



## **UTILIZATION OF CO<sub>2</sub> AS A FEEDSTOCK IN THE CHEMICAL INDUSTRY**

Lappeenranta–Lahti University of Technology LUT

Bachelor's thesis in Chemical Engineering

2025

Elias Seppälä

Examiner: D.Sc. Abayneh Demesa

## TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin insinööritieteiden tiedekunta

Kemiantekniikka

Elias Seppälä

### **Hiilidioksidin käyttäminen raaka-aineena kemianteollisuudessa**

Kemiantekniikan kandidaatintyö

2025

39 sivua, 6 kuvaa ja 1 liite

Tarkastaja: Tutkijatohtori Abayneh Demesa

Avainsanat: hiilidioksidin talteenotto, vihreä vety, vihreä urea, käänteinen veden kaasutusreaktio, Fischer-Tropsch -menetelmä

Hiilidioksidin hyödyntäminen kemianteollisuuden raaka-aineena tarjoaa mahdollisuuden arvokkaiden polttoaineiden ja kemikaalien tuotantoon vähentäen samalla kasvihuonekaasupäästöjä. Tähän mahdollisuuteen liittyy kuitenkin haasteita liittyen nykyisiin teknologioihin sekä prosessien taloudellisuuteen. Teknologian jatkuva kehitys ovat kuitenkin olennaisessa asemassa näiden haasteiden ratkaisemisessa.

Tämä työ käsittelee hiilidioksidin käyttöä kemianteollisuuden kokonaisvaltaisella tasolla ja keskittyy siihen, miten monimutkaisia prosesseja voidaan yhdistää suuremmiksi kokonaisuuksiksi. Käsiteltäviä prosesseja ovat erilaisten polttoaineiden ja joidenkin kemikaalien valmistus sekä hiilidioksidin talteenotto menetelmät, jotka liittyvät olennaisesti muihin soveluksiin. Työ suoritettiin kirjallisuuskatsauksena.

Tutkimuksessa todettiin, että hiilidioksidin käytöllä raaka-aineena kemianteollisuudessa on merkittävä potentiaali sekä taloudellisesti että kasvihuonekaasupäästöjen vähentämisen osalta. Menetelmiä on jo paljon olemassa, mutta niiden optimointi teolliseen mittakaavaan vaatii lisää kehitystä esimerkiksi katalyyttien osalta. Koordinoitu kansainvälinen yhteistyö niin teollisuuden kuin tutkimuksen ja kehityksen saralla on avainasemassa, mitä tulee laajamittaisen käyttöönoton toteuttamiseen.

## ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Engineering Sciences

Chemical Engineering

Elias Seppälä

## UTILIZATION OF CO<sub>2</sub> AS A FEEDSTOCK IN THE CHEMICAL INDUSTRY

Bachelor's thesis

2025

39 pages, 6 figures and 1 appendix

Examiner: D.Sc. Abayneh Demesa

Keywords: CO<sub>2</sub> reclaiming, green hydrogen, green urea, reverse water gas shift reaction, Fischer-Tropsch synthesis

The utilization of carbon dioxide as a feedstock in the chemical industry offers the possibility to produce valuable fuels and chemicals while reducing greenhouse gas emissions. However, challenges remain regarding current technologies and the economic viabilities of the processes. Continuous technological development is essential to overcome these challenges.

This study explores the utilization of carbon dioxide as a feedstock in the chemical industry, focusing on how complex processes can be integrated into larger production chains. The processes discussed include the production of various fuels and chemicals as well as carbon capture methods, which are closely linked to these processes. The study was carried out as a literature review.

The findings indicate that the utilization of carbon dioxide as a feedstock in the chemical industry has significant economic potential in addition to its environmental benefits in reducing greenhouse gas emissions. While various methods already exist, further research and development are needed, especially in new catalyst development and process optimization for industrial scale implementation. In this context, coordinated international cooperation in both research and industry is essential to enable large-scale deployment.

## Abbreviations

CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CLAS	Chemical Looping Ammonia Synthesis
CLC	Chemical Looping Combustion
CTL	Coal-to-Liquid
FT	Fischer-Tropsch Synthesis
GHG	Greenhouse Gas
GTL	Gas-to-Liquid
LCA	Life Cycle Assessment
LPG	Liquified Petroleum Gas
MTG	Methanol to Gasoline
MTK	Methanol to Kerosine
NRR	Nitrogen Reduction Reaction
PAS	Photocatalytic Ammonia Synthesis
RWGS	Reverse Water Gas Shift Reaction
SAF	Sustainable Aviation Fuel
SCR	Selective Catalytic Reduction
TRL	Technology Readiness Level

## Table of contents

Tiivistelmä

Abstract

Abbreviations

1	Introduction .....	6
2	Carbon dioxide reclaiming .....	8
2.1	Technologies .....	8
3	Green hydrogen and ammonia as enablers for CO <sub>2</sub> applications .....	11
3.1	Hydrogen .....	11
3.2	Ammonia .....	13
3.2.1	Sustainability of ammonia .....	14
4	Applications of CO <sub>2</sub> in the chemical industry .....	15
4.1	Urea.....	15
4.1.1	Sustainability of urea .....	16
4.2	Methane .....	16
4.3	Methanol .....	17
4.3.1	Sustainability of methanol .....	19
4.4	Other liquid fuels .....	20
4.4.1	Reverse Water Gas Shift Reaction.....	20
4.4.2	Fischer-Tropsch synthesis.....	21
4.4.3	Gasoline .....	22
4.4.4	Biodiesel .....	23
4.4.5	Kerosine .....	25
5	Technological and economic challenges and future prospects.....	28
6	Conclusion.....	30
	References.....	32

Appendix 1. Materials and methods

# 1 Introduction

The utilization of carbon dioxide (CO<sub>2</sub>) as a feedstock in chemical industry has become a relevant research topic in recent years due to the goals to restrict global warming. Greenhouse gas (GHG) emissions reached the limit of 53.0 gigatons carbon dioxide equivalents in 2023 (European commission, 2024). That is the reason why the growth of carbon dioxide concentrations is one of the most challenging issues to resolve globally. The impacts extend from economic problems to the deterioration of environmental diversity. GHG emissions can be decreased and sustainable solutions for chemical industry advanced by researching the possibilities to benefit carbon dioxide as a feedstock. Political aims and technological innovations emphasize the necessity to move towards carbon neutral society which makes the topic topical.

Earlier studies have presented promising results about the utilization of carbon dioxide to produce different kinds of products such as methanol. The convert of carbon dioxide is enabled specifically via catalytic reactions and other innovative technologies that are more energy efficient and economic. (Chihiro et al., 2014) Several research shows also indicate the opportunity to exploit the renewable energy in the production of CO<sub>2</sub>-based products which enhances the circular economy at the same time. Advancement has been significant, but a more comprehensive approach has received less attention. Thus, several studies have focused on new individual solutions. It is essential that different kinds of technologies can be combined into integrated and economically worthwhile production chains. The unification of carbon dioxide recovery and utilization into already existing processes is also a relevant question for this research which aim is not only to combine new technologies but also to assess their potential in the generation of new innovations. Figure 1 presents how all-round carbon dioxide can be benefitted.

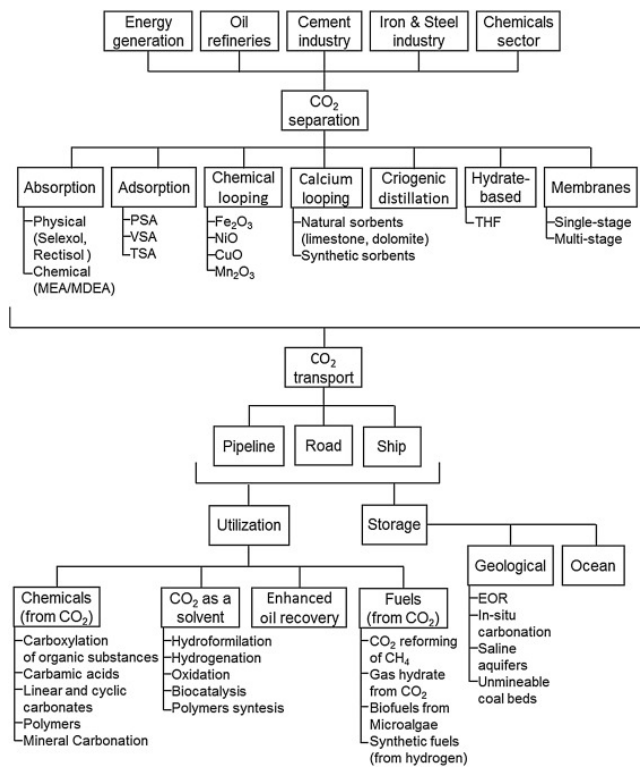


Figure 1. The use cases of carbon dioxide (da Cruz et al., 2021)

The goal of this study is to examine the utilization of carbon dioxide as a feedstock in some fields of chemical industry and investigate how efficient production chains can be created by combining different technologies. The research question is related to how the utilization of carbon dioxide can be enhanced through economically and ecologically sustainable ways, as well as which technologies are the most efficient and what challenges will be faced. Analysis is basically defined as dealing with industrial processes, technologies related to them and the driving of new technologies towards industrial scale. The structure of study moves forward followingly: the theoretical background and previous studies are dealt with at first and after that followed the conclusions.

