial ecosystems	kg NOx eq	-22	-23	-22	-16	-23	-18	-12	-18	-4.785	-3.79*	-15%
Terrestrial acidification	kg SO_2 eq	-24	-25	-24	-15	-25	-18	-7	-18	-7.372	-4.78*	-13%
Freshwater eutrophication	kg P eq	-29	-30	-27	21	-29	10	-16	-25	-0.636	-	-
Marine eutrophication	kg N eq	-32	-37	-34	5	-36	-4	-25	-31	-0.0726	-0.02*	-7%
Terrestrial ecotoxicity	kg 1,4-DCB	-38	-41	-39	-38	-39	-38	-35	-36	-10985	-10475*	-36%
Freshwater ecotoxicity	kg 1,4-DCB	-21	-30	-21	-5	-21	-9	-15	-19	-52.77	-27.38*	-9%
Marine ecotoxicity	kg 1,4-DCB	-22	-30	-22	-7	-22	-10	-17	-20	-81.3	-47.25*	-11%
Human carcinogenic toxicity	kg 1,4-DCB	-21	-23	-21	2	-22	-3	-11	-18	-59.5	-18.86*	-5%
Human non-carcinogenic toxicity	kg 1,4-DCB	-31	-33	-31	-15	-32	-19	-25	-30	-2262	-1658*	-20%

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Land use	m^2a crop eq	-24	-20	-22	-21	-25	-25	-18	-23	-45.03	-39.84*	-20%
Mineral resource scarcity	kg Cu eq	-10	-13	-12	-12	-12	-12	-11	-10	-3.261	-2.94*	-10%
Fossil resource scarcity	kg oil eq	-20	-21	-20	-16	-20	-17	-16	-18	-1168	-1034*	-16%
Water consumption	m^3	26	7	15	-25	24	-13	-23	8	1.63	-	-

Note: # -ve values indicate decrease *significant at 99% confidence level

The main difference between Scenario A1 and Scenario B1 was the increase of annual captured CO_2 and the annual recovered heat. Most of the environmental impacts were reduced in Scenario B1 compared to Scenario A1 as a result of higher yield of K_2CO_3 and increased heat recovery. However, it is essential to consider the contribution of material and energy flows to the environmental impacts especially with regards to the environmental impacts that were increased due to the MCCU system. The subsequent sections discuss more details on the global warming potential and the environmental impacts that increased in one or more provinces in Scenario A1 and Scenario B1 compared to Scenario A2 and Scenario B2, respectively.

4.5.2 Global warming potential

Capturing CO_2 and recovering heat from flue gas can be considered as the major functions of the MCCU system by which global warming potential of Natural gas-based heating system is significantly reduced ($p=0.01$). Figure 10 shows that 5% to 9% of the global warming potential of natural gas combustion was reduced by capturing CO_2 from flue gas in Scenario A1 compared to Scenario A2. The heat recovery process reduced 6% to 13% of the GWP of the entire natural gas combustion process. The CO_2 capture and heat recovery in Scenario A1 contributed with the reduction of 1100 kgCO_2-eq to 1256 kgCO_2-eq in Scenario A1 compared to Scenario A2. Similarly, the Scenario B1 reduced 7% and 16% of the GWP related to natural gas combustion by capturing CO_2 and heat recovery. The reduction of GWP by the carbon capturing was 905 kgCO_2-eq and the reduction of GWP by the heat recovery was 2000 kgCO_2-eq.

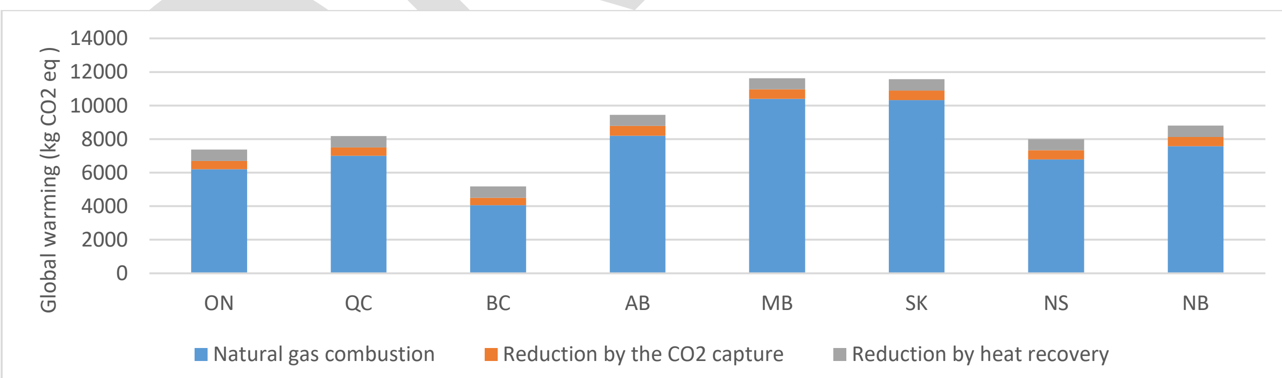

Figure 10: Contribution of CO_2 capture and heat recovery on GWP of heating system in Scenario A1

Figure 11 shows the breakdown of the global warming potential in Scenario A1 and Scenario A2. It shows the by-product transportation of material and manufacturing process of the MCCU system has negligible contribution to the total GWP. The electricity generation required for operating carbon capturing process in Scenario A1 contributed to less than 2% of the total GWP in ON, QC, BC, and MB as the major portion of the electricity in these provinces are produced by nuclear and renewable energy. The electricity consumption in NB contributes 5% of the GWP in Scenario A1. In NB, 35% of the electricity is generated using fossil fuel and rest of the energy is generated using nuclear and renewables [17]. Electricity generation contributed 896 kgCO_2-eq, 1115 kgCO_2-eq, and 1193 kgCO_2-eq to the GWP in SK, AB, and NS accordingly. All these provinces generate majority of the electricity based on fossil fuel-based thermal plants [17]. NS has the highest GWP in electricity generation compared to AB and SK although NS uses lesser fossil fuel combustion percentage for the electricity generation. This may be due to the use of large amount of heavy fuel oil in the electricity generation in NS, which has high carbon footprint compared to coal and natural gas [18].

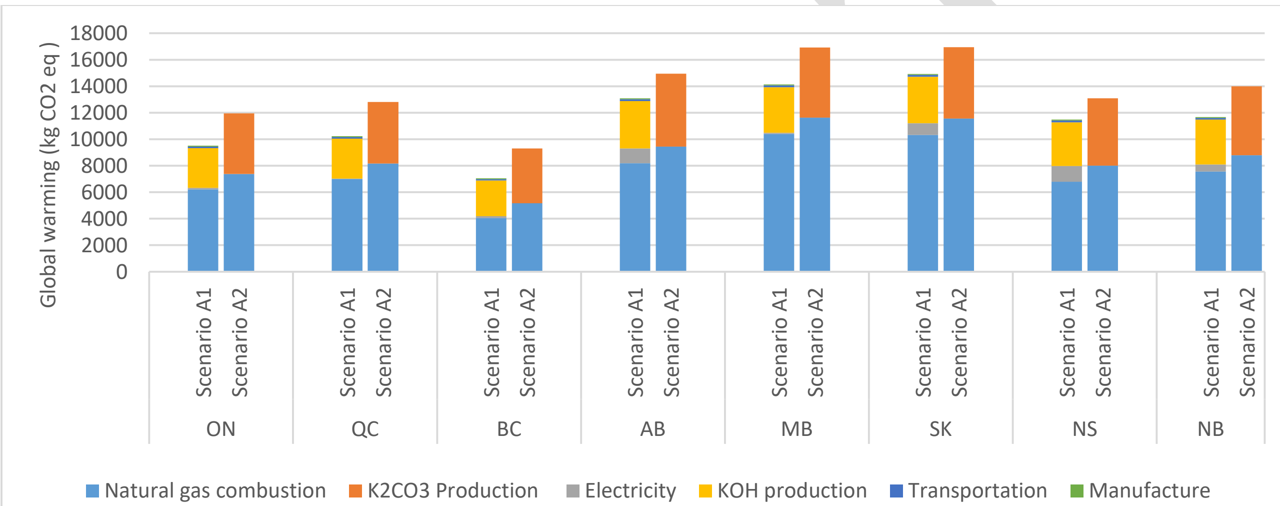

Figure 11: Global warming potential of heating systems in Scenario A1 and Scenario A2

In natural gas-based heating system in Scenario B1, the CO_2 capturing reduces the GWP by 7% and heat recovery reduces 16%. Figure 12 shows the breakdown of the global warming potential in Scenario B1 and Scenario B2. The Scenario B2 generated GWP of 20604 kgCO_2-eq annually and 8400 kgCO_2-eq was contributed by the conventional production of K_2CO_3. Scenario B1 annually generates 15100 kgCO_2-eq to 16200 kgCO_2-eq of GWP and KOH production contributes 34% - 36% of the GWP. Moreover, electricity contributes less than 1% of GWP in ON, QC, BC, and MB. The electricity generation in NB contributes 3% of the GWP and that in SK, AB, and NS contribute 6% to 7% to the GWP.

