Life cycle assessment of the power-to-gas process in the context of Quebec

by

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THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
IN PARTIAL FULFILLMENT FOR A MASTER'S DEGREE
WITH A THESIS IN ENVIRONMENTAL ENGINEERING
M.A.SC.

MONTREAL, FEBRUARY24, 2023

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

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ON FEBRUARY 03, 2023

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ACKNOWLEDGMENT

I would like to express my sincere and deep gratitude to my supervisor, Professor. Annie Levasseur, for her support, patience, and advice during these challenging years. This journey was impossible without her thoughtful and technical insight. I convey my appreciation for her financial support, which could help me during this study.

I also would like to thank all the jury members for accepting my work evaluation.

I would like to express my highest gratitude to my beloved mother and father for their love, patience, support, sacrifice, and devotion throughout my life. I am incredibly grateful to my sisters, and my brother for their love, support, and motivation throughout my life. Finally, I would like to express my appreciation to my husband, love, and soulmate for all his support, patience, faith, and advice. Nothing was possible without your sincere and unconditional love.

I want to express my gratitude to all my friends who have contributed directly or indirectly to expedite this research. I am especially indebted to Ms. Zeynab Yousefzadeh for her support and friendship.

Analyse du cycle de vie du procédé power-to-gas dans le contexte québécois

Hoda DARVISH

RÉSUMÉ

L'entreposage à long terme de l'électricité provenant de sources d'énergie renouvelables est un concept de conversion de l'électricité en gaz (PtG). Cette électricité produit ensuite des combustibles pour l'industrie, les transports et les ménages. Cependant, cette technologie a différentes variations de système avec diverses performances environnementales qui devraient être étudiées et comparées aux technologies conventionnelles avant l'industrialisation. La puissance électrique, une source d'électricité à faible émission de carbone, est le plus grand contributeur à l'électricité québécoise (environ 94 %), ce qui rend l'analyse du cycle de vie de l'électricité au gaz précieuse. Dans cette étude, l'analyse du cycle de vie des PtG au Québec a été réalisée comme scénario de référence et comparée au gaz naturel. Ensuite, l'analyse de sensibilité a été réalisée en fonction de différentes sources d'électricité provenant de différentes provinces du Canada (Alberta et Québec). Pour le scénario de référence, on a supposé que le CO_2 ait capturé des émissions de gaz de la cimenterie. La santé humaine et la qualité de l'écosystème pour le scénario de référence ont été acquises à 4,89E-06 (DALY) et 0,77 (PDF.m2.an), respectivement. De plus, les émissions de gaz à effet de serre pour le scénario de référence étaient égales à 0,04 (kg d'équivalent CO_2). Les catégories d'impact dans tous les niveaux de dommages étaient significativement plus élevées pour le gaz naturel que pour la production de méthane à partir de PtG (gaz naturel synthétique-GNS). 5,13 (kg d'équivalent CO2) ont été obtenus pour l'impact de la variation du climat pour le gaz naturel. La base de combustibles fossiles de l'électricité de l'Alberta est responsable de 60 % des impacts sur le changement climatique du gaz naturel. Des analyses de sensibilité ont été mises en œuvre sur la base de différentes sources d'électricité pour la production de GNS. Il a été conclu que si l'électricité de l'Alberta est utilisée dans le système, on peut voir plus d'impacts environnementaux. Les résultats de cette étude ont montré que l'impact du changement climatique pour le scénario de l'Alberta est cinq fois plus élevé que le scénario du changement climatique pour le scénario du Québec. L'unité de CO_2 a été calculée pour démontrer des contributions plus élevées aux impacts sur l'environnement, alors que ces impacts peuvent être atténués en utilisant plus d'électricité propre dans ce processus unitaire. Les résultats ont montré que la méthanisation avec une source d'électricité québécoise entraîne des avantages environnementaux plus importants que le gaz naturel conventionnel et d'autres sources d'électricité.

Mots clés : Analyse du cycle de vie, Stockage d'énergie, Power-to-Gas, Méthanisation, Hydro-électricité, Empreinte carbone, analyse de sensibilité

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ABSTRACT

Storing electricity from renewable energy sources for long term is a power-to-gas (PtG) concept. This electricity then produces fuels for industry, transportation, and household. However, this technology has different system variations with various environmental performances that should be investigated and compared to the conventional technologies before industrialization. Hydropower, as a low-carbon electricity source, is the highest contributor to Quebec electricity (about 94%), making the life cycle assessment of power to gas valuable to be investigated. In this study, life cycle assessment of PtG in Quebec was conducted as a baseline scenario and compared with the natural gas. Then, the sensitivity analyses were carried based on different electricity sources from different provinces in Canada (Alberta and Quebec). For the baseline scenario, CO_2 was assumed to captured from the cement plant gas emission. Human health and ecosystem quality for the baseline scenario were acquired to be 4.89E-06 (DALY) and 0.77 (PDF.m2.yr), respectively. Also, greenhouse gas emission for the baseline scenario was equal to 0.04 (kg CO_2 eq). Impact categories in all damage levels were significantly higher for natural gas compared to producing methane from PtG (synthetic natural gas-SNG). 5.13 (kg CO_2 eq) was obtained for the climate change impact for natural gas. The fossil fuel base of Alberta's electricity is responsible for the %60 of impacts on the climate change in natural gas. Sensitivity analysis were implemented based on different sources of electricity for producing SNG. It was concluded that if Alberta electricity is used in the system, more environmental impacts can be seen. The outcome of this study showed that the climate change impact for Alberta scenario is five times higher than the climate change for the Quebec scenario. CO_2 unit was calculated to demonstrate higher contributions to the impacts on the environment, whereas these impacts can be mitigated by employing more clean electricity in this unit process. Outcomes showed that methanation with Quebec electricity source leads to larger environmental benefits compared to the conventional natural gas and other sources of electricity.

Keywords: Life cycle assessment, Energy storage, Power-to-gas, Methanation, Hydropower, Carbon footprint, Sensitivity analysis

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABREVIATIONS

CCS	Carbon Capture and Storage
CCU	CO_2 Capture and utilization
CGR	Coal gasification and reforming
CIRAIG	International reference center for life cycle assessment and sustainable transition
CO_2	Carbon Dioxide
CSI	Construction Specifications institute
DRM	Dry reforming of methane
ED	Ecosystem diversity
FD	Fossil depletion
FU	Functional unit
GHG	Greenhouse gas emission
GW	Global warming
HH	Human health
HHV	Higher Heating Value
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization of Standardization
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LHV	Lower heating value
LHV	Lower heating value
MEA	Membrane electrode assembly
P2H	Power to Hydrogen

P2M	Power to Methane
PEM	Polymer Electrolyte Membrane
PtG	Power-to-Gas
PV	Photovoltaic
RA	Resource availability
RE	Renewable energy
rWGS	Reverse water gas shift
SETAC	Society of environmental toxicity and chemistry
SMES	Superconducting Magnetic Storage
SMR	Steam Methane reforming
SNG	Synthetic Natural Gas
SOEC	Solid Oxide Electrolyte

LIST OF SYMBOLS

$\boldsymbol{\eta_{sys}}$	The efficiency of energy conversion in electrolyzer
ΔH_R°	Enthalpy change reaction
ΔG_R°	Change in free energy

INTRODUCTION

Traditionally, fossil fuels have been used as a source of energy for electricity generation, where the fuel should be stored for access to energy urgently. Employing fossil fuels can be related to significant environmental impacts. Greenhouse gases (GHG) are one of the environmental impacts of using fossil fuels. Total GHG emissions in Canada were 730 megatons in 2019, a slight increase from 728Mt CO_2 eq in 2018(National Inventory report, Government of Canada, 2019).

Lower environmental impacts should be expected from the energy production of renewable sources. Renewable energy sources (hydro, biomass, geothermal, solar, wind) can decrease our dependency on fossil fuels, while storage facilities are the problem in this case. The intermittent renewable energy sources (wind, wave, tidal, and solar) cannot be stored and should be used as available. In this case, energy conversion is practical to convert these intermittent renewable sources into different forms of energy for storage (Ibrahim, Ilinca, & Perron, 2008). Therefore, fossil fuels can be replaced by intermittent renewable energy sources if suitable storage methods use (Beaudin, Zareipour, Schellenberglabe, & Rosehart, 2010; Evans, Strezov, & Evans, 2012).

Previous studies show that the provided storage technologies can be practical for short-term storage with limited capacities like Superconducting Magnetic Storage (SMES). While only pumped hydro, compressed air storage and Power-to-Gas (PtG) can be applied for long-term energy storage (Luo, Wang, Dooner, & Clarke, 2015). Thus, PtG, a significant storage technology, is used with flexible storage durations (Rehman, Al-Hadhrami, & Alam, 2015).

When the electricity converts to hydrogen by water electrolysis, the natural gas network can use this produced hydrogen as feedstock or fuel. Moreover, with the reaction of hydrogen with carbon dioxide, the Synthetic Natural Gas (SNG) can be produced, which consists of methane. After dehydrating and compression, this generated SNG meets natural gas demands, such as fuel for vehicles or injected and stored in the natural gas network (Lehner, Tichler, Steinmüller, & Koppe, 2014b).

Life cycle assessment (LCA) is a method of evaluating the potential of environmental impacts of a product system in its whole life cycle, from raw materials to final disposal. Several gaps still exist because of the limited study on the life cycle environmental performance of PtG, despite all the advantages of PtG that need to be filled. For example, most studies are on the Power-to-Hydrogen (P2H), not Power-to-Methane (P2M), or cover the limited system variations or avoid the complexity of burden allocation. A reduced number of studies is available on the other environmental impacts than climate change in P2G.

The objective of this project is to use LCA to determine the life cycle environmental performance of PtM in the case of Quebec province. Different alternative systems are compared together to fill some gaps in the PtG study in Quebec province.

CHAPTER 1

BACKGROUND AND LITERATURE REVIEW

1.1 Background

The first part of this chapter presents climate change as a global issue and the Power-to-Gas (PtG) as a solution for climate change. The energy concept in the province of Quebec and why PtG could be used in Quebec will be explained. Furthermore, a complete analysis of the process and the current situation of the PtG will be explained. Secondly, the Life Cycle Assessment (LCA) and the previous study of LCA on the PtG will make it possible to identify the gaps and the objective of this project.

1.1.1 Climate change and the role of energy

Currently, climate change is a significant problem that results in a slight increase in the planet's average annual temperature. The climate is indicated with various parameters like precipitation, temperature, soil, air humidity, snow and ice layer, for 30 years. The climate system consists of the ocean, the land, the atmosphere, the biosphere, and the cryosphere (Denisova, 2019). It is predicted that the average global temperature will be raised by 6 °C by the next century, if fossil fuels will be used like now (Mikhaylov, Moiseev, Aleshin, & Burkhardt, 2020).

The Intergovernmental Panel on Climate Change (IPCC) report estimated the carbon emissions and the role of carbon emissions in climate change. The higher temperature of the earth’s surface results from the greenhouse gas effect when the lower layers of the atmosphere become heated with greenhouse gas accumulations. Consequently, rising tempreture has results in rising sea levels, melting the glaciers, drought, and global warming caused by the greenhouse gas effect (Mikhaylov et al., 2020).

Greenhouse gas emissions are the results of these activities on the earth: fossil fuel combustion emits a massive amount of carbon dioxide and other dangerous components into the atmosphere. A wide variety of cars and trucks emit fumes by using fossil fuel and pollute the air and increase the greenhouse effects. Furthermore, deforestation with the mechanism of absorbing carbon dioxide and releasing oxygen by the destruction of forests on the earth the amount of CO_2 in the air will be increased (Table 1.1) (Mikhaylov et al., 2020).

Table 1.1 Greenhouse gas summary
Taken from Mikhaylov et al. (2020)

Compound	Formula	Concentration in atmosphere (ppm)	Gas Contribution in atmosphere (%)
Water vapor and clouds	H_2O	10- 50000	36-72%
Carbon dioxide	CO_2	~400	9-26%
Methane	CH_4	~1.8	4-9%
Ozone	O_3	2-8	3-7%

Additionally, the increasing population causes the need for food, housing, and clothes; therefore, demand for industrial activities grows sharply, which causes air pollution and greenhouse gas effects (Figure 1.1). Another important activity is burning garbage at landfills which contributes directly to the greenhouse gas effect (Mikhaylov et al., 2020).

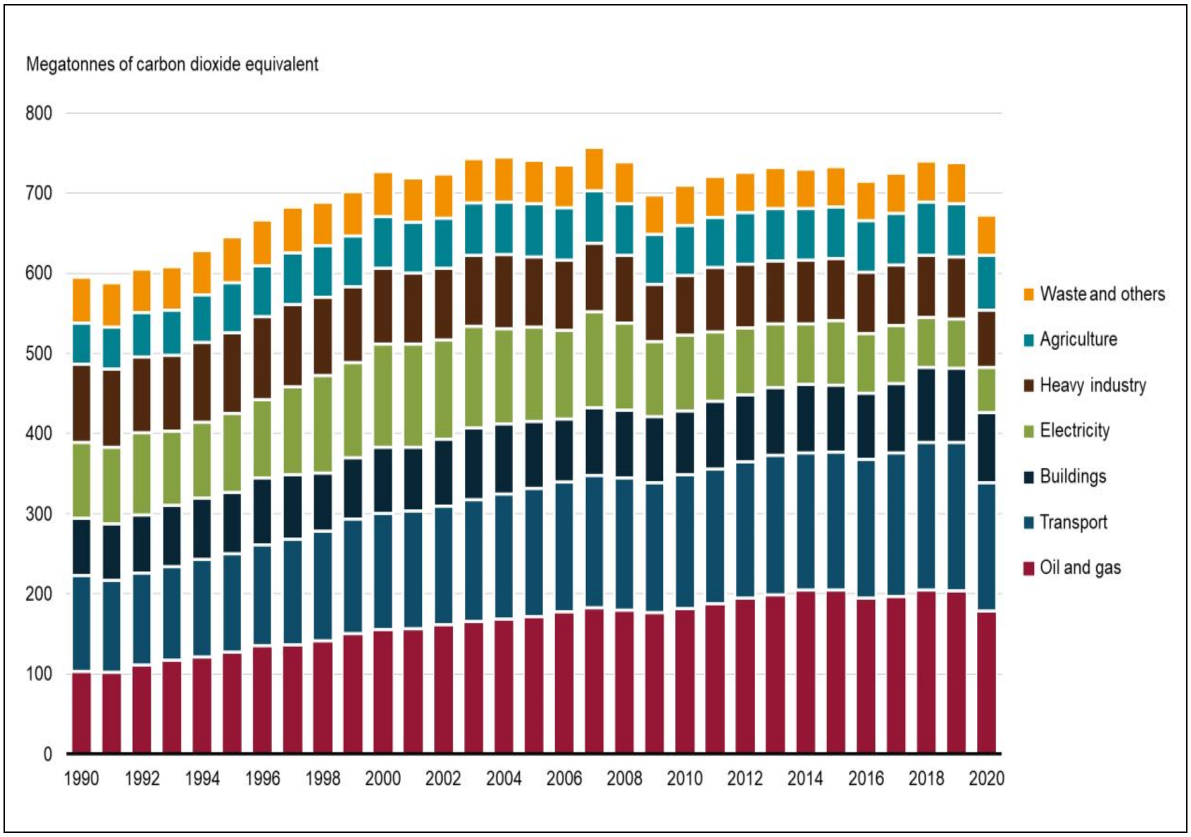


Figure 1.1 Greenhouse gas emission by economic sector in Canada
Taken from Inventory Report, Government of Canada (2020)

The Paris Protocol (world climate change agreement), adopted in 2015, aims to keep the global temperature rise, below 2℃ above pre-industrial levels. This agreement aims to force countries to deal with the impact of climate change by ending fossil fuels and developing new low-carbon technologies and adaptations to climate change.

Canada is also on the path to meeting its Paris commitment to reduce emissions and gets net-zero emissions by 2050. Canada's goal is to reduce emissions by 32-40 percent below 2005 levels by 2030, decreasing from 739 megatonnes of CO_2 in 2005 to 502 megatonnes in 2030 (Shingler & Nerestant, 2021).

In Quebec, while the emissions from transportation are on the rise, the overall emissions have decreased by 2.75 percent since 1990. The reduction will be continued to aim the goal of 37.5%

(see Figure 1.2) reduction compared to 1990 levels and to reach net-zero carbon by 2050 (Shingler & Nerestant, 2021).

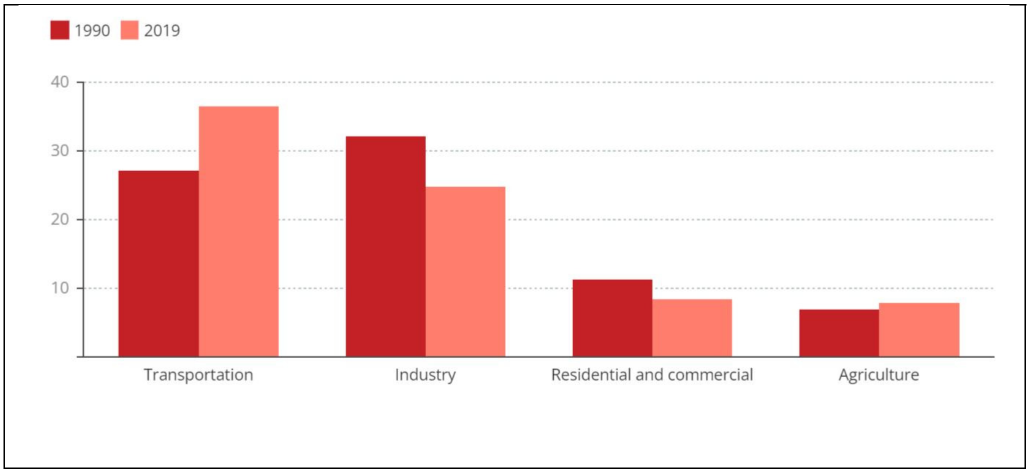


Figure 1.2 Megatons of CO_2 by sector in Quebec
Taken from Shingler & Nerestant (2021)

As a result, the carbon emissions study remains an interesting debate among researchers to develop the technologies to reach net-zero emissions by 2050.

1.1.2 PtG and Climate Change

Based on the report released by the Intergovernmental Panel on Climate Change (IPCC), numerous changes occurred in the Earth's climate in all regions. Reduction in emissions of greenhouse gases, especially Carbon dioxide (CO_2), can limit climate change. IPCC reports that human activities are responsible for the greenhouse gas emission of almost 1.1℃ of global warming from 1850-1900. A considerable reduction of global emissions is required by changing government policies in all aspects of societies, from industrial to personal level activities in the path of greenhouse gas emissions reduction(Lehner, Tichler, Steinmüller, & Koppe, 2014a).

However, climate change is not only about temperature. This future warming can bring different changes in various regions, like changes in wetness and dryness, wind, ice and snow, oceans, and coastal areas. Consequently, changing the energy system is crucial for the world to confront climate change and Global warming(Lehner et al., 2014a).

PtG is considered an appropriate option for long-term storage, which can be introduced to convert renewable electricity to chemical energy carriers. Hydrogen, methanol, methane, etc., are examples of chemical energy carriers(Lehner et al., 2014a).

According to Figure 1.3, water electrolysis uses renewable electricity to produce hydrogen and oxygen from water. Industrial processes can use oxygen or be released into the air. At the same time, hydrogen as an actual output, can be transferred to the electric power as a fuel in the transporting system for electric cars or as a feedstock in different industries. For example, chemical, petrochemical, and metallurgical industries consume a massive amount of hydrogen as a feedstock by methane steam reforming (Lehner et al., 2014a). As a result, hydrogen is the first co-product of the PtG process, while the amount of production and storage of the hydrogen is the matter in the industry. Therefore, other products can be produced by Hydrogen. The second process of the PtG is Methanation which is created when the Hydrogen and carbon dioxide (CO_2) synthesize into methane by the chemical or biologically catalyzed reaction. Synthetic Natural Gas (SNG) is the other name for this methane, and steam is the by-product of this reaction. Carbon dioxide, which can be taken from cement plants, can be transferred to fossil power plants, biogas plants, or other places. Carbon capture has a significant role in the PtG process economically and technically as pure carbon dioxide is almost unavailable. Methane, as an end-product of the PtG system, has a significant role in the gas and methane utilization infrastructure. SNG can be used as fuel in mobility systems, feedstock in the industry, and heating (Lehner et al., 2014a).

As a result of the conversion, renewable hydrogen and methane can transfer to the outside of the power grid, on a large scale and for long-term storage, as renewable energy.

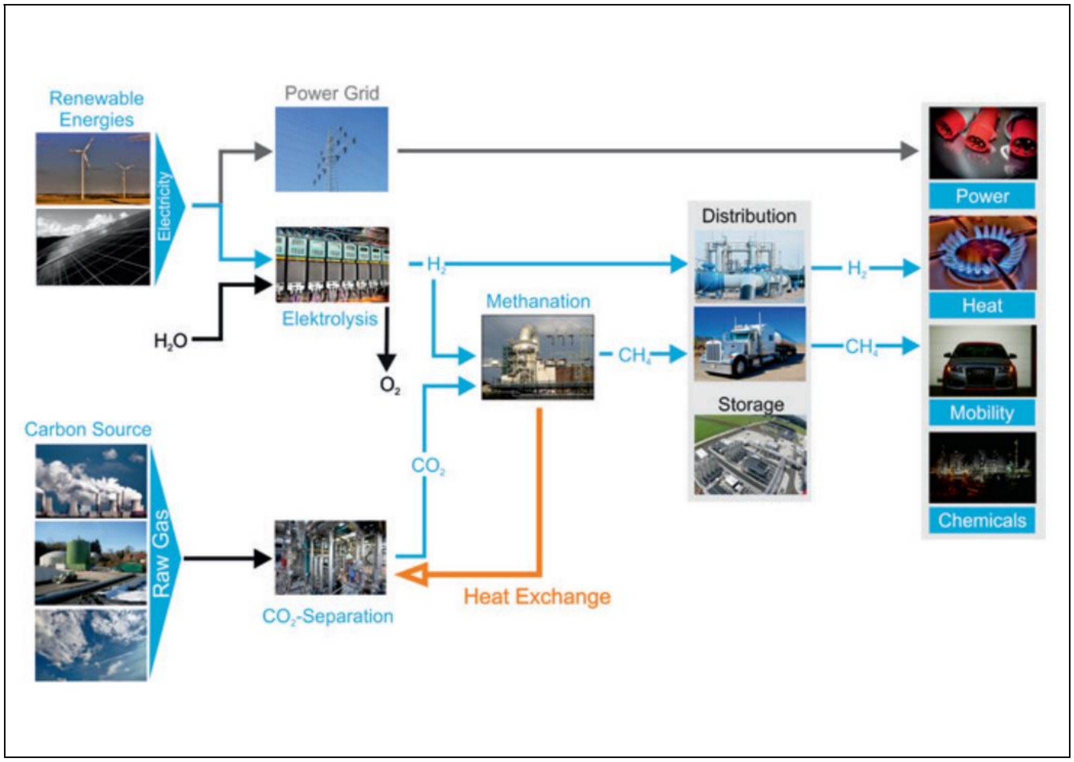


Figure 1.3 The PtG concept
Taken from Lehner et al. (2014b, p. 8)

1.1.3 Energy context in the Province of Quebec and the reason for using PtG in Quebec

Regarding hydroelectricity, Quebec is the fourth-largest producer after China, Brazil, and the United States (Hydro-Québec, 2019). Quebec produces a remarkable volume of hydroelectricity due to its water resources. Renewable sources of energy provide 96% of whole electricity produced by Quebec. After hydroelectricity, wind power has the second place, as seen in Figure 1.4 (C. E. R. Government of Canada, 2022). What made Quebec a significant hydroelectricity producer source is the geography of Quebec, which is well-suited. Electricity is the most practical form of energy in Quebec (40%), oil (39%) and natural gas (13%) (Hydro-Québec, 2019).

