

Converting CO₂ into Clean Fuels: A Sustainable Approach

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Abstract

Climate change is one of the most critical problems facing humanity. One of the most important reasons is greenhouse gas (GHG) emissions, particularly carbon dioxide. In Egypt, the cement sector is the heaviest emitting industry, accounting for 12% of the total CO₂ emissions. This study aims to capture and utilise CO₂ for methanol synthesis. The importance of methanol has been growing steadily in recent years, as it has many applications, including automotive fuel, wastewater treatment, fuel cells, and as a feedstock for many chemicals, including dimethyl ether (DME), formaldehyde, acetic acid, and olefins. The market size of methanol is expected to reach 38.98 MM in the next five years. However, the method used for 95% of the world's methanol production is through the catalytic hydrogenation of synthesis gas obtained from natural gas steam reforming. This conventional method is not viable, hence the need for a greener, yet economic, process for methanol production. This study presents the approach to designing a methanol plant with a 2 MT/year production capacity. The used methanol is synthesised through the catalytic hydrogenation of carbon dioxide, captured from a cement plant in Egypt. The process is simulated using Aspen HYSYS software V10 to monitor its performance. After designing the unit operations and estimating its costs, the designed methanol plant was found to be viable and profitable. The economic aspect is described to highlight the specific value of capital investment for the given basic design, which is 237714540 USD while the operating cost is 68,894,000,000 USD.

Keywords: CO₂ emissions, Methanol, Process Simulation, Green Hydrogen, Valorization

1. Introduction

Climate change is a long-term stationarity in temperatures and climate patterns. Since the dawn of the industrial revolution, human activities have been identified as the main causes of climate change, with massive carbon emissions coming from burning fossil fuels. Starting from the late 1800s to the present, the last decade was recorded as the warmest decade ever, which confirmed this assertion with an increase in Earth's temperature by 1.1°C [1]. A UN report identified three keyways to fight climate change: cutting greenhouse gas emissions, adapting to its effects, and funding these changes [2]. The IPCC emphasises that tackling CO₂ emissions in industries requires a multi-pronged approach. This includes controlling demand for industrial products, optimising how different stages of production work together,

maximising efficiency and material reuse, and completely revamping production methods. Additionally, switching to clean electricity sources, hydrogen fuels, and technologies that capture and manage carbon emissions are all crucial aspects of this fight [3]. According to the International Energy Agency (IEA), most CO₂ emissions from chemical plants come from burning fuels, not from actual chemical reactions [4]. In fact, the chemical industry is the biggest energy user compared to other industries, and it is the third-worst polluter for direct CO₂ emissions. In 2021, chemical production globally released a whopping 925 million metric tonnes of CO₂, a 5% increase from the year before [4].

Reducing CO₂ emissions is crucial to combating the adverse effects of greenhouse gases. More recent techniques include carbon capture and storage (CCS), which is a technology that is used to separately capture CO₂ from chemical processes or combustion products in order to reuse or store it [5]. Furthermore, the capture of CO₂ directly from the atmosphere in recent years has garnered some scientific and practical interest [6]. However, CCS does not paint the perfect picture since it only partially reduces the level of CO₂ emissions, as the costs are high, and the chances of leakage are real. This is particularly due to the conversion of captured CO₂ into value-added chemicals, which in this case indicate carbon recycling [7]. Out of all the oxidation states of the carbon element, the carbonate anion shows the highest thermodynamic stability, with an enthalpy of formation of 396 kJ/mol [8]. As a result, the possibility of using CO₂ to produce less stable thermodynamic compounds, such as Na₂CO₃, NaHCO₃, NH₄HCO₃, and salicylic acid, can be considered relatively affordable for manufacturers to solve the excessive CO₂ emissions issue [9]. Another strategy is to carry out the conversion of CO₂ into useful chemicals like methanol [10], methane [11], and hydrocarbons, in which a great deal of energy must be supplied to the CO₂ molecules. Energy-presenting candidates can be classified as conventional energy, such as petroleum, coal, and natural gas, and unconventional energy, like solar energy, wind energy, water energy, geothermal energy, biomass [12], etc.

This research highlights methanol's potential as a versatile fuel source. Andersson [13] suggests that methanol can act as a storage solution for hydrogen, a fuel itself, and even a raw material for creating hydrocarbons. For instance, some studies explore the use of methanol to generate hydrogen for powering mobile devices [14]. Methanol offers more flexibility as it can be blended with gasoline for cars, processed and mixed into diesel fuel for trucks, and even used in fuel cells for electric vehicles. However, there are ongoing concerns about using alcohols, like methanol, as fuel in specific transportation sectors, particularly shipping [15] and aeroplanes [16].

Figure 1 shows the major uses of methanol. Methanol synthesis is particularly attractive in developing countries as a liquid fuel for replacing traditional sources of energy. Specifically, the motivation of a "methanol economy" may encourage the production of methanol, as proposed in both China and the USA [17]. Manufacturing methanol using conventional pathways from natural gas or coal (as in China) may lead to water scarcity and raise GHG levels. [17]. As a result, there is a need to look for other methods of synthesising methanol than relying on fossil fuels. Manufacturing methanol from CO₂ can be done in two main ways, both involving catalysts. The first method uses a catalyst to directly hydrogenate CO₂ with hydrogen gas (H₂). The second approach takes CO₂ and converts it to carbon monoxide (CO) through a separate catalyst, then hydrogenates the CO into methanol with another catalyst. An alternative completely catalyst-free method is electrochemical synthesis, where CO₂ is directly captured and converted to methanol while water is broken down to provide the necessary hydrogen [18]. Electrochemical reduction of CO₂ can be tuned to yield specific products depending on the choice of electrocatalysts, electrolyte, and voltage [19]. According to Bhattacharjee et al. [20], the generation of methanol is possible through the reduction of

CO₂, as well as the oxidation of water in a fuel cell through the generation of oxygen. Methanol production is fueling the fight against climate change. Scientists are even exploring using sunlight in special photo-electrochemical cells to directly convert CO₂ and water into methanol [20]. This cannot be considered a theoretical approach, but it is a real-world example that is already applicable. Plants in Iceland and Japan are demonstrating the feasibility of capturing CO₂ and using renewable hydrogen to create methanol fuel [21]. The first commercial demonstration plant was also launched in Iceland by Carbon Recycling International (CRI) in 2011 as it aims to optimise the plant economics for the big plants and gain operating experience [22]. This plant is particularly advantageous because it can generate very low-cost electricity with a capacity of approximately 5 million metric tons of methanol per year [22].