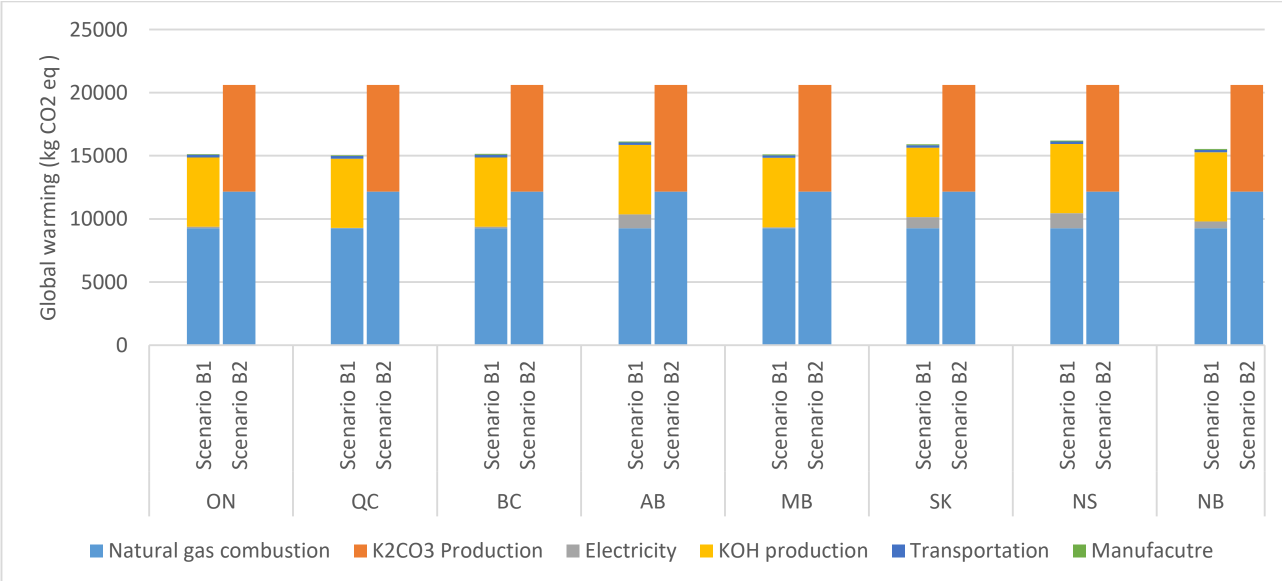

Figure 12: Global warming potential of heating systems in Scenario B1 and Scenario B2

One of the major observations that can be seen in Figure 11 and Figure 12 is the difference between the reduction of GWP in natural gas combustion and the overall reduction of GWP. The reductions of the GWP in life cycle of the natural gas combustion process by capturing CO_2 and heat recovery are 1.1 to1.3 ton CO_2-eq in Scenario A1 and 3 tons in Scenario B1, respectively. However, the overall reductions of GWP are 1.6 to 2.8 ton CO_2-eq in Scenario A1 and 4.3 to 5.6 ton CO_2-eq in Scenario B1. It indicates that there is a significant environmental benefit by the production of by-products K_2CO_3 in the MCCU system compared to the reference scenario.

4.5.3 Ionizing radiation

The ionizing radiation of the Scenario A1 and Scenario A2 is shown in Figure 13. Figure 14 shows the ionizing radiation of the Scenario B1 and Scenario B2. ON and NB had significant increase in ionizing radiation in Scenario A1 and Scenario B1 compared to Scenario A2 and Scenario B2, respectively. All the other provinces had less ionizing radiation in Scenario A1 and Scenario B2 compared to Scenario A1 and Scenario A2, respectively. The Figure 13 and Figure 14 show that the majority of the ionizing radiation was generated in ON and NB by the electricity generation. 61% of the electricity in ON and 38% of the electricity in NB are produced by Nuclear energy [17]. The results on the contribution of nuclear energy to the ionizing radiation indicate that ON and NB contribute 70% and 52% of the total ionizing radiation respectively under Scenario A1.

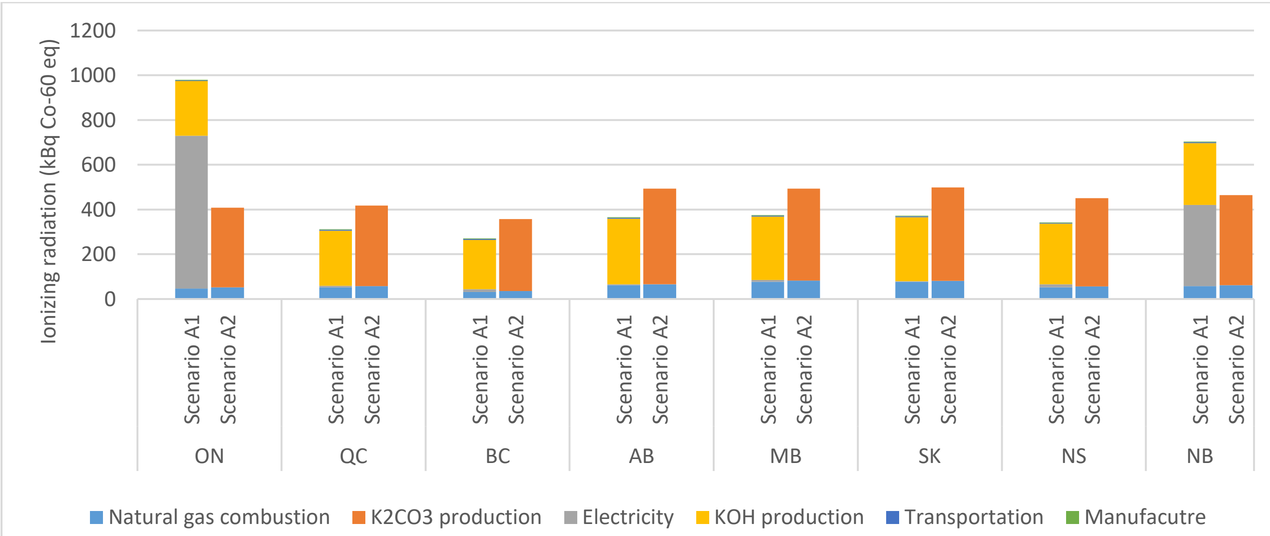

Figure 13: Ionizing radiation due to heating systems in Scenario A1 and Scenario A2

The by-product transportation of raw material and by-products, and manufacturing of MCCU unit do not significantly contribute to the ionizing radiation. Although natural gas does not emit any radioactive material, the energy consumption during the production and transportation may involve nuclear energy. Therefore, the life cycle of the natural gas combustion process contributes to the ionizing radiation by 5 – 21%.

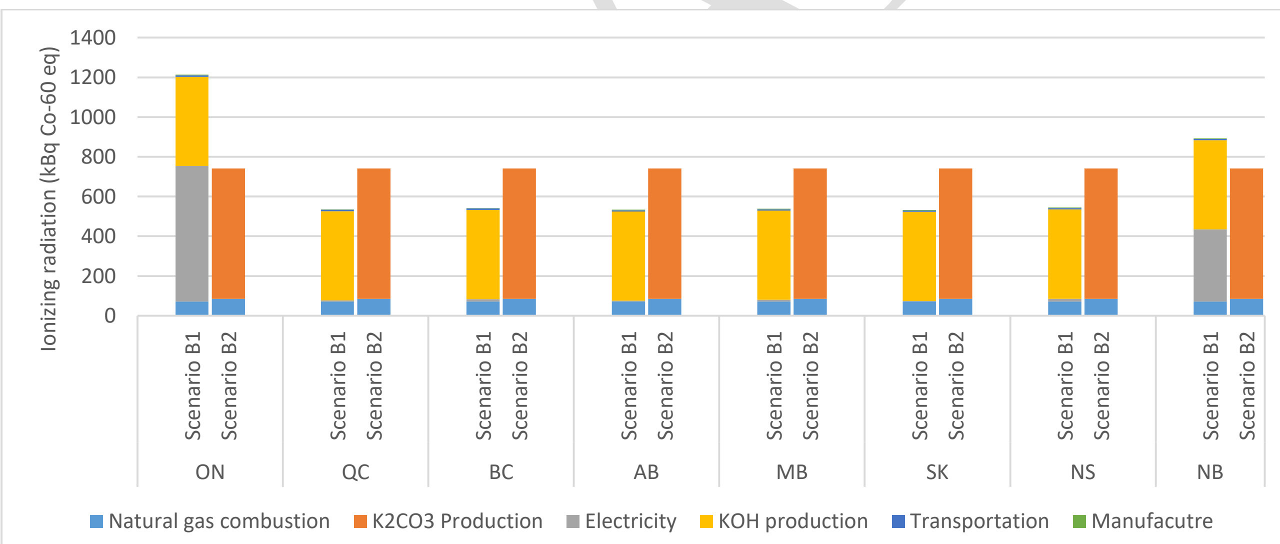

Figure 14: Ionizing radiation due to heating systems in Scenario B1 and Scenario B2

4.5.4 Terrestrial acidification

Figure 15 shows the terrestrial acidification caused by the product systems in Scenario A1 and Scenario A2. Around 70 – 80% of the terrestrial acidification in Scenario A2 is caused by the K_2CO_3 production. This can be attributed to the significant electricity consumption during the K_2CO_3 production. The Scenario A1 had lower terrestrial acidification in all provinces except NS. Transportation and manufacturing of MCCU system contributed only less than 2% of the total terrestrial acidification. The increased contribution of electricity in terrestrial acidification can be clearly observed in AB, SK, NC, and NB. AB, SK, and NB use Coal for electricity generation, which has high SO_2 content in the flue gas. In addition, NS uses heavy fuel oil for the electricity production, which results in a higher SO_2 content in flue gas [18]. SO_2 gas mixes with rainwater and creates sulphates, which in turn causes acidification of the soil. Therefore, NS had 7 kg SO_2-eq under the terrestrial acidification category due to electricity generation under Scenario A1. Figure 16 shows the terrestrial Acidification in the Scenario B1 and Scenario B2. Although the impacts of electricity generation with regards to terrestrial acidification is same as the Scenario A1, Scenario B1 shows a reduction in terrestrial acidification in all provinces compared to Scenario B2. It indicates that the conventional production of the K_2CO_3 create higher terrestrial acidification than the MCCU process.