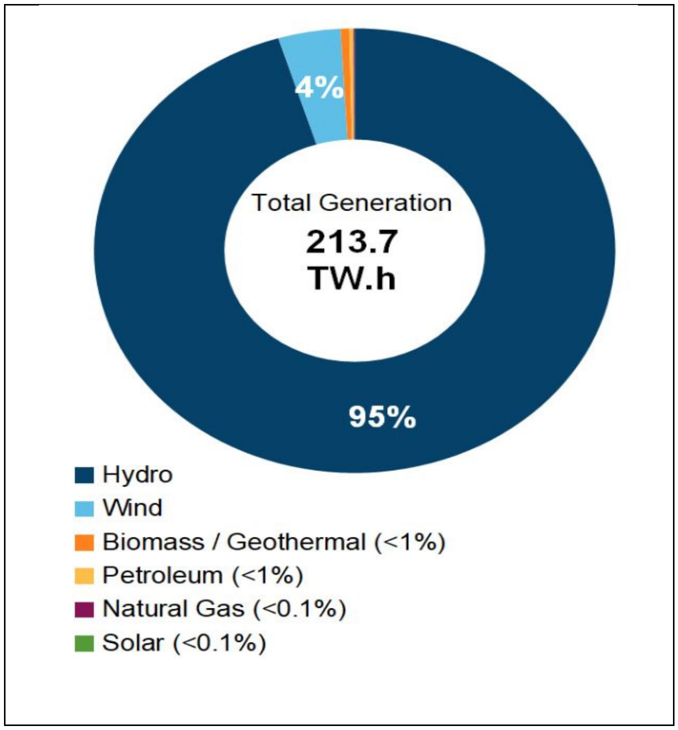


Figure 1.4 Quebec trend in generated electricity by fuel type
Taken from Government of Canada (2022, p. 85)

Half of the electricity was used in the industrial sector, although their needs decreased by 19% between 2006-2009.

Fifty percent of all natural gas in Quebec is utilized by the industrial sector (Hydro-Québec, 2019). In contrast, the residential sectors use more electricity which is 31% in Kilowatt-hours. For example, Quebec uses electricity for heating. Moreover, the commercial sector uses about 30% of all-natural gas with nearly 20% of electricity. Finally, the transportation sector consumes about 68% of the oil products and little electricity or natural gas (Hydro-Québec, 2019).

Net electricity exports reached a historical volume of 33.7 TWh and contributed $631 million to net income. By 2030, the goal would be to increase net income to $5.2 billion or more in Quebec(Hydro-Québec, 2019).

In conclusion, Quebec consumes fewer fossil fuels than other provinces, which means less oil, natural gas, and coal. As a central goal in Quebec's energy profile, hydroelectric power will be used more and more in further development. In terms of developing new energy policies, hydroelectric power could be the most promising renewable energy for environmental reasons, which has the most crucial role in the first step of the PtG process.

1.2 Power-to-Gas (PtG)

Power-to-Gas is a process of converting renewable electricity to hydrogen with water electrolysis. This produced hydrogen can be used as a final product, or even it can be converted to different chemical products like methane by different reactions and processes (Wulf, Linssen, & Zapp, 2018a). Different applications are defined as using PtG (Wulf et al., 2018a).

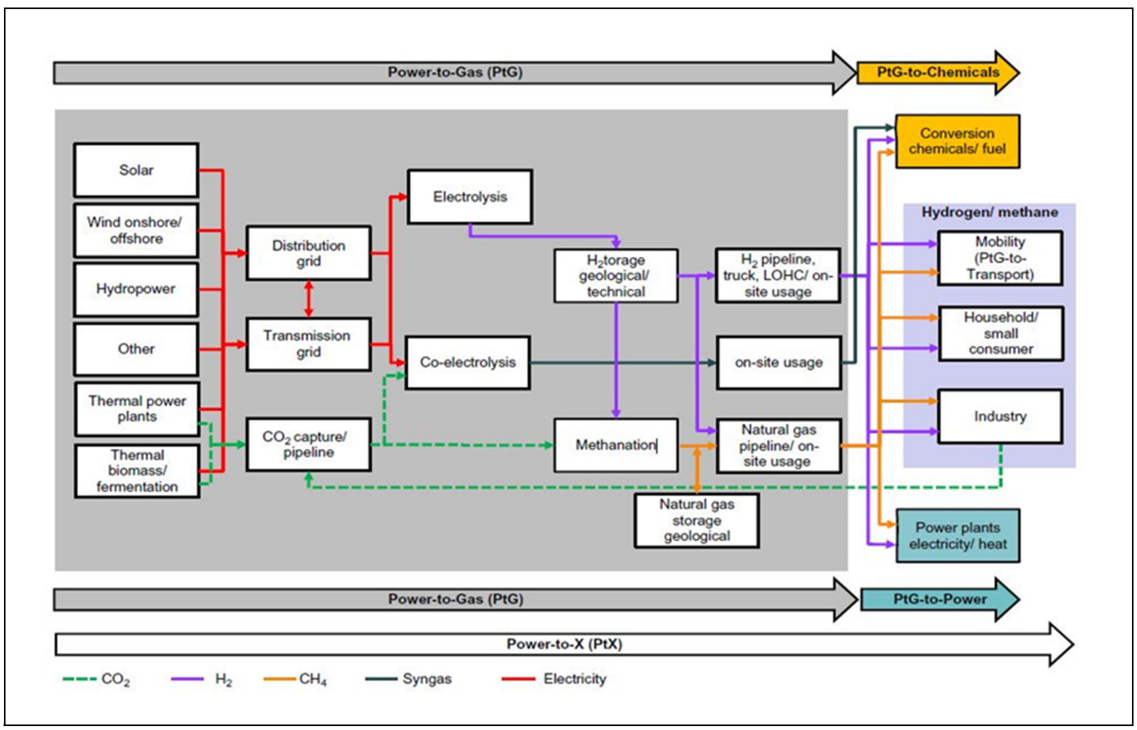


Figure 1.5 Overview of Power-to-X concepts
Taken from Wulf et al. (2018a, p. 310)

The primary aim is long-term energy storage by converting it to other quickly storable energy carriers and decreasing the electricity grid load by controlling operation (elastic demand).

Moreover, producing renewable fuels for transportation, industry, households, and chemical products may be a primary driver for PtG.

There are several reasons for choosing PtG, according to Figure 1.5 (Wulf et al., 2018a). The critical PtG pathways and the component have shown that different applications are available in the PtG process and outputs can be helpful in critical sectors, from transportation to industry and household.

By January 2017, 106 PtG projects had been operated in Europe, and 15 countries had conducted or dealt with PtG projects, which started in 2003, where between one to three projects were commissioned in the following seven years Figure 1.6.

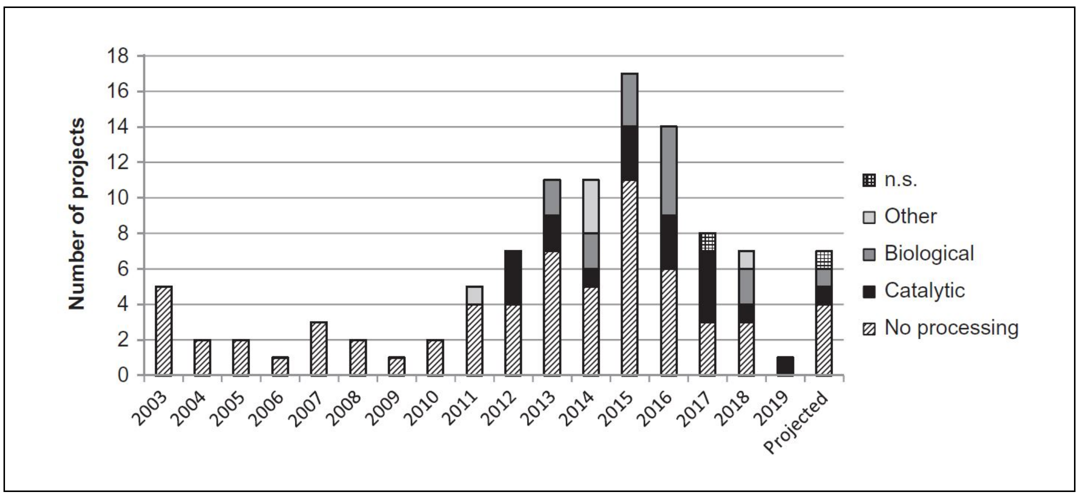


Figure 1.6 Temporary development of methanation
Taken from Wulf et al. (2018a, p. 333)

The number of commissioned projects surged from 2011, reaching its peak of 19 projects in 2015. Since 2017, eight projects have launched the plants, demonstrating a promising perspective for the following years.

The annual developments in PtG projects (electrolysis power in hydrogen and methanation projects) can be seen in Figure 1.7. Until 2019, Germany was the main location of power to gas projects (30.7MW$_{el}$), followed by Denmark (2.53 MW$_{el}$), Canada and United State of America (both about 0.45 MW$_{el}$).

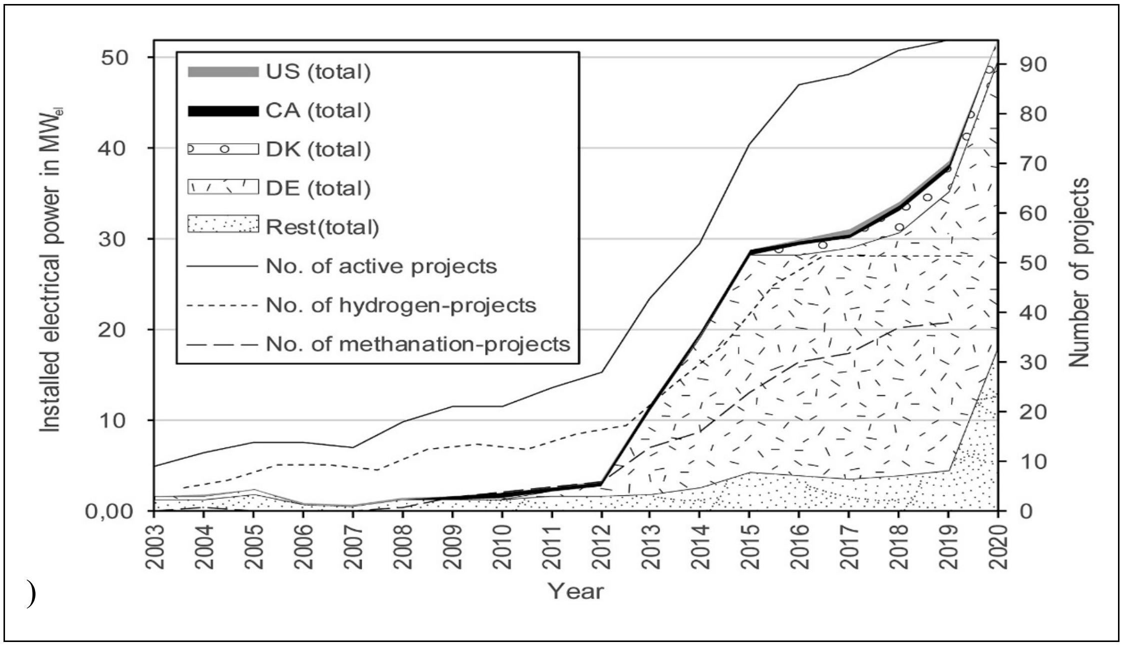


Figure 1.7 Installed electrical power in PtG project in details for different countries
Taken from Thema et al. (2019, p. 783)

Contrarily, countries like Denmark, France, Spain, and the United Kingdom, concentrated on particular applications. The main focus of PtG projects was fuel production in the United Kingdom, whereas this field was intended in Denmark and France. France and Spain carried out projects on heat production also, electricity, while Denmark focused on the merging hydrogen or methane into grids of natural gas (Blending).

Processing of hydrogen to methane or other chemicals is another crucial utilization within PtG. Hydrogen was directly employed in 65 out of 106 projects (61%), and the methanation process became more common in the following years.

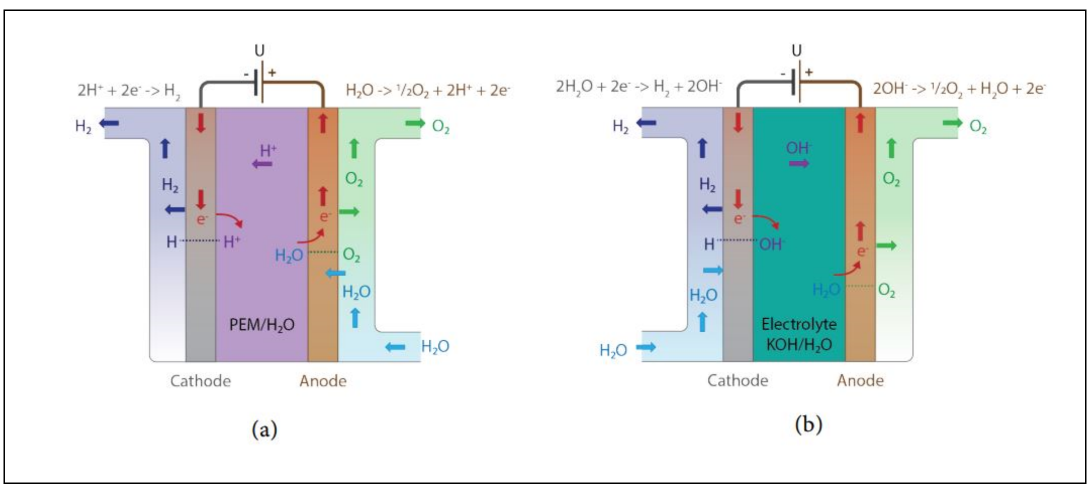
From 2016, hydrogen was processed more than other chemicals utilized directly in PtG projects. Syngas(Power-to-syngas), along with Power-to-Gas pathways to synthetic natural Gas (Power-to-Gas), was investigated by Sternberg & Bardow (2016).

1.2.1 Description of the PtG

Conversion is undeniable in an energy system based on the high integration of renewable energy. This transformation process requires new challenges like storage and utilizing excess energy. As an output of water electrolysis, hydrogen can help cope with serious challenges, as it can store and transport in different sectors of society. Methane is also another output for the PtG process. The whole process of PtG is described step by step and in detail, starting with water electrolysis and different electrolyzer on an industrial scale.

1.2.2 Hydrogen Production from water electrolysis

Water electrolysis is defined as breaking water, in which hydrogen is expanded on the cathode (-) and oxygen on the anode (+). An electrolyte is between the electrodes, acting as an ionic conductor and electrical insulator. Some ions are either H^+ , OH^-or O_2^- And can relocate and transferred between the electrodes, where the corresponding electrolyzers are known as polymer electrolyte membrane (PEM), alkaline, or solid oxide electrolyte (SOEC). Figure 1.8 shows the three types of electrolyzers and the differences between each one.



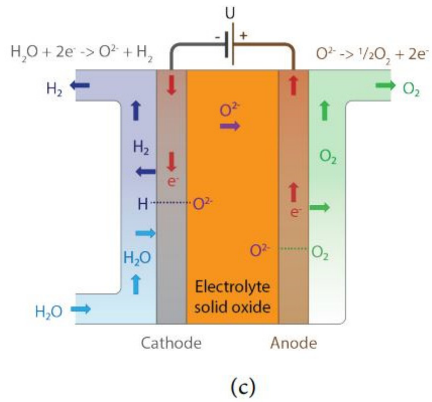


Figure 1.8 Different types of electrolysers: a.(PEM); b. (AEL); and c. (SOEC)
Taken from Gallandat et al. (2017, p. 36)

The following equation defines the efficiency of energy conversion in an electrolyzer:

$$\frac{Energy\ Output}{Energy\ Input} = \eta_{sys} \quad \rightarrow \quad \frac{Heating\ Value\ H_2}{Electrical\ Energy\ Input} \tag{1.1}$$

The energy output is hydrogen's heating value, defined by the higher heating value (HHV) or the lower heating value (LHV). The energy for water evaporation should be calculated as the liquid water is usually utilized as a feedstock. Based on that, the higher heating value of Hydrogen is employed for the system efficiency calculation.

1.2.3 Alkaline Electrolysis

Nowadays, for producing hydrogen, numerous technologies can be introduced; one is Alkaline water electrolysis (see Figure 1.9) (Wulf et al., 2018a).

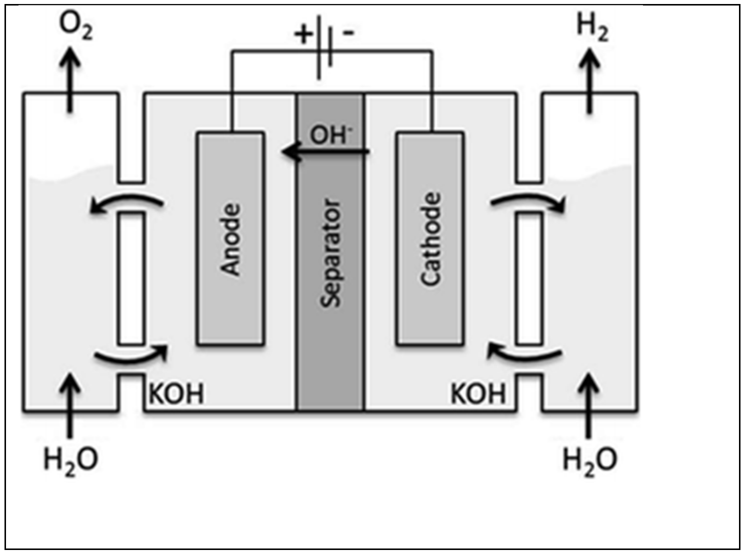


Figure 1.9 Alkaline electrolyzer operating schematic
Taken from Lehner et al. (2014b, p. 310)

As a developed technology for large-scale application, alkaline electrolyzers include a microporous separator, two electrodes, and an alkaline electrolyte of almost 30 wt% KOH or NaOH. The electrode material is Ni, with a catalytic coating like Ni, Pt, or Cu, in the anode is used, which is covered by metal oxides like Mn, W, or Ru. The migrations of the hydroxide ions are through the microporous separator; after this, oxidization occurs at the anode (Marini et al., 2012). Water is consumed during the operation, which should be supplied continuously while KOH is not consumed. The operation temperature is between 70-90°C; the operation density is between 300-500 $\frac{mA}{cm^2}$. Furthermore, the cell voltage is between 1.9-2.4V. The system's efficiency is based on the amount of pressure, size of the system, but the standard efficiency based on the HHV of hydrogen is between 60-80% (Pletcher, Li, & Wang, 2012). The most important advantages of an alkaline electrolyzer are its availability, durability, and maturity (Lehner et al., 2014b).

In conclusion, although the alkaline electrolyzer is designed based on highly developed technology, further research will be needed to make it more compatible with PtG application because its dynamic operation is in limited modes and its low density make it hard to use.

1.2.4 Polymer Electrolyte Membrane Electrolysis (PEM)

In the second place, PEM electrolyzer is less developed than the Alkaline electrolyzer and is employed for small-scale applications (see Figure 1.10). However, due to the large interest in water electrolysis, using this electrolyzer also increased in the industry. In PEM cells, the conducting membrane of the proton is used as solid polymer electrolytes, which is not similar to the alkaline being employed as liquid electrolytes. A collection of membranes and an electro-catalytic layer at each side are called membrane electrode assembly (MEA), which is the core element of the PEM electrolysis system (Ito, Maeda, Nakano, & Takenaka, 2011). Pure water in the anode moves through the separator plate and passes through the collector, where the oxidation reaction is placed. Transportation of the hydrogen ions is accrued among the proton exchange membrane on the cathode side, and the place hydrogen is generated (Lehner et al., 2014b).

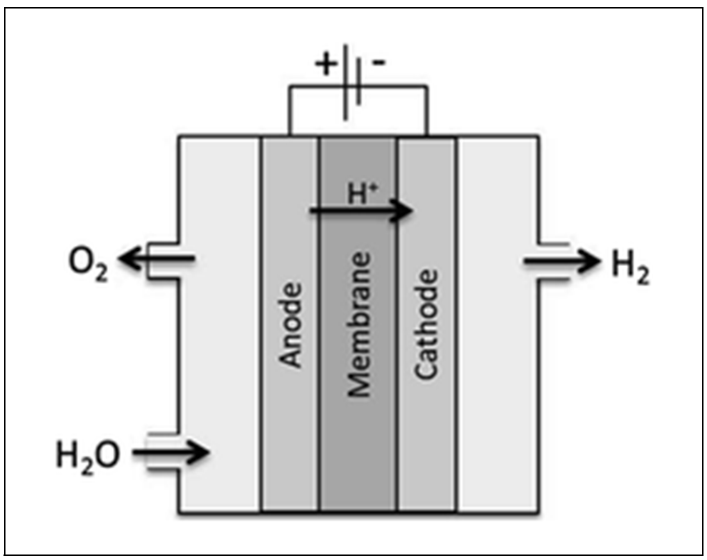


Figure 1.10 PEM Electrolysis operating schematic
Taken from Lehner et al. (2014b, p. 310)

Operation density in the PEM electrolyzer is 1-2$\frac{A}{cm^2}$ which is four times bigger than alkaline electrolyzer. The voltage is between 1.6-2 V, and the system efficiency based on the HHV of hydrogen is between 60-70%. The required temperature and pressure for the operation is between 60-80°C and 30-60bar, respectively (Lehner et al., 2014b). Additionally. Typical catalysts for the PEM electrolyzer are from the platinum group, like Pt or Pt-Pd mixture, the most common combination in this electrolyzer (Goñi-Urtiaga, Presvytes, & Scott, 2012). Although the system size increased over the years, up-scaling procedures are challenging in this system, which is the system's weakness. It is worth noting that this electrolyzer's potential to reduce the cost is more extensive. It can be considered that PEM can act as a competitor to alkaline for its large-scale hydrogen production at its high-power densities, and it can be capable of being used in the PtG process (Lehner et al., 2014b).