## 2 Carbon dioxide reclaiming

The reclaiming process of carbon dioxide is the basis for its further applications. This section deals with technologies which are utilized in carbon dioxide reclaiming and the stages after that.

### 2.1 Technologies

Carbon capture and storage (CCS) method has been in use since 1920 when carbon dioxide was separated from methane to boost oil production in the US (da Cruz et al., 2021). First, CCS was used to reclaim anthropogenic carbon dioxide, but it has become a tempting way to reduce greenhouse gas emissions. There are a few steps in how CCS is formed. The first step is the separation of carbon dioxide from different kinds of sources. These kinds of sources can be e.g. energy or industrial sources. The second step is the transport of carbon dioxide. CCS technologies are categorized into three groups in general. In the first case carbon dioxide is removed from the fuel before the burning ends. In the second case carbon dioxide can be removed during the burning from the fuel and in the third case the fuel is burned with pure oxygen and then there will be carbon dioxide as a byproduct. Carbon dioxide separation methods can also be classified as a more specific means according to the separation method. These kinds of methods are adsorption, absorption, membrane separation, chemical looping combustion (CLC), hydrate-based separation and cryogenic distillation. After reclaiming and separating carbon dioxide will be transported to storage. This kind of way of storage is e.g. ocean storage which is in deep ocean or gas and oil reservoirs. (da Cruz et al., 2021)

Adsorption is utilized widely in the separation and the purification of hydrogen from carbon dioxide and other rare gases as well as the steam reforming of methane. It has reached almost excellent hydrogen purification while the mixture included methane, carbon dioxide, nitrogen, carbon monoxide and hydrogen. The choice of right adsorbent plays a fundamental role in the process. Absorption is utilized mostly in chemical and petroleum industries to remove or separate carbon dioxide from exhaust gases. It is based on the absorption of alkanolamines such as diethanolamine which is used widely. Fast reaction rates and high absorption

capacities for carbon dioxide are reasons why amines are special to separate carbon dioxide. (Zare et al., 2019) CLC process includes two steps: reduction and regeneration. Lattice oxygen which comes from oxygen carriers is worn to combust a fuel which includes hydrocarbons. The reaction produces steam and carbon dioxide, and the condensation of steam is followed by that. Then pure carbon dioxide can be sequestered. Typical oxygen carriers are the oxides of iron, copper, nickel or manganese and the reduced metal oxide can be returned to its initial form in the regeneration by air. Iron oxides have been advantageous due to their prices, but nickel oxides have reached the highest reactivities. (Imtiaz et al., 2012)

Membrane separation has faced lots of interest due to its low energy consumption. It allows effective separation of carbon dioxide without phase changes. Currently utilized polymer membranes have still a short lifespan and their stability for carbon dioxide is limited. Zeolite membranes are promising alternative for polymer membranes due to their better stability and porosity which can make possible higher permeances. (Yu et al., 2018) The main challenge concerning hydrate-based separation of carbon dioxide is the slowness of hydrate production ratio. The hydrate production needs promoter to enhance the ratio. Thermodynamical promoters like cyclopentane are capable to produce hydrates and decrease temperature and pressure requirements via that way. Different promoters can have many kinds of strengths and that is important to consider when making the decision. (Xu et al., 2021)

Cryogenic distillation is on a developmental scale. Its development has still increased remarkably due to its promising properties. One option is to combine membrane separation with it. It would include the pre-concentration of carbon dioxide through membrane. Then is obtained cryogenic liquid carbon dioxide with high pressure and the energy requirements are low and the purity and recovery rate of carbon dioxide are high (89 % and 85 %). Carbon dioxide can also be separated from methane via cryogenic distillation. It is demonstrated that liquid carbon dioxide with very high purity (99.92 %) can be separated from methane via cryogenic distillation with suitable temperature, pressure, reflux ratio and number of plates. The energy consumption decreased at the same time. (Qiao et al., 2025)

The key elements in CCS are thus carbon dioxide formation process, separation efficiency, matters concerning the storage and technology readiness level (TRL). Another remarkable thing is to note the environmental aspects in CCS. It has been noted and researched by Life Cycle Assessment (LCA). (da Cruz et al., 2021)

Carbon capture and utilization (CCU) are nearly related to CCS. This is the reason why it can be environmentally and economically reasonable that they support each other. The result can be lower consumption of energy, increased production and remarkable part of carbon dioxide from CCS can be used straight to the production of the factory. This kind of recycling system can consume part of the carbon dioxide which is compounded from its own production. The rest of the carbon dioxide can be stored and transported to other destinations. (Colodi et al., 2017)

### 3 Green hydrogen and ammonia as enablers for CO<sub>2</sub> applications

Hydrogen is one of the cornerstones concerning the utilization of carbon dioxide. It is needed in many reactions as reactant to convert carbon dioxide into desired products. Ammonia is a relevant alternative to be used as fuel to a larger extent and one of the most important products for humanity due to its usage in the fertilizer field. This section deals with the production of these two essential products.

#### 3.1 Hydrogen

Green hydrogen can be manufactured via thermochemical technologies. Pyrolysis is based on decomposition due to heat. The raw material used in pyrolysis is a carbon-containing compound, such as biomass which decomposes in a non-oxidizing atmosphere and without additional reactants. This kind of process requires high temperatures, and they are around hundreds of degrees depending on the feedstock. Fractions between solid, liquid and gas products are determined by the operating conditions including the residence time of vapors and heating rate. The required temperature can be decreased by utilization of suitable catalysts. The products of this process are in solid, liquid or even gas and relations between different phases depend on heating rate, temperature and residence time and these products can be further processed into hydrogen. Other thermochemical techniques to produce hydrogen are gasification, combustion and liquefaction. However, achieving suitable conditions for liquefaction is challenging, and combustion produces emissions from the burning of biomass. (Singh et al., 2024) Numerous existing methods, as presented in figure 2 contribute to hydrogen production. The choice of method depends on the feedstock and other factors, through each approach presents its own challenges.

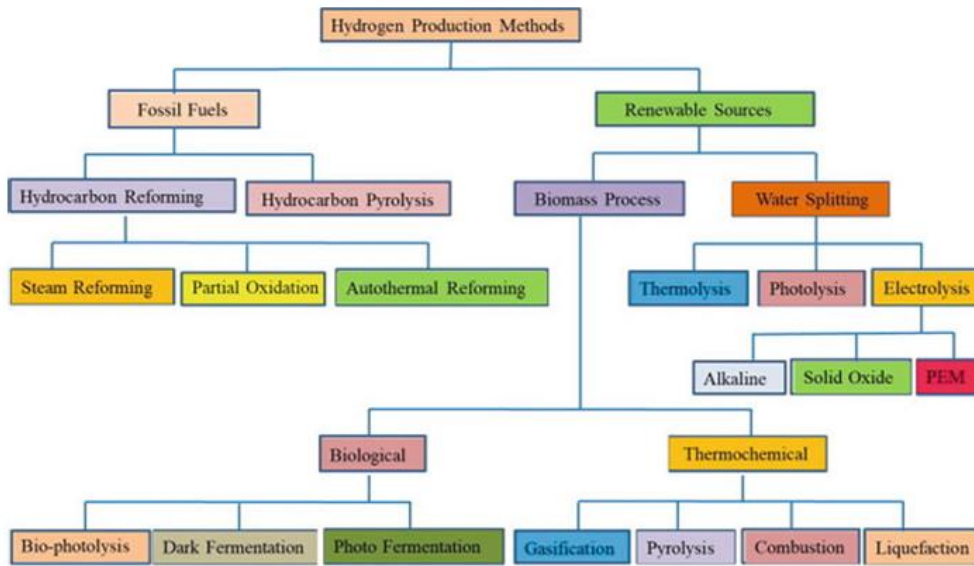


Figure 2. Methods to produce hydrogen (Singh et al., 2024)

Biological processes are likewise promising ways to produce hydrogen in the future. The most important biological processes are dark fermentation, photo-fermentation, their combination or bio-photolysis. Anaerobic bacterium are able to generate hydrogen from organic waste like sewage or agricultural waste. The generation speed of hydrogen is high which makes this system very promising. Bacterium cannot dissipate organic material completely due to thermodynamic limits. If dark fermentation and photo-fermentation are combined, the result is usually enhanced production of hydrogen if the right circumstances have been chosen. In these bacteria are also able to dissipate the organic material totally. Hydrogen can be generated from water and carbon dioxide by microalgae and cyanobacteria through bio-photolysis. Microalgae and cyanobacteria need only to capture solar energy. (Singh et al., 2024)

Clean hydrogen can be produced straight from seawater via seawater electrolysis. There are two ways to generate hydrogen via this way. Seawater electrolysis can have one or two steps. In one step electrolysis, water is electrolyzed only by simple preparations and in two step electrolysis water is purified by the reverse osmosis membrane module at first and then is performed the splitting of the water into different substances. Also, the desalination is included in two step electrolysis. (Yang et al., 2025)

Hydrogen can be liquified, which modifies it to easier form for transportation and storage. A usual way to transport hydrogen is shipping. After transforming hydrogen can be converted back into its gas form. This process is called regasification. This is executed simply by heating to an ambient temperature utilizing water at appropriate temperature. The

regasification of hydrogen can be carried out at large stations or smaller ones located near to the end users which is an essential question when planning hydrogen transforming. (Pellegrini et al., 2024)