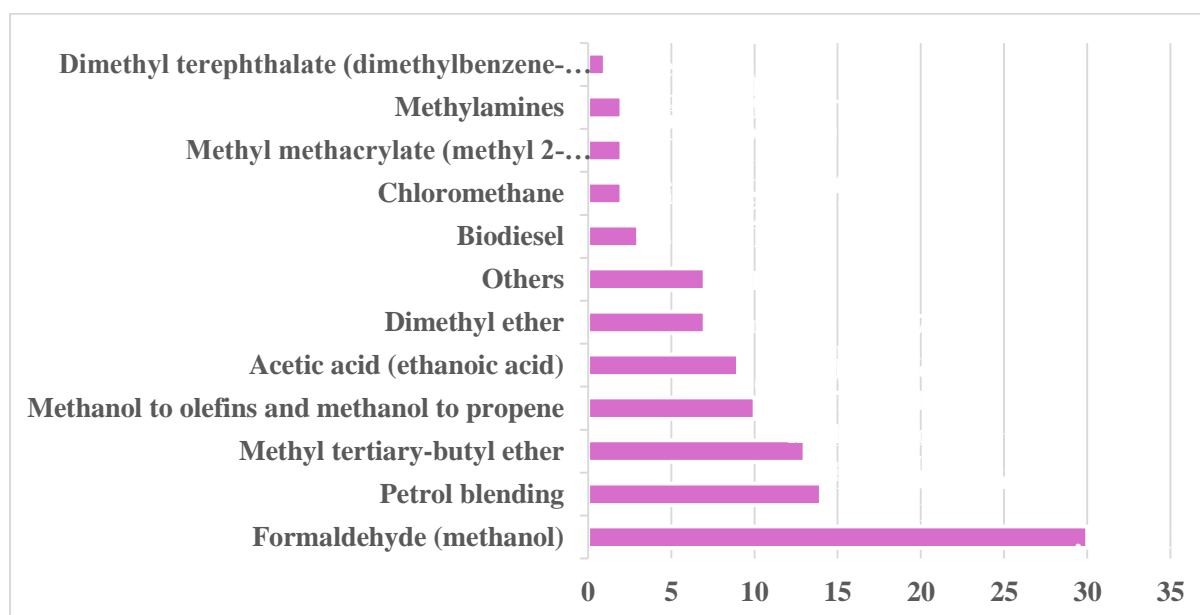


Figure 1 Major uses of methanol

1.1 Conversion Pathways of CO₂ into useful organic products

The possible catalytic conversion routes are shown in Figure 2. The final products include light olefins, methane, formic acid, gasoline, hydrocarbons, liquefied petroleum gas (LPG), aromatics, and other products. Two intermediates, CH₃OH and CO, are particularly noticeable due to the development of methanol to hydrocarbon processes, such as methanol to gasoline, methanol to olefin, methanol to aromatics, etc., and Fischer-Tropsch synthesis, which are currently widely used in the manufacturing of chemicals. Beyond its traditional applications in producing chemicals and fuels, methanol is gaining popularity as a potential replacement for oil and gas. Researchers proposed a "methanol economy" that could utilise this versatile fuel to produce gasoline and other chemicals or directly burn it in engines and fuel cells [23]. In this case, the utilization of CO₂ by hydrogenation to methanol can be considered one of the reactions that form the basis for energy recycling cycles.