Figure 15: Terrestrial acidification due to heating systems in Scenario A1 and Scenario A2

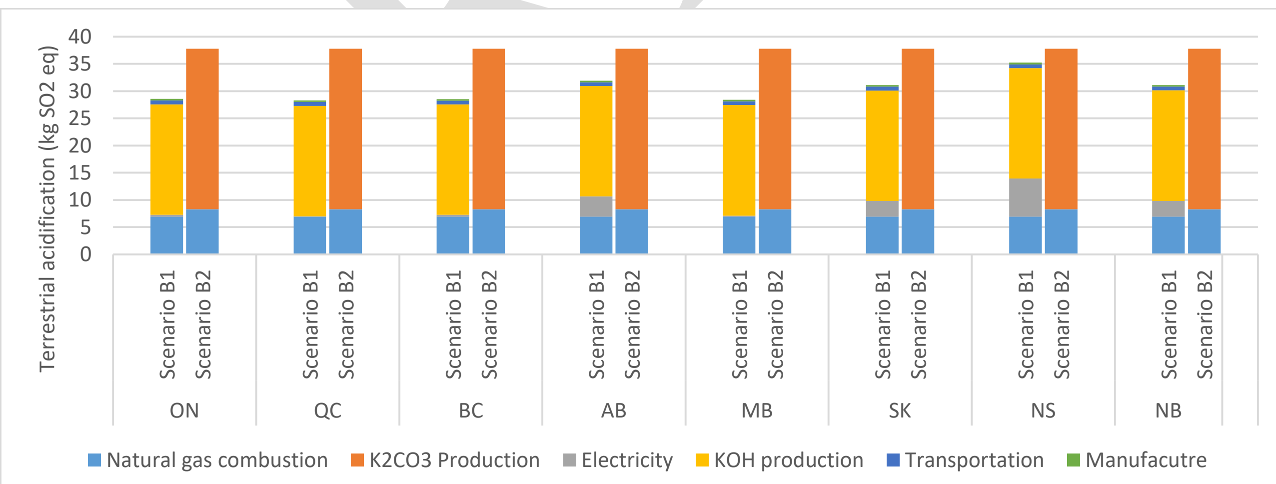

Figure 16: Terrestrial acidification due to heating systems in Scenario B1 and Scenario B2

4.5.5 Freshwater eutrophication

Figure 17 shows the freshwater eutrophication of Scenario A1 and Scenario A2. The results show the manufacturing and by-product transportation phases had negligible impact on the freshwater eutrophication. AB and SK had increased freshwater eutrophication in Scenario A1 compared to Scenario A2. These provinces show a significant increase in freshwater eutrophication due to electricity generation. AB and SK generate electricity primarily using coal combustion. The coal combustion products are responsible for immobilization of Phosphorus, which creates eutrophication in fresh water [19]. Figure 18 shows the freshwater eutrophication due to heating systems in Scenario B1 and Scenario B2. AB and SK generate considerable amount of freshwater eutrophication in Scenario B1 despite the difference between Scenario A1 and Scenario A2 is less than that in Scenario B1 and Scenario B2.

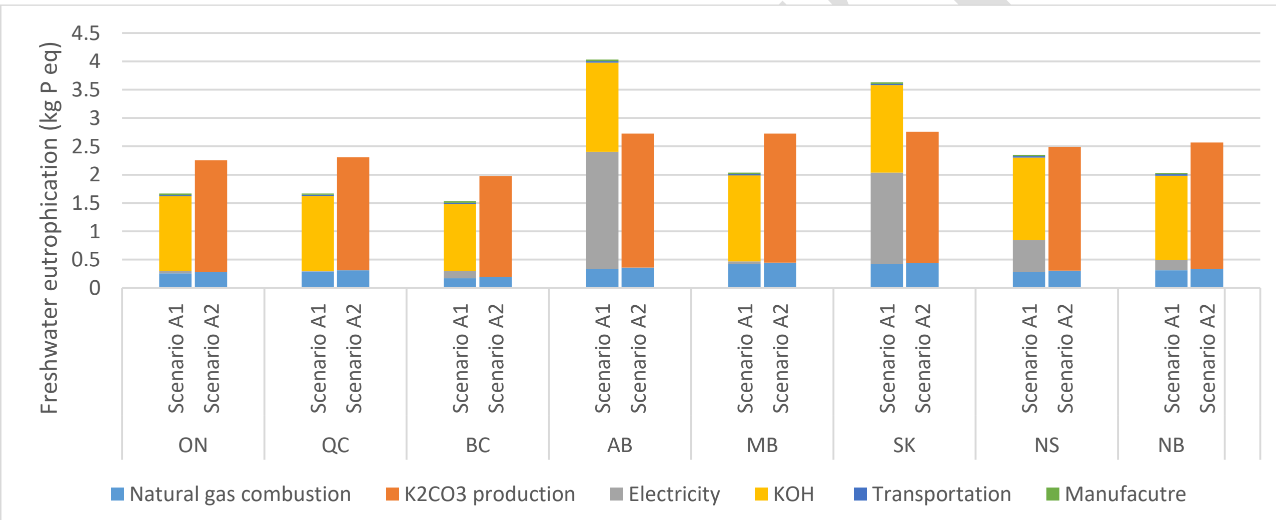

Figure 17: Freshwater eutrophication due to heating systems in Scenario A1 and Scenario A2

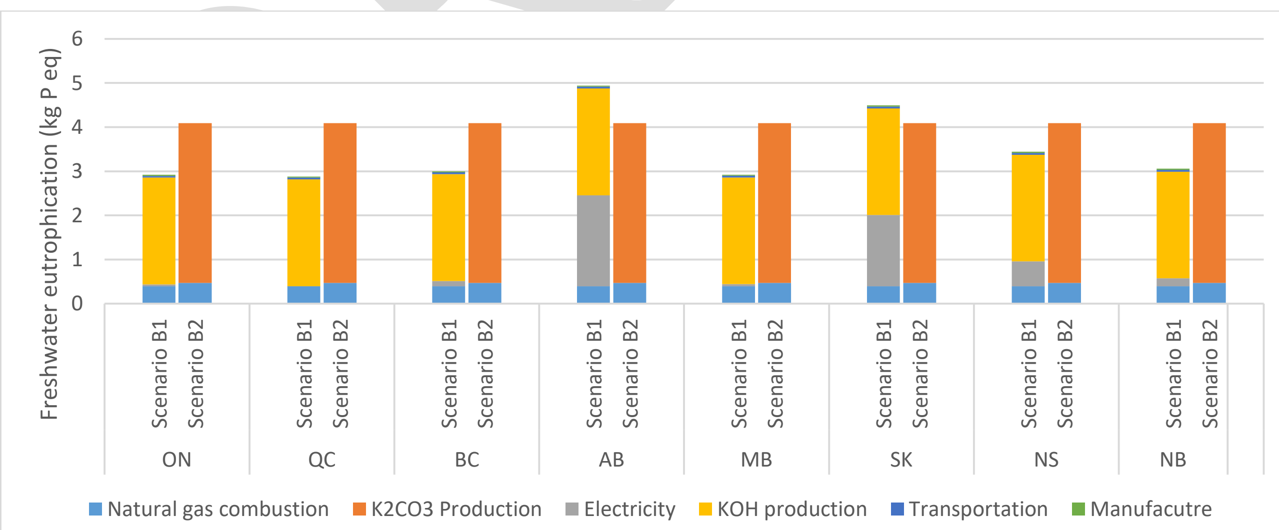

Figure 18: Freshwater eutrophication due to heating systems in Scenarion B1 and Scenario B2

4.5.6 Marine eutrophication

Figure 19 shows the breakdown of the marine eutrophication impact due to heating systems in Scenario A1 and Scenario A2. The results show that the production of K_2CO_3 contributes to 84 – 90% of the marine eutrophication in Scenario A2. The manufacturing and the transportation phases of MCCU system have negligible impacts on the marine eutrophication in Scenario A1. The electricity generation in ON and NB contributes 12% and 13% to the marine eutrophication in Scenario A1. The electricity generation in QC and MB has negligible impact on marine eutrophication. The electricity generation in BC contributes 8% to the marine eutrophication. Electricity generation in NS, SK, and AB significantly contributes to the increase of marine eutrophication, causing 23%, 42%, and 49% of the marine eutrophication respectively in these provinces. The coal combustion used for the electricity generation in above provinces should be responsible for the increase of marine eutrophication [20].

Figure 19: Marine eutrophication due to heating systems Scenario A1 and Scenario A2

Figure 20 shows the breakdown of the marine eutrophication in Scenario B1 and Scenario B2. The K_2CO_3 production contributes 90% of the marine eutrophication in Scenario B2. The percentage contribution of the electricity generation to the marine eutrophication reduced considerably under Scenario B1. Only AB had increased impacts in Scenario B1 compared to Scenario A1.