### 3.2 Ammonia

Electrochemical ammonia synthesis is an emerging and promising approach in green ammonia production. It utilizes the electrocatalytic nitrogen reduction reaction (NRR) which can lead to lower consumption of energy and safer process. Instead of hydrogen, this synthesis creates ammonia via water which can state of being environmentally friendly if hydrogen is not produced through like green hydrogen. The usage of electricity during the process is a viable enabler to the usage of renewable energy sources if the electricity is originated from them. Moreover, this process requires minimal, cost-effective infrastructure, making it both flexible and simple. (Zhang et al., 2024)

Photocatalytic ammonia synthesis (PAS) is a process which is normally operated in ambient pressure and temperature, which decreases operational intricacy in the process. The convert of nitrogen into ammonia is driven by solar energy as the main driving force. This feature makes PAS an innovative technology for green ammonia production characterized by low energy consumption, mild reaction conditions and environmental sustainability. Other innovative ammonia synthesis include chemical looping ammonia synthesis (CLAS) and plasma ammonia synthesis. CLAS is based on the fact that the conventional ammonia synthesis process is split into smaller reaction steps, which can alter the kinetics and thermodynamics compared to the Haber-Bosch mechanism by evading rival adsorption between nitrogen and hydrogen on metal catalysts. (Zhang et al., 2024)

Catalysts play a crucial role in green ammonia production and the sustainable development of ammonia production is based on new and more practical catalysts solutions. Significant efforts are underway to develop new catalytic materials that can replace the conventional metal catalysts with more environmentally friendly ones (Inamuddin et al., 2020). Moreover, these new catalysts capable of working at lower pressures and temperatures which decreases the overall energy requirements (Tekniikka & Talous, 2020).

### 3.2.1 Sustainability of ammonia

Ammonia produced via traditional Haber-Bosch mechanism consumes 1-2% of the energy supply in the world and is responsible for about 3 % of all carbon dioxide emissions (Ammonia energy association, 2017). At the same time, it is still one of the most important processes in the world due to its ability to enable food production for billions of people (Meryt, 2024). Therefore, there are several matters which must be considered concerning environmentally friendly ammonia and its future. Ammonia can also benefit as transportation fuel and the burning of ammonia does not occur CO<sub>2</sub> emissions. Instead, it causes mainly water vapor and nitrogen, and the biggest challenges are unburned ammonia and nitrogen oxide emissions. Selective catalytic reduction (SCR) has been advanced to answer that issue, and Europe is a good example in implementing solutions for decreasing nitrogen oxide emissions. It is also estimated that the utilization of ammonia as the fuel of light-duty vehicles could reduce roughly 30 % of the cumulative carbon dioxide emissions in the United States until 2040. That would reduce 96 % of CO<sub>2</sub> emissions from the transportation sector. (Cardoso et al., 2021)

## 4 Applications of CO<sub>2</sub> in the chemical industry

Carbon dioxide can be converted into high value products via new innovative solutions which development has been unprecedented fast. Same familiar products than before but the production methods are different to benefit the potential of carbon dioxide as a feedstock. This section deals with the possible production chains and ways to utilize carbon dioxide.

### 4.1 Urea

Urea was synthesized for the first time in 1870 via dehydration of ammonium carbamate from the reaction between ammonia and carbon dioxide. This process was carried out under high temperature and pressure. (Noorhana, 2018) Ammonium carbamate forms during reaction between ammonia and carbon dioxide and it subsequently decomposes into urea and water as shown in the equations 1 and 2.



The decomposition reaction of ammonium carbamate is remarkably slower than the first reaction, so the overall formation rate of urea is mainly determined by this step. The process ultimately produces an aqueous solution containing 70-87 % urea. (Noorhana, 2018)

Urea can be produced greener by synthesis between carbon dioxide and different kinds of compounds which include nitrogen, and the difference compared to the traditional process is that renewable energy is utilized, and carbon dioxide is captured from the emissions. Processes like this benefits heterogenous structures and multi-metallic alloys via catalysts. The above methods advance electron transfer reactions and the redistribution of surface charges. They improve the activity and adsorption of source materials on the nucleophilic and electrophilic surfaces of the catalyst which enhances the production of urea. This way combined with renewable energy makes the production of urea cleaner and more functional. Different kinds of yields of urea can be reached through this method depending on the catalyst. Catalyst, which includes titanium dioxide thin with palladium and copper nanoparticles is e.g.

able to form urea directly from carbon dioxide and nitrogen with high yields. (Zhao et al., 2025)

#### 4.1.1 Sustainability of urea

In 2016, total production of fertilizers was 181 million tons, with urea accounting for grossly 60 million tons (European Commission, 2019). Urea is the most widely used fertilizer among nitrogen-based fertilizers. The global use of nitrogen-based fertilizers and growth increase around two percent per year and the biggest part of new production capacity of nitrogen-based fertilizers is utilized in the production of urea. (European Commission, 2019) Therefore, transitioning to cleaner production methods for urea could significantly reduce agricultural emissions.

Green urea has about 78 percent lower carbon intensity compared to the conventional fossil-based urea. It is estimated that the production of green urea will follow an economically viable production route. That will be effect by the huge global growth of renewable urea production via new innovative solutions. Green urea is cheaper than all due to massive production scales, expecting the lowest market prices of all time. This could offer low operating costs after the initial investment and exclude the economic risks from farmers. (Palys et al., 2024)

## 4.2 Methane

Methane can be produced from carbon dioxide via methanation reaction, as equation 3 shows (Zhen et al., 2017).



The reaction is highly exothermic (-165,9 kJ/mol) and therefore favored at low temperatures. (Frey et al., 2017) Methane have also one of the highest carbon dioxide uptake rates and potential among carbon dioxide-based chemicals. This is explained by the high specific mass and large producing scale. The amount of carbon dioxide needed to produce methane is relatively lofty. Methanation provides a resource of synthetic gas at the same as a possibility to utilize carbon dioxide as a feedstock. (Uddin et al., 2022)

The relation between hydrogen and carbon dioxide as reactants impact significantly on the formation of methane. Lower ratios between hydrogen and carbon dioxide produce typically larger amounts of products with high molecular mass and higher ratios between hydrogen and carbon dioxide form more methane. An ideal mole ratio leads to a suitable atmosphere for methanation reaction and high selectivity. The best yield of methane is typically reached through ratio of 3:1 or 4:1 and 4:1 means that 95 percent of the formed hydrocarbon molecules with low molecular weights are methane. Even if methane can alternatively be produced from carbon monoxide via hydration, the hydrogenation of carbon dioxide is more selective towards products. The activation energy of hydrogenation is lower than in hydration under the same conditions. Moreover, the rate of hydrogenation is also higher. These factors explain why hydrogenation is an economically more efficient method to produce methane. The formation of water is important to observe because its removal keeps the yield of methane high and reduces the yield of byproducts. (Baraj et al., 2016)

Methanation is a catalytic reaction, and the choice of catalyst plays a great role in the reaction (Baraj et al., 2016). Many noble metals combined with oxides served as active catalysts, but nickel-based, iron-based and cobalt-based catalysts are widely researched due to their abundance, high activity and lack of noble-metals. Nickel based catalysts have demonstrated comparable selectivity and space-time yields due to their high dispersion. Smaller nanoparticles of nickel and larger number of exposed active sites for methanation can lead to higher selectivity of methane. The activation energy in the utilization of nickel-based catalysts is low as well as thermal stability is excellent, and the conversion of carbon dioxide is high. (Zhen et al., 2017)

### 4.3 Methanol

Methanol can be produced via direct hydrogenation from carbon dioxide which is an exothermic reaction (Shanshan et al., 2019). The maintenance of equilibrium is very important during methanol synthesis because higher temperatures lead to higher concentrations of undesirable water and carbon monoxide and lower concentrations of methanol. Direct hydrogenation involves also dehydration of carbon dioxide molecules after hydrogenation. In this step, carbon dioxide first forms formic acid as intermediate product during the hydrogenation. Formic acid is then reduced to methanol and the secondary and tertiary reduction and

dehydration steps proceed in a relatively linear manner (Arya et al., 2024). The formation of water occurs that one hydrogen is lost which slightly decreases the hydrogen efficiency of the process. The separation of the water is also mandatory if methanol is used in processes that are sensible to water or as a fuel. One solution to separate water is reverse combustion synthesis which means that formed water is converted to oxygen. It requires light and electricity and using light directly is a useful and ambitious innovation. Another way is the use of electrochemical cells to simplify the process at the same time. That kind of system activates carbon dioxide molecules and forms reactive carbonite ions as well as the splitting of water which enables the reduction carbon dioxide to methanol. (Dowson et al., 2015)

An active metal catalyst is also needed to produce methanol from carbon dioxide (Singh et al., 2022). It is because carbon dioxide molecules have high bond dissociation energy and stability (Debek et al., 2019). Copper, aluminum and zinc were used as catalysts before due to their profusion, but they do not withstand water very well. Low tolerance to water can occur decreasing in the activity of the catalyst due to oxidation of the metal or water adsorption. Therefore, it is needed catalysts which activity do not fall. Different catalysts are researched via heterogeneous catalysts. Copper-based catalysts enabled the highest production speed, but the selectivity of the methanol dropped off at the same time. Zinc oxide-based catalysts reached higher selectivity for methanol, but they typically require higher operating temperatures. That means greater energy input. Ruthenium-based catalysts are also explored and incorporating indium with ruthenium resulting in at least a very high selectivity of methanol. It can be more than 85%. (Arya et al., 2024)

Direct conversion of carbon dioxide to methanol is a more efficient method than other alternatives which include forming of some intermediate products and its occasional isolation. These kinds of more complicated methods to produce methanol can still be useful to integrate into already prevailing fossil-based systems. That can be done instead of constructing entirely new infrastructure which increases the economic efficiency of the process. (Dowson et al., 2015)

One example of this kind of possibility is the production of methanol from methane via partial oxidation. The reaction requires only methane, oxygen and suitable catalyst and happens as equation 4 shows.