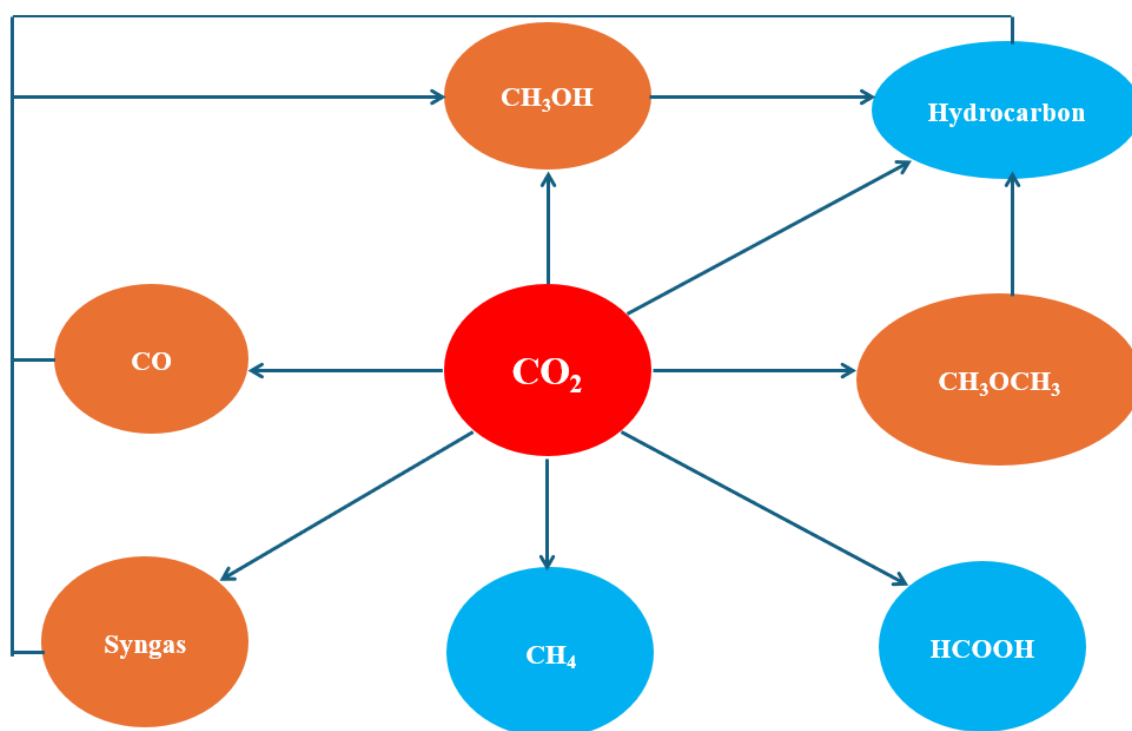


Figure 2 Pathways implied in the catalytic hydrogenation of CO_2 .

1.2 CO_2 utilization technologies

Figure 3 presents various strategies for capturing and transforming CO_2 into useful products. One method for converting CO_2 is through an electrochemical approach, which can transform it into various valuable products like carbon monoxide (CO), organic acids, alcohols, and alkenes [24]. The basic setup of an electrochemical cell consists of a cathode (negative electrode) and an anode (positive electrode) immersed in an electrolyte solution. Electricity is passed through the system, and an ion exchange membrane separates the electrodes to control the flow of ions.

A critical component for efficient conversion is the electrocatalyst. This material needs to be highly selective and active to reduce the energy required for the CO_2 conversion reaction [25]. Studies have shown that the choice of electrocatalyst significantly impacts the final product. For instance, using a ruthenium-carbonyl complex catalyst can generate valuable products like hydrogen (H_2) and formic acid (HCOOH) from CO_2 [25]. The research also explores how incorporating specific molecules can enhance the process. For example, using heterocyclic organic compounds like pyridine has been shown to promote CO_2 conversion [26].

Thermal approaches With CO_2 's environmental impact becoming a major concern, scientists and industries are focusing on capturing and utilizing this greenhouse gas. Thermal conversion offers various techniques to transform captured CO_2 into valuable products like chemical feedstocks and fuels [27]. One method is the reverse water-gas shift (RWGS) reaction. This process uses heat and hydrogen (H_2) to convert CO_2 into carbon monoxide (CO). The produced CO finds applications in various sectors, including steel production and pharmaceuticals. However, the RWGS reaction requires high temperatures (550–750 °C) and low pressure (0–5 bar) and is endothermic, meaning it absorbs heat [26]. Additionally, depending on the temperature and pressure used, the reaction can be driven either forward (CO_2 to CO) or backward (CO to CO_2). The dry reforming process is another thermal

approach. This method utilizes CO₂, natural gas, or coal to produce syngas, a mixture of CO and H₂, without generating water as a byproduct. The reaction equation is provided. This syngas can then be further converted into valuable products like hydrocarbons and chemical feedstocks. Finally, the text mentions bi-reforming as a method to produce syngas. This process combines steam methane reforming (using methane and water) with dry reforming (using CO₂ and methane), as shown in the equations [26].

Among biochemical approaches, photocatalytic and electrocatalytic reactions are the most common methods for converting CO₂. While these methods can have drawbacks like low yields and harsh operating conditions (high pressure or temperature), biocatalytic approaches offer an alternative due to their efficiency and tolerance to a wider range of conditions, including potential toxins [28]. Biocatalytic conversion utilizes enzymes or microbial catalysts to transform CO₂. Compared to photocatalytic and electrocatalytic methods, biocatalysis offers advantages like: High Selectivity: Biocatalysts are highly specific, leading to fewer unwanted side products. Milder Conditions: Biocatalytic reactions often occur under gentler temperature and pressure requirements., Photosynthesis: Plants and some bacteria naturally fix CO₂ by converting it into organic compounds using sunlight, water, and a series of biochemical pathways. and Microorganisms can convert atmospheric CO₂ into biomass through pathways such as the pentose-phosphate pathway, releasing useful intermediate products. These natural processes inspire the development of more efficient biocatalytic approaches for CO₂ conversion [26].

Chemo-enzymatic synthesis is an emerging approach that combines the power of enzymes (biocatalysis) with traditional chemical reactions to produce bulk chemicals. This method offers several advantages, including High Selectivity: Enzymes are incredibly specific, leading to fewer unwanted side products and a purer final product. Improved Yields: Chemo-enzymatic reactions can often achieve higher yields compared to traditional methods and Slighter Conditions: Enzymatic reactions often occur under gentler conditions (temperature and pressure) compared to traditional chemical synthesis, making them more energy-efficient and potentially safer. A promising new area of research is using light to convert CO₂ into valuable products. This technique, known as photocatalytic conversion, harnesses light energy to directly reduce CO₂ with the help of a special light-sensitive material called a photocatalyst [29]. Compared to other methods like electrochemical or thermal conversion, photocatalysis offers advantages in terms of energy efficiency and environmental friendliness. However, a major challenge is achieving high selectivity, meaning the process often produces a mix of products instead of focusing on just the desired one. Consequently, much research is directed at improving this aspect of photocatalytic CO₂ conversion.