1.2.5 Solid polymer electrolyte (SPE) Water electrolysis (SPE)

Solid polymer water electrolysis is another advanced water electrolysis method; instead of an alkaline solution, SPE uses proton ion exchange polymer film as an electrolyte. The temperature for the electrolyzed liquid water is the same as alkaline, but for the high-temperature steam electrolysis works at much higher temperature. Both electrolyzers are currently under development (Abe, s.d.).

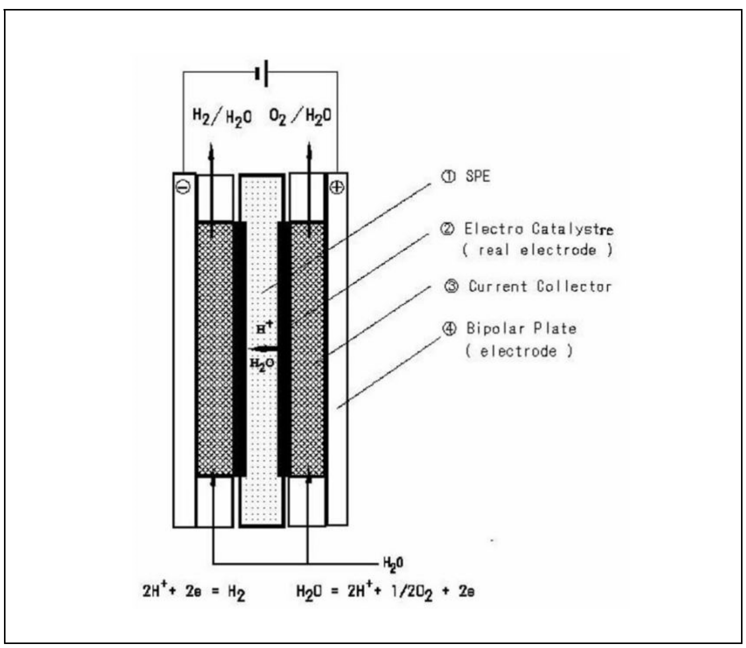


Figure 1.11 SPE Electrolysis operating schematic
Taken from (Abe, s.d.)

As seen in Figure 1.11, the film of the SPE electrolyzer in the center of it works as both a gas-separating membrane and electrolyte. The electrodes are directly attached to the surface of SPE, and the collectors are into the composite to feed electricity to electrodes (Abe, s.d.). The efficiency of the SPE can be calculated the same as alkaline electrolysis.

1.2.6 Solid Oxide Electrolyte Electrolysis (SOEC)

Increasing interest in water electrolysis technologies caused the presence of the new electrolyzer named SOEC. It is the least mature electrolyzer among all that is discussed here. The solid oxide layer in the cell is the electrolyte which can be conducive for ions at high temperatures. The collector joints the porous electrode layer on both sides of the electrolyte. Water goes through the cathode side, as seen in Figure 1.12 , where the reaction amount is reduced. Oxygen goes through the anode side, where it has the potential to evolve (Lehner et al., 2014a).

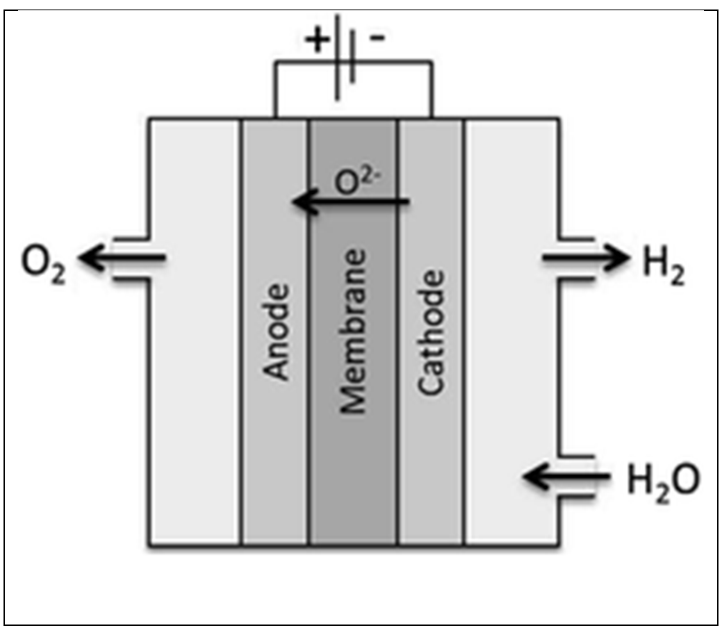


Figure 1.12 SOEC Electrolysis operating schematic
Taken from Lehner et al. (2014b, p. 310)

The temperature of the SOEC system is between 700-1000°C which is high, and it is more beneficial for thermodynamic and kinetic reasons. Several problems can occur at such a high temperature, which is fast component degradation cells. The cell voltage is between 1.2-1.3V, which results in consuming low electricity. It is concluded that the SOEC system operates at atmospheric pressure. Due to the interest in water electrolysis technologies, the system could develop to experience higher pressure of up to 25bar (Jensen, Sun, Ebbesen, Knibbe, & Mogensen, 2010). It should be mentioned that ceramic material is used as usual for the core SOEC components. In conclusion, commercializing the SOEC still takes time for the industry, while it is highly efficient and can be used in different applications

The allocation of different electrolyzers for different applications is significantly affected by their different characteristics. Exact preferences are evident for alkaline and PEM electrolysis (see Figure 1.13).

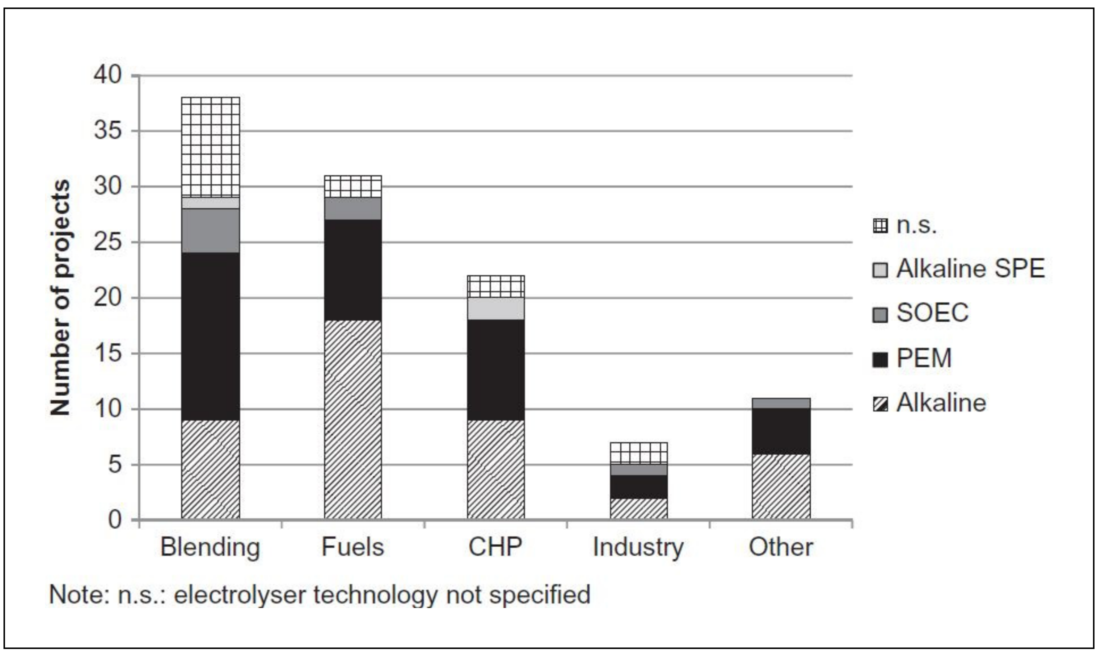


Figure 1.13 Electrolyzers regarding the field of application
Taken from Wulf et al. (2018a, p. 332)

The size of the electrolyzer is categorized into five groups based on the projects (see Figure 1.14). The capacity of the most electrolyzers is between 5 and 100 kw include alkaline, while for research-oriented projects, PEM is mainly used with (<5KW), and SOEC is not included in this category. Finally, the largest electrolyzers are only found in the alkaline category (Wulf et al., 2018a).

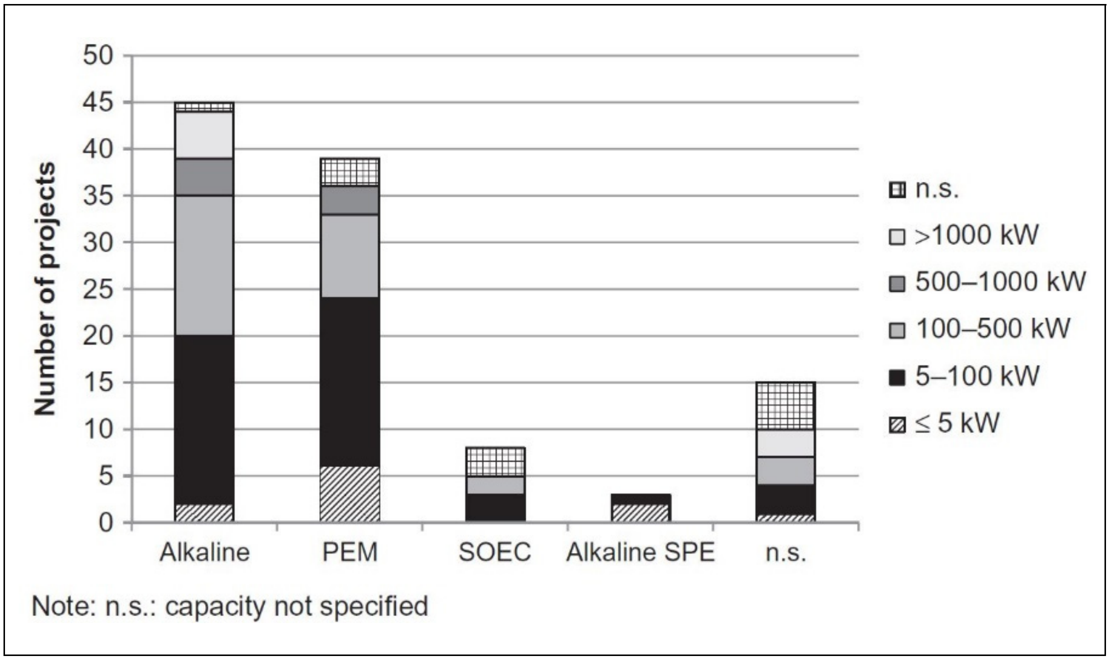


Figure 1.14 Electrolyzer's capacity
Taken from Wulf et al. (2018a, p. 332)

1.2.7 Methanation process

Besides hydrogen production, methanation is another process in the PtG concept. Producing methane and water through a combination of CO_2 and H2 occurs during the Sabatier reaction (Collet et al., 2017):

$$CO_{2\,(g)} + H_{2\,(g)} \leftrightarrow CO_{(g)} + H_2O_{(g)} \qquad \Delta H_R^{\circ} = +41.2 \quad kJ/mol \tag{1.2}$$

The result of the shift conversion would be:

$$CO + 3H_{2\,(g)} \leftrightarrow CH_4 + H_2O \qquad \Delta H_R^{\circ} = -206.2 \quad kJ/mol \tag{1.3}$$

Moreover, the result of the reaction of carbon dioxide and hydrogen can be:

$$CO_{2\,(g)} + 4H_{2\,(g)} \leftrightarrow CH_{4(g)} + 2H_2O_{(g)} \qquad \Delta H_R^{\circ} = -165.0 \quad kJ/mol \tag{1.4}$$

Methanation reaction is exothermic(Hoekman, Broch, Robbins, & Purcell, 2010), with a heat production (-165Kj/mole). In terms of the methanation process, carbon dioxide should be separated from the industrial processes, biogas, or power plants to come as an input with hydrogen. In this case, methane is the output of the PtG system. The gas products of the reaction which leave the reactor consist of carbon monoxide and steam, besides the main product, methane (Lehner et al., 2014b). Following this, the chemical methanation and biological processes will be described.

The chemical methanation processes which are developed over time can be categorized in the following categories based on Götz, Ortloff, Bajohr, & Graf, (2011):

1) 2-phase system (gas educts, solid catalyst):
   a) Fixed bed
   b) Fluidized bed
   c) Coated honeycombs
2) 3-phase system (gas educts, liquid heat carrier, solid catalyst):
   a) Bubble column (slurry)

As seen in the mentioned reactions, these chemical reactions are exothermic, and controlling the reaction temperature is challenging depending on the reactor type; this problem can be solved.

1.2.8 Fixed bed methanation:

Catalysts are used in this type, and the temperature of 250-300°C preheated gases will be increased. Based on the pressure of the operation, with the higher than 400-500°C, selectivity will be decreased. Therefore, the temperature should be controlled in a fixed bed type; otherwise, catalysts may be destroyed by the high temperature (see Figure 1.15).

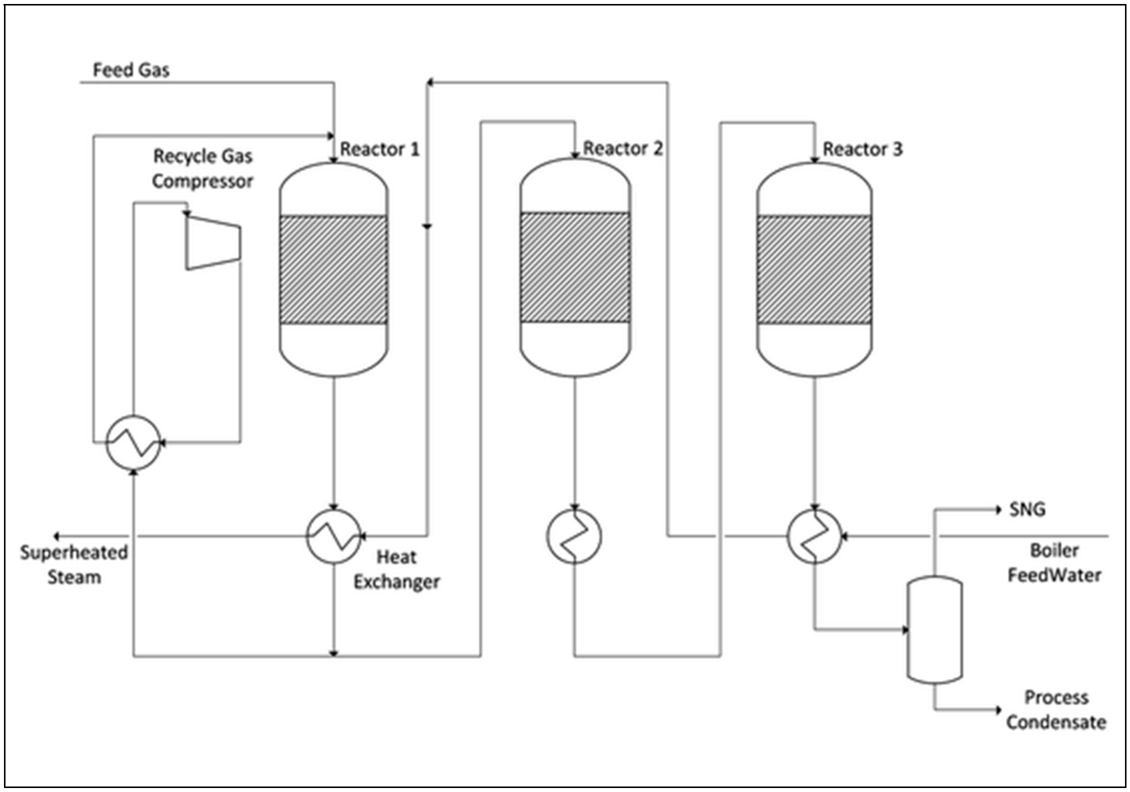


Figure 1.15 Fixed bed methanation
Taken from Lehner et al. (2014a, p. 332)

1.2.9 Fluidized Bed Methanation:

This type (see Figure 1.16) is defined by the isothermal temperature profile in the reactor, which is attained by the turbulence of the solid catalyst particle resulting from fluidization. The main benefit of this type of reactor is the excellent heat released by this reactor and the excellent surface area of the catalyst (Lehner et al., 2014b). Based on the previous works, this type of reactor is also possible to upscale the process.

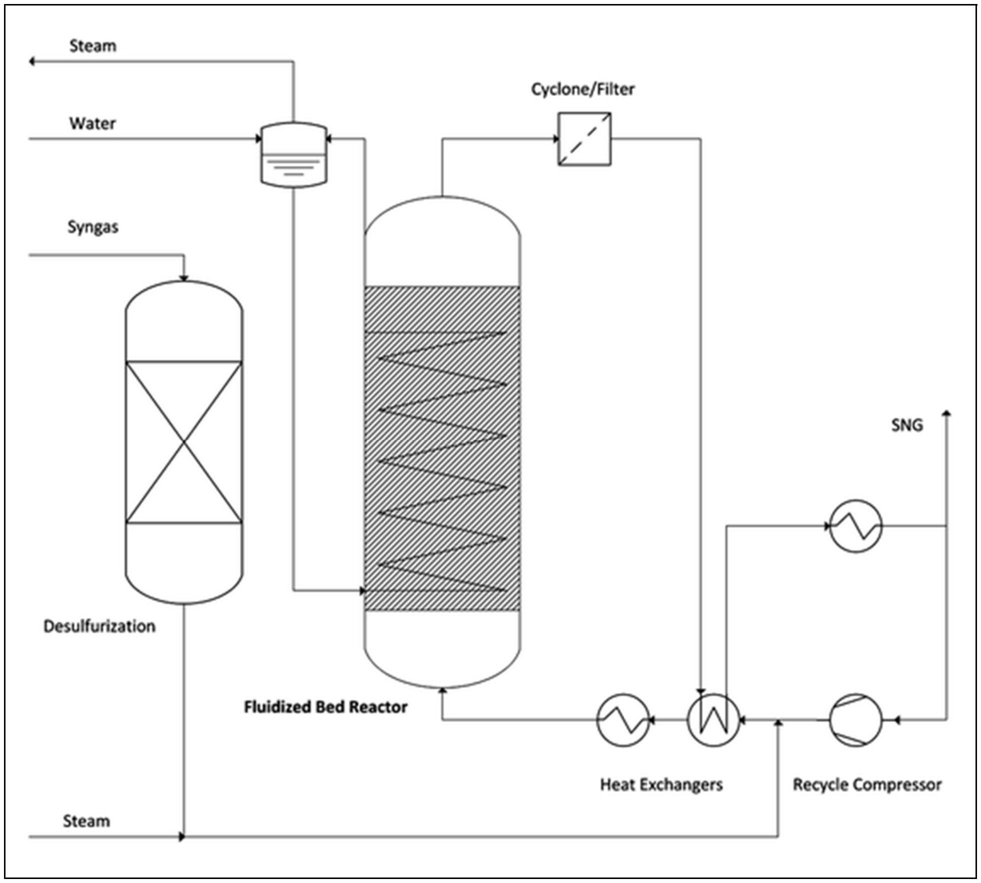


Figure 1.16 Fluidized Bed Methanation
Taken from Lehner et al. (2014a, p. 332)

1.2.10 Bubble columns

This type operates the methanation process in a 3-phase system: the solid catalyst, gaseous educts, and a liquid heat carrier medium. The presence of a liquid phase promotes the released heat from exothermic reactions(Kopyscinski, Schildhauer, & Biollaz, 2010). Therefore, the isothermal temperature profile can be acquired in the reactor (see Figure 1.17). Moreover, a reduction in catalyst corrosion can be observed in contrast with the fluidized bed reactor. The kinetics of the whole process can be negatively affected by the mass transfer resistance between the solid catalyst and the gaseous. Mineral oil as a liquid heat was used in the chemical systems, which, based on the decreasing temperature, the degradation could be observed in the mineral oil (Lehner et al., 2014b).

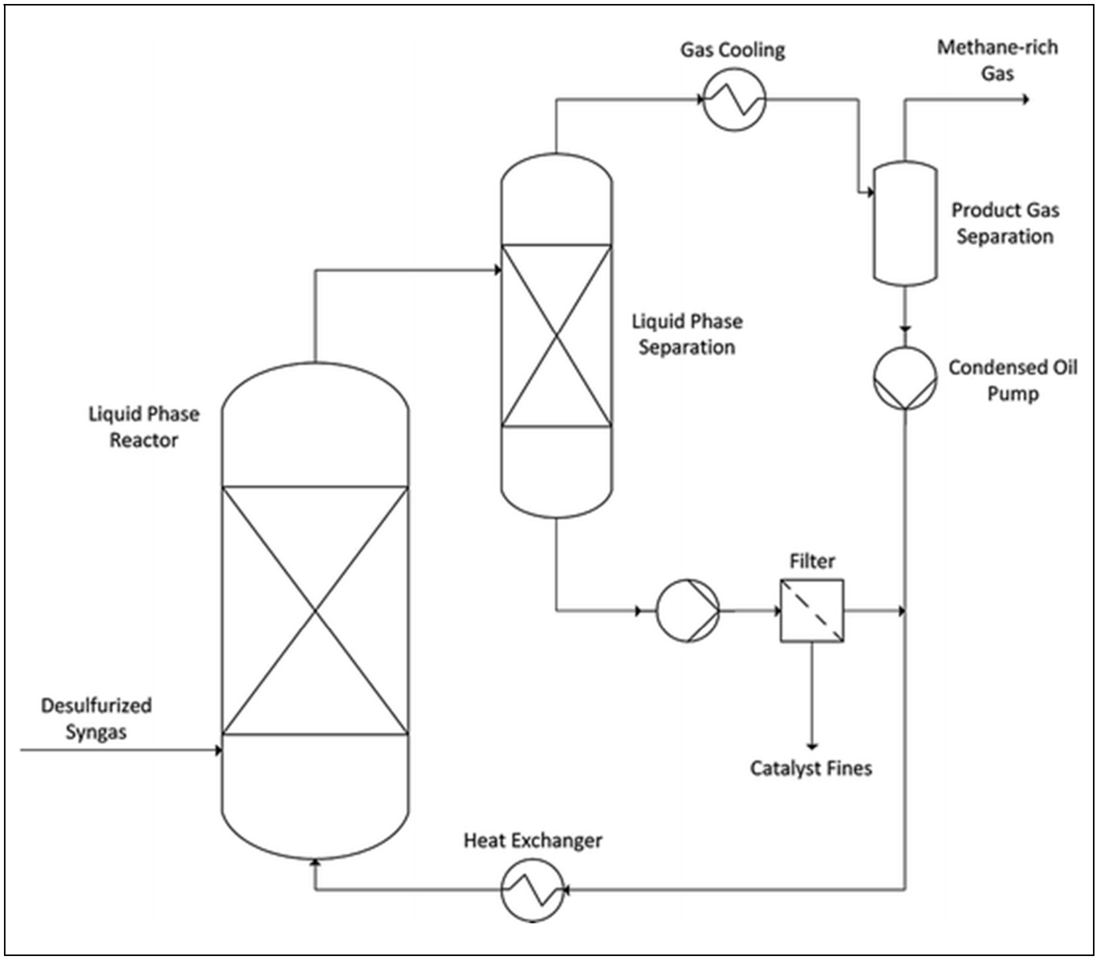


Figure 1.17 Concept of liquid phase methanation
Taken from Lehner et al. (2014a, p. 332)

The biological system works on hydrogen and carbon dioxide methanation based on biocatalysts (enzymes). Methanogenic bacteria can create the necessary enzyme, which is known in biogas processes and defined in two main reactions (Lehner et al., 2014b):

1. Acetolactic methanogenesis:

$$CH_3COOH_{(g)} \leftrightarrow CH_4 + CO_{2_{(g)}} \qquad \Delta G_R^{\circ} = -33.0 \quad kJ/mol \tag{1.5}$$

2. Hydrogenotrophic methanogenesis:

$$CO_{2(g)} + 4H_{2\,(g)} \leftrightarrow CH_4 + 2H_2O \qquad \Delta G_R^{\circ} = -135.0 \quad kJ/mol \tag{1.6}$$

In the decomposition of biomass, acids are used in methane production, and the second reaction is used in the biogas plant. Biological methanation has advantages compared with chemical methanation, such as moderate temperature (between 30-60°C), pressure in operation, and feed gases (Lehner et al., 2014b).