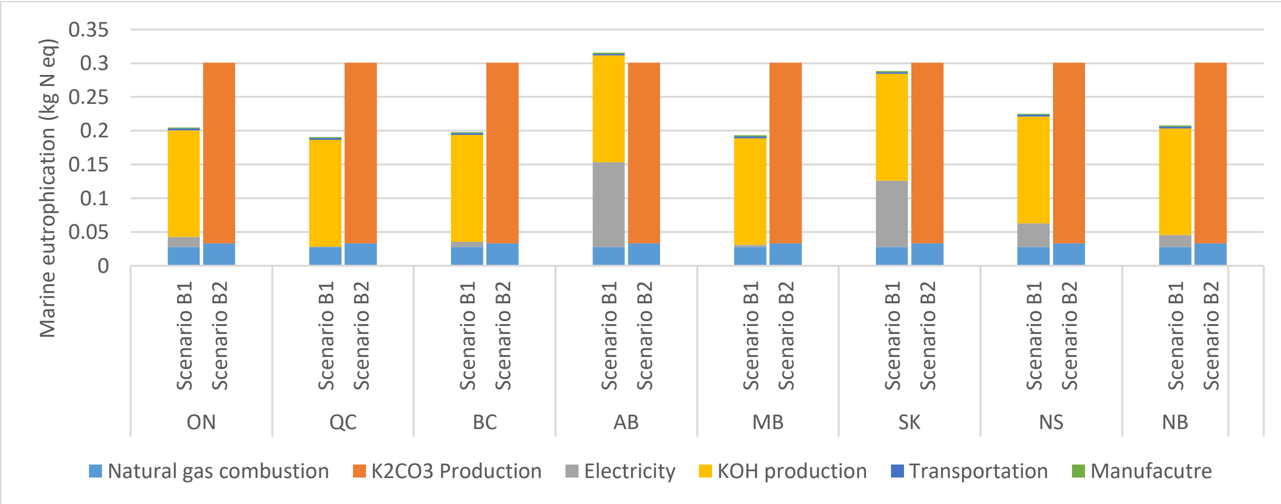

Figure 20: Marine eutrophication due to heating systems Scenario B1 and Scenario B2

4.5.7 Freshwater ecotoxicity

Figure 21 shows the breakdown of the freshwater ecotoxicity in Scenario A1 and Scenario A2. 77% – 85% of the freshwater ecotoxicity was generated by the production of product K_2CO_3 in Scenario A2. In Scenario A1, the transportation accounts 3 – 4% of the freshwater ecotoxicity, while manufacturing of the MCCU system contributes 2 – 3% of the freshwater ecotoxicity. The electricity generation in ON, BC, MB, and NB contributes to the freshwater ecotoxicity by 21%, 24%, 17%, and 21% accordingly. These provinces use hydropower for electricity generation and the water pollution created in the construction phase can be a reason for higher freshwater ecotoxicity [21]. Electricity generation in QC has negligible impact on the freshwater ecotoxicity. AB and SK had significantly high freshwater ecotoxicity that lead to an increase of impacts in Scenario A1 compared to Scenario A2. Emissions such as sulphuric acid aerosols during the coal combustion in AB and SK can be a reason for the higher ecotoxicity [20]. Figure 22 shows the freshwater ecotoxicity of Scenario B1 and Scenario B2. It shows that all the provinces have lower freshwater ecotoxicity under Scenario B1 compared to Scenario B2.

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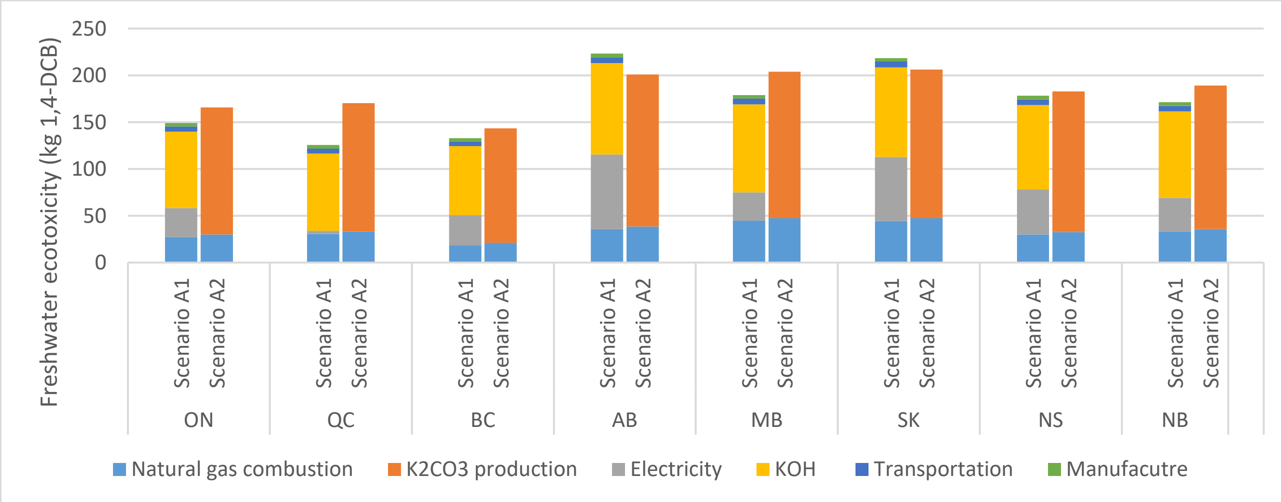

Figure 21: Freshwater ecotoxicity due to heating systems in Scenario A1 and Scenario A2

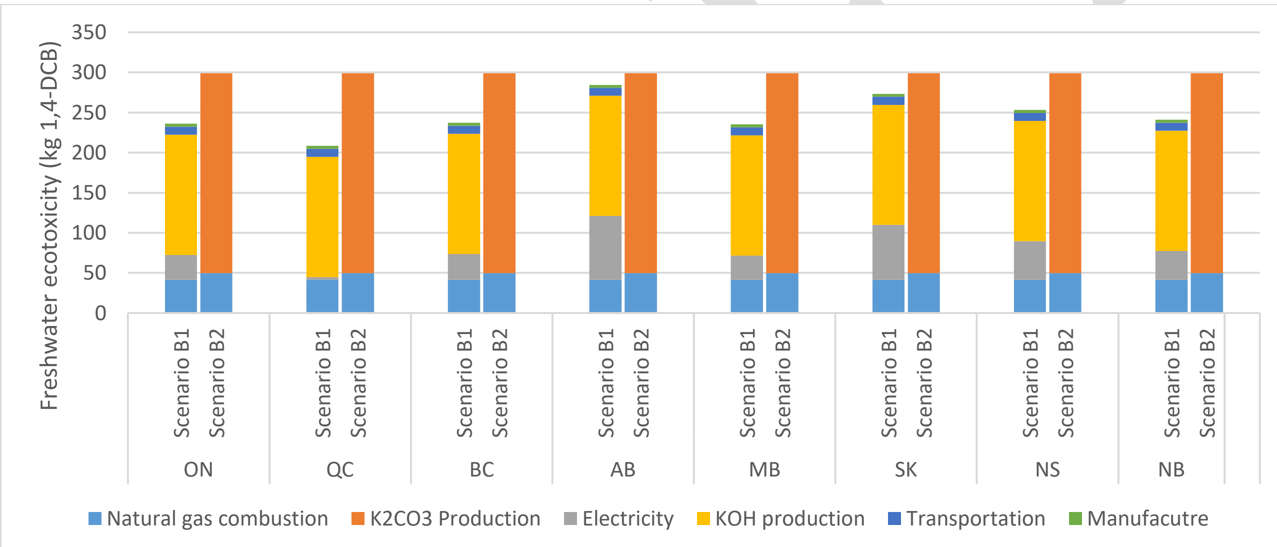

Figure 22: Freshwater ecotoxicity due to heating systems in Scenario B1 and Scenario B2

4.5.8 Marine ecotoxicity

Figure 23 shows the breakdown of the marine ecotoxicity in Scenario A1 and Scenario A2. 74% to 83% of the marine ecotoxicity was generated by the production of K_2CO_3 in Scenario A2. In Scenario A1, the transportation accounted 3 – 4% of the marine ecotoxicity, while manufacturing of the MCCU system contributed 2 – 3% of marine ecotoxicity. Water pollution created during the material extraction can be a reason for the increase in marine ecotoxicity during the manufacturing phase of the MCCU system. The electricity generation in ON, BC, MB, and NB contributed to the marine ecotoxicity by 18%, 21%, 14%, and 19% accordingly, which can be a result of higher water pollution in the construction phase of the hydropower electricity generation [21]. Electricity generation in QC has negligible impacts on the marine ecotoxicity. AB and SK have significantly high marine ecotoxicity in electricity generation that lead to an increase of impacts in Scenario A1 compared to Scenario A2. Figure 24 shows that all the provinces have lower marine ecotoxicity under Scenario B1 compared to Scenario B2.