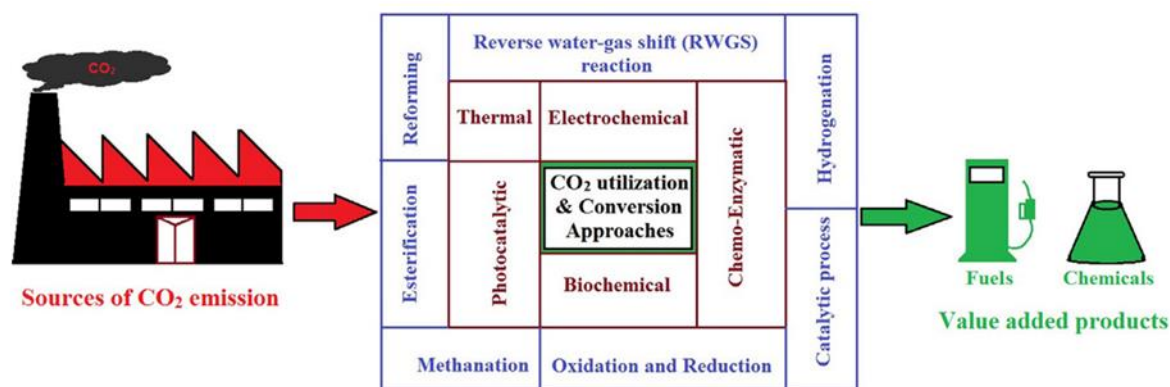
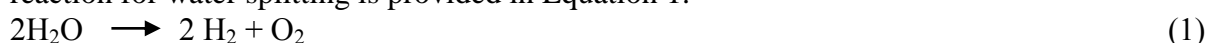


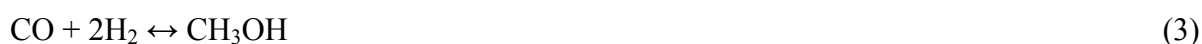
Figure 3 Approaches to capture and convert the CO₂ into useful products [26].

1.3 CO₂ Hydrogenation: From Resources to Methanol

One promising method for CO₂ utilization is its conversion to methanol through hydrogenation. Methanol is valuable because it can be used as a biofuel, solvent, or starting material for various chemicals. An eco-friendly twist on this process involves using green hydrogen produced from water electrolysis instead of traditional methods like methane reforming to obtain hydrogen [30]. Electrolysis, or water splitting, is a process that uses electricity to separate water (H₂O) into its components: hydrogen (H₂) and oxygen (O₂) gas. This requires a relatively small voltage of 1.23 volts [31]. The resulting green hydrogen can then be used for various applications, including as a clean fuel source. The general chemical reaction for water splitting is provided in Equation 1.



In the hydrogenation of carbon dioxide to methanol, there are two major reactions that must take place in the reactor. For feeds of only CO₂ and H₂, the reactions involved are the reverse water gas shift reaction and the methanol reaction, as given by Equations 2 and 3, respectively [32].



The overall reaction of methanol according to the reaction (equation (4)) [32]:



According to Le Châtelier's principle, an increase in pressure, low temperature, and high molar ratio of H₂/CO₂ encourage the thermodynamic conversion of CO₂ to methanol. At a reaction temperature higher than 240 °C, CO₂ turns out to be more active because of its greater thermodynamic stability and chemical inertness. Nevertheless, the RWGS's influence increases at high temperatures, which makes the selectivity of methanol less prominent [33]. To illustrate this, a thermodynamic analysis at a 30-bar pressure shows us that the methanol selectivity at 200 °C is more than 90%, whereas at 300 °C, it is only about 10% [33]. Pressure-wise, there is published work that shows poor catalyst performance under 2 MPa [34], but this is not cost-effective because it requires more money when it comes to installation and operation. In terms of reactant ratio, a high H₂/CO₂ is favorable to the formation of methanol and the inhibition of CO and H₂O, whereas a low ratio may have the opposite effect [33].

As shown in Figure 4, the typical process flow diagram of methanol production through carbon dioxide hydrogenation is given. The process is set up to require the reactants to be prepared and delivered to the reaction pressure by pumping before they are mixed and heated at 180–280 °C. The reaction occurs in a reactor filled with CuO, ZnO, and Al₂O₃. The reactor effluent increases the temperature of the feed and then gets cooled down to 35 °C. Then, a flash separator separates the left-over hydrogen unreacted to be recycled back. Methanol is crude-distilled in a simple distillation column to remove water and yield 99.9% pure methanol at the top of the column [35].

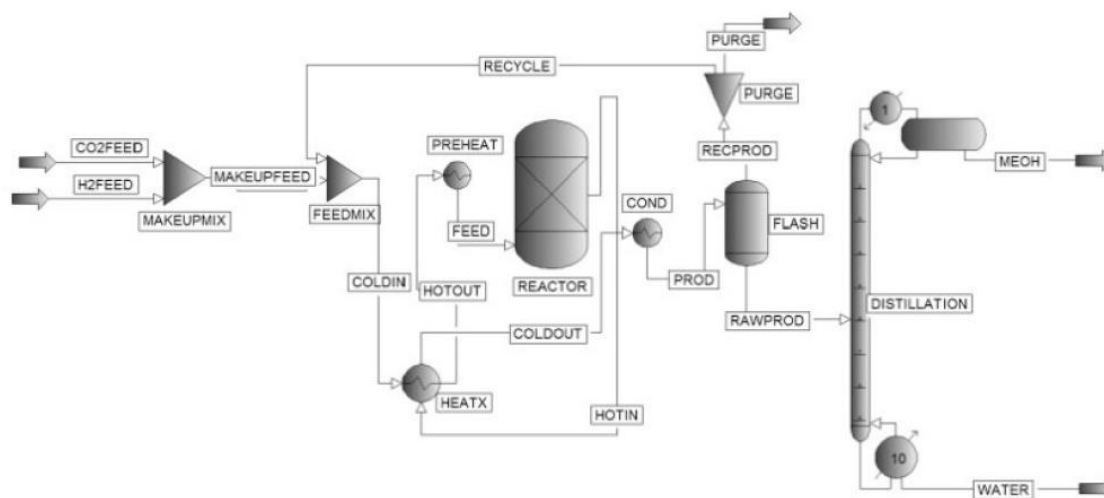


Figure 4 Schematic flow diagram of methanol synthesis through CO₂ hydrogenation [35].