Process requires typically very high temperatures due to the carbon-hydrogen bonds of methane which are inert. Even up to 600 °C temperatures can be needed. Development in catalyst design has lately allowed decreased temperature requirements. The utilization of sulfuric acid and with mercury, platinum or palladium can decrease the temperature requirement at 200 °C and lower pressures as well. One notable limit in this mechanism is that methane cannot become over-oxidized. Over-oxidization can lead to the forming of carbon dioxide, carbon monoxide or water which can cause the deactivation of catalysts. Thus, high selectivity and control in the process is needed to block undesirable byproducts. Also, the utilization of combined copper and iron or cobalt and iron can be used as catalysts or even silver-based catalysts in this process. (Arya et al., 2024)

#### 4.3.1 Sustainability of methanol

The production of green methanol can decrease carbon dioxide, nitrogen oxides, and sulfur oxides emissions by 60-95 %, 60-80 %, and 99 % (Methanol Institute, 2025). It can be mixed with commonplace transportation fuels which enables easier evolution between different kinds of fuels without any large-scale change in vehicles. In addition, it creates a potential alternative for marine transport and as a substitute for liquified petroleum gas (LPG) via dimethyl ether which is a derivation of methanol-based products. It can also benefit as a feedstock in the production of valuable materials and chemicals such as polymers, textiles and building materials. However, methanol requires twice as big a fuel tank compared to conventional fuels and the production costs are higher. (GEP, 2024)

Green methanol can be produced by completely renewable energy and the GHG emissions can be eliminated as well. That kind of system utilizes hydrogen to power utilities, but the amount of hydrogen utilized increases the price of produced methanol. Huge plants are capable of decreasing production costs closer to the conventional methanol production costs. Those kinds of plants need massive investments, and economic risks are related to them. The most essential concerning the solution of that problem is to concentrate on the rendering of hydrogen production methods and green methanol production. The production of green methanol can also decrease other environmental impacts compared to conventional methanol, but new catalyst candidates are needed to decrease the cost and energy requirements.

Overall, if more continuing development is reached and current challenges are blocked, a better way to produce methanol can widely be established. (Abbas et al., 2022)

#### 4.4 Other liquid fuels

##### 4.4.1 Reverse Water Gas Shift Reaction

Reverse water gas shift reaction (RWGS) is an endothermic reaction and reversible reaction to convert carbon dioxide to carbon monoxide for further processing. RWGS can be operated directly from the capture of carbon dioxide (equation 5) or via reforming by catalysts or gasification. Reforming can be done either dry reforming or steam reforming. Carbon dioxide reacts with methane to form carbon monoxide and hydrogen into dry reforming. A reaction between water and methane creates the same end products as dry reforming in steam reforming, as equation 6 shows. (Arya et al., 2024)



However, the viability of RWGS is bound to the suitable operational conditions which causes challenges to its development. RWGS is hard to operate at low temperatures to minimize energy consumption due to its endothermicity and thermodynamic favorability. There is also a competing reaction which typically replaces RWGS at lower temperatures. That reaction is the methanation of carbon dioxide (equation 3) which is undesirable during RWGS. (Portillo et al., 2023) The RWGS is independent from pressure instead of methanation (Benzinger et al., 2019). RWGS does not include any kind of volume change which explains the independence of pressure. Methanation is instead of a process of volume contraction and due to that any kind of increase in pressure supports it and decreases carbon monoxide molar fraction at the same time. Even coke can be formed at high pressures which typically decreases carbon monoxide molar fraction as well. (Santos et al., 2023)

At lower temperatures than 520 °C the methanation reaction is the dominant reaction and carbon monoxide becomes notable when the reaction temperature is more than 700 °C. The molar fraction of carbon monoxide crosses carbon dioxide and hydrogen molar fractions in the product at 825 °C. This points out the necessity of high temperatures needed. Also, the

molar ratio between hydrogen and carbon dioxide is one fundamental matter. Typically, the conversion of carbon dioxide is higher at bigger molar ratios but the highest selectivity for carbon monoxide can be reached at a bit lower temperature and ratio than the highest conversion of carbon dioxide. Finally, the best operating conditions are 750 °C, 20 bar and molar ratio between hydrogen and carbon dioxide 0.8 to enable favorable results in both carbon dioxide conversion (36.3 %) and carbon monoxide selectivity (96.4 %). These conditions are also economically favorable due to low consumption of hydrogen and lowest operating temperatures as possible. (Santos et al., 2023)

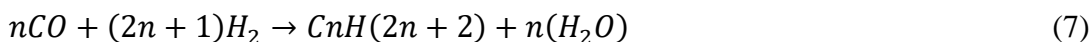
The utilization of nickel as catalyst in RWGS is a convenient alternative due to its high activity and low cost. However, it is demonstrated that the utilization of cerium oxide with nickel can increase the effect of catalyst. Also, alkalis can change the interactions of nickel catalyst to enhance the selectivity of carbon monoxide at even lower temperatures. In addition, it can suppress the competitive reaction at the cost of remotely lower carbon dioxide conversion. Overall, RWGS is a potential process to produce syngas and complement the carbon dioxide conversion cycle. Syngas is a mix of carbon monoxide and hydrogen. (Portillo et al., 2023)

#### 4.4.2 Fischer-Tropsch synthesis

Fischer-Tropsch Synthesis (FT) was developed in 1920 and contained the convert of syngas to produce liquid hydrocarbon fuels e.g. petrol and diesel. Depending on the origin of which syngas is generated the earlier point to the FT process can be coal-to-liquid (CTL) or gas-to-liquid (GTL) process. Gassing is used to produce syngas from biomass or coal in CTL process. During the process carbonaceous substances will be formed into a mix of gases including hydrogen, nitrogen, carbon monoxide and carbon dioxide. In GTL syngas are produced from methane by rectification, auto-thermal reforming or downstream separation. The use of hydrogenating carbon dioxide to manufacture liquid fuels through FT is also involved the straight transformation of carbon dioxide to fuels. That includes two upper steps: RWGS to reduce carbon dioxide from carbon monoxide and FT to hydrogenate carbon dioxide to hydrocarbons. (Arya et al., 2024)

A mix of hydrocarbons with different molecular weights are formulated during FT from hydrogen and carbon monoxide. The benefit of dry reforming is that it can utilize either

carbon dioxide or methane which decreases emissions. Generated hydrocarbons are lighter olefins and heavy paraffins, as equation 7 presents.



The yield of paraffins is usually higher than olefins. Small amounts of alcohol and ethers are produced as byproducts as well as methane as undesirable byproducts. The conditions of the reaction are set to maximize the yield of heavier hydrocarbons. FT is finally based on polymerization reaction and carbon monoxide goes through condensation polymerization which is typically very exothermic. (Arya et al., 2024)

Two typical catalysts used in FT process are cobalt and iron. Cobalt catalysts can be used alone at lower temperatures (200-240 °C) than iron catalysts which can be used at higher temperatures (300-350 °C) or lower temperatures. Typically, iron is still used as catalyst in higher temperatures. (Chen et al., 2016) The coke deposition rate of the cobalt catalyst is lower, and it must be changed seldom compared to iron catalysts. The mix of forming hydrocarbons will be different depending on the catalyst. This can happen even if the temperatures and pressures are the same. Iron catalysts have not as high selectivity as cobalt catalysts for hydrocarbons with higher molecular weight. It explains partly that higher temperatures and iron catalysts produce more gasoline products because they include hydrocarbons with lower molecular weights. Also, more diesel products can be produced at lower temperatures and by cobalt catalyst. It is also important to separate sulfur-based compounds from hydrogen and carbon monoxide because the catalysts can be poisoned by them. (Arya et al., 2024)

#### 4.4.3 Gasoline

The surface of iron(II, III)oxide is very effective to activate carbon dioxide. In addition, alkali metal is typically needed to reach the desirable selectivity and activity. Sodium is beneficial in the production of olefins. That is based on the ability of sodium to increase the alkalinity on the surface and the carburizing capacity of the iron-based catalysts. This increases its ability to modify hydrogen and carbon dioxide to light olefins. (Arya et al., 2024) Zeolites can facilitate the conversion of small hydrocarbon molecules into larger molecules with desirable qualities by oligomerization reaction, isomerization reaction and

aromatization reaction. This distinct feature is owing to their shape, selectivity and acidity (Abello et al., 2011). When zeolites are combined with iron-based catalysts in FT process, they can build multipurpose catalysts which are capable of producing aromatics and isoparaffins. The resulting products fall within the range of petrol with high octane numbers. (Wei et al., 2017)