1.2.11 Methanation as part of PtG

The concept of methanation is the reaction of hydrogen with carbon dioxide to produce methane; however, methanation in the PtG concept has too many different meanings (see Figure 1.18).

The electrolysis unit supplies hydrogen for the methanation process. While the operation of the electrolysis unit is unsteady, the chemical methanation operation should be steadily higher pressure and temperature. Even though the load flexibility is restrained, the sensitivity of the load variations is affected by the reactor concept. Consequently, periodic hydrogen storage is necessary in this case. The same observation is valid regarding carbon dioxide, as well. In terms of annual operation and plant size, methanation as a part of the PtG process may be changed. In this case, the methanation reactor and process should be developed considering the easily up-scalable reactor design, modular and load-flexible system. Another main object is the economic viability of methanation and PtG, which means the cost-effectiveness of methanation. Increasing the catalyst's lifetime and utilizing the released heat from the reaction in the PtG process can achieve the cost-effectiveness methanation reaction (Lehner et al., 2014b). The electrolysis produces hydrogen for the methanation.

Another main component in methanation as part of the PtG system is carbon dioxide. As mentioned in the previous section, in conventional methanation, carbon dioxide and carbon monoxide can be created, which can be used as a carbon source in methanation. Moreover, Carbon sources can be either from biogas (biomass gasification or biogas plant) or industrial sources like fossil fuel. The atmosphere can be considered a carbon dioxide source (Lehner et al., 2014b).

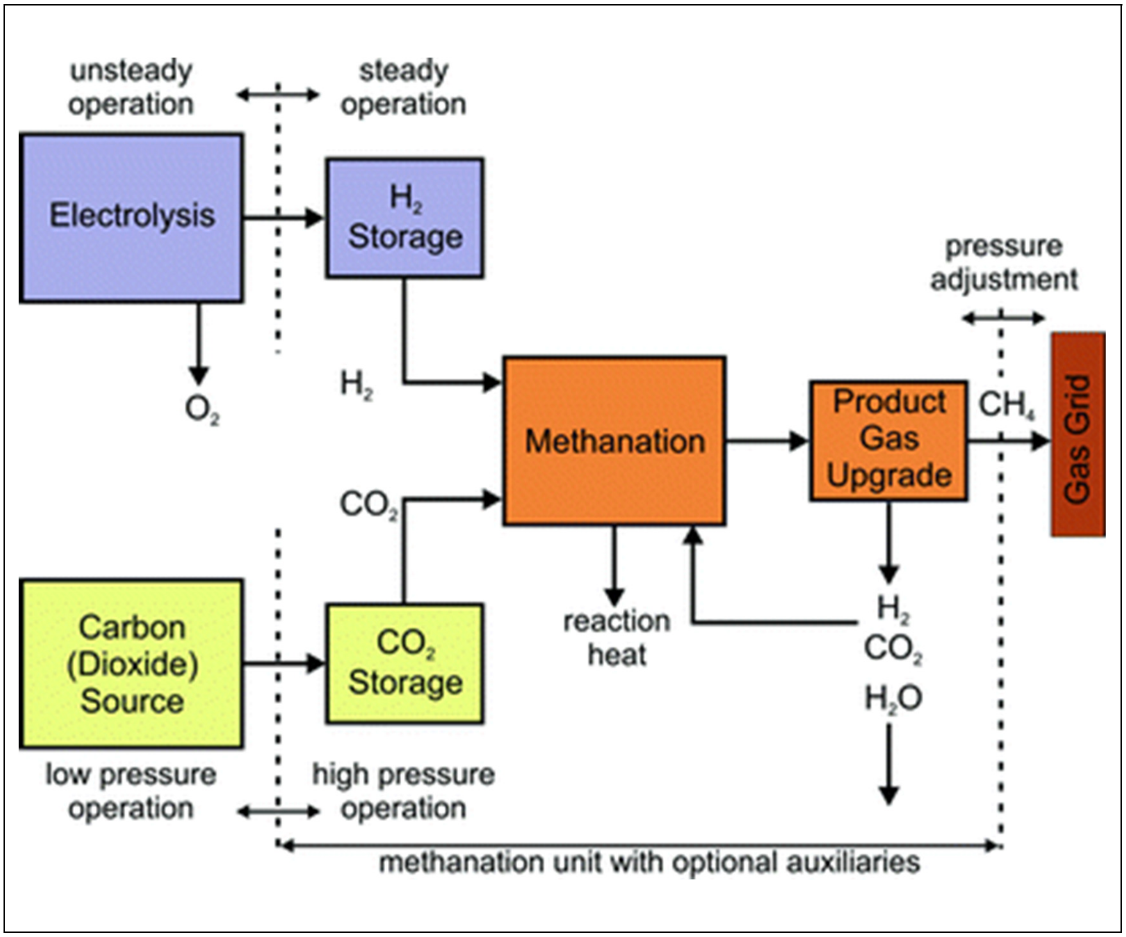


Figure 1.18 Methanation with PtG process scheme
Taken from Lehner et al. (2014a, p. 332)

1.2.12 Current situation and research activities in PtG

Methanation as a part of the PtG process has been investigated recently. Between the years 1993 to 2050, around 153 P2G projects were completed worldwide, and planned projects were found among 22 countries (Thema et al., 2019). The location of these projects on the global scale is illustrated in (see Figure 1.19). Further analysis focused on the electrolyzer, reactor type, and methanation technology. Moreover, carbon sources were quantified for projects.

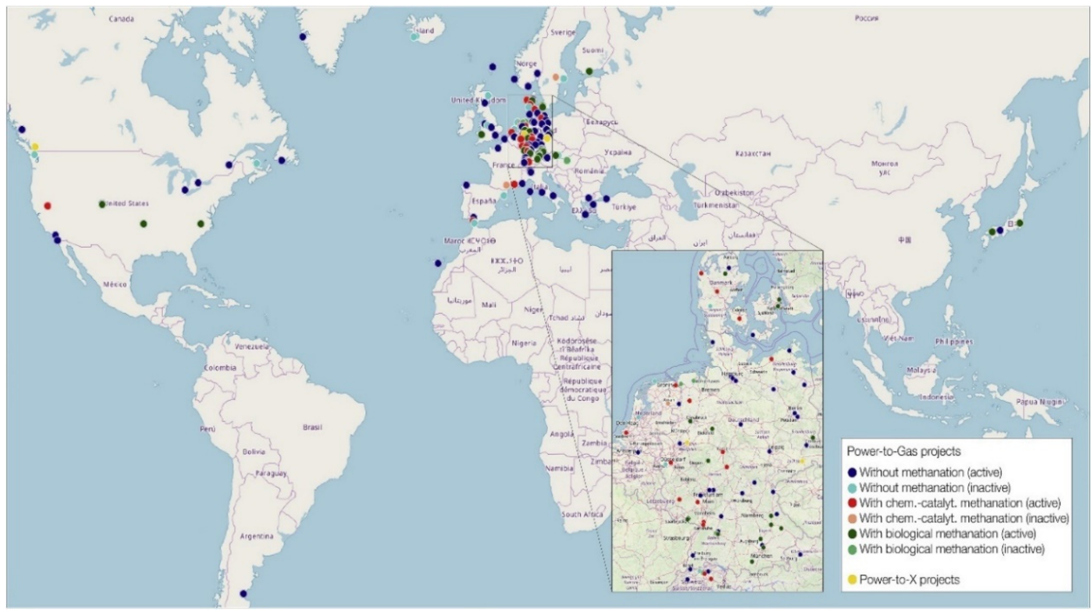


Figure 1.19 Power to Gas projects
Taken from Thema et al. (2019, p. 781)

The capacity of installation and projection of PtG was started in 1993. The most activated countries in P2G projects installed their system from 2003 to 2020, based on Figure 1.20, and for the hydrogen or methane. About 57% of all projects focus on hydrogen production(Thema et al., 2019). The rest is into CO_2-methanation; around half of the methanation projects covered chemical and half of that covered biological methanation. Figure 1.20 shows that until 2019, in Germany, the central part of P2G was installed (30.7MW), followed by Denmark (2.53MW), Canada, and the United States of America (0.45MW). Plans for increasing the capacity of P2G until the following years still exist in Netherland, France, and even Hungary.

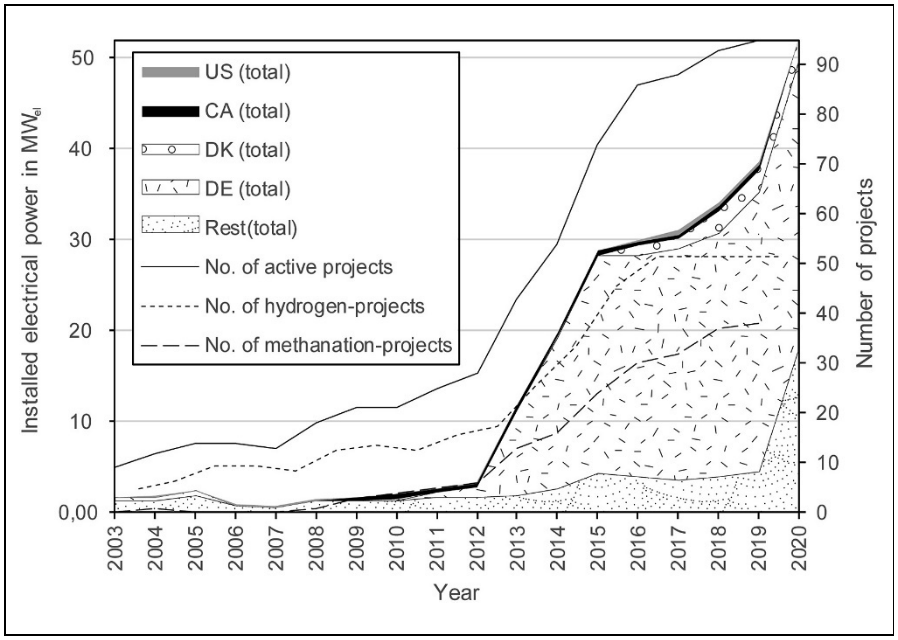


Figure 1.20 P2G projects installation and development, annually
Taken from Thema et al. (2019, p. 783)

In conclusion, if many P2G projects are pilot plants with a lifetime of 1-3 years and still need funding, large-scale implementation in the mid and long-term condition is on planning for different countries like Germany (Thema et al., 2019).

1.3 Life cycle assessment (LCA)

Environmental issues can affect all the economic, industrial, political, and individuals. Nowadays, increasing attention to environmental issue stem from the increasing environmental problems. Sustainability is a matter for the future. All the studies and operations should be followed by actions that can help decrease the environmental impacts. For example, different technological solutions should prioritize environmental cost and efficiency, and all activities should be optimized to decrease the negative impacts on the environment (Jolliet, Saade-Sbeih, Shaked, Jolliet, & Crettaz, 2015). As a decision-making tool, LCA can help to use the optimized technologies and select the better solution to reduce environmental issues. LCA covers the whole life cycle of a product or service, and it is different from the other environmental methods as it can connect environmental performance to functionality.

Consequently, LCA quantifies pollutant emissions and raw material application based on the function of the product and service.

The International Organization of Standardization (ISO) introduced the ISO 14040 series to perform the LCA and as a guideline. For environmental management and describing all phases like the inventory, impact assessment, and interpretation phase, ISO 14044 was replaced with ISO 14041,14042, and 14043. The following section will explain the LCA methodology based on the ISO 14040 series.

1.4 Description of the LCA methodology

Life cycle assessment (LCA) is a method to assess the environmental impacts of a product system from raw materials extraction to final disposal in its entire life cycle. Based on the ISO14040, for conducting a complete LCA study, four following essential steps should be checked (Jolliet et al., 2015):

- goal and scope definition,
- inventory analysis,
- impact assessment,
- interpretation of results.

Figure 1.21 shows how these four phases are lined together and how each phase reflects others by two arrows with different opposite directions.

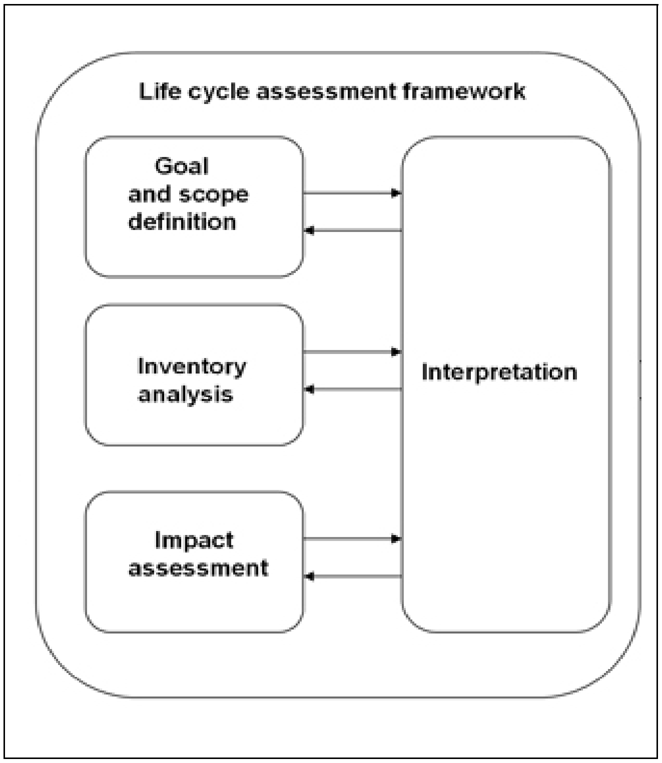


Figure 1.21 LCA structure
Taken from Jolliet et al. (2015, p. 8)

The functional unit (FU) is the base for the comparison, and it should be defined equally for all the comparative systems. Articulating the aim and the scope is the most critical step for any LCA study, followed by inventory analysis and environmental impact evaluation (Jolliet et al., 2015). The LCA interpretation phase relates the outcomes following the addressed aim and scope. The LCA study results play a significant role in decision-making, including product development, public policy making, and marketing (ISO, 2006). Here, the brief explanation of each of these stages is as follows:

1.4.1 Goal and scope definition:

The first phase of the life cycle assessment highlights the importance of describing the system. The functional unit is the basis of any LCA, and according to ISO14044 (2006), FU is the reference unit of the measurable act of a product system which is the same for all scenarios and all inventory streams and impacts for scenarios calculated per FU of system. FU is the products or services' unit under survey, which should be quantitative. For a certain FU, the reference flows are the goods or services supplied to implement the function and generate the FU (Jolliet et al., 2015b).

According to ISO14044, LCA quantifies potential environmental impacts and compares them to the available alternatives. According to ISO 14044, all the systems or products should be compared clearly and defined based on the same functional unit. Sometimes, it needs to define primary and secondary functions as the single products may have multiple functions. The primary function is standard for the different alternatives. However, the secondary functions are specific for each scenario. The environmental inputs to the system boundary are extracted resources, including primary energy and land use.

In contrast, the system's outputs to the environment are for example, emissions to air, water and soil. The system model is prepared by linking the processes recognized as unit processes. Unit processes are connected in the system by intermediary flow, which is the quantity of each unit process needed for another unit process. The connection between the unit process and environment is by elementary flow, which can be natural resources such as energy or raw material or any emissions to air, water, and soil. All the unit processes make up the system and are in the flow chart (see Figure 1.22). It can provide an overview of the system and link the unit processes (Jolliet et al., 2015).

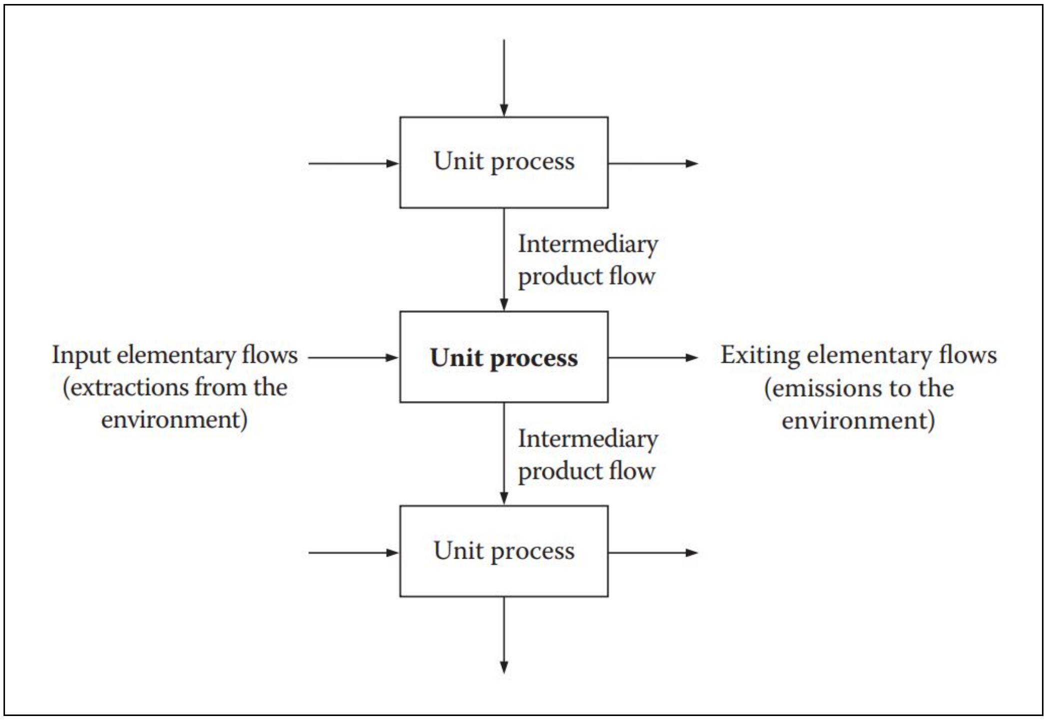


Figure 1.22 Unit processes in system boundary
Taken from Jolliet et al. (2015, p. 35)

The system boundaries should cover the same function matter for all scenarios. Based on ISO14044, when the contribution of the process is less than the cut-off percentage (1%) to the product mass, the process can be excluded. Otherwise, cut-ff criteria should be described clearly for each process among system boundaries (Jolliet et al., 2015). Moreover, when identical processes exist in different scenarios, they can be excluded when the effect is the same on the reference or intermediary flow (Jolliet et al., 2015).

1.4.2 Inventory analysis:

The inventory analysis is the second phase in LCA and involves collecting data for inputs and outputs. To achieve the inventory of emissions and extractions, the total demand per FU is multiplied by the emission of each unit process. For calculating the elementary flow, all the inputs (raw material and energy) and outputs (emission to air, water, or soil) come from the literature review, industrial partners, or even databases which are the essential source of data (Jolliet et al., 2015).

Most of the life cycle assessment database was developed in 1980 in Europe, and data came from university studies or consultants working in the industrial sectors. Databases are developed according to some main categories: construction materials and processes, chemicals, energy source, waste treatment services, agricultural products and its processes, and transportation. Different databases were created in different countries; however, the development of more databases was in Switzerland, which studied the environmental impacts of different types of packaging, for example, plastic and paper. In response to this, another energy database was created, which caused the collaboration of these institutions to create a more complete database called eco-invent (Jolliet et al., 2015). In ecoinvent, inventory data exist for many products or services, which results from the production from the year 2000. This database is often updated, and recent data can be found there. This database is categorized and organized into energy sources, construction materials and processes, chemicals, water treatment services, and agricultural products.

1.4.3 Impact assessment

The link between the inventory results and the environmental damages are with impact assessment methods. The inventory results are organized into the impact categories called the midpoint category. For example, global warming as a one-impact category illustrates the impact of greenhouse gases. Impact assessment calculates impact for different categories using indicators developed to assess potential environmental impacts of inventoried emissions and resource extractions. Different impact assessment methods can be applied to different studies.

Each midpoint category is assigned to one or more categories which shows the damage in the different areas of protection (see Figure 1.23), like Human Health (HH) or Ecosystem that are in the damage category (Jolliet et al., 2015).