1.4 Catalysts

1.4.1 Syngas Catalyst

Alumina pellets coated with copper and zinc oxides CuO/ZnO/Al₂O₃ catalyst which facilitate syngas development of methanol are poorly active for low-temperature CO₂ hydrogenation (<250°C). Temperature increase makes activation of CO₂ easier and RWGS shape unwanted CO and H₂O. This reduces yield of methanol and consumes additional H₂. Moreover, water speeds up the Cu and ZnO crystallization, resulting in fast sintering. Other products are also formed besides methanol, like higher alcohols and hydrocarbons [36].

1.4.2 Other Cu-based Catalysts

While several types of metal catalysts for methanol synthesis were investigated and tested, Cu is still the most common active catalyst component used in methanol synthesis, along with a variety of promoters. Cu, Zn, Cr, and Pd are used to lower the accumulation of by-products and optimize the production of methanol and selectivity. A support such as Al₂O₃ can further enhance selectivity [37].

1.4.3 New-generation catalysts

A new class of inter-metallic catalysts has been found to be more involved at atmospheric pressure. The Ga₃Ni₅ proved to be promising [38].

1.5 Reaction Conditions

Equation (3) is extremely exothermic, with the effect that molecules are decreased. Although the total CO₂ hydrogenation reaction is exothermic, Equation 3's rate-determining step activates CO₂ in the RWGS reaction [39]. Thermodynamically, reducing the reaction temperature or increasing the reaction pressure will favor methanol production [32]. A reaction temperature above 240 °C makes CO₂ easier to activate, making methanol easier to form. Because of the kinetic limitation at low temperatures versus equilibrium at high temperatures, there is an optimum operating area. The equilibrium values for conversion of CO₂ and selectivity of methanol at 250 °C and 5 MPa are 27 and 68%, respectively, using an H₂/CO₂ feed ratio equal to 3. The pressure of ~30 MPa can reach high CO₂ (>80%)

conversion at 125 °C [40]. The typical syngas catalyst can be used to hydrogenate CO₂ at a temperature close to 533 K and 80 bar [40].

1.6 Improved safety protocols for large-scale catalytic hydrogenation of CO₂

Consequently, it is imperative that, as the various CO₂ utilization technologies are developed and implemented on a large scale, there are proper safety measures in place that will protect the lives of the workers, the community, and the environment [41].

1.6.1 Hydrogen Management

Leak Detection and Prevention: To reduce hydrogen leakage, install high-sensitivity hydrogen sensors and implement good maintenance measures. Check for the possibility of equipment leakage. **For ventilation strategies:** Use efficient ventilation systems to create enough airflow to avoid hydrogen concentration, keeping it below the lower explosive limit. **Emergency Response Plans:** draw up comprehensive contingency measures in the event of hydrogen fire and explosion situations, with emphasis on the former. These plans should also contain details on how the evacuation would be done, special firefighting techniques that should be used using the correct agents, in this case water for non-metallic fires, and how communication with the emergency responders would be done. **Worker training:** ensure adequate consultation with the workers and educate them on appropriate behaviour when handling hydrogen. This training should include information about how to detect leaks, the correct use of proper personal protective equipment, including hydrogen-resistant gloves and respirators, as well as emergency response procedures. As CO₂ utilization technologies progress towards large-scale implementation, robust safety protocols are paramount to ensuring the well-being of workers, communities, and the environment. Here's a comprehensive breakdown of key safety considerations for catalytic hydrogenation of CO₂ [42].

1.6.2 High-temperature and pressure operations

When designing and constructing the equipment for the catalytic hydrogenation processes, ensure that the engineering standards used in the construction can withstand high temperatures and pressures. Use materials that can get along well with hydrogen and are not easily corroded. Safety devices such as pressure relief valves and rupture discs should be incorporated to control pressure buildup and prevent equipment damage and explosions. They should also be properly inspected and maintained most of the time. For safe operating protocols, develop specific and stringent guidelines that should be put in place for the safe use of the equipment at high temperatures and pressures. It should incorporate processes such as temperature and pressure measurement and control with alarms for breaching the recommended tolerances and safe operating procedures during start-up, shutting down, and emergencies [43].

This paper aims to develop an innovative integrated process for capturing CO₂ from cement plant flue gas and converting it into methanol. This approach offers a two-fold benefit: reducing CO₂ emissions from industries and minimizing dependence on fossil fuels for methanol production. The study focuses on the CO₂ capture component, which uses an established industrial-scale amine-based absorption-regeneration process with monoethanolamine (MEA) as the sorbent. The project will estimate the economic viability of the entire process, encompassing CO₂ capture, purification, and conversion into methanol. The current dominant method for methanol production involves reforming natural gas to produce syngas as a feedstock [44]. Globally, over 80% of methanol is synthesized from

natural gas [44]. CO₂ hydrogenation offers several advantages over traditional methods. Direct CO₂ hydrogenation into methanol is less exothermic (it releases less heat), resulting in lower energy consumption. Additionally, it generates fewer byproducts and emissions compared to syngas-based methanol synthesis. However, both approaches face limitations due to thermodynamic and kinetic constraints, which require further optimization.

2. Methodology

This study investigates the valorisation of CO₂ emissions from a cement plant, aiming to convert them into a valuable product: methanol. Figure 5 visualizes the key stages of the simulation design process, including flowsheet simulation, process flow diagram (PFD) construction, and data evaluation for final case development.