The reaction benefits the abilities of each component of the multipurpose catalyst to produce valuable hydrocarbons from carbon dioxide via more effective reaction with higher selectivity. First, carbon dioxide becomes reduced to carbon monoxide by RWGS. Secondly, carbon monoxide is hydrogenated to form olefins via FT reaction. In this stage carbon monoxide and hydrogen react with (iron (II, III) oxide catalyst to form different kinds of hydrocarbons including olefins and alpha olefins. These hydrocarbons are formed into gasoline range hydrocarbons by utilization of zeolites as catalyst in oligomerization reaction, isomerization reaction and aromatization reaction. (Wei et al., 2017)

Petrol can also be produced directly via methanol to gasoline (MTG) process from methanol. In the MTG process, methanol can be produced from carbon dioxide. The MTG process consists of three steps (Arya et al., 2017). First, methanol is converted to dimethyl ether through dehydration by creating chemical equilibrium between water, dimethyl ether and methanol (France et al., 2015). The dehydration of methanol forms methoxy as intermediate product. Dimethyl ether is produced from methoxy via nucleophilic attack with another methanol molecule acting as an electrophile. Second, the dimethyl ether is converted to olefins via dehydration using zeolite catalysts. Finally, these olefins undergo further conversion into a mixture of paraffins, aromatics and other heavier olefins with carbons atoms more than four. The convert mechanism involves the formation of carbocation and simultaneous transfer of hydrogen atom (Arya et al., 2024). These products fall within the range of gasoline, and separation is required to achieve the desired fuel components.

#### 4.4.4 Biodiesel

Biodiesel produced by FT process has higher energy density than conventional diesel produced from fossil fuel (Medrano-García et al., 2022). In addition, it has a higher cetane number compared to fossil diesel, resulting in higher energy efficiency. (Schemme et al., 2017)

Biodiesel can also be produced via other innovative solutions, such as microalgal biotechnology (Huang et al., 2010).

Light energy and carbon oxide can be transformed into hydrocarbons and other beneficial products via photosynthesis by microalgae. Microalgae have high photosynthetic efficiency and rate of growth compared to many other plants. The growth of microalgae can be operated in an open pond system and the operating costs in this kind of system are moderate. The needed carbon dioxide can be found out straight from some source of carbon dioxide emissions. The typical flue gas of coal plant contains about 13 percent of carbon dioxide and enhances the transport rate of carbon dioxide in the open bond system. Additionally, wastewater can be used in the growth of microalgae. This kind of concept creates a sustainable way to recycle carbon dioxide into biodiesel, as presented in figure 3. (Huang et al., 2010)

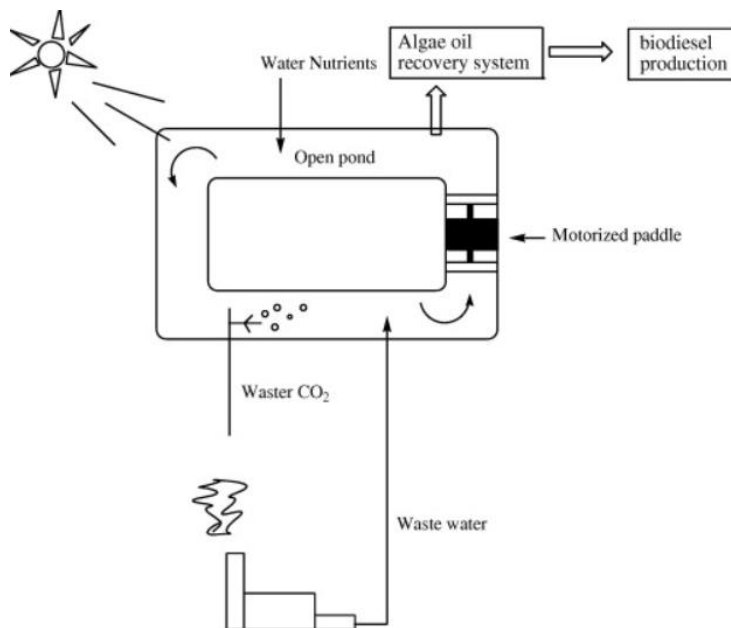


Figure 3. Biodiesel production via microalgae biotechnology in open bond system. (Huang et al., 2010)

Different kinds of microalgae have been investigated for biodiesel production. The reached lipid contents can vary pretty much depending on the microalga. Microalgae called *Chlorella vulgaris* reached the highest lipid content (27 %) in the same conditions than the other researched microalgae. The used reactor was a bubble column photobioreactor in all measurements and it has also the highest lipid productivity compared to time and intermediate cell growth which were essential matters in the study as well. The lipid productivity is double

higher than the highest value of 30 other microalgae. The composition of biodiesel produced via *Chlorella vulgaris* is shown in figure 4. Produced triglycerides which are one feedstock of biodiesel include glyceride, fatty acids which have different lengths of carbon chain as the number of insatiable bonds. (Francisco et al., 2010)

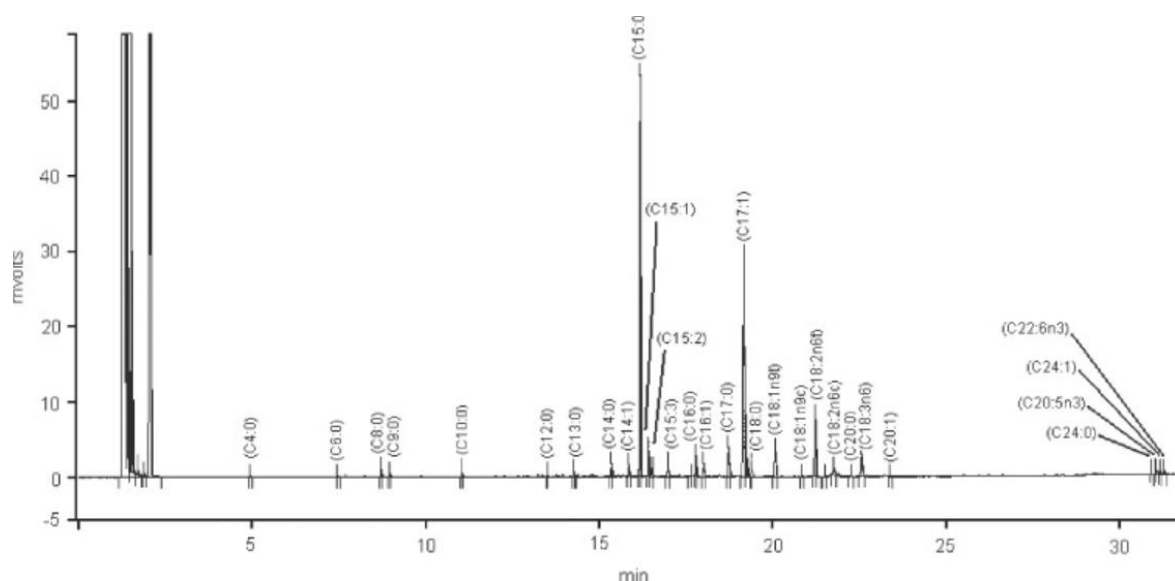


Figure 4. Gas chromatogram of biodiesel produced via *Chlorella vulgaris* (Francisco et al., 2010)

*Chlorella vulgaris* produced biodiesel has also convenient degree of unsaturation which decreases the viscosity to support the mechanical features of diesel engine. However, high degree of unsaturation increases slightly nitrous oxide exhaust emissions. All things considered, *Chlorella vulgaris* is a potential microalga to produce biodiesel due to its high lipid productivity and high quality including cetane number and degree of unsaturation. All the quality parameters passed the limits given by the US Standard (ASTM 6751) and European Standard (EN 14214). (Francisco et al., 2010)

#### 4.4.5 Kerosine

E-kerosine can be produced via FT, such as gasoline or biodiesel. The difference is largely only the control of the structure and length of carbon chains. Typically, e-kerosine or sustainable aviation fuel (SAF) consists of cycloalkanes and isoalkanes with carbon chain length from eight to eighteen. The compression is needed to increase their pressure into 25

bars to ease the upcoming FT before hydrogen and carbon dioxide can be entered RWGS reactor. Then composed carbon monoxide is converted into another reactor via FT process. The heat formed by the exothermic FT reaction can be benefitted in the endothermic RWGS reaction. The effective remove of heat is definitive important in FT due to the exothermicity. Optimal control and heat transfer within the reactor are necessary to verify the quality of the forming SAF and effective reaction speed. There are four different kinds of reactor types which are commonly utilized in FT: slurry phase reactor, tubular fixed bed reactor, fluidized bed reactor and circulating fluidized bed reactor. Every alternative has its own benefits concerning selectivity, reaction kinetics and heat transfer. Producing one-kilogram SAF is needed roughly 14 kilograms of carbon dioxide and 1.4 kilograms of hydrogen if iron or cobalt-based catalysts are used as usual. The latest innovations have demonstrated that iron-based catalysts combined with transition metals as promoters can lead higher selectivity of SAF and conversion rates of carbon monoxide. The selectivity reached is typically a little under 50 % for hydrocarbons with length carbon chain. The lowest productions costs can be achieved via sourcing carbon dioxide from ammonia or ethanol plants. Other factors influencing profitability are the recycling ratio of hydrogen and carbon dioxide as well as the conversion rate of carbon monoxide. (Arya et al., 2024)