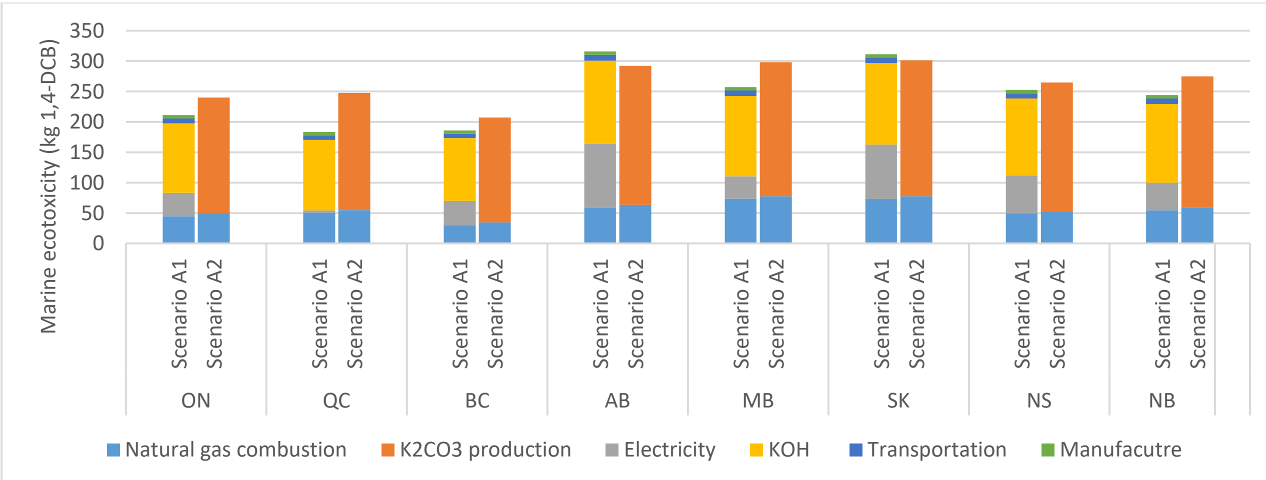

Figure 23: Marine ecotoxicity in Scenario A1 and Scenario A2

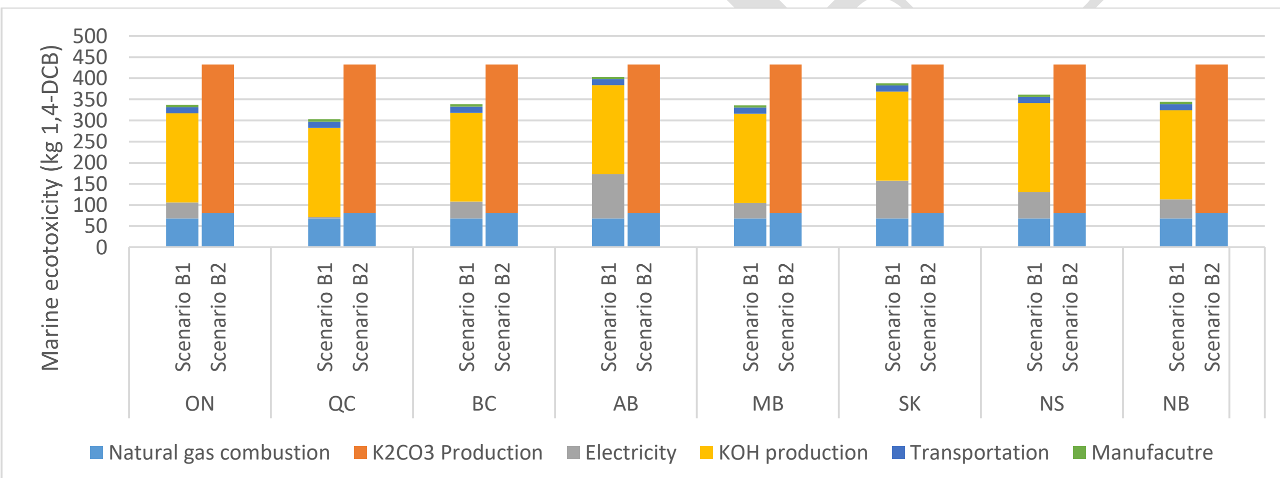

Figure 24: Marine ecotoxicity in Scenario B1 and Scenario B2

4.5.9 Human carcinogenic toxicity

Figure 25 shows the breakdown of the human carcinogenic toxicity in Scenario A1 and Scenario A2. 71 – 81% of the human carcinogenic toxicity in Scenario A2 was contributed by the K_2CO_3 production. The electricity consumption during the conventional K_2CO_3 production can be a reason for higher human carcinogenic toxicity. Around 70% of the global electricity [22] is produced using fossil fuel, which can create toxicity [20]. Under Scenario A1, the by-product transportation contributed only 2 – 3% of the human carcinogenic toxicity, while manufacturing of MCCU system generates 7 – 14%. Electricity generation in ON, BC, MB, and NB contributed to the human carcinogenic toxicity by 4%, 7%, 3%, and 9% and QC had less than 1%. AB, SK, and NS have significantly higher human carcinogenic toxicity compared to other provinces, the majority of which is caused by electricity generation. These three provinces have increase in human carcinogenic toxicity in Scenario A1 compared to Scenario A2. Figure 26 shows the breakdown of the human carcinogenic toxicity in Scenario B1 and Scenario B2. It indicates that AB is the only province that had increased human carcinogenic toxicity in Scenario B1 compared to Scenario B2 as the conventional production of K_2CO_3 may use more energy than the MCCU process.

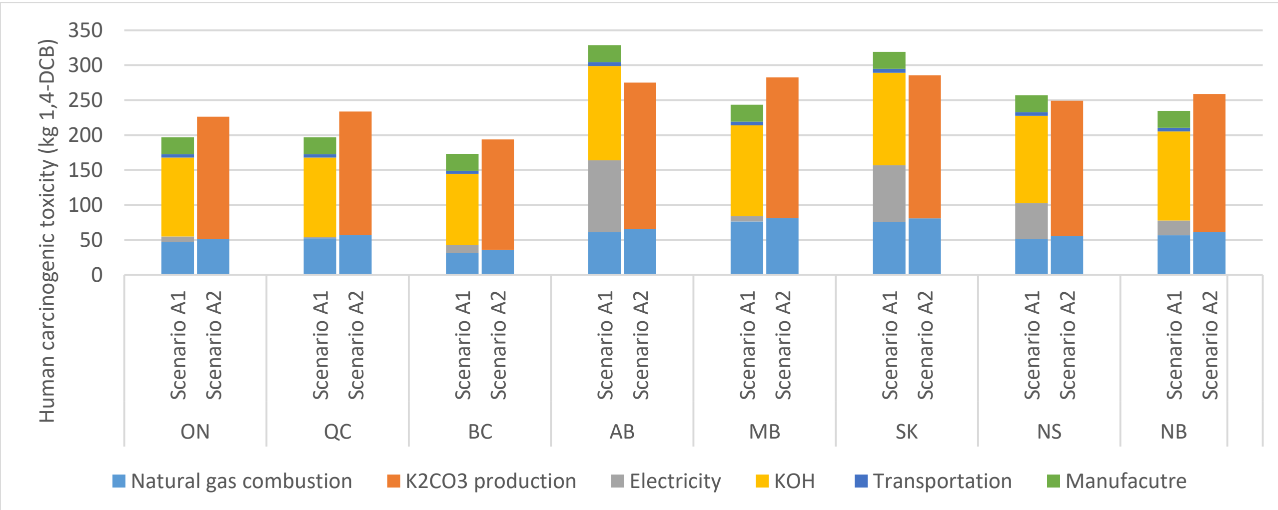

Figure 25: Human carcinogenic toxicity in Scenario A1 and Scenario A2

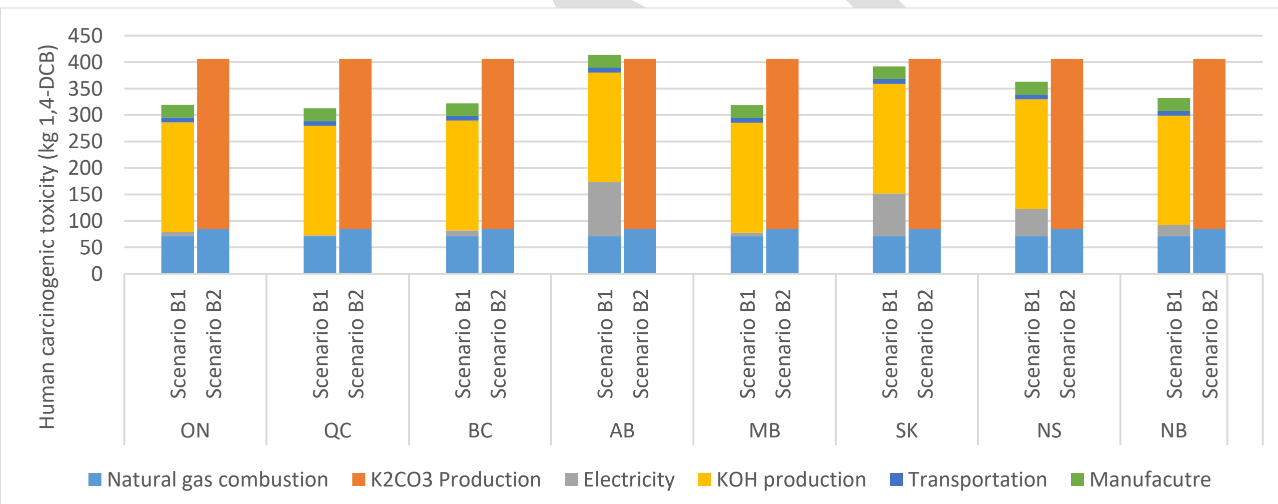

Figure 26: Human carcinogenic toxicity in Scenario B1 and Scenario B2

4.5.10 Mineral resource scarcity

Figure 27 shows the breakdown of the mineral resource scarcity in Scenario A1 and Scenario A2. The K_2CO_3 production has the highest contribution of 72 – 82 % to the mineral resource scarcity under Scenario A2. Electricity generation had less than 6% of the contribution to the mineral resource scarcity under Scenario A1. Transportation has 2 – 3% of contribution to the mineral resource scarcity. The manufacturing stage of the MCCU system showed more than 33% of contribution to the mineral resource scarcity in all provinces as the results of the material extraction. Figure 28 shows the breakdown of the mineral resource scarcity of Scenario B1 and Scenario B2. It indicates the Scenario B1 has lower mineral resource scarcity than the Scenario B2 in all provinces.