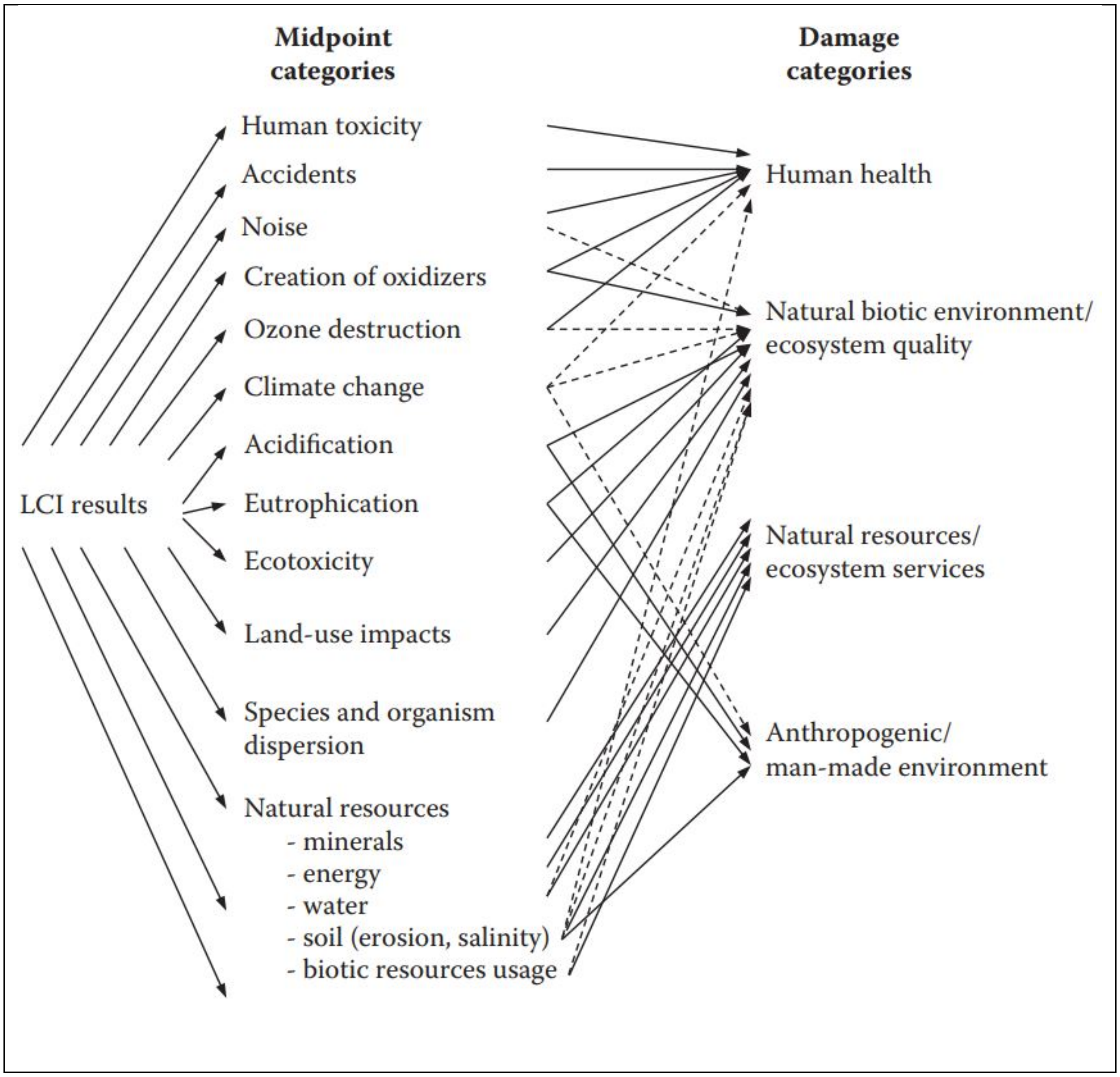


Figure 1.23 Impact assessment framework for IMPACT2002+
Taken from Jolliet et al. (2015, p. 108)

There are several impact assessment methods, and the most used LCIA methods are ReCiPe, ILCD2011, IPCC2013, or IMPACT2002+. Either IMPACT2002+ or ReCiPe2008 provide the results on assessing the impacts at both midpoint and endpoint categories(Jolliet et al., 2015). The ReCiPe2008 method is shown in Figure 1.24;

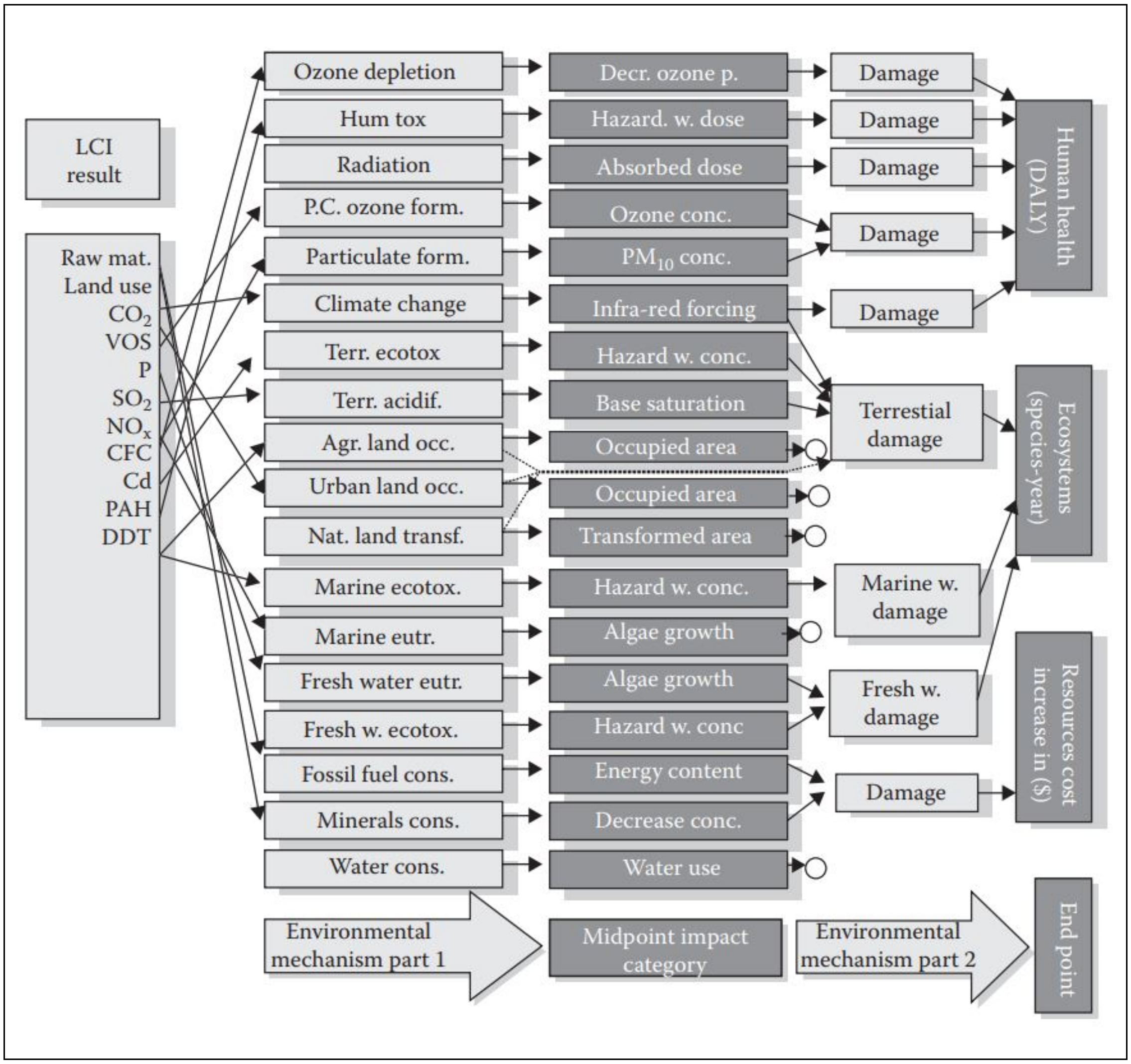


Figure 1.24 Structure ReCiPe2008 method
Taken from Jolliet et al. (2015, p. 135)

This structure shows the link between the life cycle inventory, midpoint, and damage indicators. Three different damage categories used in ReCiPe2008 are damage to human health (HH), ecosystem diversity (ED), and resource availability (RA) (Jolliet et al., 2015).

1.4.4 Interpretation:

The main goal of the interpretation phase is to understand which impact category can substantially decrease the environmental impact of the studied system or product and consequently analyze the uncertainties. This stage can be achieved by combining results from previous phases with methodological choices (allocation or limiting the system) or data from similar studies.

1.4.5 LCA applied to PtG

Power-to-Gas convert electricity into gas and mainly focus on using water electrolysis to convert electricity into hydrogen (Gerloff, 2021). Hydrogen can react with carbon dioxide and make synthetic natural gas (SNG). The main component is CH_4 (Gerloff, 2021). This technology has been developed for its capability of long-term and flexible storage duration (Zhang, Bauer, Mutel, & Volkart, 2017). To minimize greenhouse gas emissions, Power-to-Methane (PtM) is a promising technology, producing SNG that can be fed into the NG grid for further utilization (Gerloff, 2021).

Life cycle assessment (LCA) as a tool has been developed to help and address the need of the industry to understand and improve the environmental impacts of their operations since 1963(Bjørn, Owsianiak, Molin, & Hauschild, 2018). The society of environmental toxicity and chemistry (SETAC) developed the LCA code of practice, and International Organization for Standardization (ISO) started developing a set of LCA standards. ISO 14040 was about the framework and principle of LCA, released in 1997. ISO 14041, ISO 14042, and ISO 14043 provided the LCA guidelines (Bjørn et al., 2018). LCA's general methodological framework was established through ISO14044 by the year 2006, which all these ISO can help the industry to conduct the LCA in the standard way (Bjørn et al., 2018).

Power-to-Gas projects were investigated and introduced by the Europe countries in 128 demo-projects to achieve the experience with integrating systems of PtX components from 2002 until now (Wulf, Linssen, & Zapp, 2018b). Environmental and economic aspects of LCA studies on PtG were performed in different countries and scenarios. Most of the previous studies focused on the techno-economic aspects o the life cycle assessment and less paid attention to the environmental aspects. Additionally, the power of hydrogen was investigated by researchers (Gerloff, 2021). Therefore, this study focuses only on the environmental aspects of PtG, specifically P2M technology.

LCA of carbon capture and storage (CCS) in power generation was investigated by Volkart, Bauer, & Boulet (2013) in Switzerland. A comparison was made between the LCA of fossil fuel and wood plants and focuses on the cement production in Europe for the following years until the year 2050 with and without CCS. Hard coal, lignite, natural gas, and biomass power plants in different conditions with and without CCS were assumed for electricity sources. The options for CO_2 capture were assumed to be post-combustion, oxy-fuel combustion, and pre-combustion technologies. A cement plant was modeled based on the plant located in Switzerland, and CO_2 pipelines were assumed to have 200km and 30 years of a lifetime. Based on the ReCiPe impact assessment method, results were extracted. Results illustrated that CCS could significantly reduce GHG emissions from power generation. For coal and natural gas, both with CCS, the life cycle GHG emission of power generation was similar, contrary to without CCS.

Furthermore, wood power generation without CCS is estimated to have low life cycle GHG emissions similar to the fossil fuel power plant assumed with CCS. All in all, due to the fuel and CO_2 capture technology applied, the trade-offs in environmental impacts were reported in this study. CCS can tremendously decrease GHG emissions. However, the heat source and CO_2 capture could affect the environmental burdens.

The LCA methodology was employed in Germany by Sternberg & Bardow (2016), who compared the process of PtG with synthetic natural gas (power-to-SNG) and syngas (power-to-syngas). They compared the three considered pathways: two Power-to-Syngas processes (assumed reverse water gas shift (rWGS) and dry reforming of methane (DRM)) and one power-to-SNG process by LCA. In this study, in the rWGS reaction, H2 and CO_2 react to CO. Meanwhile, in DRM, natural gas and CO_2 react to CO and H2. It is assumed that the CO_2 source is the coal-fired power plant, and hydrogen is supplied by water electrolysis. Steady-state and part-load operations were considered for the electrolyzer. The environmental impact categories selected for comparing these different processes were global warming (GW) and fossil depletion (FD) impacts. Based on the ReCipe 1.08 midpoint, the environmental impact was assessed. In the steady state operation, both power-to-syngas processes were shown lower global warming impacts than the conventional syngas production. For the part-load operation of electrolysis, intermittent renewable electricity like solar or wind has been used in the electrolysis. Results have shown that all power-to-gas pathways had lower global warming impacts than conventional processes.

Moreover, DRM had the highest environmental benefit when all the PtG pathways used the same amount of wind electricity. CO_2 supply also was crucial for the environmental performance of PtG pathways. It is concluded that PtG can have lower environmental impacts than conventional processes when the CO_2 from a coal fire plant is captured, which is otherwise emitted. If not, the SNG process even shows higher global warming impacts than conventional natural gas (Sternberg & Bardow, 2016).

Similarly, Gerloff (2021) analyzed the LCA of Power to Methane (P2M); however, here, concerning different water electrolysis technologies and CO_2 sources in different scenarios in Germany. The ecoinvent database processes for Europe (Europe without Switzerland) were chosen, and two transportation potions were selected, each 250km. FU of 1kg of SNG was assumed and produced for 20 years. The first scenario was assumed to be SNG production with the goal of storing in the natural gas grid with the CO_2 source from the atmosphere. The question was which P2M technology may have a less environmental impact and CO_2 Equiv. Then, the results were compared with the environmental impacts of natural gas production. The second scenario investigated the production of SNG regarding the different electrolysis technology. The study concluded that P2M with SOEC electrolysis technology shows the less environmental impact and is more environmentally friendly for the energy scenarios. For the cement as CO_2 sources scenario, P2M with PEM electrolyzer was the best choice. Finally, for the renewable energy (RE) scenario, it is concluded that P2M with an alkaline electrolyzer was more environmentally friendly. Moreover, this study reported trade-offs for the NG production; less environmental impact potential could be seen in all energy scenarios than the SNG production.

Saunier et al. (2019) investigated the life cycle assessment for the bio-catalyzed and potassium carbonate processes and amin-based carbon capture technologies in the Quebec, Canada context. Data was based on the three technologies consisting of CSI (Enzym-accelerated potassium carbonate solvent technology), MEA (Amine solvent technology), and UNO MK3 separation technology based on a precipitating potassium carbonate solvent) Moreover, the impact assessment method used in this study was the Impact 2002+ method(Saunier et al., 2019). This impact assessment method includes four indicators at the endpoint (climate change, human health, ecosystem quality, and resources) and sixteen at the midpoint level, such as ozone formation. This study's functional unit (FU) was the separation of 1 t of CO_2 from the flue gas stream in the midwestern USA in 2017. The inventory data was collected by CIRAIG (International reference center for life cycle assessment and sustainable transition) and CSI (construction specification institute) and consisted of material used, energy consumed, waste, and emissions for each unit process. This study confirmed that CSI carbon capture technology was better than MEA and UNO MK3 in case of environmental impacts when hot water comes from the power plant. The electricity and steam for the MEA and UNO MK3 were the main contributors to these technologies' environmental impacts. Other inputs like chemicals, waste, and emissions to air and water makeup are reported to have a less environmental impact. A sensitivity analysis confirmed that CSI technology has lower potential environmental impacts than the MEA and UNO MK3(Saunier et al., 2019).

Another investigation on the life cycle assessment of P2G was done by Zhang et al. (2017) in Switzerland in 2017 to investigate some critical aspects of the LCA of P2G. The authors studied the different approaches for CO_2 capture and utilization (CCU), different technologies for supplying the electricity and comparison of them with conventional natural gas, and further environmental impacts of P2G on global warming. Simapro 8.0.4.30 is used as a software in this study, and the result is based on the ILCD2011 Midpoints(Zhang et al., 2017).

For P2H, 1MJ of hydrogen generated is assumed. At the same time, for P2M (with SNG as a fuel for mobility), 1km of distance traveled was assumed in the subdivision approach for CCU, which reference products are the same as functional units. Electrolysis consumes 1kWh of electricity as a functional unit for the system expansion. For electricity supplying to electrolysis, authors assumed different sources of electricity from renewable energy sources (power from solar photovoltaics and wind turbines) in Switzerland, the European average grid supply, and the Swiss grid supply. The technologies for the electrolysis unit process are assumed to be Alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis. Different sources of CO_2 are considered in this paper based on previous works like CO_2 capture from a power plant with various fuels via post-combustion capture technology, besides cement plants with different energy supplies. Additionally, CO_2 from the atmosphere is considered in this paper. Steam methane reforming (SMR) and coal gasification and reforming (CGR) are the two technologies for production of conventional hydrogen(Zhang et al., 2017).

Assuming the subdivision system, life cycle GHG emissions of P2H compared to conventional hydrogen by the authors, higher variability than the wind could be seen in solar PV (photovoltaic). Furthermore, wind power as a source of electricity that should be injected as a feed in the electrolysis unit process could achieve a higher reduction of emissions. This outcome is due to wind's lower GHG emissions per kWh than the PV. While the essential part of the P2G system is the electricity inputs, as it has the most significant contribution concerning climate change impacts, the electrolysis facility is also effective in its contribution. For example, alkaline electrolysis performs somewhat less than PEM electrolysis in terms of life cycle GHG emissions with the same electricity supply. Life cycle GHG emissions can be reduced by about 90% by employing electricity with very low GHG intensity compared to the conventional production of hydrogen from fossil fuels(Zhang et al., 2017).

In addition, the electricity source and electrolysis technology are the same for all scenarios, while the difference is in CO_2 sources. Post-combustion capture is assumed for CO_2 at power plants and cement plants. CO_2 collected by wood power plants and the atmosphere was reported to have the minimum life cycle GHG emissions.

The number of co-products was different in all scenarios based on the technologies used for CO_2 capturing and CO_2 sources. The CO_2 sources and electricity supplied to the electrolysis are the main factors in reducing GHG emissions in the overall system. Higher life cycle GHG emissions reduction could be achieved with supply from PV in P2G with wind power as a source of electrolysis. It was reported that the GHG emission reduction system can always work even with the worst wind power act. When the CO_2 capture source was the wood power plant for the P2G, the highest GHG emissions reduction was observed. The lowest potential reduction was achieved if CO_2 was from a cement plant and heat from CO_2 capture of complex coal combustion. Generally, higher GHG emissions reductions at the capture source could be provided by good CO_2 sources determined by the amount of co-product produced and the emission reduction per unit of co-product. Overall, system expansion reported better results. These outcomes demonstrated that if the source of CO_2 was a fossil fuel, the employment of system expansion could permit a meaningful outcome. The total potential of P2M in reducing GHG is revealed by system expansion. Finally, a comparison between P2H and P2M revealed that P2H, as a replacement for hydrogen from fossil sources, could be more effective than natural gas, replaced by SNG as a vehicle fuel for GHG emission reduction.

In conclusion, many scenarios were investigated in the Power to Gas system, which demonstrates the differences in the environmental performance of P2G with renewable sources of hydrogen and Gas with the conventional processes. The previous studies illustrated that the electricity type and sources of CO_2 could have the most crucial role in the life cycle of GHG emissions in P2G. The results showed that only using system expansion can have meaningful results in the case of fossil sources of CO_2. The comparison of P2H and P2M illustrated in P2H, using hydrogen from fossil sources could contribute more to GHG emission reductions than SNG replacing natural gas as vehicle fuel. Additionally, it could be concluded that all power-to-gas pathways have lower global warming impacts than the conventional processes if 100% wind or solar electricity is used for electrolysis. The DRM process could experience the best environmental benefit if all the power to gas pathways uses the same amount of wind electricity. As CO_2 is crucial for environmental performance, power-to-gas pathways could achieve lower global warming impacts if CO_2 from the coal power plant is captured and not emitted into the air.

Furthermore, CSI technology has lower potential environmental impacts than the MEA and UNO MK3 for capturing CO_2. It is concluded that PtG can have lower environmental impacts than conventional processes when the CO_2 from a coal fire plant is captured, which is otherwise emitted. If not, the SNG process shows higher global warming impacts than conventional natural gas. Finally, implementing CCS can tremendously contribute to low-carbon electricity mixes and industrial production. The studies concluded that P2M with SOEC electrolysis technology shows the less environmental impact and is more environmentally friendly for the energy scenarios. Finally, for the cement as CO_2 sources scenario, P2M with PEM electrolyzer was the best choice. In contrast, for the renewable energy (RE) scenario, it was concluded that P2M with an alkaline electrolyzer was more environmentally friendly.

1.5 The knowledge gaps and objective of the study

Nowadays, countries have set ambitious GHG emission reduction targets. Methanation (P2M) might be an interesting solution for the energy transition as it can replace natural gas. The power-to-Gas process has been investigated from different aspects and in different scenarios. These investigations include the environmental performance and techno-economical assessment of PtG with the life cycle assessment method. Different technologies and alternatives have been defined to compare P2G with conventional technologies. However, there is still a need to do more case studies in different countries and cities based on natural resources with considering different resources and alternatives.

Quebec produces almost the largest hydroelectric in Canada which has the potential to study more about P2G and its environmental impacts. There is a need to develop case studies in Quebec, assuming different scenarios and technologies.

The main objective of this study is to assess the potential environmental impacts of power-to-gas in Quebec to produce methane from CO_2 captured (from cement plants) and hydrogen (from hydropower). Additionally, it compares the different sources of hydrogen as one of the most effective components in terms of environmental impact in this process. Moreover, finally, the results will be compared with the natural gas to investigate this methanation's advantages.

CHAPTER 2

METHODOLOGY

This study focuses on the life cycle assessment of PtG process, which can provide an extensive and flexible storage capacity for a long time, as described in the previous chapter. However, for the case of Quebec, this is not the main reason, because electricity mostly produced from hydropower, including many reservoirs. Reservoirs are excellent ways of storing energy (with less production and let the water accumulate in the reservoirs). Therefore, for the Quebec context, the storage capacity might not be a real advantage of PtG. With PtG process, the emissions like CO_2 can be covered and produce useful material to use in other reactions. Cleaner technologies and smart energy networks can help to end society's reliance on carbon-based fuels and emissions, which is the goal of using renewable energies and methods.

An LCA has been performed (based on the ISO 14040 and 14044 guidelines) on methane production from renewable electricity sources, which is called synthetic natural gas (SNG), and this is assumed to be the baseline scenario (using Quebec electricity and CO_2 emission from cement plant unit). Different scenarios compared to the baseline scenario, like natural gas and Alberta scenario, to compare the environmental aspects of each scenario and sensitivity analysis. Additionally, Data has been normalized and checked based on the impact assessment methods. Functional unit, system boundaries, scenarios, life cycle impact assessment (LCIA) methods, different scenarios, and comparison cases are specified below. OpenLCA as a software and ecoinvent database (version 3.1) as a source of background LCI data are used in this study.

2.1 Overview of life cycle assessment

2.1.1 Goal and scope definition

The first phase of each life cycle assessment, goal, and scope definition focus on the study's two key aspects: functional unit and system boundary. The study's goals, audiences, inclusion, and exclusion will be discussed in this section.

The system boundary, as a critical aspect of the goal and scope of the study, includes the processes, and all the inputs and outputs for each process are shown in Figure 2.1. This is all the considered cradle-to-gate study, which does not include the use-phase and post-use-phase like waste management. Because End-of-Life in not matter in this case study, as it assumed that gas burned and there is no waste. Therefore, the cut-off approach is not relevant to this study.