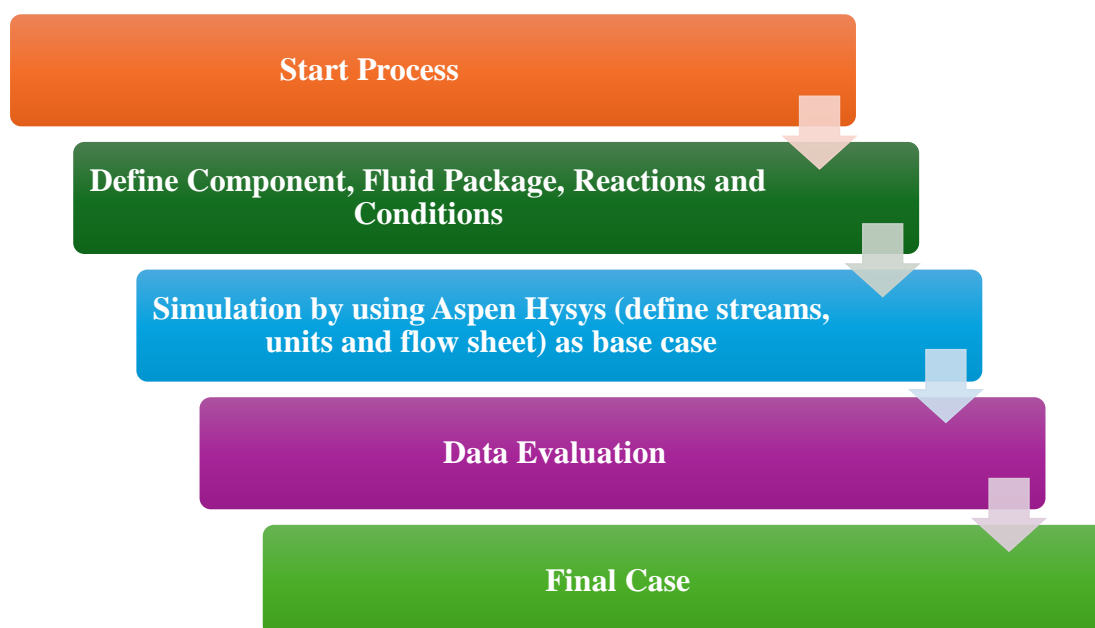


Figure 5 Simulation design steps

2.1 Start Process

The first step is simulating the process via HYSYS models in Aspen V10 to create and design a methanol plant. The model starts with the chemical list input consisting of H₂, CO₂, CO, H₂O, N₂, NO, NO₂, oxygen, monoethanolamine, and methanol. Acid gas, chemical solvents, and SRK were the fluid packages selected, followed by reaction and kinetics.

2.2 Building PFD

The second step involves the development of the PFD by specifying each stream by adding pressure, temperature, flow rate, and composition. Later, the mass and energy balances were performed, and the results were obtained, and the base case was validated as well. Figure 6 depicts the entire methanol production method, with captured CO₂ emissions and renewable electricity from sources such as solar or wind power as the primary components. Using an electrolyser, electricity breaks water molecules (H₂O) into hydrogen (H₂). CO₂ and H₂ are subsequently supplied to a catalytic reactor. Under pressure and at a controlled temperature, the catalyst persuades them to react and produce methanol

(CH_3OH). Moreover, the product stream is purified to obtain the methanol from unreacted CO_2 , H_2 , and other gases, which, in turn, could be recycled back into the process to enhance efficiency.

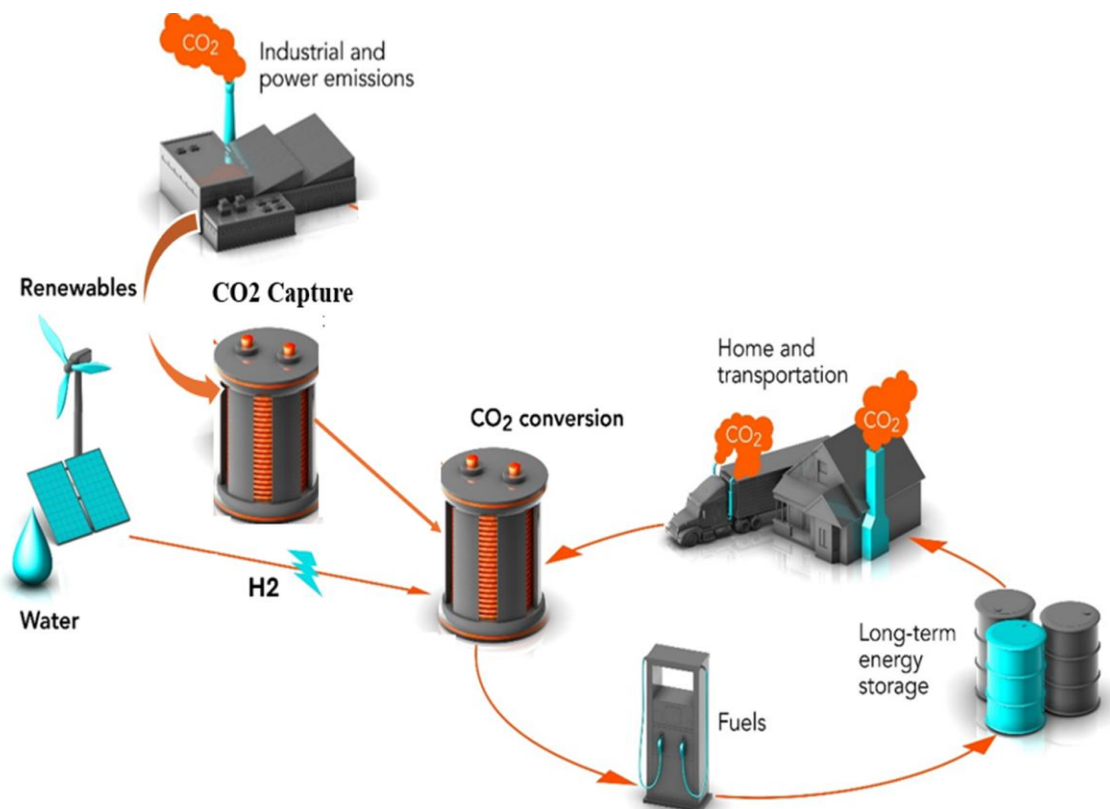


Figure 6 Overall process flow diagram of methanol preparation using green Hydrogen

2.2.1 CO_2 Source

This paper specifically examines cement plants considering the projected growth in the cement production market. When fossil fuels are burned for heat energy, they produce a flue gas containing 4 to 15% carbon dioxide (CO_2) by volume, depending on the type of fuel. In the case of cement production, the flue gas typically contains 22–28 mol% of total cement flue gas, and for every tonne of cement produced, approximately 0.9 tonnes of CO_2 are emitted [45].