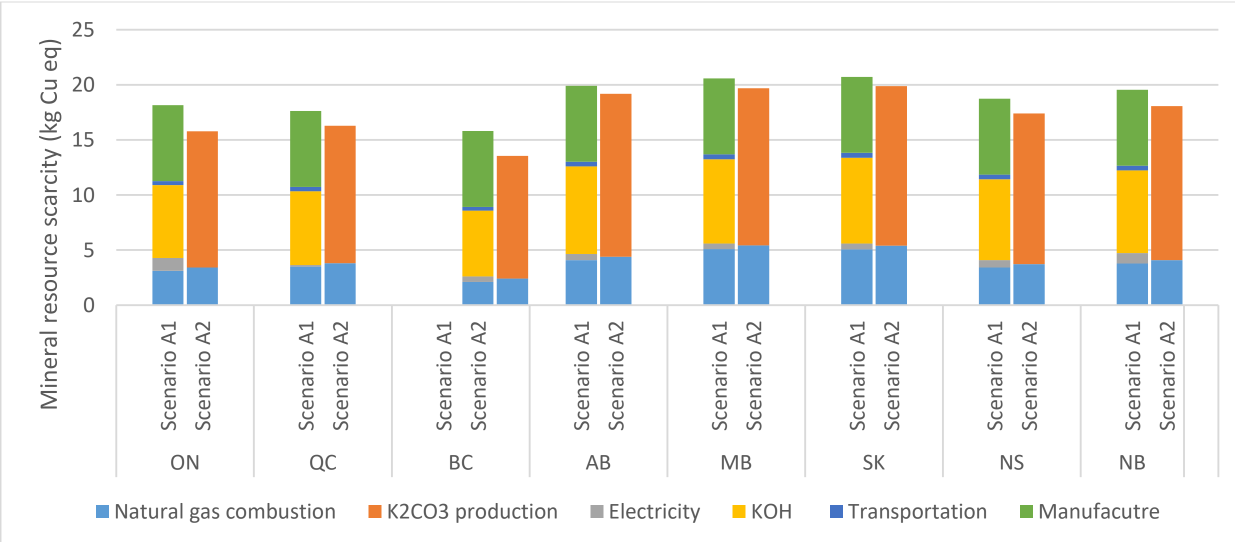

Figure 27: Mineral resource scarcity in Scenario A1 and Scenario A2

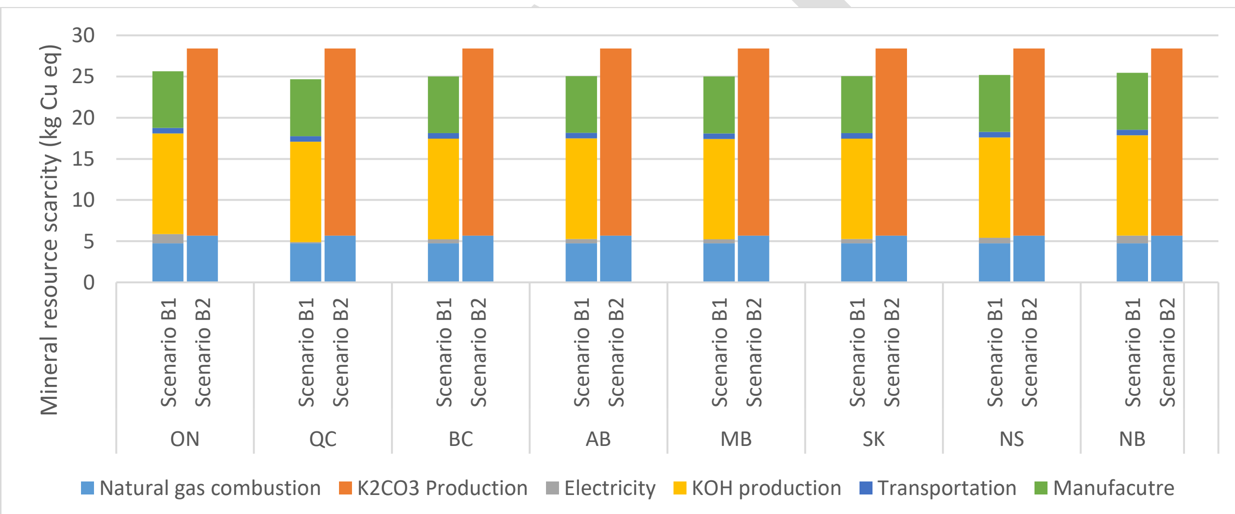

Figure 28: Mineral resource scarcity in Scenario B1 and Scenario B2

4.5.11 Water consumption

Figure 29 shows the breakdown of the water consumption of Scenario A1 and Scenario A2. The operational phase of the conventional K_2CO_3 production in Scenario A2 consumed 24kg of water per 1kg of K_2CO_3 [7]. In addition, the process consists of sub processes such as material extraction and electricity generation that may also consume water. Therefore, more than 85% of the life cycle water consumption in Scenario A2 is due to the conventional production of K_2CO_3. The results show that the manufacturing of MCCU system and the by-product term transportation have lower impact on water consumption in Scenario A1. The percentage water consumptions for the electricity generation in AB, SK, and NS were 10%, 21%, and 15%, respectively in Scenario A1, while the percentage water consumption for the electricity generation in ON, QC, BC, MB, and NB was higher than 47%. The higher requirement of water in these provinces can be a result of primarily using renewable energy such as hydro power generation that has a significant water footprint [23]. Figure 30 shows the breakdown of the water consumption of Scenario B1 and Scenario B2. It shows the same provinces mentioned above have a higher water consumption in Scenario B1 compared to Scenario B2.