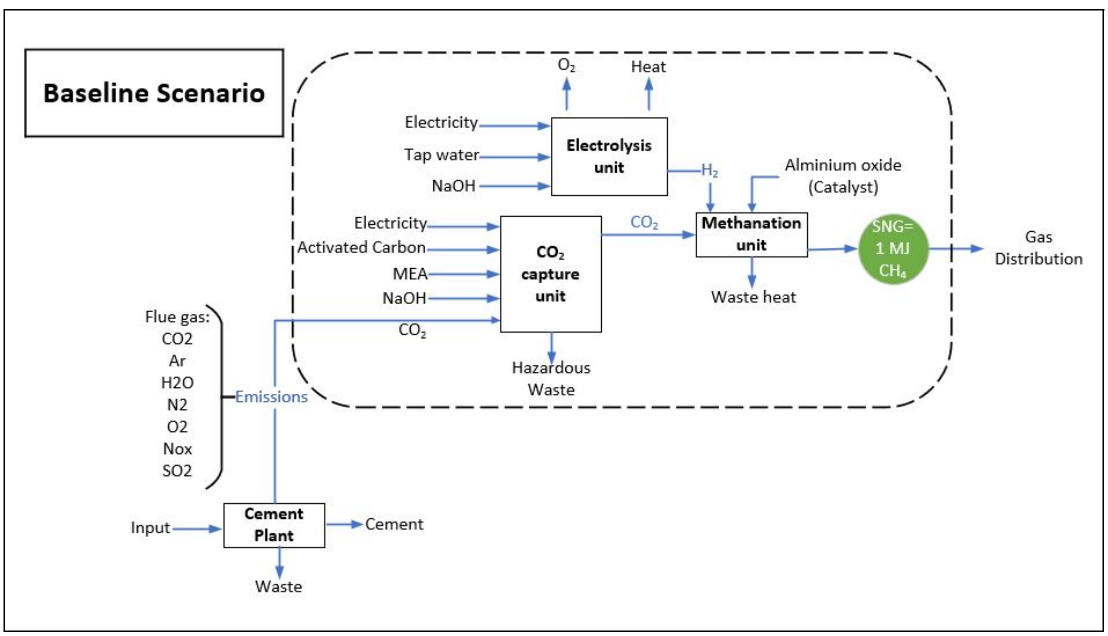


Figure 2.1 System boundary of studied Power-to-Gas

In life cycle assessment (LCA), a functional unit provides a measurable function upon which all the alternatives are evaluated. Here, the functional unit is defined as the production of 1MJ methane through power-to-gas in Quebec called synthetic natural gas (SNG).

It is assumed that the power-to-gas plant is built beside the CO_2 provider, which the impact of the CO_2 transportation and pipeline can be excluded based on the lack of data. Therefore, only the environmental assessment of the subject is evaluated. Electricity as a feedstock for the electrolysis unit is chosen from renewable energy sources (hydroelectricity) in Quebec.

Alkaline electrolyzer is chosen because it has higher efficiency and produces more hydrogen than Polymer Electrolyte Membrane (PEM) electrolysis. Data for the electrolysis units is according to the previous studies from Zhang et al., (2017).

The cement plant was chosen as a source of CO_2 in the system because it is more economical than capture from a power plant or atmosphere. Flue gas contains CO_2, which is the emission of the cement plant. Carbon dioxide from the flu gas should be captured, and after purification, it can be used as a source of CO_2 in the system. Therefore, the upstream processes in the cement plant were excluded and only the waste and treatment of the waste and produced CO_2 were included in this study. CO_2 captured data in this study is based on Saunier et al. (2019) and includes CO_2 captured from cement production. MEA (Amine Solvent) technology is chosen for the capturing of CO_2.

This case study compares the P2G system to conventional natural gas. For comparison, the environmental impacts of the two system and sensitivity analysis is implemented based on different source of electricity, Quebec and Alberta.

In order to achieve the objectives of this research, summarized details are as follow in the Table 2.1 and for each unit process, separately.

Table 2.1 The process component details

Process Name	Coverage of process
Electrolysis	consumption of Quebec or Canada electricity, raw materials required for electrodes, electrolyte (for alkaline electrolysis only), materials required as a feedstock in operation
CO_2 capture	capture from cement production: all the activities related to CO_2 capture units, electricity and heat, Flue gas stream coming from the cement plant, solvent
Methanation	consumption of CO_2 and H_2, raw material for methanation reactor, Al-based catalyst

2.1.2 Life Cycle Inventory (LCI)

The system was modeled with the openLCA version 1.10.3 software, including the ecoinvent database. This database contains a life cycle inventory (LCI) of various environmental inputs (e.g., raw material, energy, water, and…) and outputs (e.g., emissions to air, water, and land) from raw material extraction, material processing, and electricity generation. Data and assumptions for the model were obtained from experimental data from both Zhang et al. (2017) and Saunier et al. (2019). Ecoinvent 3.4 LCI database provides LCI data (input and output) for thousands of processes, products, and associated supply chains in this study.

2.1.3 Electrolysis unit process

Electricity generated is based on a Quebec hydroelectricity source and low voltage electricity selected from the eco-invent data source. Quebec, in Canada, has the most extensive hydroelectricity facilities. About 94.7% of Quebec’s electricity is hydropower, based on Levasseur, Mercier-Blais, Prairie, Tremblay, & Turpin (2021). Around 79.99% is generated from Quebec province, 11.93% comes from Newfoundland and Labrador, and only 2.55% comes from other regions based on Levasseur et al., (2021).

Table 2.2 Produced hydrogen from electrolysis, alkaline electrolyzer
Taken from Zhang et al. (2017)

	Items	Amount for FU	Unit	LCI Data Source
Inputs	**water, deionized, from tap water, at the user**	0.27	kg	Ecoinvent dataset market for tap water
	electricity, low voltage	5.2	kWh	Ecoinvent dataset for low voltage electricity, Canada, Quebec
	sodium hydroxide, without water, in a 50% solution state	0.00006	kg	Ecoinvent dataset for sodium hydroxide, without water, in 50% solution state
Output	**hydrogen, gaseous, 350-700 bar, from alkaline electrolysis**	1	Nm3	-
	waste heat from electrolysis	0.07	kWh	-
	Emission to air	0.02	kg	-
	oxygen	0.35	kg	-

Alkaline Electrolyzer equipment is not considered in the study as data could not be found in the ecoinvent database. Moreover, the sensitivity analysis provided by the literature reviews shows that the electrolyzer size, lifetime, and equipment have much less influence on the impacts and conclusions, based on Zhang et al., (2017). In contrast, the operation data of the electrolyzer is important for the life cycle assessment and is considered in this study.

For alkaline electrolysis, the LCI data based on the literature review is shown in Table 2.2

2.1.4 CO_2 capture and utilization in power-to-methane:

CO_2 can be supplied from different sources as a feedstock in the methanation unit. In this study, capturing CO_2 from cement production is chosen as it is more economical than capturing it from a power plant or atmosphere. Additionally, there is no thermal power plant in Quebec. Also, biogas is not chosen because for the moment, biogas carbon capture it is not too much industrialized and practical to assume biogas as a source of CO_2. Therefore, the best choice is the cement plant as a provider of CO_2 source, which is used here.

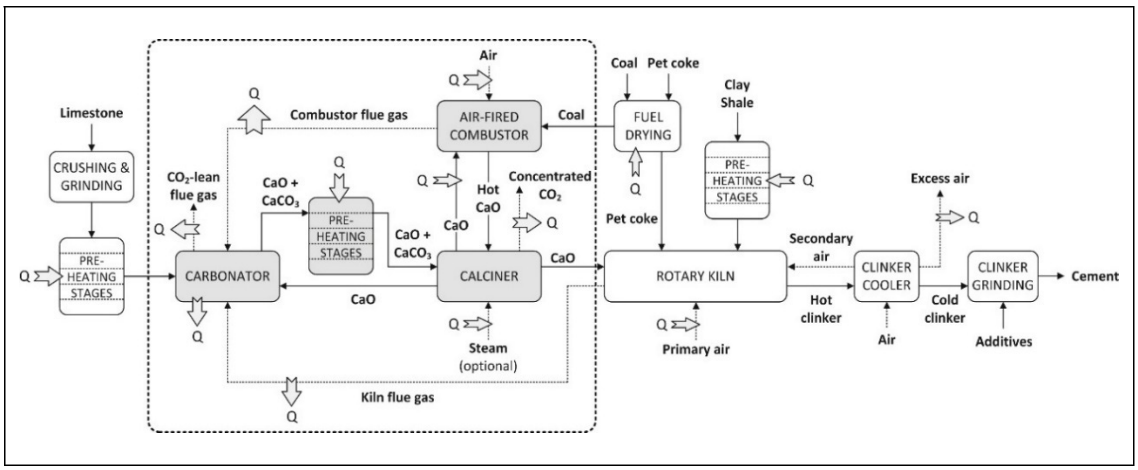


Figure 2.2 Process Upstream for CO_2 captured from cement production
Taken from Diego et al. (2016)

The upstream process of capturing CO_2 from cement production is shown in Figure 2.2 studied by Diego, Arias, & Abanades, (2016).

CO_2 as a part of emission is in the flu gas which system aimed to capture and purify it. In this study, the process of cement production was excluded, and only flue gas and its treatment were considered in the LCA of the PtG process.

Cement production and P2G plant were assumed in the same place, and inventory data for the CO_2 unit is according to Saunier et al. (2019).

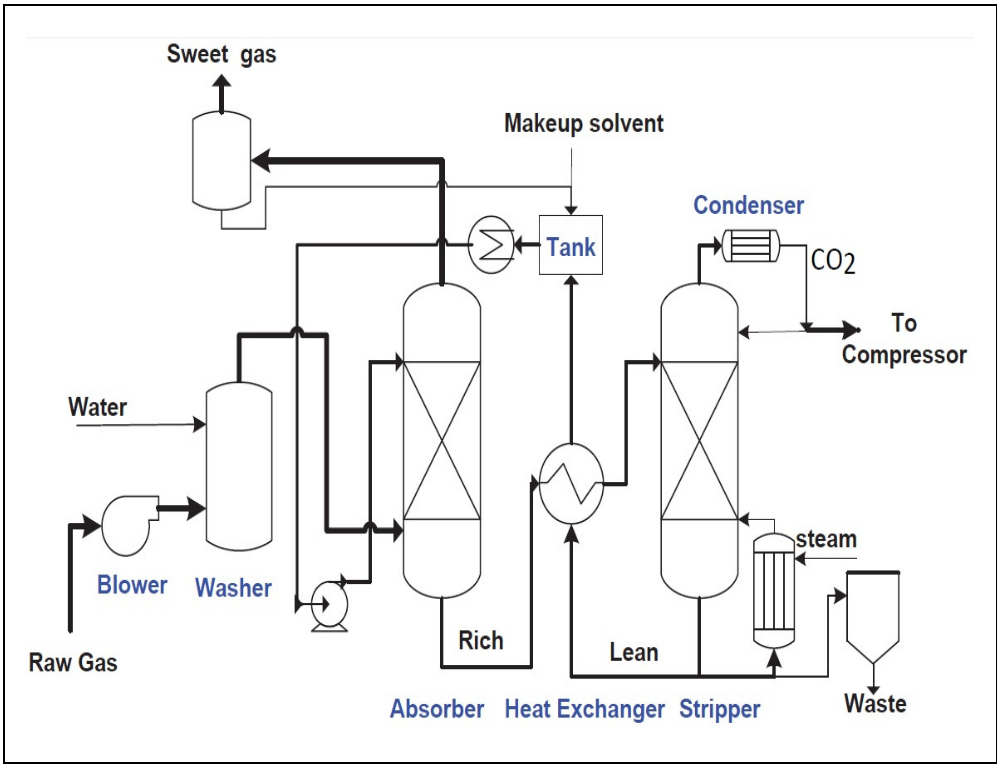


Figure 2.3 MEA CO_2 Capturing unit flowsheet
Taken from Roussanaly et al. (2013)

It is assumed that Amine solvent technology or Monoethanolamide (MEA) as a chemical amin solvent is used in the post-combustion application as a CO_2-capturing technology. MEA technology has an absorber, a stripper, a reboiler, pumps, and heat exchangers, as shown in Figure 2.3. MEA system is supposed to use steam already available at the power plant produced by the boiler to turbinate in electricity, thus reducing the plant's total electricity production. Steam input was modeled as an additional electricity consumption from the grid in the model (representing the non-produced electricity that will be produced elsewhere in the grid). Therefore, steam input is expressed in “electricity equivalent” in Table 2.4. Therefore, our model's electricity includes the electricity needed to produce steam and the electricity needed for running the system. Electricity sources used in the CO_2 model in OpenLCA were Quebec electricity in the case study.

As shown in Table 2.3, the composition of the flue gas stream is as follows:

Table 2.3 Flue gas characteristics
Taken from Saunier et al. (2019)

Composition	
CO_2	13.53%mol
Ar	0.82%mol
H_2O	15.17%mol
N_2	68.08%mol
O_2	2.4%mol
NOx	67ppm
SO_2	<10ppm
Conditions	
Temperature	57℃
Pressure	102kPa
Flow	74 091kmol/h

The primary data and assumption used for the LCI of the foreground system in MEA, are shown in Table 2.4. Steam in MEA technology is needed for generating electricity in the power plant. Assumptions have been made by CSI based on their literature to estimate this data.

Table 2.4 Primary data used for building the LCI of the foreground system.
MEA technology
Taken from Saunier et al. (2019)

Parameters/ Operation	**MEA**	**Comments**	**LCI Data source**
Chemical make-up (kg/tCO_2)	Activated carbon:0.075 NaOH:0.13 MEA:1.5 Water:0	-	NaOH: Ecoinvent database for NaOH, without water, in 50% solution state MEA : Ecoinvent database for MEA, Cutoff, U- GLO
Energy consumption: (kWh/tCO_2)	Electricity: 24.93 Steam: 194.8 ($3.69GJ/tCO_2$)	Hot water and steam are expressed in electricity equivalent.	Electricity: Ecoinvent database for market for electricity, medium voltage, cutoff, U-CA-QC
By-products	n/a		
On-site emissions	MEA degradation to air and water		
Waste to incineration (kg/tCO_2)	Activated carbon:0.075 MEA degradation products (HSS and polymers):1.485 NaOH(from reclaimer):0.13	-	Ecoinvent database for activated carbon, Granular, cutoff,U-GLO
	*Hazardous waste, for incineration(ROW) market for hazardous waste, for incineration/Alloc Rec, U		
Waste to wastewater (kg/tCO_2)	None	-	
	Process: wastewater, average(GLO) market for/Alloc Rec,U		

2.1.5 Methanation:

As mentioned before, in this study, H2 is provided from water electrolysis and CO_2 from cement production plant emission and after capturing and purifying. Methanation reaction is exothermic (Hoekman et al., 2010), with a heat production (-165Kj/mole) of input CO_2.

Table 2.5 Methanation unit process components

Items		Amount/FU (Producing 1MJ Methane)	Unit	LCA Data Source
Inputs	**Carbon Dioxide**	0.053	kg	Provided from CO_2 unit
	Hydrogen, not compressed	0.11498	Nm3	Provided from the electrolysis unit
	Al-based catalyst for methanation	0.000002	kg	Ecoinvent data source of market for aluminium oxide
Outputs	**Methane**	1	MJ	-
	Water	0.08623	kg	-
	Waste Heat	0.30354	MJ	-

The heat required for the input hydrogen and CO_2 is assumed to be met by the waste heat released from methanation. The reactor's cooling and energy for the compression of gas is not considered in this study, as there is no ecoinvent data for this specific study based on the study of Zhang et al., (2017). Additionally, because the contribution of the construction and installing the equipment is not considered in this study. The Al-based catalyst consists of 81% aluminum alloy by mass (Zhang et al., 2017). Due to limited data, this study does not consider catalyst manufacturing facilities, energy, treatment, and disposal of catalyst materials. The product gas from methanation is synthetic natural gas (SNG) which assumed to have equivalent composition and energy content as conventional natural Gas based on the study of Zhang et al., (2017).

Data for the methanation unit process are from Zhang et al. (2017) article, and ecoinvent processes are used in Table 2.5.

2.1.6 Life cycle Impact Assessment (LCIA)

This section aims to link the inventory data to environmental damage, and all the same inventory results should be collected in an impact category defined as a midpoint indicator. By multiplying the characterization factor by each inventory flow, the contribution to the midpoint category can be calculated. Results are based on the "IMPACTWolrd+ (Default_Recommended_Midpoint1.29)" method and "IMPACTWorld+ (Default_Recommended_Damage1.47)" method, which was implemented in OPENLCA software for this study. Currently, the IMPACWorld+ method is only developed and defined for these two specified impact categories (Human Health and Ecosystem quality), so this scenario compared impacts in two endpoint categories.

This method is the updates of the IMPACT 2002+, EDIP, and LUCAS methods. With this method, the LCIA profile can be presented into two viewpoints of impacts: 1. Midpoint impacts, and 2. Damage impacts. At the first step, all the inventory results with the same effects should be grouped into an impact category called the midpoint category (see Figure 2.4). There is midpoint indicator for each midpoint category. For characterize the contribution of each inventory flow, the characterization factor is needed to be multiplied by each inventory flow. The term midpoint can connect inventory results with damage. For example, global warming is a midpoint category in which greenhouse gas emissions represent by that. This method accounts for 30 midpoint indicators regrouped into 10-15 categories for better results. Each midpoint category is then allocated to one or more damage categories which shows the damage in different areas of protection. These damage for chosen methods are 1. Human health. 2. Ecosystem Quality. 3. Resources and ecosystem services (Jolliet et al., 2015).

It should be noted that this method contains two midpoint categories for climate change: the short term uses GWP100 and the long term, GTP100 (Bulle et al., 2019). Therefore, this method (the midpoint of this method) is used, as a new and under-development method, to calculate the Global warming and carbon footprint.

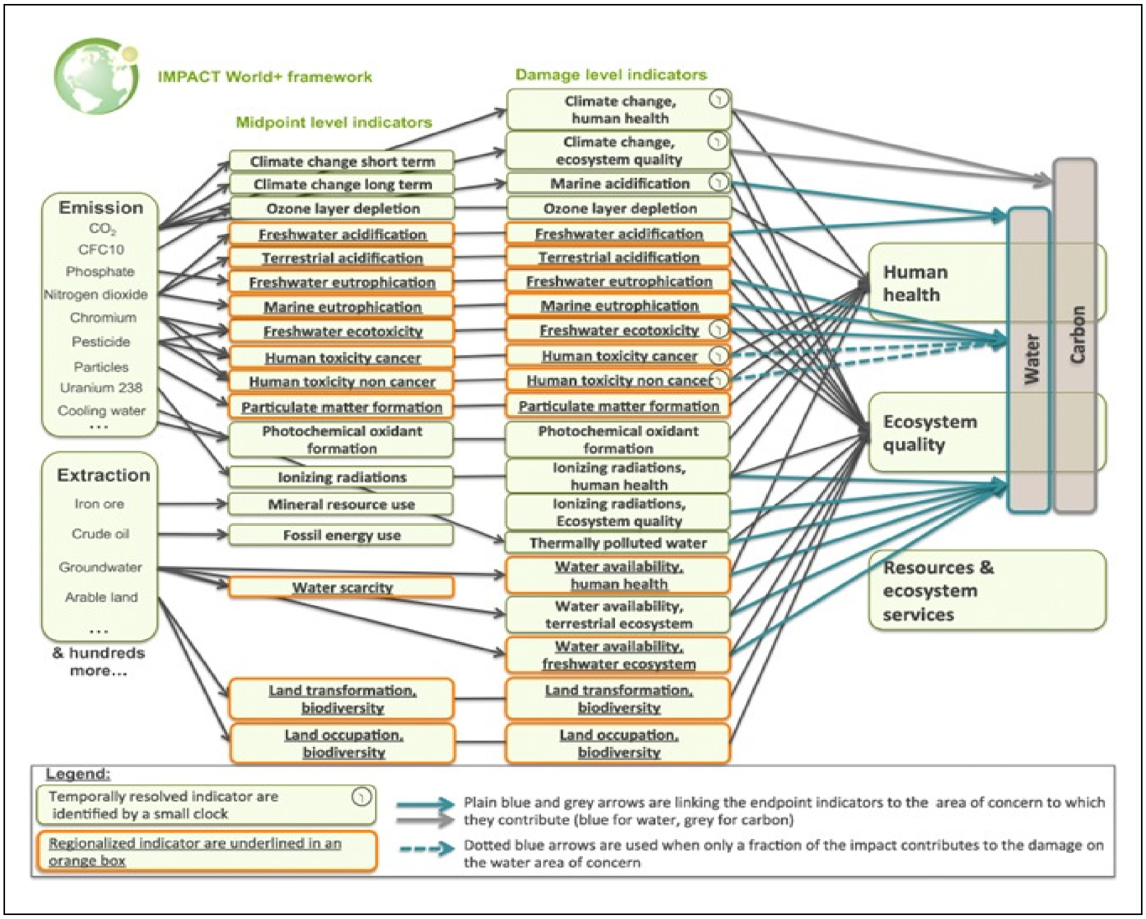


Figure 2.4 Impact world+ LCIA method framework
Taken from Bulle et al. (2019, p. 1656)

For example, Human health in this method is the accumulation of the damage category of climate change, Ozon layer depletion, human toxicity, cancer/non-cancer, particular matter formation, photochemical oxidant formation, Ionizing radiations, human health, water availability human health.

The accumulation of the midpoint indicators into 3 damages (endpoint) categories can help to better understand the results for decision-makers. The potential damage associated with climate change is measured in carbon dioxide equivalent (with the unit kg CO_2 eq.), an indicator of potential damage to life support systems from climate change.