Another way to produce SAF is the Methanol-to-Kerosene (MTK) process. SAF can produced via this route without RWGS reaction. However, the biggest focus has been on converting methanol into smaller hydrocarbons and SAF-specific concept is newer. The MTK process includes the formation of olefins via hydration and oligomerization into heavier olefins are followed by that. Methanol is compressed into the reactor to generate olefins and then washed out of carbon dioxide and dried before the oligomerization. After that unsaturated hydrocarbons are converted into alkanes via hydrogenation and fractioning forms the desirable fuel fractions via distillation in the end. MTK is analogical to common alcohol-to-hydrocarbon formations and the combination of dehydration and oligomerization is a vital matter to the product formed. The operating conditions of kerosene range oligomerization reaction are 150-300 °C and 40-100 bar. After that the reactor is cooled for the separation of light alkanes and other light hydrocarbons to maximize SAF output. Typically, light fractions are recycled into the oligomerization reactor, but multi-stage oligomerization is also possible. FT-based and MTK-based SAF productions are presented in figure 5. (Bube et al., 2024)

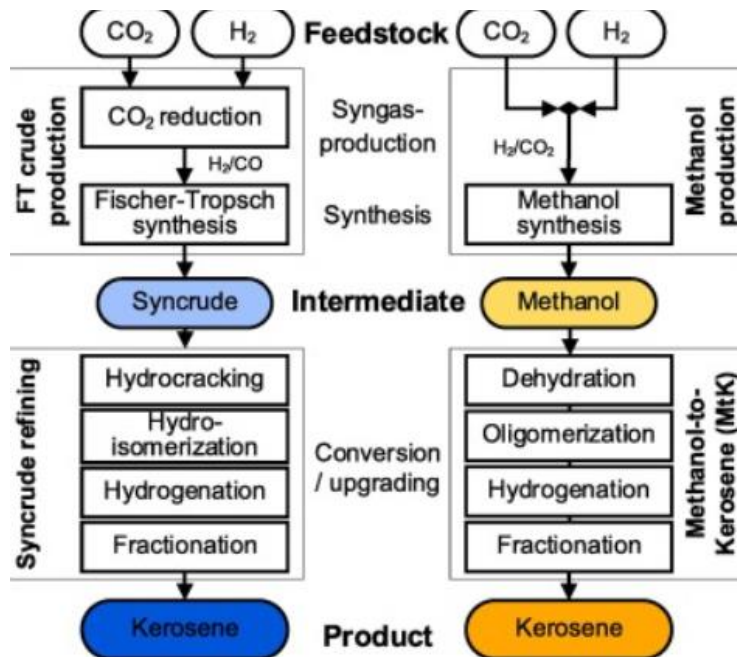


Figure 5. FT-based and MTK-based SAF production ways (Bube et al., 2024)

MTK process has slightly higher carbon efficiency than FT-based process due to its smaller product distribution and the recycling of light olefin fractions. However, the operating conditions and catalysts of FT process are helping to regulate the chain growth probability which makes the optimizing of process towards better SAF efficiencies more realistic. In addition, FT-based SAF is more uniform and easier to get standards acceptable than MTK-based which includes higher amounts of light components. The energy efficiency of MTK-based SAF is also six percent higher. (Bube et al., 2024)

## 5 Technological and economic challenges and future prospects

There are fundamental issues concerning CCU even if the growth has increased remarkably last years, as figure 6 presents.

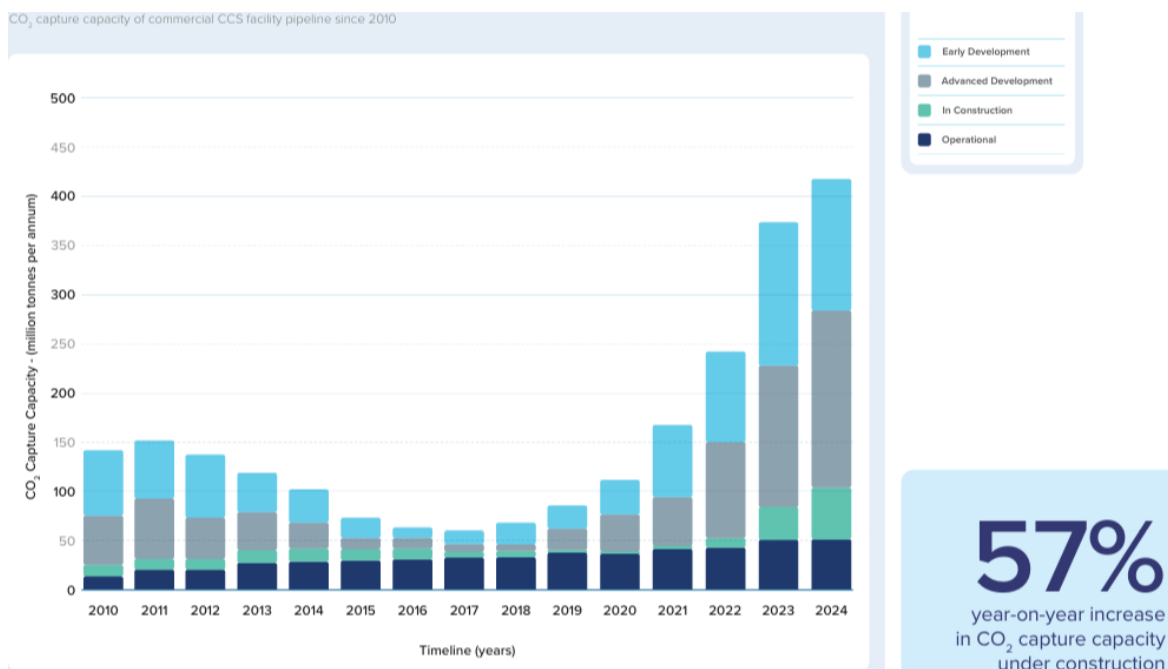


Figure 6. The growth of CCU capacity (Global CCS Institute, 2024)

However, many CCU technologies are energy intensive and complicated to execute. That causes the necessity to improve the processes to reach implementation on a large and industrial scale. Effective catalysts are needed to decrease the consumption of energy and increase the selectivity in the carbon dioxide convert processes to liquid fuels which requires high quality research. (A Garifullina et al., 2024) The convert of methane to fuels is an example of a process which demands harsh reaction conditions to be able to put into effect. That is a consequence of the completely symmetrical tetrahedral structure which occurs very high bond energies. (Sun et al., 2020)

Even if carbon dioxide-based fuel production can decrease GHG emissions and help forward circular economy the top problem is profitability compared to fossil-based fuels. The production of fossil fuels is cheaper due to established and well-organized infrastructure and low energy requirements. The initial investments for carbon dioxide conversion facilities are high as well as CCU technologies integration into already existing systems. (Arya et al.,

2024) The construction and commissioning of new CCU infrastructure can also face caution by the public due to facilitating current wasteful lifestyles or might obstruct necessary societal change (Jones et al., 2014).

The role of policy is massive in the energy sector transition. Its task is to create the circumstances for industry to move forward CO<sub>2</sub>-based production. Without suitable policy, industries must justify the new systems themselves which makes the totality more difficult to realize. The expansion of stricter GHG emission requirements and carbon pricing mechanisms are keys to supporting new CO<sub>2</sub>-based products as well as investments in development and further research. In addition, market demand is still for fossil-based solutions, a limiting factor due to their domination in the global energy sector. These problems can be overcome via not only new and innovative solutions and catalysts but also supportive frameworks to the deployment of sustainable alternatives. (Castillo Castillo et al., 2019)

Despite the technological and economic challenges there is hope concerning the fast advancement of new technologies and methods. Fast advancement can lead to inevitable change for current systems. It is also important that further research focus on developing knowledge about principles to appropriate catalysts as well as optimizing the processes. (Saeidi et al., 2021) 50 % of fossil-based fuels used in transport can be replaced by new generation solutions e.g. renewable hydrogen or CO<sub>2</sub>-based fuels until 2040 (Neste, 2022). There are around 300 projects under different levels of progress due to remarkable momentum over the last years. The developers have aimed to reach more than 220 million tons of captured carbon dioxide annually by 2030 (Arya et al., 2024). However, 75 % of operated or planned CCU capacity is in Europe or North America. Strong policy and cooperation are needed to spread CCU facilities to all regions, particularly developing economics and emerging markets (IEA, 2023).

## 6 Conclusion

The utilization of carbon dioxide in the chemical industry plays globally a significant role in the transition towards a sustainable future. It is capable to reduce GHG emissions as well as advancing the principles of circular economy which means that industry can move to closed loop production systems. In this way, carbon dioxide can circulate continuously by being converted into new products instead of accumulating in the atmosphere.

New innovative and effective catalysts are essential due to their ability to enhance the selectivity of processes and decrease the need for energy by decreasing the activation energies of reactions. Therefore, the conversion of carbon dioxide into valuable products like fuels or chemicals is becoming possible on an industrial scale. The greener production methods of ammonia, urea and other fuels can reduce agricultural, transport and aviation emissions thereby supporting the sustainable development of industry.