2.2.2 CO_2 Capture

This study assesses the feasibility of incorporating a monoethanolamine (MEA) capture system into an existing cement production scheme. The analysis will determine the capture efficiency of the MEA system and estimate the amount of CO_2 that can be captured.

2.2.3 Water electrolysis

Solar power and other renewable energy sources (wind, geothermal, hydro) can be used to reduce CO_2 footprints since they can provide electricity that can be used for water electrolysis

to supply hydrogen. As a result, a sustainable methanol production process should include the use of green H₂ through water electrolysis. Even on an industrial scale, water electrolysis is the most advanced and well-established technology. It is also a safe choice for obtaining hydrogen at the point of use in limited amounts. However, electrolyser facilities are more costly than steam reforming plants [46].

2.2.4 CO₂ Conversion

A process design, modelled in Aspen Plus® software, will simulate the catalytic conversion of captured CO₂ into methanol. To improve overall process efficiency, this design will explore the integration of the exothermic heat from the methanol reaction with the MEA regeneration process.

2.3 Data Evaluation

The economic feasibility will be evaluated by considering factors such as capital costs (equipment, plant construction), operational costs (utilities, catalyst replacement), and the net present value (NPV) of the proposed system [47].

3. Case study

Cement production is a major contributor to global CO₂ emissions. This case study investigates the potential of CO₂ valorisation, specifically the conversion of captured CO₂ into methanol, as a strategy for reducing the environmental impact of a cement plant located in Ain Al-Sokhna Port, Egypt (MENA region). Table 1 shows data relevant to CO₂ emissions and plant operations.

Table 1 Operating condition and composition of the flue gas stream

Variable	Value
Total flow rate	987788 m ³ /h
Temperature	150 °C
Pressure	1 bar
Compositions	Mass fraction
CO ₂	8.7
CO	0.00247912
NO ₂	0.00075451
NO	0.024064
H ₂ O	12.5
O ₂	10.35
N ₂	68.42

4. Results and discussion

4.1 CO₂ Capture Process Description

The flue gas stream used for CO₂ capture originates from a cement plant. It has a total flow rate of 987,788 m³/h at 150 °C and 1 bar pressure. Figure 7 illustrates the capture process for these flue gases. Before the flue gas arrives at the CO₂ capture unit, it is preconditioned to remove impurities and increase its pressure to 1.2 bar to make up for the pressure loss inside the absorber column. The absorber captures 90% CO₂, while the stripper achieves 98 mol% CO₂ purity. Table 2 shows the operating conditions of the absorber and stripper. The absorbed gas travels to the bottom of the absorber column. This is where the chemical absorption process between CO₂ and the lean monoethanolamine (MEA) solvent takes place. The lean MEA solution flows from the top down, countercurrently to the rising flue gas. A rich amine solution, loaded with captured CO₂, flows out of the bottom of the absorber. The richest amine solution is pumped (2 bar) to the top of the stripper column. It flows through a lean/rich heat exchanger, preheating the rich solvent while the hot, regenerated lean solvent flows back from the stripper. The regenerated lean MEA exits the stripper, cools down through the heat exchanger, and returns to the absorber for CO₂ capture. The vaporised fraction of MEA and water exiting the absorber is condensed through the flash column. This provides effective MEA recycling and prevents solvent losses. The basic characteristics of the absorption as well as the stripper columns are shown in Table 3.

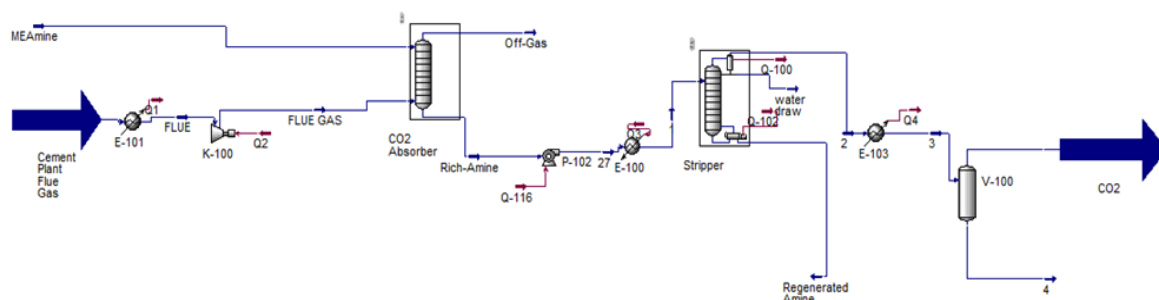


Figure 7 CO₂ Capture process with MEA scrubbing

Table 2 Operating conditions of absorber and stripper columns

	Absorber	Stripper
Inlet temperature	105°C	120°C
Inlet pressure	1.2 bar	4.2 bar

Table 3 Dimensions and purity of absorber and stripper columns

	Absorber	Stripper
Diameter	8.7 m	
Height	17 m	10 m
No of stage	20 trays	20 trays
CO ₂ Purity	-	98%

4.2 Methanol Production

The first inlet stream is hydrogen, with a molar flow rate of 247035.621 kmol/hr. The pressure and temperature of this stream are 30 bar and 25 °C, respectively, which are then compressed to 69.2 bar and heated to 134.8 °C. While the second inlet stream of flue gas has a molar flow rate of 2051.54 kmol/hr, the pressure and temperature of the stream are 30 bar and 5 °C, respectively. This stream passes through multistage compressors and coolers to reach 69 bar and 135 °C. Subsequently, the two inlet streams are mixed in Mix-101, then heated to 400 °C; later, this stream enters two series PFR reactors to form methanol with a conversion 58%.