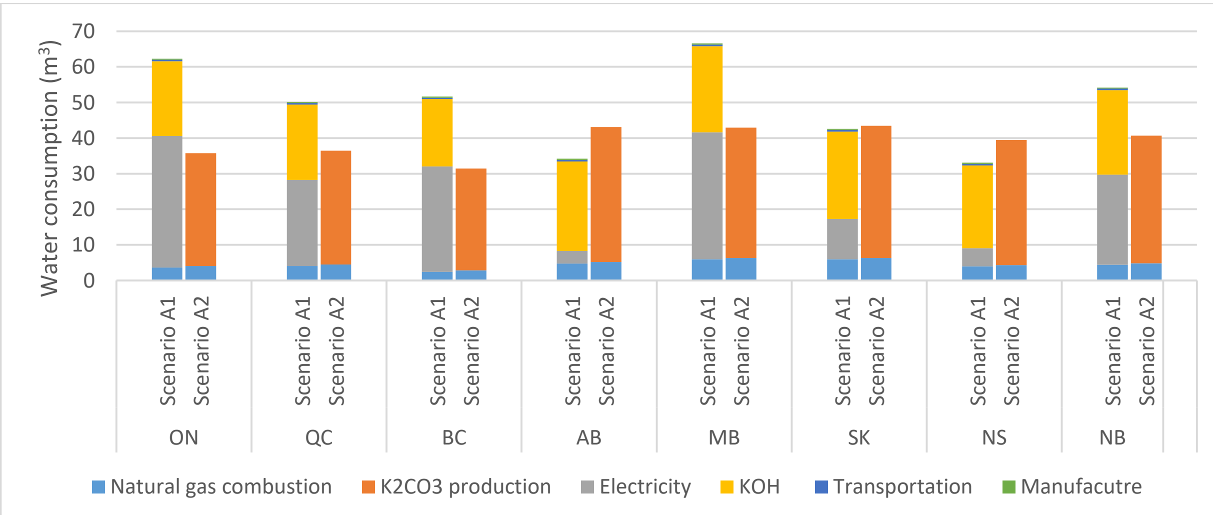

Figure 29: Water consumption in Scenario A1 and Scenario A2

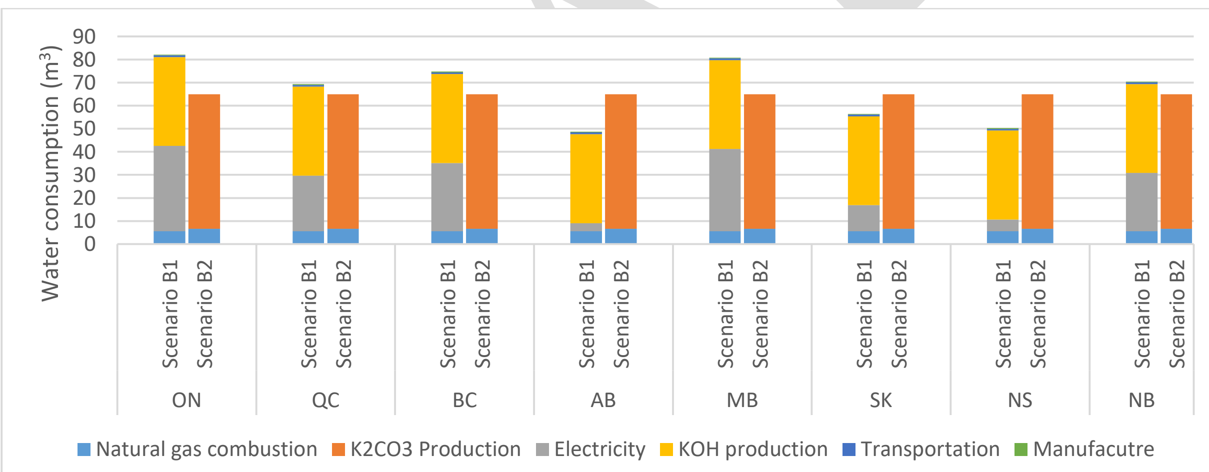

Figure 30: Water consumption in Scenario B1 and Scenario B2

4.6 Overall life cycle impacts

The results provide an insight to the potential life cycle environmental impacts of integrating MCCU system in residential space heating systems and commercial domestic hot water systems. Although the MCCU system has the same performance under both Scenario A1 and Scenario B1, it can also be seen that the Scenario B1 captured more CO_2 and produced more K_2CO_3. The reason for that is the constant heat generation for water heating in DHW systems in contrast to very low heat generation in summer period in space heating systems. In addition, Scenario B1 had a higher heat recovery as a result of higher water usage in the office building. Therefore, Scenario B1 had more environmental benefits than the Scenario A1, even when Scenario A1 had less annual natural gas consumption than Scenario B1.

The LCA results show that integrating a MCCU system on a natural gas residential space heating system can reduce the GWP by 12% -24% compared to the reference space heating without MCCU with the production of K_2CO_3 by-products. In addition, integrating MCCU system on a DHW in medium-sized office building can reduce the GWP by 21% - 27%. The highest percentage reduction of GWP can be observed in the buildings located in BC and the lowest percentage reduction of global warming potential was observed in NS. The results also indicate that integrating MCCU can reduce non-GHG environmental impacts such as "stratospheric ozone depletion" and "land use" in all the provinces compared to the reference systems. However, environmental impacts such as "ionizing radiation" and "terrestrial acidification" were increased in some provinces, such as ON and AB. The results also show that the electricity usage of the MCCU system contributed significantly to a major fraction of the environmental impacts. Therefore, there needs to be more focus on reducing the electricity consumption when optimizing the MCCU system performance.

5 Discussion

The results show that the environmental performance of the MCCU system is significantly influenced by the energy mix used to generate electricity in each province. The MCCU integrated scenarios had a higher reduction of GWP in provinces such as BC (24% reduction) and lower reduction in provinces such as NS (12% reduction). This significant variation of the GWP due to the different energy mixes used for electricity generation of each province, which highlights the importance of considering the electricity consumption by the MCCU system when optimizing the performance of the system. In addition, some of the non-GHG environmental impacts [24] were also significantly increased as a result of the energy mixes for electricity generation. Ionizing radiation was increased when MCCU system is located in ON and NB, where the majority of electricity is generated using nuclear energy. The terrestrial acidification, eutrophication and ecotoxicity increased significantly in the regions that use coal and heavy fuel oil for electricity generation such as NS and AB. Water consumption increased in provinces where the electricity is generated using renewable energy, such as BC and QC.

The increase in non-GHG environmental impacts that are increased mainly due to the electricity generation was substantial compared to the reference heating systems. Therefore, it is necessary to consider the actual increase in electricity consumption of the buildings due to the MCCU system. The average annual energy intensity for appliances, lighting, and space cooling in a single-family detached house can be calculated as 0.137 GJ/m^2 using 2017 residential energy use data [25]. Since the annual energy consumption of the MCCU system is 4 GJ, the energy intensity for MCCU in the residential house considered in this study becomes 0.02 GJ/m^2, which is 14% increment compared to the residential electricity energy intensity. Therefore, the increase of the non-GHG environmental impacts in the residential building is significant relative to the impacts due to the total electricity consumption. Similarly, the energy intensity for auxiliary equipment, auxiliary motors, lighting, and space cooling in commercial and institutional building sector can be calculated as 0.487 GJ/m^2 using the 2017 commercial/institutional energy use data [25]. The energy intensity increment of MCCU in the office building considered in this study becomes 0.00143 GJ/m^2, which is 0.3% increment compared to the electricity intensity of the office building. Therefore, the increase of the non-GHG LCA impacts due to the electricity consumption of the MCCU system in the commercial building is relatively insignificant compared to the impacts due to the total electricity consumption of the office building.

The study assumes average sizes for the residential and office buildings. With the change in building size the percentage change of environmental impacts due to MCCU system may change. However, the absolute change of environmental impacts per unit MCCU system (device) remains the same. The study also

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revealed that the power of the largest heating system that can be integrated with the MCCU system is 44 kW. When the system is larger than 44 kW, a fraction of the flue gas has to be diverted away from the MCCU system. As a result, the capacity of the system must be increased to get the same environmental performance when it is used in larger buildings.

The study assumed global average data on the production of raw materials, such as KOH and K_2CO_3 due to the lack of specific data on material importers and manufacturers. The results may change considerably when the location of the raw material manufacturing is changed. In particular, the results indicate that the change in electricity consumption of the production process can change the overall environmental impacts significantly as the electricity mix depends highly on the region. Similarly, if the location of KOH manufacturing has higher environmental impacts, the carbon capturing process may have higher life cycle environmental impacts. Moreover, global average data was used for modeling the life cycle inventory of the conventional K_2CO_3 manufacturing. Here, 70% of the global average electricity mix consists of fossil fuel based energy [22]. Therefore, electricity used for the avoided K_2CO_3 production has a considerable carbon footprint and other environmental impacts. It indicates that the percentage GWP reduction of the MCCU Scenarios used in this study can be much lower if the avoided industrial K_2CO_3 is produced using a cleaner electricity mix.

The study assumed standard distances for transportation of raw materials and products in industrial production of K_2CO_3 and KOH due to the lack of specific data on the manufacturers [15]. Furthermore, an average value of 50 km distance was considered for by-product transportation of raw materials and by-products [14]. Moreover, the generated by-product K_2CO_3 was assumed to be consumed in the same city, as the consumers such as soap manufacturers may be located in the same large city. If K_2CO_3 is consumed at a distant location, this distance should be considered accordingly in LCA, which may reduce the environmental benefits of the use of avoided K_2CO_3. Therefore, the actual transportation of by-products can be significantly higher in certain provinces that do not have a considerable local demand of the by-products. In addition, it was considered that the MCCU process can entirely avoid the industrial production of K_2CO_3. If the demand of the industrial K_2CO_3 is reduced, the generated by-product K_2CO_3 of MCCU system may not be completely utilized. Furthermore, the production rate is limited by the capacity of the MCCU system and the space available in the building for the additional carbon capturing process.

6 Conclusion

The study conducted an LCA on natural gas heating systems integrated with MCCU systems. It was considered that a space heating system in a single-family residential house and a DHW system in a medium-sized office building were integrated with the MCCU system. The buildings were envisaged to be located in different Canadian provinces to incorporate regional variability in the study. The selected provinces are ON, QC, BC, AB, MB, SK, NS, and NB. Since the MCCU system has a by-product (K_2CO_3), the study used system expansion method to compare the life cycle environmental impacts of the system. The expanded product system fulfills the annual heating requirement of the respective building heating system, while producing an equivalent amount of K_2CO_3 similar to that of the MCCU system.

The study revealed that integrating MCCU system in a residential space heating system can significantly reduce the GWP (by 12% to 24%) compared to the reference scenario. In addition, the MCCU system is capable of significantly reducing 21% to 27% of the GWP in a DHW system in a medium-sized office building. The study also indicates that the energy mix of electricity generation of each province has a substantial influence on the environmental performance of the MCCU system. The MCCU system has higher GWP reduction in provinces with a lower carbon footprint in electricity generation and vice versa.

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Furthermore, the study shows that some of the non-GHG environmental impacts such as stratospheric ozone depletion and ozone formation are also significantly reduced when integrating MCCU due to the impact of the avoided K_2CO_3 production. However, some environmental impact categories showed an increase by using MCCU systems in certain provinces, but remarkably only mineral resource scarcity is increased in both building types in all provinces. Moreover, effect of the electricity mix on environmental performance of MCCU system is reduced when the annual carbon capture rate is increased. It indicates that the production of heat and K_2CO_3 in the MCCU process are environmentally friendlier than combination of the conventional processes as a result of avoidance of the higher energy use in sub-processes in the conventional process such as production of liquid CO_2.