2.2 Different scenarios

2.2.1 Comparative system: Baseline scenario V.S Natural Gas scenario

This section compared the life cycle assessment of the baseline scenario with conventional natural gas. The composition of natural gas in percentage is as follows based on the CIRAIG, (2020):

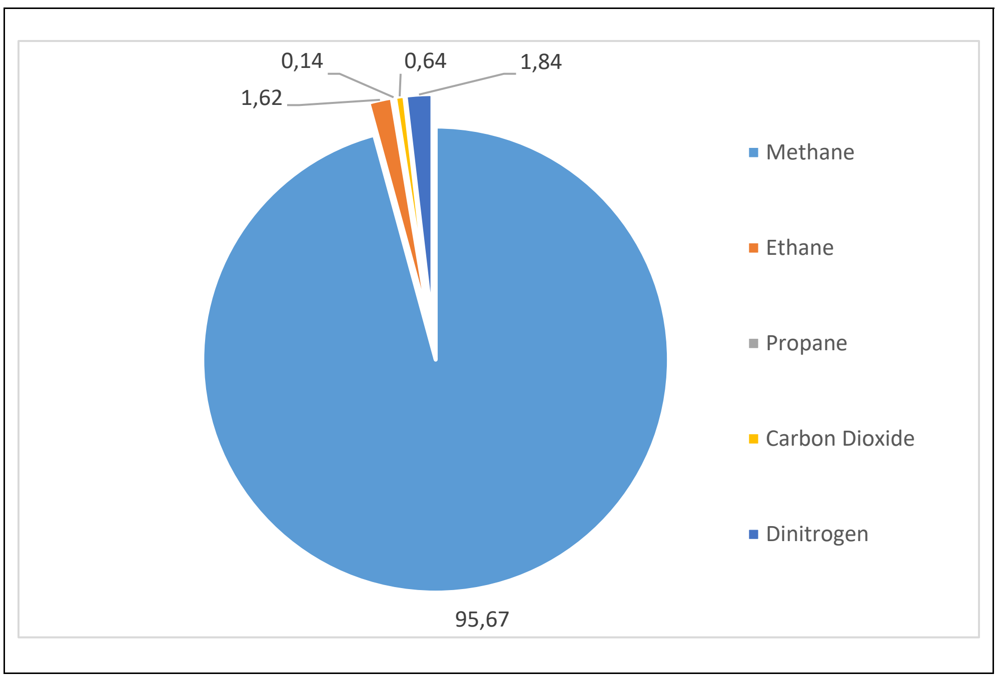


Figure 2.5 Natural gas composition (volume)
Taken from CIRAIG, (2020, p.59)

As around 95.67% of natural gas (see Figure 2.5) is methane, methane can replaced by natural gas in the system. More importantly, the methane produced from PtG process will be injected into the natural gas system. Therefore, the life cycle assessment comparison is based on methanation and conventional natural gas.

The reference data source for natural gas is chosen from ecoinvent database in OpenLCA software which is: market for natural gas, high pressure | natural gas, high pressure | Cutoff, U- CA-QC.

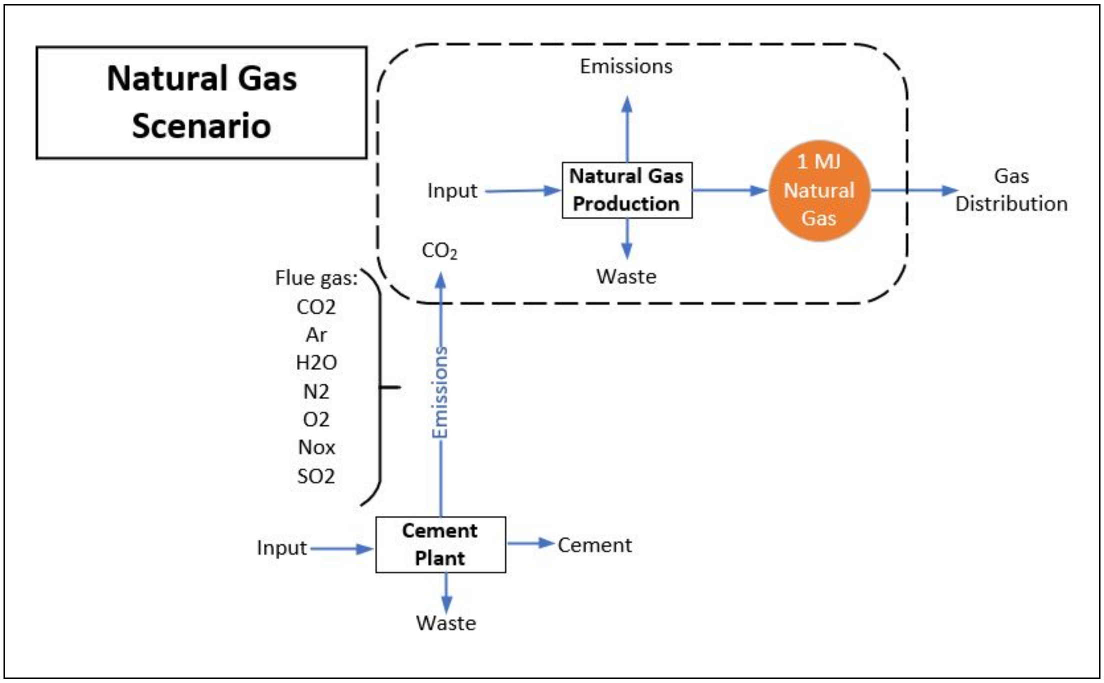


Figure 2.6 Natural Gas system

Figure 2.6 shows the comparative Natural gas system. To make the apple-to-apple and exact comparison with methanation process, it is necessary to find the amount of high-pressure natural gas heat in (MJ), which means heat value or calorific value. Heat value is the amount of heat released during fuel combustion. Based on the (CIRAIG, 2020) for the natural gas, the heat value or the calorific value is between 32.5 and 37.4 MJ/m^3. For Quebec province, 35.5MJ/m^3 is considered based on the International reference center on the life cycle of products, processes and services, (2020). This amount should be calculated for the 1MJ of natural gas to have the apple-to-apple comparison, as methane. Furthermore, methanation systems use CO_2 from the cement plant to produce methane. However, this amount of carbon dioxide is emitted to the air if natural gas is considered. Consequently, for the apples-to-apples comparison, the amount of CO_2 as an input in the methanation should be considered in the output (emission) of the natural gas system.

2.2.2 Sensitivity Analysis: Quebec scenario vs. Alberta scenario

Sensitivity analysis is done to test the power of the results and their sensitivity to data and models used. Either changing parameters or certain percentage of inputs can help to examine the results variation of the model. In this study, sensitivity analysis is done to show how different sources of electricity can affect the impacts and carbon footprint.

The life cycle assessment of methanation with Quebec electricity (baseline scenario) is compared with Alberta source of electricity which is Alberta scenario. While the electricity grid is based on the province, these scenarios are defined to compare the cleanest source of electricity in Canada with the Alberta sources, mostly fossil-based electricity. This comparison is made to evaluate the sensitivity analysis where the electricity source is changed.

Results are shown based on the normalized data. Because different midpoint categories are based on the different units. Therefore, comparison between these irrelevant data is not meaningful. To have a better interpretation normalization is needed. The results of the impact characterization are reported relative to total reference values or normalization values.

2.3 Scope and limitations of this study

Many scenarios could be studied for a better and more robust understanding of the results in Quebec context. All the experimental data and assumptions are from literature reviews. The assumption, scenarios, and scope that could vary from one study to another can be caused to the different LCA results. This variation may cause to be confusing, especially for non-experts. Therefore, trustable results from LCA study can be achieved when a large amount of data is available. Also, in all aspects, a comprehensive LCA should be assessed. If data collection is poor or insufficient, the results will not be trustable. Therefore, it would be more trustable if we could have our database from the experiment.

CHAPTER 3

RESULTS AND DISCUSSION

Based on the methodology and all the system boundary, functional unit, and inventory data, the life cycle impact assessment results are collected and explained in this chapter.

3.1 Life cycle assessment results of Baseline scenario (i.e., Quebec)

3.1.1 Results

Table 3.1 illustrate the results in the human health damage category for the baseline scenario, acquired by the IMPACTworld+ method in the endpoint categories. Based on this table, the most impact is assigned to "water availability, human health," which is 4.70E-06 (DALY). The total amount for human health would be 4.89E-06 (DALY).

Table 3.1 Human Health impact results -
Damage category- baseline scenario

Human Health		
Name	**Impact result**	**Unit**
Human toxicity non-cancer, long term	8.26E-09	DALY
Climate change, human health, long term	1.17E-07	DALY
Water availability, human health	4.70E-06	DALY
Climate change, human health, short term	3.83E-08	DALY
Human toxicity cancer, short term	7.43E-09	DALY
Particulate matter formation	1.35E-08	DALY
Human toxicity cancer, long term	2.74E-10	DALY
Ionizing radiation, human health	2.97E-10	DALY

Name	Impact result	Unit
Photochemical oxidant formation	3.14E-12	DALY
Human toxicity non-cancer, short term	3.55E-09	DALY
Ozone layer depletion	3.74E-12	DALY
Human Health	4.89E-06	DALY

Results for the ecosystem quality impact category for the baseline scenario is shown in Table 3.2 which the total amount would be 0.774883 (PDF.m2.yr). According to the below table, the most significant impacts in this category are assigned to the "Land transformation, Freshwater ecotoxicity, and land occupation," which are "0.34, 0.23, 0.09" PDF.m2.yr, respectively.

Table 3.2 Ecosystem Quality impact results –
Damage category- baseline scenario

Ecosystem Quality		
Name	**Impact result**	**Unit**
Marine acidification, long term	0.00592	PDF.m2.yr
Marine acidification, short term	0.00064	PDF.m2.yr
Water availability, terrestrial ecosystem	4.88E-07	PDF.m2.yr
Water availability, freshwater ecosystem	1.26E-05	PDF.m2.yr
Land occupation, biodiversity	0.09934	PDF.m2.yr
Land transformation, biodiversity	0.39487	PDF.m2.yr
Freshwater acidification	0.00017	PDF.m2.yr
Ionizing radiation, ecosystem quality	4.60E-11	PDF.m2.yr
Terrestrial acidification	0.00121	PDF.m2.yr
Marine eutrophication	3.29E-05	PDF.m2.yr

Name	Impact result	Unit
Climate change, ecosystem quality, long term	0.02565	PDF.m2.yr
Freshwater ecotoxicity, long term	0.23866	PDF.m2.yr
Freshwater ecotoxicity, short term	9.49E-05	PDF.m2.yr
Thermally polluted water	8.36E-08	PDF.m2.yr
Freshwater eutrophication	2.15E-06	PDF.m2.yr
Climate change, ecosystem quality, short term	0.00828	PDF.m2.yr
Ecosystem Quality	0.774883	PDF.m2.yr

Table 3.3 shows the total amount of greenhouse gas (GHG) emissions, defined as a carbon footprint. For the methanation with the Quebec electricity source, the carbon footprint for the climate change impact category would be as follows.

Table 3.3 Climate change impact- Baseline scenario

Climate change		
Climate change, long term	0.04443	kg CO_2 eq (long)
Climate change, short term	0.04682	kg CO_2 eq (short)

3.1.2 Contribution

Figure 3.1 shows the contribution of each unit process to climate change. The most contribution of climate change impacts in the system is assigned to the CO_2 capture unit as it is about two times higher (67.27%) than the electrolysis unit. The contribution amounts for the CO_2 capture unit and electrolysis unit are (i.e., 0.03 kg CO_2 eq) and (i.e., 0.01 kg CO_2 eq), respectively.

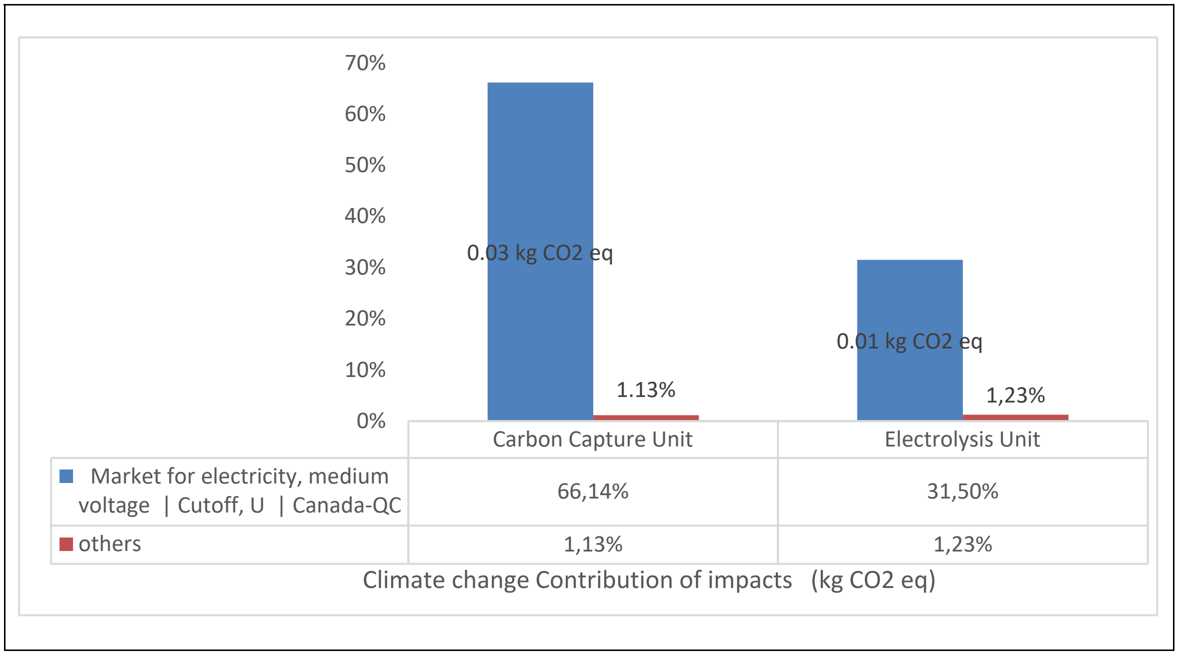


Figure 3.1 Contribution of climate change impact of the unit processes in the baseline scenario

It should be noted that the highest impact from both unit processes is because of the electricity in the system. The contribution of the electricity in CO_2 unit is more than 66%, and about 31.5% of impacts are assigned to the system's electricity for the electrolysis unit process.

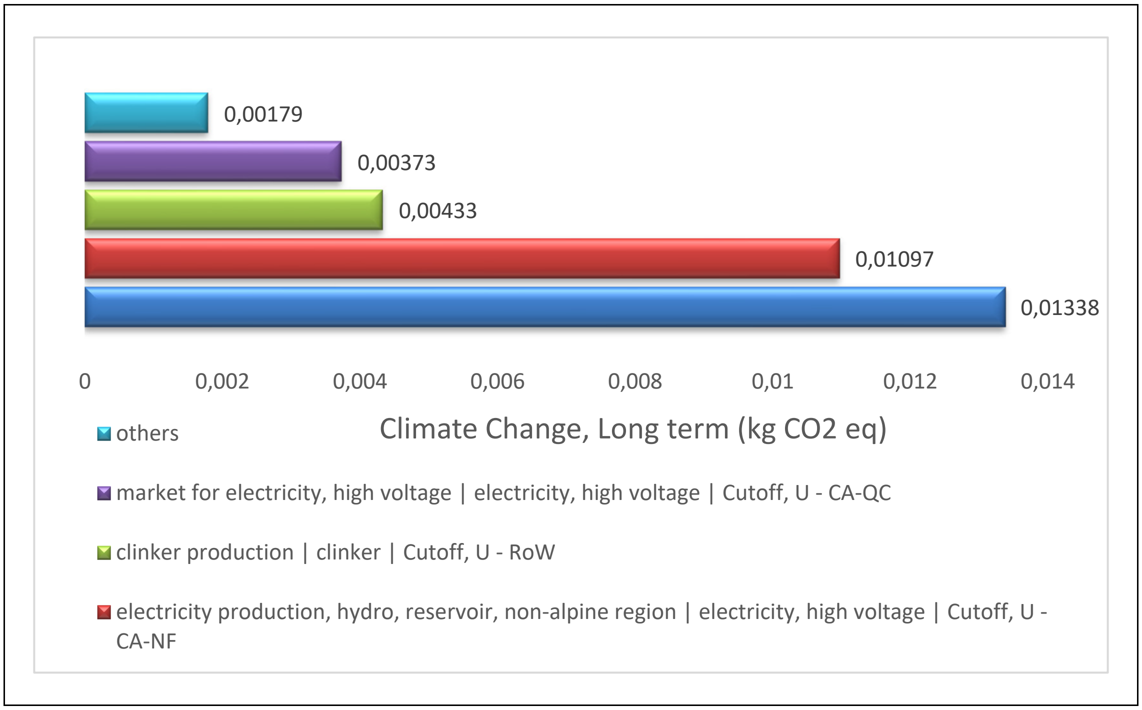


Figure 3.2 Contribution of the electricity in the climate change impact category (kg CO_2 eq)

Figure 3.2 shows detailed impacts on the climate change, long term in the baseline scenario. Electricity production, from the non-alpine region reservoir has the highest impacts on the climate change among the others which is 0.013 kg CO_2 eq.

Results from the baseline scenario illustrate that electricity has the most significant contribution in the impact of the baseline scenario and each unit process. Therefore, it is essential to consider electricity to make it more efficient and environmentally friendly. It can be practical to use more green electricity in the system to reduce the environmental impacts of the methanation on the baseline scenario.

3.2 Comparative system results- Baseline scenario vs. Natural Gas

Figure 3.3 compares the environmental impacts in the midpoint level for two different comparative systems: methanation with Quebec electricity source (baseline scenario) and natural gas as conventional gas. These results are based on the normalized data, which helps better interpret and understand the impacts in different systems compared to each other. As can be seen in Table 3.4 and Figure 3.3, natural gas generates the highest impacts in most midpoint categories, except for water scarcity, land transformation, freshwater ecotoxicity, human toxicity, and land occupation.

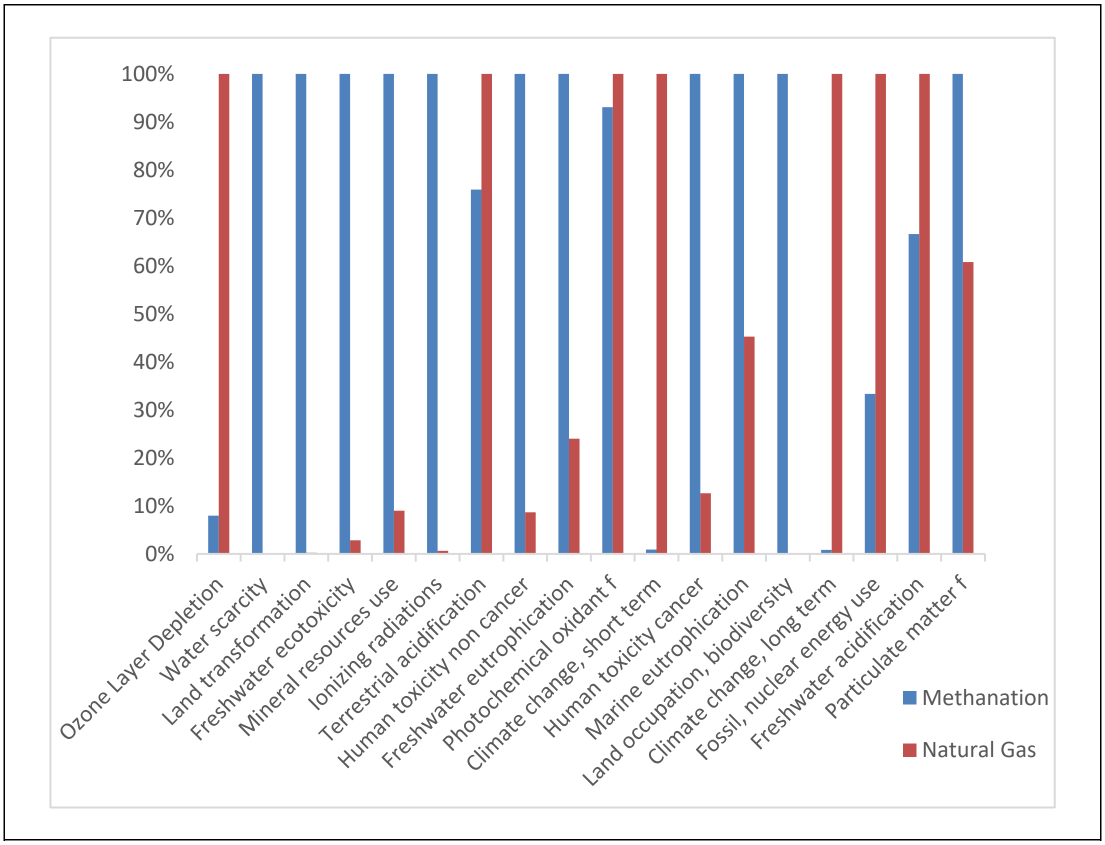


Figure 3.3 Comparison of normalized results for Midpoint impact category – Baseline scenario vs. Natural gas

Natural gas is estimated to have higher potential impacts than methanation with Quebec electricity in the following midpoint categories; Ozon layer depletion, terrestrial acidification, photochemical oxidant formation, climate change long and short term, fossil and nuclear energy use, freshwater acidification.

Table 3.4 Midpoint categories impact for baseline scenario and natural gas

Impact Name	Methanation	Natural Gas	Unit
Ozone Layer Depletion	1.75E-09	2.20E-08	kg CFC-11 eq
Water scarcity	1.70697	0.00059	m3 world-eq
Land transformation, biodiversity	0.00156	3.69E-06	m2 arable land eq
Freshwater ecotoxicity	424.18167	11.95715	CTUe
Mineral resources use	0.00256	0.00023	kg deprived
Ionizing radiations	1.41574	0.0089	Bq C-14 eq
Terrestrial acidification	4.04E-10	5.32E-10	kg SO2 eq
Human toxicity non cancer	7.65E-09	6.61E-10	CTUh
Freshwater eutrophication	5.99E-08	1.44E-08	kg PO4 P-lim eq
Photochemical oxidant formation	8.16E-05	8.77E-05	kg NMVOC eq
Climate change, short term	0.04682	5.31772	kg CO_2 eq (short)
Human toxicity cancer	3.10E-09	3.92E-10	CTUh
Marine eutrophication	1.84E-06	8.35E-07	kg N N-lim eq
Land occupation, biodiversity	0.14178	1.15E-05	m2 arable land eq .yr
Climate change, long term	0.04443	5.31287	kg CO_2 eq (long)
Fossil and nuclear energy use	0.33214	0.99634	MJ deprived
Freshwater acidification	5.73E-16	8.61E-16	kg SO2 eq
Particulate matter formation	1.13E-05	6.86E-06	kg PM2.5 eq

Based on the selected impact method in OpenLCA software, 3 different impact categories can be compared in this comparative system. By allocating one or more midpoint categories to one or more damage categories, like human health or ecosystem, the endpoint categories or damage categories results can be achieved. Figure 3.4 shows the damage categories with a comparison between the baseline scenario and natural gas. As can be seen, the impact of natural gas in all damage categories is higher than the baseline scenario.

Based on Figure 3.4, for example, a system with the highest environmental impacts was assigned a value of 100%. In the climate change impact category (long term and short term) for the natural gas scenario, results are reported with the highest environmental impact (100%). In comparison, the impact for the methanation is approximately 8%. Climate change or GHG emission impact for natural gas is (5.31287kg CO_2 eq (long)) while for the methanation, this number is calculated (as 0.04443kg CO_2 eq (long)).