The output stream will be cooled, then separated in a two-phase separator to be split into two streams: the top stream consists of gases, while the bottom stream consists of methanol and water. The top stream is compressed and then recycled with the inlet streams in Mix-101. To enhance separation efficiency, the bottom stream enters a second, two-phase separator. The bottom stream from the second separator is heated to increase the temperature from 37 °C to 70 °C. This stream will enter a distillation column with a specification 27 stages, a reflux ratio of 1.3, and a purity of methanol of 99% to produce methanol in the distillate stream with a flow rate of 1272.19 kmol/hr, and water the bottom stream with 1200 kmol/hr, as shown in figure 8. Table 4 illustrates the main parameters of the process.

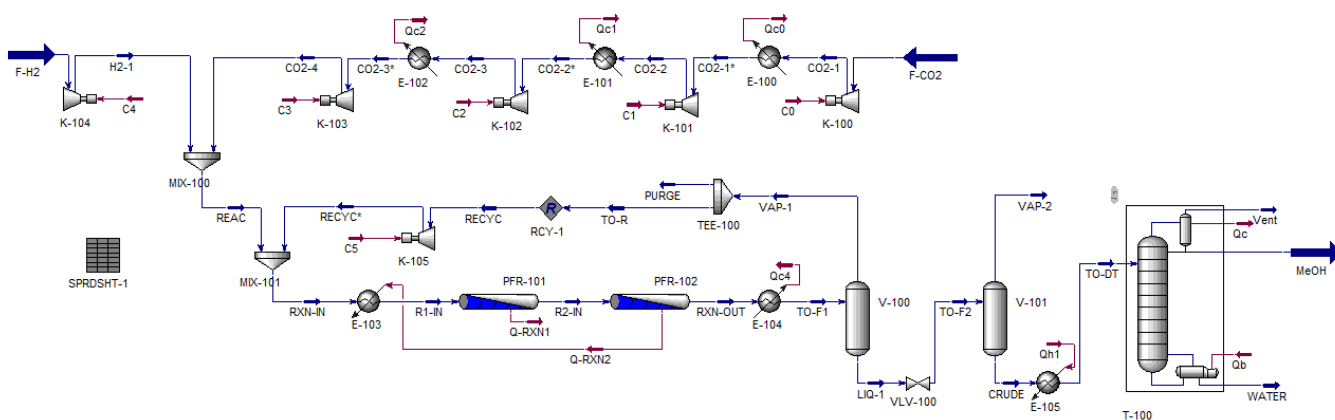


Figure 8 Process flow diagram of methanol production.

Table 4 Main parameters simulation for the feed stream, reactor, and column.

H ₂ Feed stream	
Temperature	25 □
Pressure	1 bar
Flow Rate	247035.62 kgmol/hr
Reactor	
Temperature	Inlet temp = 400 □

	Outlet temp = 499.7 °C
Pressure	69 bar
Molar flow rate	249087.16 kgmol/hr
Reactor length = 8 m Diameter = 7.7e-2 m Number of tubes = 4650 Void fraction = 0.4	
Distillation	
Temperature	70°C
Pressure	69 bar
Molar flow rate	13834.69

4.3 Economic Evaluation

An economic analysis was carried out to ensure the feasibility and success of the project. The results of the economic evaluation based on HYSYS database calculations, including total purchased equipment's cost, raw material cost, utility cost, operating cost, etc., are presented in Table 5. All calculations were made in USD [16, 38]. The proposed basic design requires a capital cost of 237714540 USD, while the operating cost is around 2.06894e8 USD. The estimated time for plant startup, construction, and processing was about two years. The payback period (PBP) of the project is 2.5 years.

Table 5 Summary table for the economic results for the different simulation models

Results	(Base case)
Total Capital Cost [USD]	237,714,540
Total Operating Cost [USD/Year]	2.06894E+8
Total Product Sales [USD/Year]	791,442,432
Total Utilities Cost [USD/Year]	1.91568E+6
P.O.Period [Year]	2.5

Conclusion

This study aims to develop efficient process technologies that convert CO₂ streams into high-energy liquid fuels. This approach would create cleaner solutions with minimal carbon emissions. From an energy and economic perspective, synthesising methanol using captured CO₂ emerges as a viable alternative to traditional biomass-based methanol production. These methods can be effectively applied to utilise CO₂ emissions from various industrial sectors, including power plants, steel production, petroleum refining, and cement manufacturing. The actual industrial data obtained from cement plants in Egypt in the MENA region, which is in Ain Al-Sokhna, shows that it is required to reduce emissions from cement. Catalytic hydrogenation of CO₂ to produce methanol appears to be a promising technology that will be an alternative solution for facing the ever-increasing demand for energy carriers and

environmentally friendly fuels. In this paper, a comprehensive design methodology for methanol production is presented, with the aim of simulating a plant for producing a capacity of 1.9 million tonnes per year using Aspen HYSYS software. An economic evaluation was considered. The design of the plant is separated into two sections; one model was done in the first section to capture the CO₂ from the flue gas exit from the cement plant, and the second model was done to produce methanol using two series PFR reactors for the highest conversion of methanol. The results showed 790,815.69 ton/y of CO₂ emissions will produce 1,978,606.08 ton/y of methanol. The economic analysis is presented, showing the capital cost needed for the proposed basic design, which is 237714540 USD, and around 2.06894E+8 USD for the operating cost.

list of abbreviation

Greenhouse Gas	GHG
Dimethyl Ether	DME
Intergovernmental Panel on Climate Change	IPCC
International Energy Agency	IEA
carbon capture and storage	CCS
Carbon Recycling International	CRI
liquefied petroleum gas	LPG
Reverse water-gas shift	RWGS
Monoethanolamine	MEA
Process Flow Diagram	PFD
Net Present Value	NPV
Plug Flow Reactor	PFR

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