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Appendix

Table A1: Experimental results

Date	***Carbon capture Efficiency (%)***	***Carbon capture rate (kg/day)***	***Carbon inflow (kg/day)***	***Heat transfer rate (kg/l$_{water}$)***	***CO_2 from exhaust gas (kg/day)***	***Percentage of CO_2 diverted through the MCCU 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%
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%

Table A2: LCA results of Scenario A1

Impact category	***ON***	***QC***	***BC***	***AB***	***MB***	***SK***	***NS***	***NB***
Global warming (kg CO2 eq)	9501.02	10234.06	7050.89	13087.72	14132.44	14917.05	11475.04	11674.82
Stratospheric ozone depletion (kg CFC11 eq)	0.0032	0.0034	0.0025	0.0042	0.0045	0.0047	0.0038	0.0039
Ionizing radiation (kBq Co-60 eq)	980.05	311.72	270.25	365.11	374.68	372.68	342.72	703.44
Ozone formation, human health (kg NOx eq)	11.17	11.59	9.14	15.28	14.76	16.08	14.65	13.90
Fine particulate matter formation (kg PM2.5 eq)	8.25	8.43	7.26	11.06	10.35	11.24	11.38	10.22
Ozone formation, terrestrial ecosystems (kg NOx eq)	11.47	11.92	9.37	15.67	15.20	16.53	15.00	14.26
Terrestrial acidification (kg SO2 eq)	16.62	17.00	13.99	23.66	21.13	24.00	24.93	21.64
Freshwater eutrophication (kg P eq)	1.67	1.67	1.53	4.03	2.04	3.63	2.35	2.03
Marine eutrophication (kg N eq)	0.12	0.11	0.10	0.26	0.14	0.23	0.15	0.14
Terrestrial ecotoxicity (kg 1,4-DCB)	10987.37	10569.17	9534.57	13063.29	12950.49	13321.92	12823.43	12789.24
Freshwater ecotoxicity (kg 1,4-DCB)	148.98	125.47	132.79	223.15	179.04	218.43	178.12	171.25
Marine ecotoxicity (kg 1,4-DCB)	210.95	183.39	185.99	315.76	257.22	311.45	252.75	243.85
Human carcinogenic toxicity (kg 1,4-DCB)	196.64	196.87	172.99	328.64	243.56	318.89	256.96	234.75
Human non-carcinogenic toxicity (kg 1,4-DCB)	3359.60	3294.24	2961.37	5428.26	4103.17	5232.82	4172.67	3954.52
Land use (m^2a crop eq)	87.70	96.68	80.50	110.07	101.69	103.81	108.07	100.80
Mineral resource scarcity (kg Cu eq)	18.17	17.62	15.82	19.92	20.57	20.71	18.74	19.54

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Fossil resource scarcity (kg oil eq)	3174.68	3429.83	2327.87	4292.44	4756.77	4956.39	3760.70	3887.51
Water consumption (kg m^3)	62.30	50.12	51.64	34.20	66.59	42.61	33.07	54.18

Table A3: LCA results of Scenario B1

Impact category	***ON***	***QC***	***BC***	***AB***	***MB***	***SK***	***NS***	***NB***
Global warming (kg CO2 eq)	15143	15045	15147	16131	15109	15912	16210	15550
Stratospheric ozone depletion (kg CFC11 eq)	0.0051	0.0051	0.0052	0.0053	0.0051	0.0053	0.0055	0.0053
Ionizing radiation (kBq Co-60 eq)	1212	536	542	534	539	533	544	893
Ozone formation, human health (kg NOx eq)	18.86	18.70	18.86	20.35	18.73	19.98	21.24	19.82
Fine particulate matter formation (kg PM2.5 eq)	14.24	14.13	14.45	15.29	14.22	15.02	16.56	15.03
Ozone formation, terrestrial ecosystems (kg NOx eq)	19.34	19.18	19.34	20.84	19.21	20.46	21.74	20.31
Terrestrial acidification (kg SO2 eq)	28.56	28.28	28.54	31.93	28.40	31.10	35.21	31.11
Freshwater eutrophication (kg P eq)	2.92	2.88	3.00	4.94	2.92	4.49	3.44	3.06
Marine eutrophication (kg N eq)	0.2049	0.1905	0.1980	0.3156	0.1932	0.2883	0.2251	0.2077
Terrestrial ecotoxicity (kg 1,4-DCB)	17930	17234	17735	18051	17701	17956	18830	18422
Freshwater ecotoxicity (kg 1,4-DCB)	236	208	237	285	235	273	253	241
Marine ecotoxicity (kg 1,4-DCB)	337	303	338	403	336	388	361	344
Human carcinogenic toxicity (kg 1,4-DCB)	319	313	322	414	318	392	363	332
Human non-carcinogenic toxicity (kg 1,4-DCB)	5779	5616	5819	7166	5758	6848	6266	5917
Land use (m^2a crop eq)	154	161	156	159	151	152	165	155
Mineral resource scarcity (kg Cu eq)	25.65	24.65	25.01	25.05	24.99	25.03	25.18	25.44
Fossil resource scarcity (kg oil eq)	5038	5004	5037	5273	5009	5218	5321	5151
Water consumption (kg m^3)	82.12	69.29	74.74	48.66	80.78	56.46	50.25	70.42

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Table A4: LCA results of Scenario A2

Impact category	***ON***	***QC***	***BC***	***AB***	***MB***	***SK***	***NS***	***NB***
Global warming (kg CO2 eq)	11957	12809	9310	14948	16929	16947	13078	13985
Stratospheric ozone depletion (kg CFC11 eq)	0.0037	0.0039	0.0029	0.0046	0.0051	0.0051	0.0040	0.0043
Ionizing radiation (kBq Co-60 eq)	408	417	358	493	493	499	451	465
Ozone formation, human health (kg NOx eq)	13.67	14.27	11.40	16.76	17.76	17.88	15.03	15.75
Fine particulate matter formation (kg PM2.5 eq)	10.52	10.84	9.08	12.78	13.03	13.16	11.61	12.03
Ozone formation, terrestrial ecosystems (kg NOx eq)	14.01	14.64	11.66	17.19	18.25	18.37	15.40	16.15
Terrestrial acidification (kg SO2 eq)	21.05	21.76	17.99	25.63	26.43	26.68	23.20	24.12
Freshwater eutrophication (kg P eq)	2.25	2.31	1.98	2.72	2.72	2.76	2.49	2.57
Marine eutrophication (kg N eq)	0.1654	0.1691	0.1453	0.1998	0.1995	0.2020	0.1828	0.1884
Terrestrial ecotoxicity (kg 1,4-DCB)	15939	16288	14016	19247	19187	19429	17611	18148
Freshwater ecotoxicity (kg 1,4-DCB)	166	170	143	201	204	206	183	189
Marine ecotoxicity (kg 1,4-DCB)	240	248	207	292	298	301	265	275
Human carcinogenic toxicity (kg 1,4-DCB)	226	234	194	275	283	286	249	259
Human non-carcinogenic toxicity (kg 1,4-DCB)	4637	4750	4056	5609	5628	5695	5122	5287
Land use (m^2a crop eq)	111	113	98	133	132	134	122	126
Mineral resource scarcity (kg Cu eq)	15.78	16.29	13.56	19.20	19.68	19.87	17.40	18.07
Fossil resource scarcity (kg oil eq)	3689	3982	2811	4637	5351	5349	4028	4333
Water consumption (m^3)	35.73	36.49	31.45	43.13	42.95	43.49	39.48	40.67

Table A5: LCA results of Scenario B2

Impact category	*ON*	*QC*	*BC*	*AB*	*MB*	*SK*	*NS*	*NB*
Global warming (kg CO2 eq)	11957	12809	9310	14948	16929	16947	13078	13985
Stratospheric ozone depletion (kg CFC11 eq)	0.0037	0.0039	0.0029	0.0046	0.0051	0.0051	0.0040	0.0043
Ionizing radiation (kBq Co-60 eq)	408	417	358	493	493	499	451	465
Ozone formation, human health (kg NOx eq)	13.67	14.27	11.40	16.76	17.76	17.88	15.03	15.75
Fine particulate matter formation (kg PM2.5 eq)	10.52	10.84	9.08	12.78	13.03	13.16	11.61	12.03
Ozone formation, terrestrial ecosystems (kg NOx eq)	14.01	14.64	11.66	17.19	18.25	18.37	15.40	16.15
Terrestrial acidification (kg SO2 eq)	21.05	21.76	17.99	25.63	26.43	26.68	23.20	24.12
Freshwater eutrophication (kg P eq)	2.25	2.31	1.98	2.72	2.72	2.76	2.49	2.57
Marine eutrophication (kg N eq)	0.1654	0.1691	0.1453	0.1998	0.1995	0.2020	0.1828	0.1884
Terrestrial ecotoxicity (kg 1,4-DCB)	15939	16288	14016	19247	19187	19429	17611	18148
Freshwater ecotoxicity (kg 1,4-DCB)	166	170	143	201	204	206	183	189
Marine ecotoxicity (kg 1,4-DCB)	240	248	207	292	298	301	265	275
Human carcinogenic toxicity (kg 1,4-DCB)	226	234	194	275	283	286	249	259
Human non-carcinogenic toxicity (kg 1,4-DCB)	4637	4750	4056	5609	5628	5695	5122	5287
Land use (m^2a crop eq)	111	113	98	133	132	134	122	126
Mineral resource scarcity (kg Cu eq)	15.78	16.29	13.56	19.20	19.68	19.87	17.40	18.07
Fossil resource scarcity (kg oil eq)	3689	3982	2811	4637	5351	5349	4028	4333
Water consumption (m^3)	35.73	36.49	31.45	43.13	42.95	43.49	39.48	40.67