Even if carbon dioxide utilization technologies have remarkably developed, large-scale implementation is still facing challenges related to infrastructure and economy. Large initial investments are needed due to the high cost of CO<sub>2</sub> infrastructure and fossil-based production remains more economically competitive. There are also technological challenges related to process optimization and catalyst development, although much progress has already been made. Each alternative has its own pros and cons in terms of performance, cost and availability, and the optimization demands high quality research taking all factors into account. In addition, the strong market demand for fossil-based products slows the adoption of new and more sustainable options.

The role of policy is decisively important. Without suitable regulations like emission limitations, industry will not move to new more sustainable processes so fast. However, it is still necessary that these regulations should be accepted by the general public to maintain support for new technologies. In addition, global cooperation and political actions are essential to create conditions needed for the large-scale commissioning of new technologies. For instance, microalgal biotechnology and many carbon dioxide recovery methods are developing but not yet commercially viable at an industrial scale. These technologies require further development and investment to become financially competitive.

Cooperation between society and industry combined with investments into research and development is key to enabling the utilization of carbon dioxide as a central part of the chemical industry's future.

Continued research should focus on the integration of already existing processes as well as optimizing and creating new processes that are strongly linked to new catalysts. Supportive regulations and policies are necessary to create favorable conditions for this transition.

In summary, although significant challenges remain, technological development has been exceptionally rapid, and more new innovations are expected in the near future. In this regard, large-scale recovery of carbon dioxide is a realistic goal and can become a cornerstone of a sustainable future. Ultimately, the solution to the problem may lie within the problem itself.

## References

- Abbas, A., Qadeer, K., Al-Hinai, A., Tarar, M.H., Qyyum, M.A., Al-Muhtaseb, A.H., Abri, R.A., Lee, M., Dickson, R., 2022. Process Development and Policy Implications for Large Scale Deployment of Solar-Driven Electrolysis-Based Renewable Methanol Production. *Green chemistry: an international journal and green chemistry resource* 24.19. 763–7643. <https://doi-org/10.1039/d2gc01993k>
- Abello, S., Montane, D., 2011. Exploring Iron-Based Multifunctional Catalysts for Fischer-Tropsch Synthesis: A Review. *Chemistry & Sustainability, Energy & Materials* 4.11. 1538–1556. <https://doi-org.ezproxy.cc.lut.fi/10.1002/cssc.201100189>
- A Garifullina, C., Klimov, D.S., 2024. CCU Technologies as a Tool to Achieve Scope and ESG Goals. *E3S web of conferences* 498. 1015-. <https://doi.org/10.1051/e3sconf/202449801015>
- Ammonia energy association, 2017. US DOE funding research into sustainable ammonia synthesis [Online]. {Accessed 5.3.2025}. Available: <https://ammoniaenergy.org/articles/us-doe-funding-research-into-sustainable-ammonia-synthesis/>
- Arya, R.K., Verros, G.D., Verma, O.P., Hussain, C.M., 2024. *From Waste to Wealth*. 1st ed. Singapore: Springer.
- Baraj, E., Vagasky, S., Hlincik, T., Ciahotny, K., Tekac, V., 2016. Reaction Mechanisms of Carbon Dioxide Methanation. *Chemical papers* 70.4. 395–403. <https://doi.org/10.1515/chempap-2015-0216>
- Benzinger, W., Daymo, E., Hettel, M., Maier, L., Antinori, C., Pfeifer, P., Deutschmann, O., 2019. Reverse Water Gas Shift (RWGS) over Ni – Spatially-Resolved Measurements and Simulations. *Chemical engineering journal* 362. 430–441. <https://doi.org/10.1016/j.cej.2019.01.038>
- Bube, S., Bullerdiek, N., Voß, S., Kaltschmitt, M., 2024. Kerosene Production from Power-Based Syngas – A Technical Comparison of the Fischer-Tropsch and Methanol Pathway. *Fuel (Guildford)* 366. 131269-. <https://doi.org/10.1016/j.fuel.2024.131269>

Cardoso, J.S., Silva, V., Rocha, R.C., Hall, M.J., Costa, M., Eusebio, D., 2021. Ammonia as an Energy Vector: Current and Future Prospects for Low-Carbon Fuel Applications in Internal Combustion Engines. *Journal of cleaner production* 296. 126562-. <https://doi.org/10.1016/j.jclepro.2021.126562>

Castillo Castillo, A., Angelis-Dimakis, A., 2019. Analysis and Recommendations for European Carbon Dioxide Utilization Policies. *Journal of environmental management* 247. 439–448. <https://doi.org/10.1016/j.jenvman.2019.06.092>

Chen, Q., Lv, M., Tang, Z., Wang, H., Wei, W., Sun, Y., 2016. Opportunities of Integrated Systems with CO<sub>2</sub> Utilization Technologies for Green Fuel & Chemicals Production in a Carbon-Constrained Society. *Journal of CO<sub>2</sub> utilization* 14. 1–9. <https://doi.org/10.1016/j.jcou.2016.01.004>

Chihiro, M., Yuki, M., Tadashi, E., 2014. Recent Progress in Catalytic Conversions of Carbon Dioxide. *Catalysis science & technology* 4.6. 1482–1497. <https://doi.org/10.1039/c3cy00993a>

Collodi, G., Azzarro, G., Ferrari, N., Santos, S., 2017. Demonstrating Large Scale Industrial CCS through CCU – A Case Study for Methanol Production. *Energy procedia* 114. 122–138. <https://doi.org/10.1016/j.egypro.2017.03.1155>

da Cruz, T.T., Perrella Balistieri, J.A., de Toledo Silva, J.M., Vilanova, M.R.N., Avila, I., 2021. Life Cycle Assessment of Carbon Capture and Storage/Utilization: From Current State to Future Research Directions and Opportunities. *International journal of greenhouse gas control* 108. 103309-. <https://doi.org/10.1016/j.ijggc.2021.103309>

Debek, R., Azzolina-Jury, F., Travert, A., Mauge, F., 2019. A Review on Plasma-Catalytic Methanation of Carbon Dioxide – Looking for an Efficient Catalyst. *Renewable & sustainable energy reviews* 116. 109427-. <https://doi.org/10.1016/j.rser.2019.109427>

Dowson, G., Styring, P., 2015. Conversion of Carbon Dioxide to Oxygenated Organics. 141-159. <https://doi.org/10.1016/B978-0-444-62746-9.00009-8>

European Commission, 2019. Fertilisers in the EU: Prices, trade and use. [Online]. [Accessed 15.1.2025]. Available: [http://ec.europa.eu/agriculture/markets-and-prices/market-briefs/index\\_en.htm](http://ec.europa.eu/agriculture/markets-and-prices/market-briefs/index_en.htm)

European Commission, 2024. GHG emissions of all world countries. [Online]. [Accessed 25.1.2025]. Available: <https://publications.jrc.ec.europa.eu/repository/handle/JRC138862>

France, L.J., Edwards, P.P., Kuznetsov, V.L., Almegren, H., 2015. Chapter 10 – The Indirect and Direct Conversion of CO<sub>2</sub> into Higher Carbon Fuels. Carbon Dioxide Utilisation. 161-182. <https://doi.org/10.1016/B978-0-444-62746-9.00010-4>

Francesco, E.C., Neves, D.B., Jacob-Lopes, E., Franco, T.T., 2010. Microalgae as Feedstock for Biodiesel Production: Carbon Dioxide Sequestration, Lipid Production and Biofuel Quality. Journal of chemical technology and biotechnology 85.3. 395–403. <https://doi.org.ezproxy.cc.lut.fi/10.1002/jctb.2338>

Frey, M., Bengaouer, A., Geffraye, G., Edouard, D., Roger, A., 2017. Aluminum Open Cell Foams as Efficient Supports for Carbon Dioxide Methanation Catalysts: Pilot-Scale Reaction Results. Energy technology (Weinheim, Germany) 5.11. 2078–2085. <https://doi.org.ezproxy.cc.lut.fi/10.1002/ente.201700188>

GEP, 2024. What's so special about green methanol?. [Online]. [Accessed 8.3.2025]. Available: <https://www.gep.com/blog/mind/green-methanol-types-pros-cons>

Global CCS Institute, 2024. Collaborating for a net-zero future. [Online]. [Accessed 7.3.2025]. Available: <https://www.globalccsinstitute.com/resources/global-status-report/>

Huang, G., Chen, F., Wei, D., Zhang, X., Chen, G., 2010. Biodiesel Production by Microalgal Biotechnology. Applied energy 87.1. 38–46. <https://doi.org/10.1016/j.apenergy.2009.06.016>

IEA, 2023. Tracking Clean Energy Progress. [Online]. [Accessed 9.3.2025]. Available: <https://www.iea.org/reports/tracking-clean-energy-progress-2023>

Imtiaz, Q., Kierzkowska, A.M., Müller, C.R., 2012. Coprecipitated, Copper-Based, Alumina-Stabilized Materials for Carbon Dioxide Capture by Chemical Looping Combustion. *Chemistry & Sustainability, Energy & Materials* 5.8. 1610–1618. <https://doi-org.ezproxy.cc.lut.fi/10.1002/cssc.201100694>

Inamuddin, Boddula, R., Asiri, A.M., 2020. Sustainable Ammonia Production. 1st ed. Cham: Springer International Publishing AG.