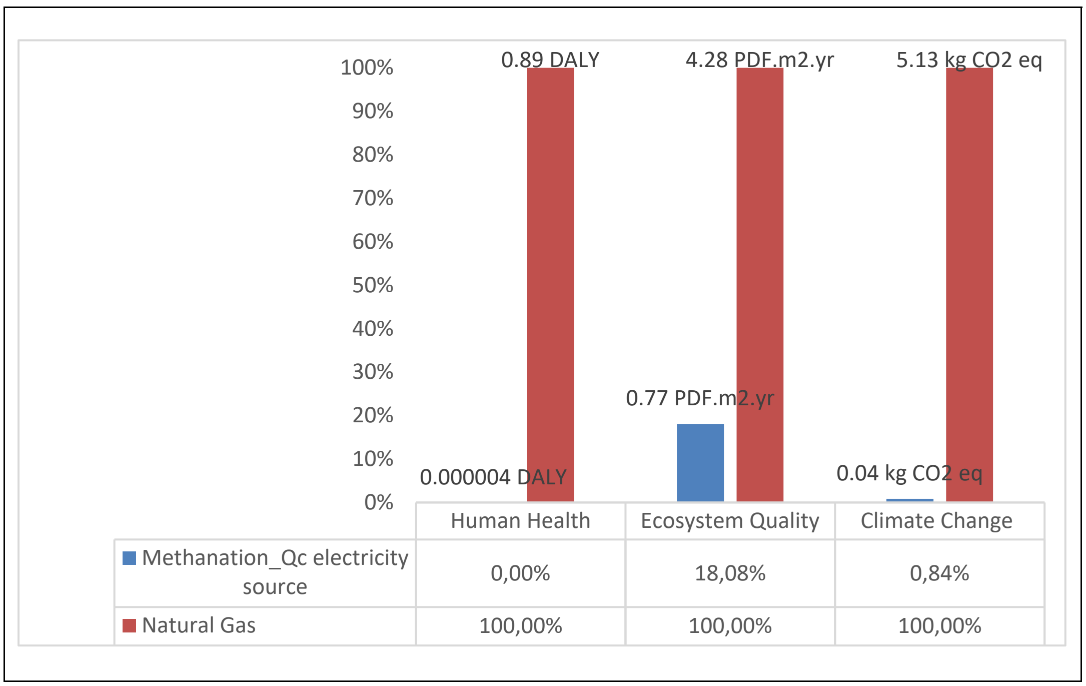


Figure 3.4 Impact categories based on the IMPACT World+ method
(Methanation Quebec electricity vs. natural Gas)

Figure 3.5 shows more than 60% of the impacts for the natural gas is because of the Alberta source of natural gas and about 21% of the impacts is assigned to the pipelines from the Alberta to Quebec. Transportation contributes to the impact about 12% which cause higher impacts for the natural gas compared with the methane from the PtG system.

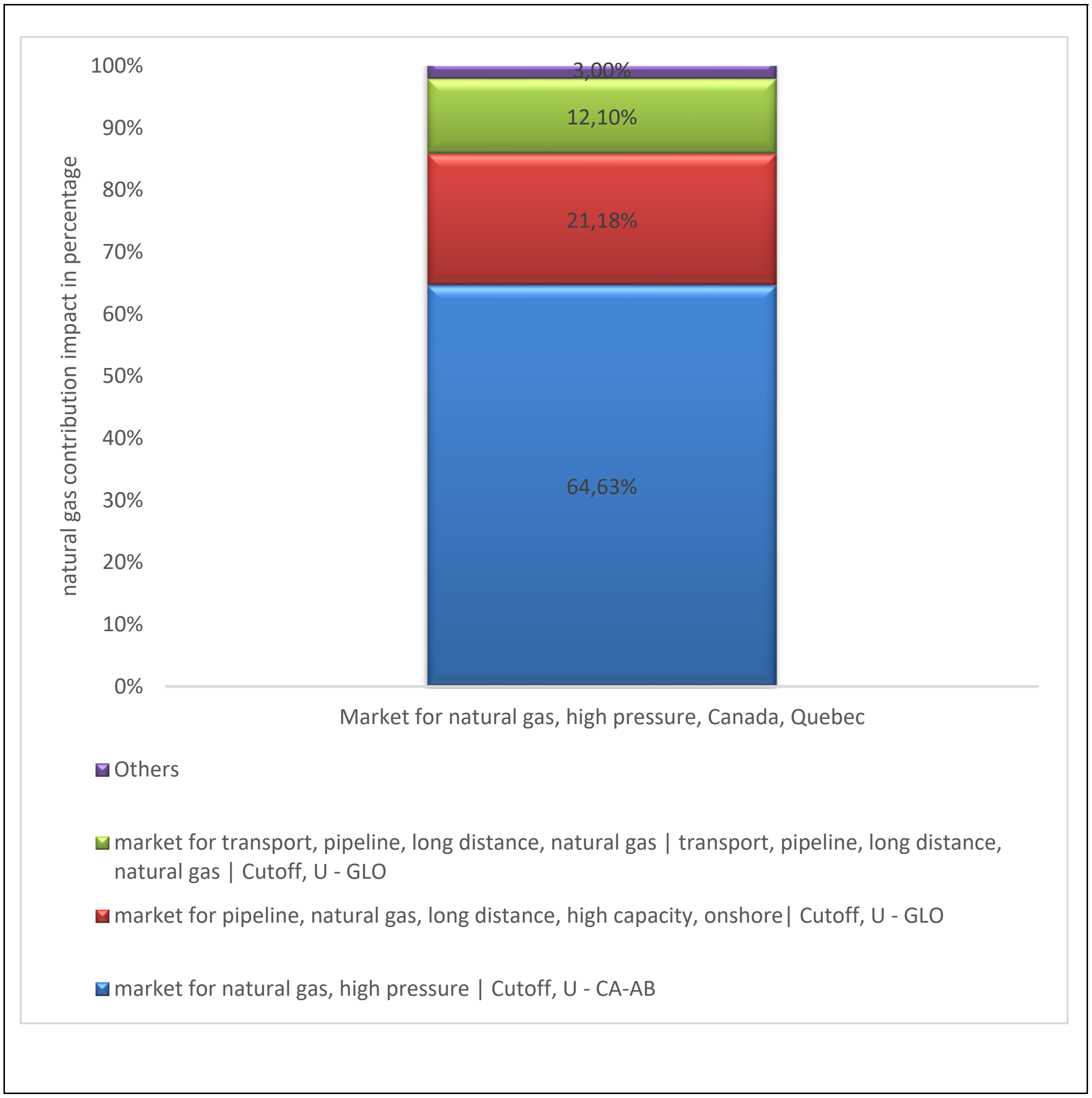


Figure 3.5 Natural Gas contribution percentages in climate change, long term

3.2.1 Results and discussion

Methanation with Quebec electricity source (Baseline scenario) is compared with the natural gas in the comparative system. Firstly, produced methane with the PtG system can be injected into the natural gas system. Moreover, natural gas can be replaced with methane as more than 90% of natural gas is methane which makes them replaceable. Finally, results are obtained based on comparing 1Mj of methane with 1Mj of natural gas.

In all the impact categories, natural gas shows the highest impact, as seen in Figure 3.3 and Figure 3.4. For example, the ecosystem quality category for natural gas has 4 times higher impact than the methanation system which is 4.28 (PDF.m2.yr) and for the methanation is 0.77 (PDF.m2.yr). The climate change for the methanation is 0.04 (kg CO_2 eq), while for the natural gas would be 5.13 (kg CO_2 eq). Based on the data from ecoinvent (Figure 2.4), more than 60% of the impacts from natural gas is because of the natural gas source from Alberta which is mostly from conventional power plant and hard-coal and oil which is not environmentally friendly and cause too much impact on different area of protection. Moreover, pipeline and transport system have a significant contribution on the climate change impacts.

Meanwhile, producing methane from PtG system, is more environmentally friendly as it uses the CO_2 emitted from cement plant which would be emitted otherwise. Therefore, it can cause lower environmental impacts and global warming impacts than the conventional processes. Additionally, methane produced from PtG system, uses hydropower electricity from Quebec source of electricity. Hydropower -as a largest source of renewable energy and low-carbon electricity source based on Levasseur, Mercier-Blais, Prairie, Tremblay, & Turpin, (2021)- is used in the baseline scenario. This source is not lead to GHG emission while producing electricity from fossil fuel combustion causes the GHG emission and global warming, directly.

3.3 Sensitivity Analysis: Quebec scenario vs. Alberta scenario

A sensitivity analysis is calculated with considering different sources of electricity, to understand which system is environmentally preferable for each region and what should be considered in each province more. Our baseline scenario (use Quebec electricity) is compared with the methanation with the Alberta electricity sources (AB Scenario), which is mostly from fossil fuels, including coal and natural gas.

Figure 3.6 compares different damage categories for the Quebec scenario (baseline scenario) and Alberta scenario. As illustrated, PtG with Alberta electricity shows significant impacts on human health, ecosystem quality and climate change. The GHG emission or carbon footprint in the PtG with Alberta electricity is 5 times higher than the baseline scenario. Carbon footprint in Alberta scenario would be 3.63 (kg CO_2 eq) while in Quebec scenario is 0.09 (kg CO_2 eq).

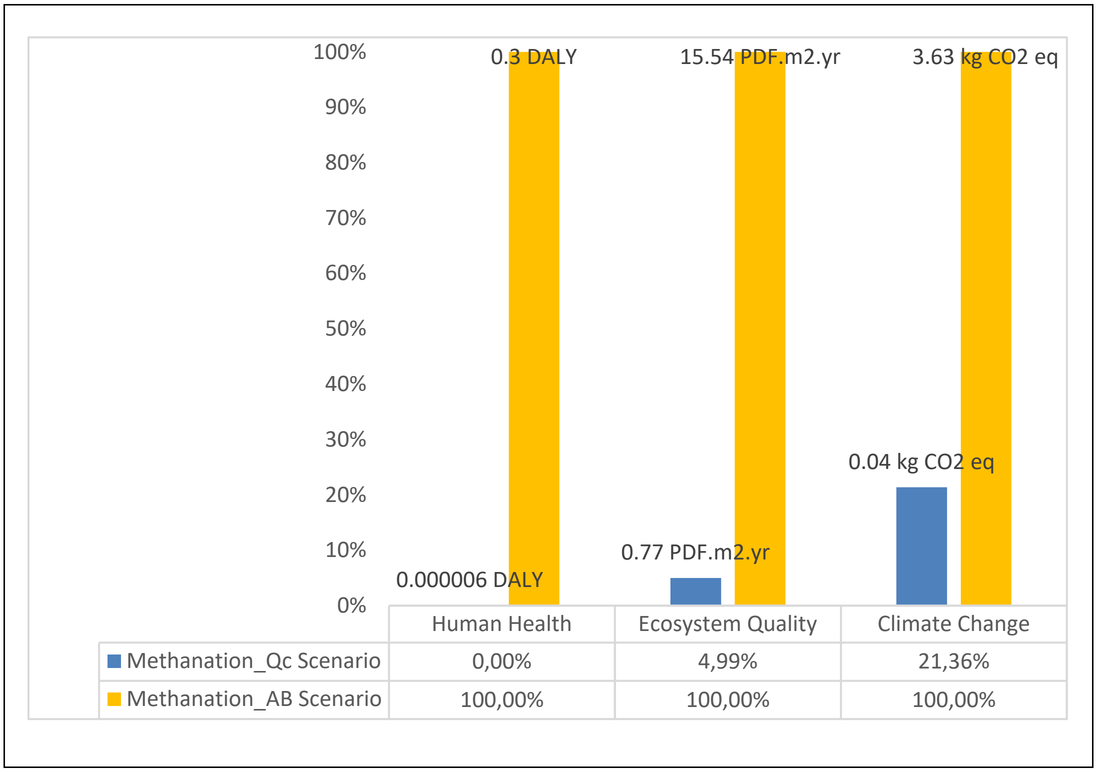


Figure 3.6 Impact categories with IMPACT World+ method
(Quebec Scenario vs. AB Scenario)

Table 3.5 and Table 3.6 shows detailed results data for both scenarios in different impact categories, separately.

Table 3.5 Human health impact results for both Quebec scenario
and Alberta Scenario

Human Health	**Quebec scenario**	**Alberta Scenario**	**Unit**
Human toxicity non-cancer, long term	8.26E-09	2.86E-07	DALY
Climate change, human health, long term	1.17E-07	0.26973	DALY
Water availability, human health	4.70E-06	0.02928	DALY

Human Health	Quebec scenario	Alberta Scenario	Unit
Climate change, human health, short term	3.83E-08	5.11E-06	DALY
Human toxicity cancer, short term	7.43E-09	0.00011	DALY
Particulate matter formation	1.35E-08	1.77E-06	DALY
Human toxicity cancer, long term	2.74E-10	4.59E-07	DALY
Ionizing radiation, human health	2.97E-10	0.00083	DALY
Photochemical oxidant formation	3.14E-12	0.00731	DALY
Human toxicity non-cancer, short term	3.55E-09	1.49E-06	DALY
Ozone layer depletion	3.74E-12	1.99E-07	DALY
Human Health total	4.89E-06	3.07E-01	DALY

Table 3.6 Ecosystem quality impact results for both Quebec scenario and Alberta scenario

Ecosystem Quality	Quebec scenario	Alberta scenario	Unit
Marine acidification, long term	0.00592	0.01411	PDF.m2.yr
Marine acidification, short term	0.00064	4.02E-07	PDF.m2.yr
Water availability, terrestrial ecosystem	4.88E-07	1.27E-11	PDF.m2.yr
Water availability, freshwater ecosystem	1.26E-05	0.08936	PDF.m2.yr
Land occupation, biodiversity	0.09934	0.00076	PDF.m2.yr
Land transformation, biodiversity	0.39487	1.12255	PDF.m2.yr
Freshwater acidification	0.00017	1.28E-08	PDF.m2.yr
Ionizing radiation, ecosystem quality	4.60E-11	13.99073	PDF.m2.yr

Ecosystem Quality	Quebec scenario	Alberta scenario	Unit
Terrestrial acidification	0.00121	1.41E-10	PDF.m2.yr
Marine eutrophication	3.29E-05	0.00241	PDF.m2.yr
Climate change, ecosystem quality, long term	0.02565	3.81E-06	PDF.m2.yr
Freshwater ecotoxicity, long term	0.23866	1.28E-10	PDF.m2.yr
Freshwater ecotoxicity, short term	9.49E-05	2.24E-07	PDF.m2.yr
Thermally polluted water	8.36E-08	7.52E-06	PDF.m2.yr
Freshwater eutrophication	2.15E-06	9.85E-11	PDF.m2.yr
Climate change, ecosystem quality, short term	0.00828	0.32261	PDF.m2.yr
Ecosystem Quality total	0.774883096	15.54254196	PDF.m2.yr

Figure 3.7 shows the contribution of climate change impacts on each unit among Alberta scenarios. CO_2 capture unit shows the highest impact contribution in climate change than the electrolysis unit. Around 66.5% of the impacts caused by CO_2 unit and only 32% of the impacts assigned to the electrolysis unit. Among this, the biggest impact is caused by the electricity source produced from lignite and coal in Alberta which is about 80% of the total contribution. Less than 10% of the electricity is produced by renewable sources of energy, in Alberta province. Climate change impact caused by lignite and coal is about 1.42 (kg CO_2 eq), totally in both unit processes.

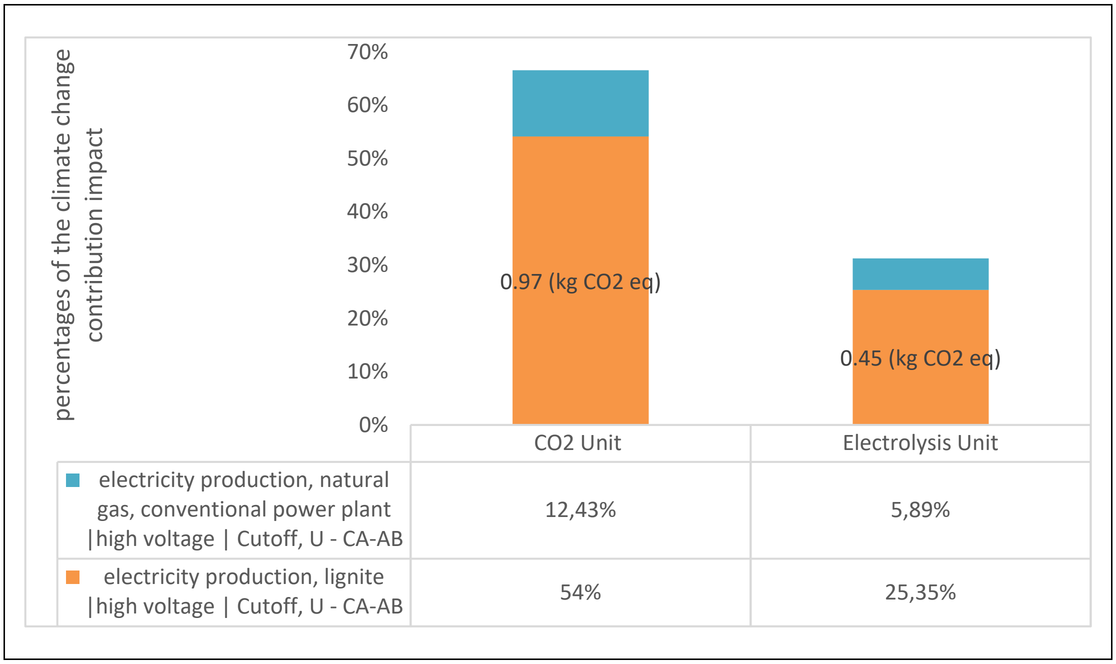


Figure 3.7 Climate change impact contribution for AB scenario

As a result, by changing the source of electricity from Quebec to Alberta, it can be seen that impacts on human health, ecosystem quality, and climate change become higher. Therefore, electricity is the most contributor to the impacts, which should be considered by using more clean electricity like hydropower instead of electricity from coal or lignite which cause too many impacts on a different area of protection. In addition, using less electricity among system can help increase the system's efficiency in terms of the environmental aspects. This solution can lead to less impact on climate change, human health, or ecosystem quality.

CONCLUSION

This study analyzes the life cycle assessment of power to gas or methanation- a baseline scenario which is the methanation with Quebec electricity for understanding the hotspots of this system and its different impacts on the environment. This system then compared with the conventional natural gas system as this methane should be injected to the natural gas system and then distribute. Besides comparison, sensitivity analysis is accessed based on different electricity sources from different provinces, Quebec, and Alberta to check electricity source as the main contributor in the climate change and how it can affect the system and global warming if provinces is changed.

Methane produced from PtG process (SNG) is synthesized from conversion of CO_2 and hydrogen. CO_2 is captured from cement plant emission and after purification, it was used among the system. Electricity is supplied by Quebec electricity source which is mostly hydropower electricity. Human health and ecosystem quality for the baseline scenario are 4.89E-06 (DALY) and 0.77 (PDF.m2.yr), respectively. In addition, GHG emission for the baseline scenario is calculated as 0.04 (kg CO_2 eq). The contribution of the CO2 unit in climate change impacts should be noted 2 times higher than the electrolysis unit which are 67% and 33%, respectively. The most contributor to climate change was electricity production, a non-alpine region from Quebec. Comparison of 1Mj of natural gas with 1Mj of SNG is shown higher impacts for human health, ecosystem quality and climate change in natural gas system. The ecosystem quality category for natural gas has 4 times higher impact than the SNG system, which is 4.28 (PDF.m2.yr), while the SNG is 0.77 (PDF.m2.yr). Human health for the natural gas is calculated 0.89 (DALY). The climate change for the methanation is 0.04 (kg CO_2 eq), while for the natural gas would be 5.13 (kg CO_2 eq). More than 60% of the impacts on the climate change for the natural gas is caused by the Alberta source of electricity, which is mostly from fossil fuels and coal and oil. Pipelines and transport system also play a pivotal role in the impacts of natural gas system on a different area of protection like human health, ecosystem quality and climate change. Therefore, SNG system is more environmentally friendly than the natural gas as renewable sources of electricity are used for its production. Also, CO_2 from cement plants is used for producing SNG, which is otherwise emitted. Natural gas is reported to have 5 times higher carbon footprint than the SNG, which cause severe global warming than the SNG.

Sensitivity analysis is done for producing SNG from different sources of electricity and it is concluded that Quebec scenario of producing methane is more environmentally friendly. While results from Alberta scenario shows higher impacts in all areas of protection. Human health, ecosystem quality and climate change is reported 0.3 (DALY), 15.54 (PDF.m2.yr) and 3.63 (kg CO_2 eq), respectively. Climate change impact in Alberta scenario is 5 times higher than this impact category for Quebec scenario. Therefore, with changing location for producing SNG from Quebec to Alberta, more global warming impacts and GHG emission can be seen. Because most of the contribution in the impacts in both CO_2 and electrolysis unit processes is caused by electricity. While Alberta electricity is based on the coal, lignite and fossil fuels which can cause too many impacts on the different damage categories. Additionally, CO_2 unit needs more consideration as it contributes to the impacts 2 times more than the electrolysis unit in both scenarios and the most contributor in this unit process is electricity in all scenarios.

Overall, PtG system is a promising technology to decease dependency on the fossil fuels. Producing SNG with renewable source of energy in Quebec province has numerous advantages. Because the highest contributor in the impacts in all unit processes is electricity. Therefore, more clean electricity cause more clean and green processes. Also, there is already infrastructure and reservoir in Quebec for electricity and there is no need to use pipeline or transportation system which causes increase GHG emission. Also, using CO_2 from emission of cement plant can help to decrease the impacts in different categories, in Quebec scenario.

RECOMMENDATIONS

Methanation is essential as they can replace and injected to the natural gas system. Its circular economy and recycling viewpoint make it very important to study from different aspects.

This study does not have possibility of using experimental, actual, and exact amount of data. Assumption for this study comes from literature reviews while this study would be stronger if data comes from the experiment or actual data. For example, data for gas make up from cement plant, or data for electrolysis unit.

In both provinces, Quebec, and Alberta, we should more pay attention to the electricity and work on it. As electricity is the most contributor in the PtG system and methanation unit processes, there should be more study on the electricity. Especially, this subject is more important when it comes to the Alberta and fossil-based electricity. Furthermore, CO_2 unit contribution in impacts is 2 times higher than the electrolysis unit process. There should be more study on this unit process to decrease the amount of electricity and consequently, impacts on climate change and all impact categories.

Life cycle assessment of power to gas can be done concerning other types of electrolysers or different sources of CO_2 in the Quebec province.

Although many scenarios are explored in this field, a comprehensive life cycle assessment must be done to compare power to gas (methanation) with Quebec's electricity source with natural gas. Our analysis only focuses on the environmental aspects, while other social and economic aspects should be considered in the comparison.

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