Jones, C.R., Radford, R.L., Armstrong, K., Styring, P., 2014. What a Waste! Assessing Public Perceptions of Carbon Dioxide Utilisation Technology. *Journal of CO2 utilization* 7. 51–54. <https://doi.org/10.1016/j.jcou.2014.05.001>

Medrano-Garcia, J.D., Charalambous, M.A., Guillen-Gosalbez, G., 2022. Economic and Environmental Barriers of CO<sub>2</sub>-Based Fischer–Tropsch Electro-Diesel. *ACS sustainable chemistry & engineering* 10.36. 11751–11759. <https://doi.org/10.1021/acssuschemeng.2c01983>

Methanol Institute, 2025. Methanol price and supply/demand. <https://www.methanol.org/methanol-price-supply-demand/>

Meryt, 2024. The Catalyst That Changed the World: The Story of Haber-Bosch Ammonia Catalyst [Online]. [Accessed 4.3.2025]. Available: <https://www.meryt-chemical.com/the-catalyst-that-changed-the-world-the-story-of-haber-bosch-ammonia-catalyst/>

Neste, 2022. Päästöistä ratkaisuihin: neljä tapaa, joilla hiilidioksidista saadaan arvokasta raaka-ainetta. [Online]. [Accessed 8.3.2025]. Available: <https://www.neste.fi/yrietyksille/asiakkuus/inspiroidu/edellakavijyys/paastoista-ratkaisuihin-nelja-tapaa-joilla-hiilidioksidista-saadaan-arvokasta-raaka-ainetta>

Noorhana, Y., 2018. Green Urea: For Future Sustainability. Singapore: Springer.

Palys, M.J., Daoutidis, P., 2024. Techno-economic optimization of renewable urea production for sustainable agriculture and CO<sub>2</sub> utilization. *Journal of Physics: Energy* 6.1. <https://doi.org/10.1088/2515-7655/ad0ee6>

Pellegrini, L.A., Spatolisano, E., Restelli, F., De Guido, G., de Angelis, A.R., Lainati, A., 2024. Green H<sub>2</sub> Transport through LH<sub>2</sub>, NH<sub>3</sub> and LOHC: Opportunities and Challenges. Cham: Springer Nature Switzerland.

Portillo, E., Gandara-Loe, J., Reina, T.R., Pastor-Perez, R., 2023. Is the RWGS a Viable Route for CO<sub>2</sub> Conversion to Added Value Products? A Techno-Economic Study to Understand the Optimal RWGS Conditions. *The Science of the total environment* 857. 159394–159394. <https://doi.org/10.1016/j.scitotenv.2022.159394>

Qiao, S., Xu, M., Lv, X., Zhao, H., 2025. Analysis and Optimization of Cryogenic Distillation Systems: For Reducing Distillation Energy Consumption. *Chemical engineering & technology* 48.1. <https://doi-org.ezproxy.cc.lut.fi/10.1002/ceat.202400296>

Saeidi, S., Najari, S., Hessel, V., Wilson, K., Keil, F.J., Concepcion, P., Suib, S.L., Rodrigues, A.E., 2021. Recent Advances in CO<sub>2</sub> Hydrogenation to Value-Added Products — Current Challenges and Future Directions. *Progress in energy and combustion science* 85. 100905-. <https://doi.org/10.1016/j.peccs.2021.100905>

Santos, M.F., Bresciani, A.E., Ferreira, N.L., Bassani, G.S., Alves, R.M.B., 2023. Carbon Dioxide Conversion via Reverse Water-Gas Shift Reaction: Reactor Design. *Journal of environmental management* 345. 118822–118822. <https://doi.org/10.1016/j.jenvman.2023.118822>

Schemme, S., Samsun, R.C., Peters, R., Stolten, D., 2017. Power-to-Fuel as a Key to Sustainable Transport Systems – An Analysis of Diesel Fuels Produced from CO<sub>2</sub> and Renewable Electricity. *Fuel* 205. 198–221. <https://doi.org/10.1016/j.fuel.2017.05.061>

Shanshan, D., Haiyan, Y., Peng, G., Hui, W., Xiaopeng, L., Wei, W., Yuhuan, S., 2019. A Review of Research Progress on Heterogeneous Catalysts for Methanol Synthesis from

Carbon Dioxide Hydrogenation. *Catalysis today* 330. 61–75. <https://doi.org/10.1016/j.cattod.2018.04.021>

Singh, H., Li, C., Cheng, P., Wang, X., Liu, Q., 2022. A Critical Review of Technologies, Costs, and Projects for Production of Carbon-Neutral Liquid e-Fuels from Hydrogen and Captured CO<sub>2</sub>. *Energy advances* 1.9. 580–605. <https://doi.org/10.1039/d2ya00173j>

Singh, P., Agarwal, A.K., Thakur, A., Sinha, R.K., 2024. *Challenges and Opportunities in Green Hydrogen Production*. 1st ed. Singapore: Springer.

Sun, L., Wang, Y., Guan, N., Li, L., 2020. Methane Activation and Utilization: Current Status and Future Challenges. *Energy technology* 8.8. <https://doi-org.ezproxy.cc.lut.fi/10.1002/ente.201900826>

Tekniikka & Talous, 2020. Yksi maailman tärkeimmistä reaktioista voi mullistua: Uusi katalyytti tekee ammoniakkia 150 astetta viileämmässä, kasvihuonepäästöt laskevat roimasti [Online]. [Accessed 12.1.2025]. Available: <https://www.tekniikkatalous.fi/uutiset/yksi-maailman-tarkeimmista-reaktioista-voi-mullistua-uusi-katalyytti-tekee-ammoniakkia-150-astetta-viileammassa-kasvihuonepaastot-laskevat-roimasti>

Uddin, Z., Yu, B., Lee, H., 2022. Evaluation of Alternative Processes of CO<sub>2</sub> Methanation: Design, Optimization, Control, Techno-Economic and Environmental Analysis. *Journal of CO<sub>2</sub> utilization* 60. 101974-. <https://doi.org/10.1016/j.jcou.2022.101974>

Wei, J., Ge, Q., Yao, R., Wen, Z., Fang, C., Guo, L., Xu, H., Sun, J., 2017. Directly Converting CO<sub>2</sub> into a Gasoline Fuel. *Nature communications* 8.1. 15174–15174. <https://doi.org/10.1038/ncomms15174>

Xu, G., Xu, C., Wang, M., Cai, J., Chen, Z., Li, X., 2021. Influence of Nickel Foam on Kinetics and Separation Efficiency of Hydrate-Based Carbon Dioxide Separation. *Energy* 231. 120826-. <https://doi.org/10.1016/j.energy.2021.120826>

Yang, M., Hou, J., 2025. *Green Hydrogen Production by Water Electrolysis*. 1st ed. CRC Press.

Yu, L., Holmgren, A., Zhou, M., Hedlund, J., 2018. Highly Permeable CHA Membranes Prepared by Fluoride Synthesis for Efficient CO<sub>2</sub>/CH<sub>4</sub> Separation. *Journal of materials chemistry. A, Materials for energy and sustainability* 6.16. 6847–6853. <https://doi.org/10.1039/c8ta01240g>

Zare, A., Khanipour, M., Sarverstani, H.K., Hojjat, K., Kakavandi, I.A., Shokroo, E.J., Farniaei, M., Baghbani, M., 2019. Hydrogen and Carbon Dioxide Recovery from the Petrochemical Flare Gas to Methanol Production Using Adsorption and Absorption Combined High-Efficient Method. *Applied petrochemical research* 9.2. 127–145. <https://doi.org/10.1007/s13203-019-0232-2>

Zhang, Z., Zhang, H., Jiang, H., Li, L., 2024. Green Ammonia: Revolutionizing Sustainable Energy for a Carbon-Free Future. *Journal of materials chemistry. A, Materials for energy and sustainability* 12.48. 33334–33361. <https://doi-org.ezproxy.cc.lut.fi/10.1039/D4TA07339H>

Zhao, T., Ren, Q., 2025. The Art of Catalysis: Unveiling the Secrets of CO<sub>2</sub> and Nitrogen Molecule Coupling to Synthesize Urea. *Molecular catalysis* 572. 114787-. <https://doi.org/10.1016/j.mcat.2024.114787>

Zhen, W., Gao, F., Tian, B., Ding, P., Deng, Y., Li, Z., Gao, H., Lu, G., 2017. Enhancing Activity for Carbon Dioxide Methanation by Encapsulating (111) Facet Ni Particle in Metal–Organic Frameworks at Low Temperature. *Journal of catalysis* 348. 200–211. <https://doi.org/10.1016/j.jcat.2017.02.031>

## Appendix 1. Materials and methods

This literature review thesis involved gathering information from various search engines and databases. Initially keywords such as sustainable ammonia, green hydrogen, carbon dioxide recovery, sustainable methanol production and e-fuel production were used. The primary databases utilized include LUT Primo, Scopus, and ScienceDirect. Moreover, relevant information was sourced from articles published in online broadsheets and websites of various enterprises and organizations.

Search terms became more specific as the work progressed, incorporating various keyword combinations. More detailed search terms were used to find more exact resources. Most of the resources utilized consisted of academic articles, scientific studies, and scholarly books.